Development of Open Space Management System to Response Scenario Earthquake in Dhaka Metropolitan Area

A Thesis Submitted in Fulfillment of the Requirements for the Degree of

Doctor of Philosophy (Ph.D.) in Disaster Science and Climate Resilience

Submitted by
A K M Aminul Haque
Department of Disaster Science and Climate Resilience
Faculty of Earth and Environmental Sciences
University of Dhaka
Registration No.: 33/2017-2018

Supervisor
Dr. A. S. M. Maksud Kamal
Professor
Department of Disaster Science and Climate Resilience
Faculty of Earth and Environmental Sciences
University of Dhaka

Co-supervisor
Dr. Md. Zillur Rahman
Professor
Department of Disaster Science and Climate Resilience
Faculty of Earth and Environmental Sciences
University of Dhaka

September 2022

Certification

It is hereby certified that the student is bearing Registration No.:**33/2017-2018** and has carried out the research work entitled "**Development of Open Space Management System to Response Scenario Earthquake in Dhaka Metropolitan Area**" for the fulfillment of his Doctor of Philosophy (Ph.D.) degree from the University of Dhaka under the supervision of the undersigned in the Department of Disaster Science and Climate Resilience, University of Dhaka.

…………………………………………………………………..

Supervisor
Dr. A.S.M. Maksud Kamal
Professor
Department of Disaster Science and Climate Resilience
University of Dhaka
Dhaka-1000, Bangladesh

…………………………………………………………………..

Co-supervisor
Dr. Md. Zillur Rahman
Professor
Department of Disaster Science and Climate Resilience
University of Dhaka
Dhaka-1000, Bangladesh

Acknowledgment

All praises are for Allah (SWT), the Most Beneficent, the Most Merciful.

I express my sincere gratitude towards my supervisor, Professor Dr. A S M Maksud Kamal, and co-supervisor, Professor Dr. Md. Zillur Rahman, who has helped me to formulate the problem and continuously guided me to understand the core issues and have taken me all the way to complete the research.

My special thanks to the Department of Disaster Science and Climate Resilience for all its support rendered to me, including lab facilities, and for facilitating my understanding of scientific reasoning. I must mention Associate Professor Shakhawat Hossain for his tremendous helping attitude. I thank Nazma Ahmed for her help in preparing the GIS shape file of the open spaces. I also extend my thanks to the team who has helped me with field and lab tests. I also express my gratitude to Abul Kashem Faruki Fahim, Aishia Fyruz Aishi, Anika Samm-A, and Momtahina Mitu for supporting me with various data collection, analysis, GIS mapping and for their help in performing different steps and for the meaningful discussions which helped me to understand the complicated scientific topics. I thank the Armed Forces Division, Air Defence Artillery, and Signal Brigade for the unconditional support for the physical demonstration and preparation of the Model Open Space Shelter at the Bangladesh University of Professional Field. Two projects have partially funded this Ph.D. research, namely, “Developing a standard open space management system for Dhaka City for earthquake crisis response and recovery plans” from the Ministry of Science and Technology and “Development of an Open Space Model for Emergency Shelter After a Disastrous Earthquake in Dhaka City, Bangladesh” from the Faculty of Earth and Environmental Sciences, University of Dhaka. I would also like to take the opportunity to thank the unsung contribution of those who I have not named here, especially the staff of my department and my staff.

Finally, I thank my parents and family, who have always supported me despite all my difficulties. May Allah forgive their sins and allow me to serve them without tire. During the submission, I think of my late mother, who expired on the date I signed up to do a Ph.D. at the University of Dhaka on 15 May 2018.

Abstract

The urbanized areas of Bangladesh are subjected to potential earthquake hazards and risks due to the proximity of seismically active zones. Dhaka Metropolitan Area, the capital of Bangladesh, is ill-planned and highly urbanized with a large population. The inhabitants of the city contribute thirty-six percent of the national GDP. These factors make the city highly vulnerable to earthquakes. The seismic hazard assessment carried out by the Comprehensive Disaster Management Program (CDMP) showed significant risks, yet preparedness measures for the city are lacking. Open spaces are essential in earthquakes as they can provide various options, from immediate evacuation to long-term sheltering of the resulting homeless population. Cases worldwide have benefitted from utilizing open spaces, and even the contingency plans suggest its use.

Nonetheless, no comprehensive research or data is available regarding the open spaces. This study addressed that gap in the immediate response to urban mega-disaster. The present study aimed to develop an open space management system for responding to a scenario earthquake in Dhaka. The first step was to assess the suitability of existing open spaces in the Dhaka Metropolitan Area to serve as emergency shelters using the modified Comprehensive Open Space Suitability Index (COSI). For that, the available open space footprints were mapped using satellite imagery. Then, these open spaces were ranked according to their area, connectivity, accessibility, hazard exposure, and nearness to facilities. Among the one thousand one hundred and ninety-seven identified open spaces, two hundred and seventeen were found to be suitable. At the same time, hundred and fifty-one were moderately suitable, and the rest were deemed less suitable (not to be interpreted as unusable).

Out of the two hundred and seventeen suitable sites, fourteen sites had to be left out of consideration since they are within the Key Point Installation premises and include National Parliament, Airport, Prime Minister's Office, various country's High Commissions/Embassies, and High Court. After that, generalized liquefaction analysis based on geomorphological classes revealed that thirty-seven sites had to be excluded as they exhibited high to very high liquefaction potential. It means only one hundred and sixty-six open spaces were selected as safe sites for long-term shelter establishment. Given that liquefaction may render potential sites unusable due to earthquakes, much importance was emphasized on its effect in the study area. Furthermore, eight sites across the city were selected as a case study for detailed liquefaction potential investigations. Probabilistic seismic hazard assessment and site response analysis were conducted, and all eight sites showed less than 0.15g Peak Ground Acceleration (PGA) value for a ten percent probability of exceedance in fifty years. The results were used to calculate liquefaction potential through deterministic, probabilistic, and artificial neural network approaches. All results stated that the eight sites were safe for post-earthquake shelter placement.

The deterministic approach was basically used for safety-based analysis. In contrast, the probabilistic approach is the likelihood of liquefaction, meaning it is probability-based. Still, the artificial neural network approach is more robust than the three approaches and gives realistic results by establishing precise nonlinear relationships. All eight sites revealed a very low (less than five) liquefaction potential index value in an earthquake of 7.5 magnitude scenario with PGA 0.15g. This was followed by establishing standard requirements of the shelters that would be placed in the open spaces, including living space per person (2.3 m^2 per person, considering population density), appropriate shelter materials (waterproof, lightweight and strong), essential water, sanitation and hygiene services (accounting for gender sensitivity), health and nutrition items, emergency infrastructures and service facilities, security and cultural considerations, and operation and maintenance of the shelters.

The parameters were standardized based on literature review and expert opinions, thus ensuring an ideal model appropriated in the context of the Dhaka Metropolitan Area. Finally, a field demonstration was conducted on the Bangladesh University of Professionals Playground to validate the established model shelter standards. This study gives the main guidelines for identifying and establishing a network of open spaces according to suitability, ensuring the sites are safe and what standards the shelters must maintain to be effective in the post-earthquake scenario. Implementing that will be a significant step towards building an earthquake-resilient Dhaka Metropolitan Area from the viewpoints of response and recovery.

Table of Contents

List of Tables

List of Figures

List of Acronym

AFD Armed Forces Division
ANN Artificial Neural Network
BBS Bangladesh Bureau of Statistics
BDRCS Bangladesh Red Crescent Society
BH Borehole
BMD Bangladesh Meteorological Department
BNBC Bangladesh National Building Code
BR Bangladesh Railway
BRTA Bangladesh Road Transport Authority
BUERP Bangladesh Urban Earthquake Resilience Project
BUET Bangladesh University of Engineering & Technology
BUP Bangladesh University of Professionals
CAAB Civil Aviation Authority of Bangladesh
CC City Corporations
CDMP Comprehensive Disaster Management Programme
COSI Comprehensive Open Space Suitability Index
CPA Chittagong Port Authority
CPT Cone Penetration Test
CRR Cyclic Resistance Ratio
CSR Cyclic Stress Ratio
DAP Detailed Area Plan
DCC Dhaka City Corporation
DRR Disaster Risk Reduction
DRRM Disaster Risk Reduction and Management
EPA Environmental Protection Agency
FAO Food and Agricultural Organization
FS Factor of Safety
GDP Gross Domestic Product
GIS Geographic Information System
GMPE Ground Motion Prediction Equation
GSB Geological Survey of Bangladesh
HaZUS Hazards United States
HVRA Hazard Vulnerability Risk Assessment
KPI Key Point Installation
LPI Liquefaction Potential Index
LSF Limit State Function
M/Mw Magnitude
MF Madhupur Fault
MoDMR Ministry of Disaster Management and Relief
NEHRP Natural Earthquake Hazards Reduction Program
NGA Next Generation Attenuation
PGA Peak Ground Acceleration
SPT Standard Penetration Test
SA Spectral Acceleration
UHS Uniform Hazard Spectrum
UNDP United Nations Development Programme

UNICEF United Nations Children's Fund
UNOCHA United Nations Office for the Coordination of Humanitarian Affairs
Vs Shear Wave Velocity
WFP World Food Programme

Chapter 1:
Introduction

1.1 General

Although most earthquakes are not damaging in nature, sometimes larger magnitude earthquakes may occur, and their impacts can be devastating. Large earthquakes cause massive loss of lives, livelihoods, and damage to property (Akason et al., 2006; Kroll et al., 1991; Okuyama, 2004). Unlike most natural hazards, earthquake is extremely difficult to predict with sufficient accuracy and adequate time (Knopoff, 1996). This makes them even more dangerous. Given Bangladesh's location in the vicinity of seismic sources, it may experience large magnitude earthquake (Kamal, 2013). Therefore, it is necessary to improve preparedness in addition to mitigation measures. Having spaces where people can take shelter during and after an earthquake is part of preparedness and help with efficient response and recovery.

The concept of pre-disaster response planning in managing disaster risk has attained widespread recognition, importance and appreciation as the international disaster risk reduction agreement Sendai Framework for Disaster Risk Reduction (2015-2030) prioritizes 'strengthening disaster preparedness for emergency response as one of its four priority areas for comprehensive management of disaster risks. One of the prime strategies in improving disaster response preparedness in the pre-disaster context is the identification and provision of suitable emergency shelter sites before the disaster occurs (Chandler, 2007; Tai et al., 2010). Earthquake, being a rapid onset and inherently unpredictable natural disaster, poses greater response and preparedness challenges for the emergency response planners as the lead time for preemptive evacuation is non-existent and pre-event planning for emergency shelter placement for a collaborative and coordinated response in the disaster aftermath is critical (Wright, 2010).

Earthquakes are natural geological occurrences having the potential to impose devastating effect on mankind. As there prevails no way of forecasting an earthquake beforehand, the hazard is regarded as one of the most perilous types of natural disasters possible, especially for modern civilization. As this havoc caused by earthquake event usually takes place within the duration of few seconds to minutes, people fail to take any action to protect themselves against the devastation. Consequential effects in the aftermath of an earthquake is equally distressing- landslides, tsunami, fire, liquefaction, floods, and long-term damages like regional sinking or appearance of land masses, regional changes in groundwater levels, etc. (Sattar et al., 2014).

Bangladesh is one of the most disaster-prone countries in the world intrinsically due to hazards like cyclones, floods, drought, and earthquakes. According to the Asia Pacific Disaster Report 2015, Bangladesh ranked 10th for exposure to natural disasters and in the 5th position from disaster risk consideration (Sattar et al., 2014). The Dhaka Metropolitan Area is positioned among the twenty most vulnerable cities of the world in the earthquake disaster risk index (PreventionWeb, 2010). Adding to that, seismicity data also backs the notion that Dhaka might experience earthquakes in the future (Islam et al., 2010). It is noteworthy that the terms Dhaka, Dhaka City have been used interchangeably with Dhaka Metropolitan Area.

Among all, one of the most threatening forms of natural disasters for this South Asian nation is earthquake. From geological point of view, Bangladesh lies in one of the most active tectonic regions in the world where three dynamic tectonic plates collide - Eurasia, India, and Burma, making it prone to seismic activities. Consequentially, the country has experienced considerable number of seismic tremors in the past 200 years, varying in magnitude. Since 1971, the country has felt more than 250 earthquakes, some of them greater than the magnitude of 6.0 at the Richter scale (Zaman et al., 2018). A list of some of the quakes near Bangladesh is given in table 1.1. It was compiled from Banglapedia, USGS, Bangladesh Metrological Department, National Geophysical Data Center, Local newspapers (https://bdnews24.com/bangladesh/4-killed-18-bangladesh-districts-affected-in-earthquake-says-govt), ASC India (http://asc-india.org/lib/20100910-bangladesh.htm).

Table 1.1 List of Earthquakes near Bangladesh.

Year	Description of the Earthquake
1548	The first recorded earthquake was a terrible one. Sylhet and Chittagong were violently shaken, the earth opened in many places and threw up water and mud of a sulphurous smell.
1642	More severe damage occurred in Sylhet district. Buildings were cracked but there was no loss of life.
1663	Severe earthquake in ASSAM, which continued for half an hour and Sylhet district was not free from its shock.
1762	The great earthquake of April 2, which raised the coast of Foul island by 2.74m and the northwest coast of Chedua island by 6.71m above sea level and also caused a permanent submergence of 155.40 sq km near Chittagong. The earthquake proved very violent in Dhaka and along the eastern bank of the MEGHNA as far as Chittagong. In Dhaka 500 persons lost their lives, the RIVERs and *JHEEL*s were agitated and rose high above their usual levels and when they receded their banks were strewn with dead fish. A large river dried up, a tract of land sank and 200 people with all their CATTLE were lost. Two volcanoes were said to have opened in the Sitakunda hills.
1775	Severe earthquake in Dhaka around April 10, but no loss of life.
1812	Severe earthquake in many places of Bangladesh around May 11. The earthquake proved violent in Sylhet
1865	Terrible shock was felt, during the second earthquake occurred in the winter of 1865, although no serious damage occurred.
1869	Known as Cachar Earthquake. Severely felt in Sylhet but no loss of life. The steeple of the church was shattered, the walls of the courthouse and the circuit bungalow cracked and in the eastern part of the district the banks of many rivers caved in.
1885	Known as the Bengal Earthquake. Occurred on 14 July with 7.0 magnitude and the epicentre was at Manikganj. This event was generally associated with the deep-seated Jamuna Fault.
1889	Occurred on 10 January with 7.5 magnitude and the epicentre at Jaintia Hills. It affected Sylhet town and surrounding areas.
1897	Known as the Great India Earthquake with a magnitude of 8.7 and epicentre at Shillong Plateau. The great earthquake occurred on 12 June at 5.15 pm, caused serious damage to masonry buildings in Sylhet town where the death toll rose to 545. This was due to the collapse of the masonry buildings. The tremor was felt throughout Bengal, from the south Lushai Hills on the east to Shahbad on the west. In Mymensingh, many public buildings of the district town, including the Justice House, were wrecked and very few of the two-storied brick-built houses belonging to ZAMINDARs survived. Heavy damage was done to the bridges on the Dhaka-Mymensingh railway and traffic was suspended for about a fortnight. The river communication of the district was seriously affected (BRAHMAPUTRA). Loss of life was not great, but loss of property was estimated at five million Rupees. Rajshahi suffered severe shocks, especially on the eastern side, and 15 persons died. In Dhaka damage to property was heavy. In Tippera masonry buildings and old temples suffered a lot and the total damage was estimated at Rs 9,000.
1918	Known as the Srimangal Earthquake. Occurred on 18 July with a magnitude of 7.6 and epicentre at Srimangal, Maulvi Bazar. Intense damage occurred in Srimangal, but in Dhaka only minor effects were observed.
1930	Known as the Dhubri Earthquake. Occurred on 3 July with a magnitude of 7.1 and the epicentre at Dhubri, Assam. The earthquake caused major damage in the eastern parts of Rangpur district.
1934	Known as the Bihar-Nepal Earthquake. Occurred on 15 January with a magnitude of 8.3 and the epicentre at Darbhanga of Bihar, India. The earthquake caused great damage in Bihar, Nepal and Uttar Pradesh but did not affect any part of Bangladesh.
	Another earhquake occured on 3 July with a magnitude of 7.1 and the epicentre at Dhubri of Assam, India. The earthquake caused considerable damages in greater Rangpur district of Bangladesh.
1950	Known as the Assam Earthquake. Occurred on 15 August with a magnitude of 8.4 with the epicentre in Assam, India. The tremor was felt throughout Bangladesh but no damage was reported.

Year	Description of the Earthquake
1988	This earthquake occurred on 6th August with a magnitude of Mw 7.3. the reported duration of it was 2 minutes. Its epicenter is located at the Myanmar-India border. It took the lives of two people and injured more than 30 people. In the Jamuna river, a ferry capsized due to the seiches originated from this earthquake
1989	It occurred on 12th June (Mw 5.8). The epicenter was located at 49 km south of Sarankhola, Bangladesh. The reported focal depth of the earthquake is 5.8 km. it was felt throughout the Eastern part of Bangladesh with one casualty, at least a hundred injured people, and minor damage in Banaripara.
1997	The earthquake occurred on 22 November with magnitude 6.0 in Chittagong causing minor damage around the Chittagong Town.
1999	An earthquake of magnitude 5.2 occurred on 22 July, at Maheskhali. Some houses collapsed and others were cracked
2001	Occurred on 19th December with a magnitude of 4.5. According to reports, the epicenter is close to Dhaka. In the Dhaka region, the earthquake was felt strongly, which caused many individuals to run from their homes and places of business in fear. A stampede at the Dhaka Central Jail on Nazimuddin Road injured 100 prisoners. 25 of the injured were hospitalized.
2002	On June 25, 2002, around 11:40 a.m. local time, a mild earthquake rocked northern Bangladesh, injuring several people in the Rajshahi division of Bangladesh. It was Mw=5.1 in magnitude and was felt for around 45 seconds. 50 people were hurt as a result of stampedes caused by the earthquake in Rangpur and 5 in Thakurgaon in Rajshahi division, northern Bangladesh. Bogra, Sirajganj, and Syedpur districts all experienced significant aftershocks, which spread panic. At Rangpur, it lasted for 45 seconds, causing fractures to appear in a number of historic structures, including the Co-operative Bank on Station Road, the District Commissioner's Office, and the Police Superintendent's office. It's believed that a multi-story structure in Alamnagar tilted after the tremor. It was also felt in Chittagong, Joypurhat, Kurigram, Sherpur, and Panchagarh.
2003	On July 26, 2003, at 05:18 AM local time, a moderate earthquake struck the Chittagong Hill Tracts close to the Bangladesh-India border, resulting in some property damage and 3 fatalities. The earthquake, which had Mw=5.7 magnitude, was felt in several locations in southern Bangladesh. The earthquake left 25 persons injured. In Rangamati, a mud house collapsed, killing two ladies. A few days later, another person passed away after a heart attack he had during the earthquake. This earthquake is reported to trigger earthquake-induced landslides in Bangladesh. A pipeline that was damaged after the earthquake at the Bakhrabad Gas Systems Limited in Fauderhat, Sitakunda, caught fire. The earthquake also caused tremors to be felt in Comillah, Feni, Khagrachari, and Noakhali.
2007	On November 7, 2007, at 13:10 local time, a moderate earthquake shook the Chittagong Hill Tracts in southeast Bangladesh. It caused little damage, at least one fatality, and some injuries with a magnitude of Mb=5.2 and was strongly felt in the area. In Chittagong, where the tremor was felt for about 25 seconds, a freshly built 5-story structure on Rajakpukur Lane in the Andarkillah neighborhood started to show signs of cracking. A pipeline that was damaged by the earthquake at the Bakhrabad Gas Systems Limited in Fauderhat, Sitakunda, caught fire. The earthquake also caused tremors to be felt in Comillah, Feni, Khagrachari, and Noakhali.
2008	This earthquake, also known as the Mymensingh earthquake, struck in the middle of the night on July 27, 2008. The epicentre was about 120 kilometers north of Dhaka and 12 kilometers northeast of Mymensingh city. On the Richter scale, it was assessed to have a magnitude of 5.1. Apart from Mymensingh, where the earthquake triggered panic, the Dhaka metropolitan area as a whole felt the tremors of this earthquake.
2009	This earthquake is known as eastern Bhutan earthquake. A strong earthquake occurred on the day of Eid-ul-Fitr, 21 September 2009. The epicenter was situated in eastern Bhutan, 410 km north-northeast of Dhaka. It originated from the Main Central Thrust (MCT). This distant quake had a magnitude of 6.1, but shook most of Bangladesh including Dhaka.
2010	This occurred on 10 September night at 11:30 pm local time, with magnitude 4.8. The epicenter was near Narayanganj district. The tremor was felt in Dhaka and its surrounding areas. The epicentre was 45 km southwest from Dhaka.

2011	Occurred on 6:30 pm local time with magnitude 6.8, with 2 minutes of shaking. The tremor was felt strongly in Capital city Dhaka and the districts of northern part of Bangladesh. The epicentre was 500 north from Dhaka in Indian Sikkims's capital Gangtok.
2015	Tremors of repeated earthquakes with epicenters in Nepal (Mw 7.8 and 6.7) was also felt in Bangladesh. There were reports of casualties (at least 4), injuries (around 200 people) and building damage (17 buildings tilted or cracked)

The capital city of the country, Dhaka (including the Metropolitan Area) is equally threatened by the risks of earthquake as well. The people of Bangladesh have not experienced any major earthquake with great magnitude and intensities lately, and this has caused ignorance among the people regarding the risks of earthquake that is looming over the population. But in the past few years, the appearance of many earthquakes that caused minor damages (magnitude between 4 and 6) inside the country or in nearby regions, has alarmed the people and caused the government to recheck their earthquake preparedness (Saha, 2011).

Comprehensive Disaster Management Program (CDMP) carried out a seismic hazard assessment study with the help of the Asian Disaster Preparedness Center (ADPC). The assessment had the best case scenario which is the default scenario in this research - a 7.5 Mw earthquake in Madhupur Fault at a depth of 10 km from the surface and the dip angle is 45 degrees. In this scenario 72,313 buildings are projected to be completely damaged (table 1.2). However, in the worst case scenario (8.5 Mw) the figures are significantly worse, about 270,604 buildings (83% of the total buildings) will just be moderately damaged. No matter the scenario, all data points towards a catastrophe if a major earthquake happens near Dhaka. The possibility of such an incident calls for immediate contingency planning for proper response and recovery. For Dhaka Metropolitan Area, it has become essential to designate the potential shelter places as soon as possible and take necessary preparation measures.

Table 1.2 Expected building damage by building type in Dhaka Metropolitan Area for best case scenario earthquake of CDMP (2009a)

	None		Slight		Moderate		Extensive		Complete	
	Count	**(%)**	**Count**	**(%)**	**Count**	**(%)**	**Count**	**(%)**	**Count**	**(%)**
Steel	8	0.01	14	0.03	125	0.24	324	0.98	948	1.31
Concrete	101,832	81.51	17,066	39.47	15,152	28.5	12,866	38.81	38,648	53.44
Masonry	6,353	5.09	10,784	24.94	26,558	49.95	17,328	52.26	21,611	29.89
Tin Shed	16,745	13.4	15368	35.55	11,331	21.31	2,635	7.95	11,108	15.36
Total	124,939		43,232		53,166		33,153		*72,316*	

Therefore, emergency response and recovery plans are essential and have to be developed for seismic risk management of the city. Emergency shelter placement planning and preparation is recognized as an important component of earthquake contingency planning in an urban context (Humanitarian Charter, 2011). In an emergency, open space plays an important role in providing sheltering facilities for people affected by disaster. Documented responses to earthquakes from around the world show that presence of open spaces contributes to improved recovery after an earthquake (Godschalk, 2003).

A great number of post-earthquake rescue and rehabilitation efforts in the past have been found to utilize open spaces to operate response and recovery programs. Bryant and Allan, (2013) showed the importance and use of open spaces in Kobe Earthquake 1995. First the displaced were placed in rigorously built structures like schools. When the space ran out the rest of the population was sheltered in open spaces. This also highlighted the facilities required at the shelter sites in order for easy living, since some people had to live there for over eight and a half months. (Horwich, 2000; Liedtke, 2020a). Manandhar et al., (2017) revealed the important role open space played in Gorkha Earthquake 2015. The spaces enabled households to seek shelter there when the built structures were damaged. Their importance was realized and was included in future plans as part of structural resilience (Ray, 2017). Saxena, (2016) goes on to summarize the crucial role of open space in Disaster Management especially in post disaster period. A number of research has been carried out in different parts of the world for developing a sustainable open space management system for increasing resilience (Anhorn & Khazai, 2015; Bryant & Allan, 2013; Chou et al., 2013; Jayakody et al., 2016; Lahoti et al., 2019; Reja, 2012a; Shrestha, Sliuzas, et al., 2018; Soltani et al., 2014; Unal & Uslu, 2016).

Emergency coordinators in disaster response and management can be highly benefitted by a sound technique that recognizes appropriate sheltering places where shelter services ought to be improved. Emergency shelter placement planning and preparation is an important component of earthquake contingency planning in an urban context (Humanitarian Charter, 2011). The purpose of emergency or short-term sheltering is to provide required residence, security and dignity for earthquake inflicted population. Shelters need to be placed in appropriate sites where it is the most convenient for the victims to access in the immediate aftermath of disaster occurrence. Selection of sites has to be performed based on some specifically defined criteria on site characteristics. Without proper planning and strategical selection process, authorities may end up choosing potentially unsuitable, hazard-prone or inappropriate places which may lead to resistance to use the site in the actual aftermath of disaster (Soltani & Ardalan, 2019). Therefore, it is well established that open spaces are quite important for post- earthquake response and recovery and that proper shelter placement requires a good shelter management model where standards are defined to suit the needs of the local people.

1.2 Study Area

Dhaka Metropolitan Area being one of the world's most densely populated areas along with infrastructures mostly being unplanned, massive humanitarian crisis may be expected to rise in case of an earthquake and the rescuers will face numerous challenges in providing aid to the distressed. In confronting this, the authorities should ensure the prevalence of a detailed emergency response plan in case a large-scale earthquake hits the city. An important issue to be considered is the proper resources availability beforehand to assist the emergency response personnel to conduct their activities. One of the most important resources include open space for establishing temporary public sheltering facilities (Zaveri, 2019).

In case of a catastrophic earthquake, Dhaka Metropolitan Area may incur significant loss of life and property due to the ill-planned city development and risky establishments which may lead to long lasting detrimental effects on the entire nation. Although only about 12.2% of the country's population reside here, but their activity contributes about 36% towards Bangladesh's Gross Domestic Product (GDP) (Muzzini & Aparicio, 2013).

The extent of the study area is the boundary of Dhaka Metropolitan Area, located in Dhaka, the capital and the largest metropolitan area in Bangladesh (Fig. 1.1 and Fig. 1.2). Each thana in Figure 1.1 is further subdivided into wards. The names of each corresponding ward can be found in Appendix: A1. The Metropolitan Area is seismically vulnerable for its location close to convergent plate boundary, soft sedimentary cover, and high population density.

Bangladesh itself is located near the boundary between the Eurasian and Indian plates with numerous faults (Fig 1.3). The figure 1.3 was taken from the 2009 CDMP study named "seismic hazard and vulnerability assessment of Dhaka, Chittagong and Sylhet City Corporation area (available at https://www.scribd.com/document/261700155/Earthquake-Vulnerability-Assessment-of-Dhaka-Chittagong-Sylhet-City-Corporation-Area-2009).

The cities and towns have not developed following appropriate urban planning. Dhaka Metropolitan Area too suffers from the same problem (Ahmed & Morita, 2018). Although disastrous earthquakes have not occurred within Bangladesh during the last hundred years, historical records of earthquakes indicate that several disastrous earthquakes occurred near Bangladesh since 1762. Among them, the 1762 Bengal-Arakan, 1985 Bengal, 1897 Great Assam, and 1918 Srimangal Earthquakes caused severe disaster in Bangladesh. In Dhaka Metropolitan Area, most of the masonry buildings were severely damaged and collapsed during the 1897 Great Assam Earthquake (Oldham, 1899). At that time, Dhaka Metropolitan Area was sparsely populated, and the buildings were low-rise (1 to 3 story) and confined to the present old part of the city covering the Pleistocene terrace. Now the city has expanded even more (Rahman et al., 2015). Researchers predicted that large earthquakes today, may cause even deadlier consequences in Dhaka Metropolitan Area (CDMP, 2009b).

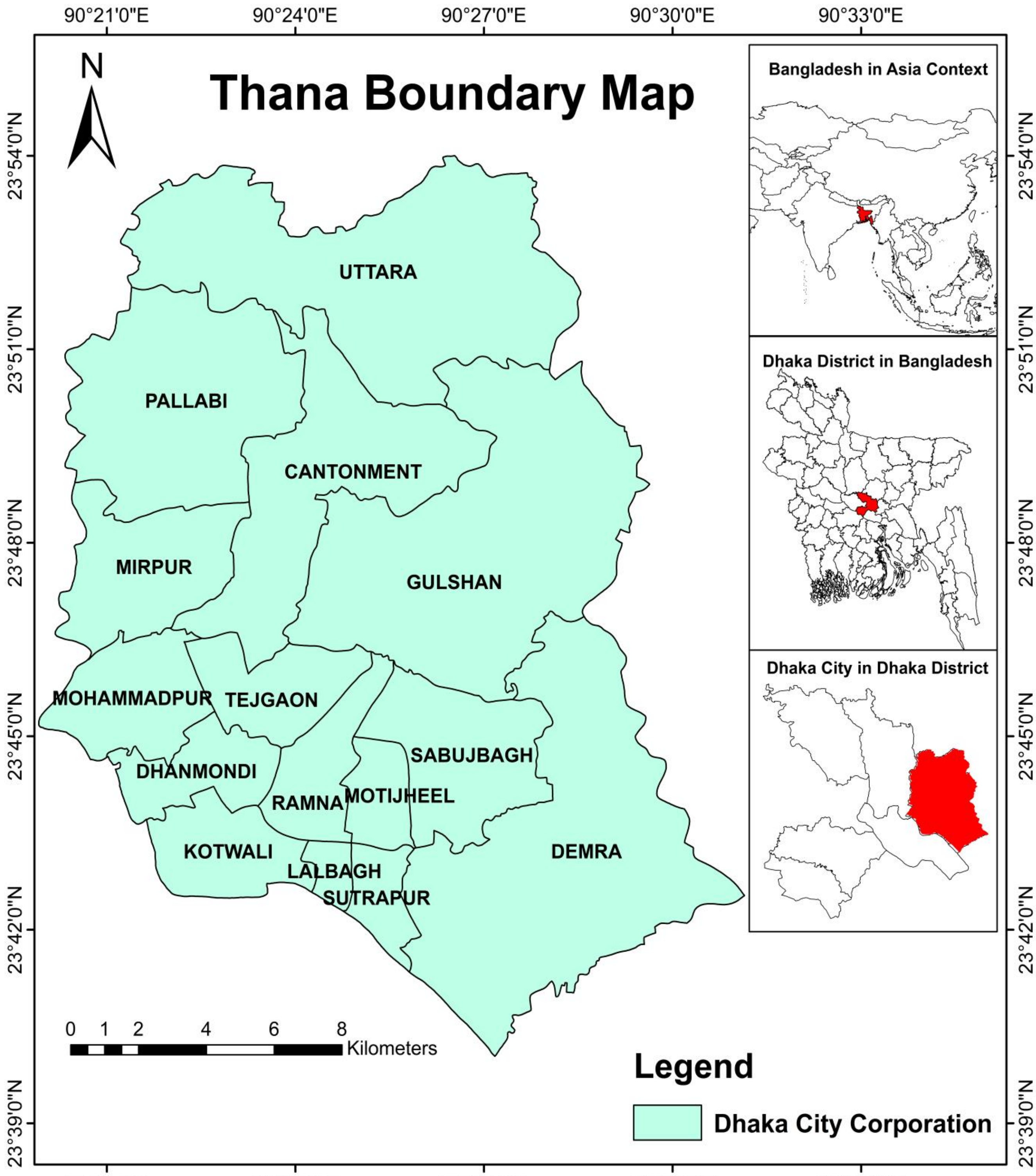


Figure 1.1 Thana Map of Dhaka City.

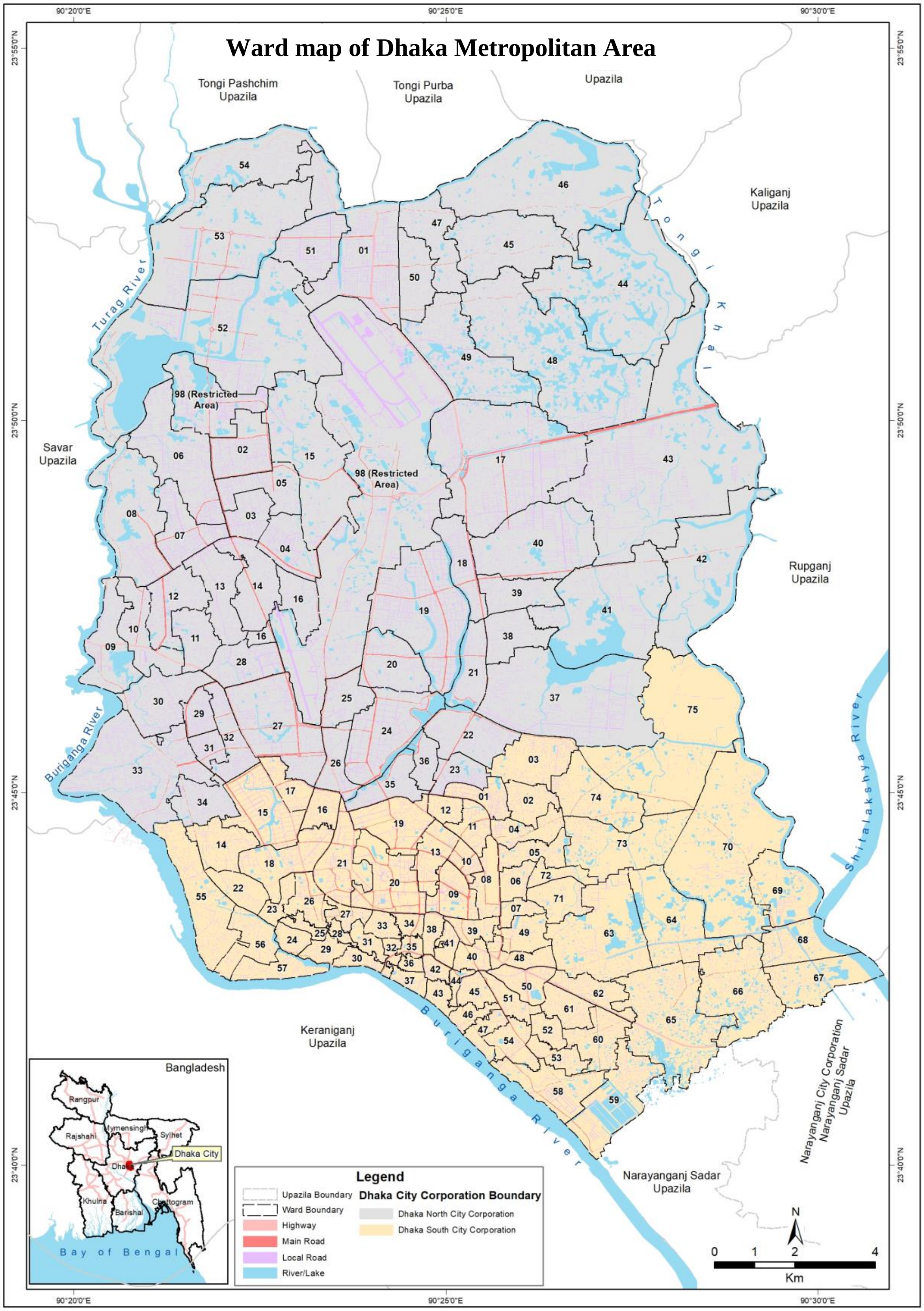


Figure 1.2Ward map of Dhaka Metropolitan Area.

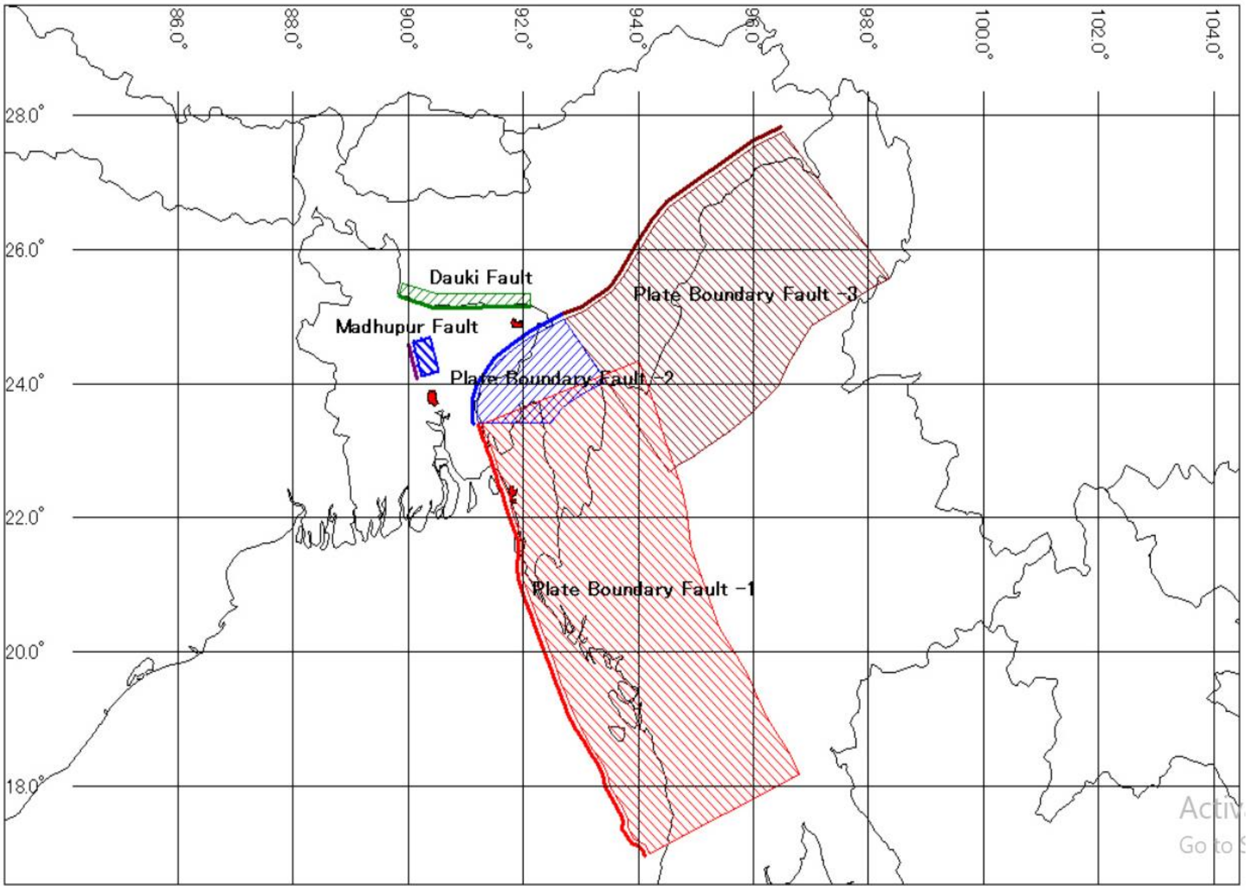


Figure 1.3 Map showing Dauki Fault, Madhupur Fault, and Eastern Plate Boundary Faults. The Madhupur fault in the central region can be clearly seen. This study considers a scenario earthquake from this source.

Given that the 400-year-old city has been taking in migrants from all over the country, the need for land is tremendous to accommodate the growth (Islam, 1999). The metropolitan area urbanized in an unregulated manner and often into reclaimed lands shown in Fig 1.4 (Morshed et al., 2017). The artificially filled areas are actually reclaimed into built up areas from low land and water bodies (Ahmed et al., 2014). Rahman et al. (2015) along with Rahman and Siddiqua (2017) found the liquefaction risk for such areas is quite high. This has further aggravated the seismic risk.

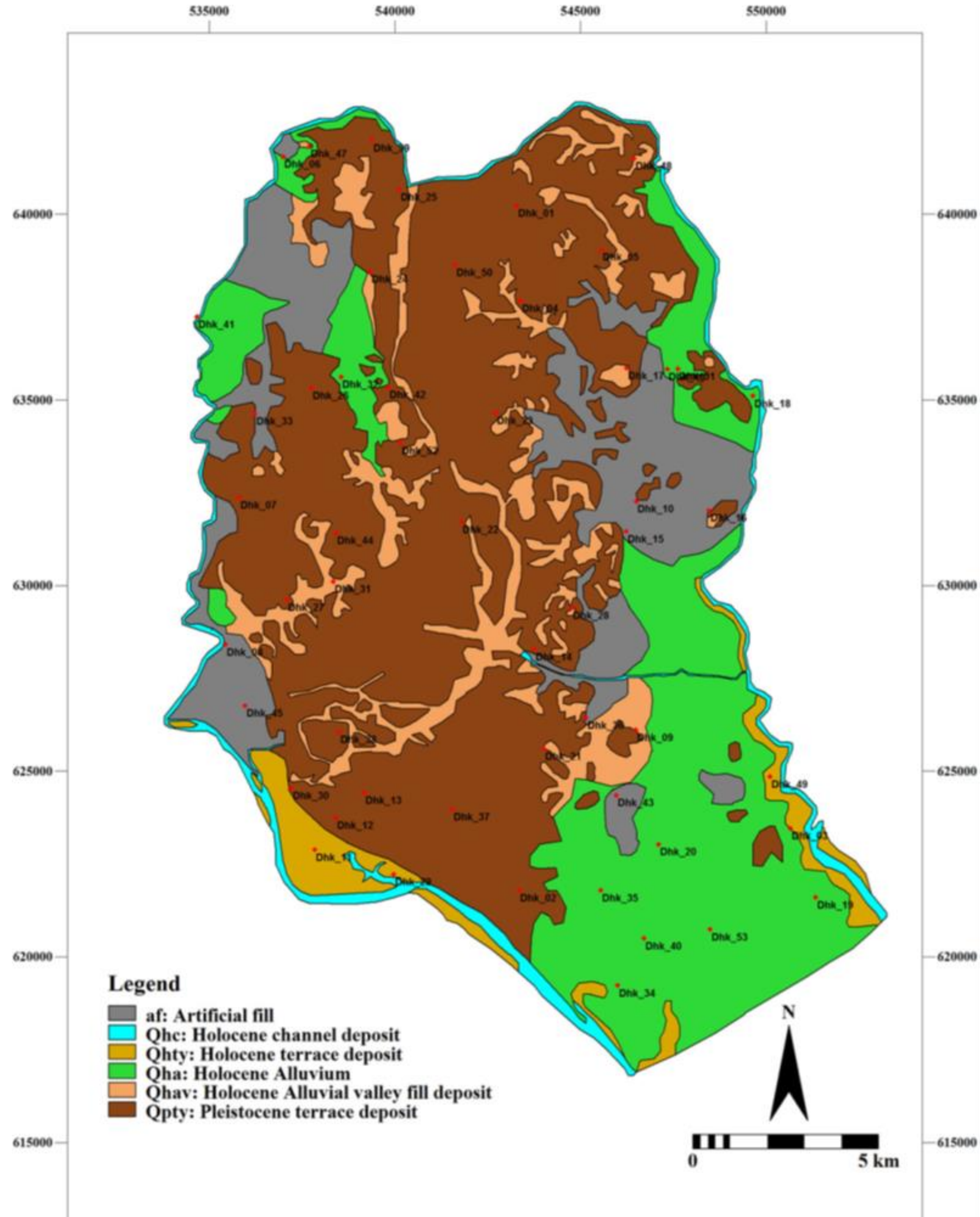


Figure 1.4 Map of the surface geology of Dhaka Metropolitan Area by Rahman, et al. (2015).

Dhaka Metropolitan Area is a very densely populated with a population of more than 20.28 million in 2019, whereas the entire country's population was around 163 million during the same time (The World Bank, 2020). The official data from Bangladesh Bureau of Statistics is from 2011 and that value of Dhaka's population stands at 8.906 million (BBS, 2011). The former value is a projection of the latter by the World Bank. The amount of displaced people, used in this study was taken from this projection. However, this value is an unofficial projected value, since census had not been performed on time due to the Covid-19 pandemic. That census did take place later, but the preliminary data (i.e. summary published on 27th July, 2022) could not be utilized as ward wise data is not available yet. The combination of unsafe urban environment, concentration of economic activities coupled with the large population further indicates the severity of probable losses Dhaka Metropolitan Area might face.

As a professional in the field of national defense, I've always found it to be my duty to play a role in the protection of the civilians during the times of emergency. The high population and building density, unplanned urban infrastructure along with developing economy, insufficient resources to tackle seismic risks, impacted my philosophical reasoning and made me pursue this topic so that my research findings can eventually help the people of this country.

It is well known that urban open spaces are essential resources for emergency response and recovery operations during and after an earthquake. Researchers like Reja, (2012) have found that open spaces in Dhaka Metropolitan Area too, could be useful for rescue and recovery for an effective post-earthquake emergency crisis management. Rapid growth in Dhaka Metropolitan Area increased the need for more and larger open spaces (to accommodate the large population), and on the other – the supply of open spaces have been reduced (through utilizing the spaces for construction) (Hackenbroch, 2012). The Botanical Garden, Suhrawardy Udyan and Ramna Park are the three major green patches in the metropolitan area. Apart from those, other noticeable patches include the National Parliament Bhaban, Chandrima Park, Bahadur Shah Park, and the National Zoo. These collectively represent a small proportion of the city, which is fairly inadequate in terms of the population: green space ratio (Byomkesh et al., 2012).

This illustrates the importance to document the existing open spaces (of different sizes, including green spaces) in Dhaka Metropolitan Area. The information can serve as an important planning tool to the emergency planners and responders in improving preparedness for timely and effective post-earthquake crisis management. Surprisingly, even a database of existing open spaces for Dhaka Metropolitan Area was not found. The need for the use of open spaces in earthquake response planning has been recognized but detailed earthquake contingency planning incorporating open spaces in an extensive urban setting is yet to be addressed in Bangladesh.

Moreover, not all open spaces have the same qualities to make them equally appropriate for post disaster sheltering. The application of a combined methodology in exploring the suitability of different open spaces to be used as public emergency shelter sites based on their characteristics, accessibility and capacity constraints is required. At the same time, given the seismic scenario in Dhaka, there is also need for estimating seismic risk and liquefaction potential, so that identified open spaces do not become unusable for sheltering purposes after earthquake. In addition, once safe sites are identified, the shelters themselves should have the appropriate characteristics and design in the context of Dhaka Metropolitan Area so that the people using them are comfortable and safe. This research intends to address these gaps, which collectively contributes to an open space management system. Therefore, the objectives have been set accordingly.

1.3 Objectives

The main objective of the present study is to develop an open space management system to response scenario earthquake in Dhaka Metropolitan Area. The specific objectives to accomplish the main objective are as follows:

1. To identify the existing open spaces in Dhaka Metropolitan Area
2. To analyze the suitability of the open spaces and rank them based on their characteristics
3. To perform seismic site characterization of the selected open spaces
4. To develop a model open space shelter

1.4 Outline of the Thesis

The study has been presented in six chapters as follows:

Chapter 1 gives an introduction of the damaging nature of earthquakes and how open spaces can be useful, the problem statement for the research, a brief section on the study area and finally giving the objectives of the study along with the thesis outline followed by a methodological framework.

Chapter 2 narrates the literature review on open spaces and the context in which they are needed today. It includes planning requirements and past lessons learnt. It starts off by showing that researchers widely agree the need for open spaces for emergency uses. Ten previous major earthquakes were studied as well to see where and how open spaces were used and the impact of the lack of open spaces. The planning suggestions were picked up from several studies that suggested what factors should be considered in case of open spaces.

Chapter 3 gives details of the methodology adopted specifically for determining the suitability of open spaces based on the size, connectivity, accessibility, nearness to facilities (hospital and fire station) and flood hazard level. Before that could be achieved a database of open spaces first had to be developed since none were available. Based on open source satellite imagery a visual investigation was done followed by digitization. Then rank-ordering and categorization was done among the 1197 identified open spaces, where 217 were found to be suitable while 151 were moderately suitable and the rest were deemed to be less suitable (which does not in any way mean unusable). Out of the 217 suitable sites 14 sites had to be left out of consideration since they are within key point installation premises, which cannot afford to be occupied in the long term owing to quick recovery needs. Finally, 203 suitable open spaces are initially selected for sheltering displaced population beyond the short term needs. At the same time population accommodation capacity and limitations were calculated. This chapter addressed objective 1 and 2.

Chapter 4 first discusses the liquefaction risk of the 203 sites based on general analysis focusing on the geomorphological nature of the individual sites. This is required as it is able to provide a general idea of liquefaction without requiring individual field data. 36 sites were found to have high liquefaction possibility and therefore had to be excluded. Based on that result and the suitability index scores, 166 sites are taken. Out of them 8 spaces were selected as case study for detailed investigations to confirm their effectiveness as long term shelter sites. In order to perform detailed tests, the seismic risk needed to be known. As such, Probabilistic Seismic Hazard Assessment was performed through source region and magnitude identification, distance and attenuation calculation. As the seismic shaking interacts with the ground differently, One-Dimensional Seismic Site Response Analysis was also computed. After gathering enough data, detailed liquefaction investigation was performed in three distinct approaches- deterministic, probabilistic and artificial neural network approach. The final results from all data sets and approaches had a good match, showing low liquefaction potential at the 8 sites selected as case study. This chapter addressed objective 3.

Chapter 5 comprises of a more focused and in depth literature review for the purpose of deriving the different standards or facilities required for sheltering in open spaces in Dhaka Metropolitan Area beyond the short term. Many physical and social factors were taken into consideration, namely accommodation space and facilities, tent placement and size, tent features, WASH facilities, healthcare, security, cultural needs, emergency facilities etc. Finally, based on the findings a demonstration was made in the field for verification purposes by experts. The 4th objective was addressed in this chapter.

Chapter 6 gives a summary of the thesis and ends with a set of recommendations for the future.

1.5 Methodological Framework

The methodological framework shows how the work has progressed. Since no database of open spaces were present for Dhaka, one had to be generated from visual identification with Google Earth Imagery. Later their characteristics like size, road connectivity, accessibility, nearness to facilities (hospital and fire station) and highest flood level data were used to rank them in order of suitability for sheltering populations. Geospatial techniques were utilized in these steps. The weights used here are based on expert opinions.

Then out of the 1197 spaces, 203 suitable ones are selected for the purpose of sheltering displaced population beyond the short term. However, given that liquefaction potential at these places are not known, a generalized analysis based on the geomorphology reveals the risk. From the generalized liquefaction and suitability scores, 166 sites are taken as safe.

8 sites are selected as case study for detailed liquefaction potential investigation. Seismic hazard and site response analysis and secondary hazard (namely liquefaction through deterministic, probabilistic and artificial neural network approach) is conducted for the 8 sites and the results confirm their low risk.

Given that each society have different norms of acceptability and varying needs, a thorough review of literature was conducted to find what facilities are actually required for attracting people to shelter in open spaces in a post-earthquake scenario. Also, when they do shelter, it will ensure that needs are met sufficiently and does not create unwanted problems. This helped determine the requirements and standards of shelter facilities according to the context of Dhaka Metropolitan Area. Finally, an on-field demonstration was made for verification purpose. Details of the materials and methods used are given in respective chapters.

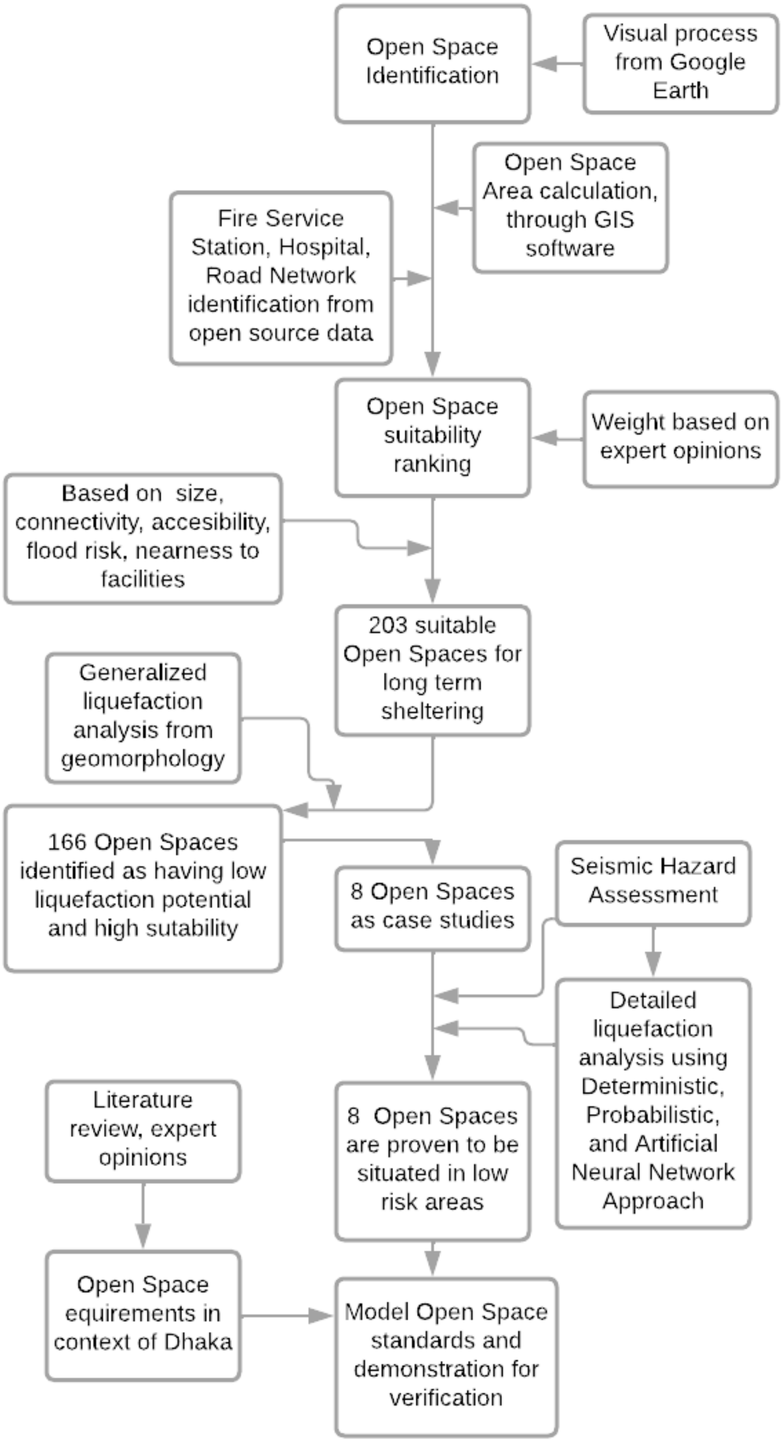


Figure 1.5 Methodological Framework for the study

Chapter 2:
Literature Review

2.1. General

Emergency shelters are a crucial part of post-disaster crisis management planning. In the immediate aftermath of any disaster occurrence, one of the priorities is to arrange shelter for protecting the people surviving after devastation. In case of earthquakes, one of the response is setup of potential temporary shelter placement site. Emergency shelter placement in the immediate aftermath of earthquake in an extensive urban setting, the use of open or green spaces are considered to be highly effective. Open spaces in urban areas are potentially useful resources to be used to place temporary to even long-term shelters with a view to facilitating considerate numbers of distressed population in the immediate aftermath of earthquake (Reja, 2012b).

The systematic review of literature can help to recognize the patterns and trends of open space shelter management for post-disaster planning and recovery.

2.2. Key Themes Considered for Planning and Designing of Open Spaces

French (2017) and French et al. (2019) identified how open spaces can be proactively planned and designed by relevant professionals to support after earthquake emergencies. It was based mainly on literature review of grey (government, professional and design-firm reports) and peer-reviewed papers. Six key themes were identified, namely, (1) multi-functionality (recognizing different needs, conditions, uses that support not only post-emergency but also improves quality of life); (2) network (ability to access the site, number of redundancy, distribution across the Dhaka metropolitan area); (3) site location (placement in little or no risk areas and avoid creation of new risks); (4) size (according to the target population needs) & function (the facilities available in the open spaces determining suitability, like shade for weather elements); (5) site elements (availability of water, sanitation, electricity, food); and (6) social resilience (designing of spaces that respects social and cultural fabric promotes social cohesion and therefore resilience and support though awareness activities).

Bryant and Allan, (2013) showed the importance and use of open spaces in Kobe Earthquake 1995. Although the built structures were first prioritized but due to their limited availability people were sheltered in open spaces. This also highlighted the facilities required at the shelter sites in order for easy living, since some people had to live there for over eight and a half months. The lack of sanitary facilities, privacy functions, electricity (for heating and lighting), water supply and exposure to weather elements turned out to be a major disadvantage. On the other hand, the well spread out presence of open spaces throughout the city meant many people could shelter there easily and many stakeholders have said this was really beneficial, especially those that were in close proximity to residential hubs. (Horwich, 2000; Liedtke, 2020a).

World Bank & United Nations (2010) suggest that the population of the major cities at risk of earthquakes will be doubled by 2050, which means their earthquake risks will be significantly increased since more people and properties will be exposed to earthquake disaster. Therefore, six key themes should be considered to improve the plan and design of open spaces for developing seismic resilience of the cities.

2.3. Lessons Learned from Post-Disaster Response and Recovery

In this section first the lesson from other countries are presented where individual examples were prioritized then the literature review goes towards open spaces considerations.

During the **Mexico earthquake 1985** more than 10,000 people died, some 30,000 others were injured while approximately 2,50,000 people became homeless. Over 400 structures collapsed while damage occurred to thousands more (History, 2016). Many of the buildings that were damaged did not follow building codes. The water supply system suffered serious losses and the system was unable to serve even 30% of the population. Due to the distinctive topography of Mexico City, the destruction was concentrated in the city. The loose lacustrine sediments in the dry Lake Texcoco bed that made up the central city's subsurface enhanced the shock wave and caused the strongest shaking. Buildings in the city with five to fifteen stories were most affected because the harmonic resonance that resulted from their interaction with the shock waves increased the amount of swaying. In response of the earthquake, government first denied to accept international assistance offers and tried to play down the damage the earthquake caused. As a result, the citizens organized their own rescue plans and operations. The relief offers were led by the local residents. To assist the more affected low-income cities, less affected citizens went there and gave them immediate response and shelter materials. The fact that several of the city's major medical centers had been affected made it difficult to provide medical care for the tens of thousands of injured people (Britannica, 2021). There were not any efficient contingency plans, and there are reports that even after one year more than 80,000 people were living in the streets and parks that were serving as temporary shelters (Orme, 1986). 34 open spaces were used as shelter camps and for other post-disaster activities but later on, those spaces either disappeared or were made private (Montejano-Castillo & Moreno-Villanueva, 2016).

1995 Kobe earthquake was the most devastating disaster for Japan. The earthquake struck on 17 January 1995 and caused a total 6,279 deaths. Most of the deaths (about 90%) was the direct result of building collapse. Another cause of increasing death numbers was fire outbreak following the earthquake. Following the earthquake, there were about 300 fires that quickly outgrew the capacity of the area's firefighting equipment. The sheer volume of fires, water shortages brought on by system problems, inability to utilize fire hydrants, and blocked and debris-filled roadways that impeded access to the fires all greatly hindered firefighting efforts. Numerous people, including a sizable senior population, were forced to leave their homes as a result of lifeline failures that left the bulk of the population in the impact region without access to electricity, gas, or water. The victims opted to evacuate to open spaces that were usually within ten minutes walking distance from their residences (Liedtke, 2020b). The government gave 32,346 units of temporary housing during recovery period following the earthquake. Provision of emergency shelter was crucial because thousands of homes were made uninhabitable immediately following the earthquake. To accommodate 1,000 individuals, the Japanese government built 48,000 temporary housing units. Temporary shelters were set up in the center city's slightly damaged parks and schools, but the majority of them were situated in the city's outskirts on vacant lots or in parking lots, two hours distant by bus or train (Tierney & Gotlz, 1997;Orr, 2007). This showed the importance of use of open spaces post-earthquake scenario. Hence, after the Kobe earthquake, a network was formed by roads connecting open spaces of different sizes, providing shelter at various places (Wei et al., 2020).

The **Chi Chi earthquake 1999** struck on 21 September leaving at least 2,400 people dead and 8,700 injured. 600,000 people were homeless as a result of the damage to 82,000 housing units. In monetary terms, 14 billion U.S. dollars damage was estimated. Immediately after the quake, over 5,000 people had to be rescued from collapsed or damaged structures. Local fire departments and organized volunteer teams carried out the majority of rescue operations. But there was lack of efficiency in coordinating the major response operations (Chan et al., 2006). Damaged roads, bridges and remote mountain areas created a great response challenge for the rescuers. After temporary roads were constructed, successful evacuation of 4,685 people from the remote areas were performed. After the first four months of the earthquake, more than 1,000 individuals continued to occupy tents. By the conclusion of the four months, the central government hoped to have them relocated. From the lessons of the earthquake, the government had been developing their policies and plans for recovery and reconstruction following any earthquake (Report, 2003). The master plan for reconstructing Chi-Chi emphasized on development of the parks and open spaces. The government also made land acquisition for temporary housings (Murao et al., 2004).

The **Bhuj earthquake 2001** caused considerable damages in Ahmedabad. The newly isolated buildings were more damaged where their adjacent building had minor damage. More than 75 multistoried reinforced concrete buildings collapsed in the city killing over 200 people. However, open spaces played a crucial role in saving lives of the children attending assembly in the open grounds and also after the earthquake, people preferred to stay in the open areas close to their houses. Because they were scared to be inside the houses yet needed to be near their houses to retrieve their belongings. This necessitated acquisition of accommodation tents (M. R. Saxena, 2016). The initial response following the earthquake was not noteworthy due to the absence of government intervention immediately after the earthquake. The response efforts initiated almost 24 hours after the earthquake. Due to disruption, all communication systems, such as - telephone system, cellular phone system, police wireless and air traffic control system, authentic information about the damage was not reaching to the response teams. That was one of the major reasons for delayed response. For response work, only one channel of communication worked and preliminary information for response was sent to Ahmedabad. No access to communication made common people or urban and rural areas more helpless. They did not get sheltering facilities immediately after the disaster. For sheltering the population of Bhuj, Bachchao and Anjar, they were migrated where temporary shelter and relief assistance was available (Varyani, 2001). But within a week, a network of 22 local organizations focused on building interim, transitional shelters using low-cost materials. Even though the selection of beneficiaries was not inclusive, a large number of people could be provided with shelters (Ashmore, 2008).

Around 85 percent of Bam's housing stock was damaged by the **2003 Iran earthquake**, forcing up to 75,600 people to leave their homes. Nearly 155,000 individuals required sheltering in Bam and adjoining villages due to the confluence of migrants from nearby areas. The Iranian government delivered shelters in the urban areas of Bam to accommodate the affected population in 3 phases:

- Temporary tent shelters in urban areas: on original residence spaces or in camp-grounds on the city's outer areas.
- Intermediate or semi-permanent shelters: structures made of prefabricated parts, either situated where the original residences once stood or in campgrounds outside the city. A single room measuring 16 to 20 square meters (typically 3 by 6 or 4 by 4 meters in plan) is the size of the intermediate shelter made of prefabricated components, and it costs around $2,500 to $3,000 to assemble.
- Permanent houses in the urban areas

Though the government prepared around 10000 units of shelters in 23 campsites; one-third of units remained vacant initially due to people's unwillingness to leave their residence area for the outskirt camps. Most of the victims were farmers who were more interested in staying in the units located on the private lands near their residence due to the fear of losing their lands. Moreover, the campsites lacked shading, whereas the tall trees provided cool shade in the private spots. However, the campsites had more organized water supply, sanitation, and reticulation system. Cultural aspect played a significant part for the intermediate shelters. The Iranian people were upset with the sanitation system as they are not used to the latrines being located inside the shelter units. Moreover, for women, the non-segregated toilet/shower facilities were not welcome owing to modesty concerns (Khazai et al., 2005). These shelters actions continued for about a year before reconstruction plan was mobilized. But it was realized that reconstruction of permanent housings was delayed due to people getting used to living in the temporary shelters and shortage of suitable construction materials (Hosseini et al., 2008). Out of all the things the Iranian government considered in the aftermath of the earthquake, they could not realize the need for designated open spaces as evacuation sites after earthquakes, but rather focused on other aspects of emergency preparedness.

The **2005 Pakistan earthquake** in northeastern Pakistan killed 74 people, leaving 3.5 million people homeless. The disaster response efforts in the early days were extremely uncoordinated and accommodating the displaced people in the shelter camps were a massive challenge (Earthquake Engineering Research Institute, 2006). There were various formal and informal camps established in the limited open spaces, e.g., parks, playgrounds, stadiums etc. of the affected towns (Qazi, 2010). People either stayed at their wrecked homes due to the fear of losing their spots or took shelter in the designated camps. While constructing the shelter houses, emergency managers considered both earthquake and landslide risks. The shelter building materials were lightweight and earthquake resistant. The shelters had low walls with sand sacks at the base, bags with lighter crop materials at higher wall parts, and a dome-shaped iron roof. These materials were selected so that victims could use them later as house-building materials. Locals collected these materials and toolkits (containing an axe with handle, a cold chisel, a crowbar, a 2 kg hammer, a claw hammer, pliers, handsaw, etc.) from the designated distribution points. They played significant roles in building their shelters. The main challenge for building the shelters was finding suitable land due to the risk of repeated earthquakes and landslides. Cooksets, stoves, and coals were provided for cooking. Quilts and blankets were also provided to the victims due to the winter (Shelter Projects, 2008). However, households headed by females, large families and the elderly people had to seek shelter in smaller unauthorized camps receiving less assistance (Girard et al., 2015).

In **2008 Sichuan earthquake**, some 87,500 people were killed and 45.5 million were affected. Due to the earthquake, 81 billion U.S. dollars was estimated as economic losses. The Chinese government was the first to start responding to the earthquake. Along with national resources, the government invited some international humanitarian agencies for emergency response. Following the earthquake, the government prioritized patient triage, the mobilization of competent volunteers, and effective management, as well as broad medical care and monitoring, the provision of tents for accommodation, and security the maintenance. Additionally, for immediate response purpose and avoiding chaotic situation, the relocation of people was limited in the affected areas. Every household in the Allai Valley in Sichuan (population: roughly 100,000) chose to migrate to camps at a lower elevation or go to live with relatives abroad due to a lack of emergency shelters. Again, manufacturing shelter was not quick enough (due to material shortage) so 12 individuals had to share one family-size tent. But following the earthquake there was no cluster meeting so, disaster response tools and mechanisms were used. One issue that was discovered after the earthquake response is that the government had not made data readily available (Lingling et al., 2008). The government also lost the pre-earthquake level of surveillance and control of the public spaces as the parks and stadiums were turned into emergency shelters. However, the earthquake completely changed the physical landscape of the area and also the way open spaces were being accessed and utilized. Open and accessible public spaces were created as a result of the earthquake that served as mega emergency shelters supporting more than ten thousand earthquake evacuees and the emergency response activities (Gao, 2020).

The exact number of casualties from the **2010 Haiti earthquake** may remain unknown, but according to government estimates, 222,750 people were killed and 300,72 were injured. Eight out of every ten people were directly impacted by the earthquake, and one in every fifteen people died. The Post-Disaster Needs Assessment (PDNA) revealed 105,000 fully demolished residences and more than 208,000 damaged, while the government believes that 250,000 dwellings and 30,000 commercial structures were seriously damaged. The initial response was spearheaded by the Haitian people themselves. Numerous individuals were saved, and local communities helped the injured. People started to gather spontaneously in the open spaces of Port-au-Prince after the earthquake and started building makeshift camps. Due to the approach of the rainy season, water-proof shelter materials were urgently needed (Margesson & Taft-Morales, 2010). For shelter and Camp Management, immediately after the earthquake, the target population for the distribution of emergency shelter supplies (tents or tarpaulins) had been exceeded; during the first four months of the operation, large-scale distributions reached an average of 100,000 people each week. In these four months, tents and tarpaulins for sheltering were distributed where necessary and replaced when they reached their lifespan. Due to space limitations, tarpaulins were prioritized as shelter-covers over tents and Haitians themselves were skilled enough to build shelters under tarpaulins. For providing long term shelter, the shelters were made of steel or timber structure that are stronger than tents or tarpaulins. For long-term use, more than 125,000 transitory shelters were planned. 20 out of the 21 spontaneously generated settlements that were determined to be in dire need of administration already had camp management organizations in place. 54 percent of all major camps (those with more than 1,000 households) were controlled by certain organizations, and 60 percent of relocation places had organizations that were easily identified as being in charge of managing camps (IASC, 2010). However, various challenges were faced during the implementation of the transitional shelter program, for instance – crime and gangs, land occupancy, scarcity of space, population density, renters and owners, beneficiary selection, rubble to reconstruction, dangerous structures, shelter design and construction, procurement and logistics, accountability, monitoring and evaluation (Hirano, 2012).

Before the **2015 Nepal earthquake**, the government had identified 488 open spaces among which 83 were designated to evacuate the people of Kathmandu Valley. But not all the open spaces showed equal potential of utilization in the aftermath of the earthquake (Rimal & Lal, 2021). The selection of escape destination was fairly based on the escape route the people could access at that moment (Shrestha, Romão, et al., 2018). The population in need of immediate sheltering in the areas that were impacted were targeted to be provided with accommodation in the first phase. The supply of critical in-kind shelter materials or cash-transfer programs was viewed as a first step in gradually contributing to self-recovery and therefore longer term solutions (Pacific, 2016). The National Planning Commission anticipated that 600,000 temporary shelters were required in Nepal as a result of the earthquakes to accommodate those who could not stay in their residences. From post disaster need assessment, humanitarian assistance covered wide number of affected and only 11% rural areas had not received any assistance. The assistance also helped the household to be prepared for advance winter. Since the earthquakes, overall 77 percent of households say they have gotten housing aid and the shelter needs existed even more than two years after the disaster (Shelter Cluster Nepal, 2015; Shrestha, Sliuzas, et al., 2018).

2.3.1. Cultural Adequacy

Sukhwani et al. (2021) explores lessons related to cultural adequacy in relation to Sichuan-earthquake (2008), Merapi eruption (2010) and Tohoku earthquake (2011). The term signifies the expression of respective communities' cultural diversity and identity for whom the temporary housing is intended. In terms of housing-policy, public space, cultural-background, and co-design of the temporary housing for the 3 disasters revealed that cultural inadequacy was present in them in various forms. Although its importance is stated by the United Nations Charter on Sustainable Housing (UNECE, 2015), the issue often gets ignored in the emergency scenarios. Sometimes, they are culturally inadequate and locally inappropriate, causing alienation, as they are designed or constructed by experts based primarily on structural standards or because the stakeholder opinions were not included (top-down approach) (Félix et al., 2013b, 2013a). Moreover residing in such units may create stress, psychological trauma (Perrucci & Baroud, 2018). Locals in different disasters have complained about social disruptions, poor quality of design or materials, concerns of domestic violence, lack of privacy, causing insomnia. The cultural adequacy must include spiritual and psychological needs of the community (Hadafi & Fallahi, 2010). This can include religious spaces to help the people cope with (Aten et al., 2019; Gianisa & Le De, 2018). Finally, the Sukhwani et al., (2021) suggested that feasible strategies to overcome the inadequacies have to be according to local context. Another important point was highlighted that establishing clear policy directions and pre-disaster recovery planning must incorporate these ideas to avoid adopting ad hoc mechanisms, which may overlook the cultural aspects and create similar problem all over again.

2.3.2. Suitability of Open Spaces

Anhorn and Khazai (2015) recognized that availability of spaces for sheltering is crucial for people affected by disasters. They developed a methodology for ranking the suitability of open spaces for disaster preparedness planning and for identification of the services that required to be improved. This is termed as 'Open Space Suitability Index'. It uses various qualitative and quantitative criteria to assess the suitability of the open spaces. The qualitative criteria include: (1) current land ownership and use, future plan for that open space (whether it will remain an open space); (2) possibility of pollution and secondary hazards like flooding; and (3) utility supplies like water, electricity and nearness to hospitals. The quantitative criterion is the population wise shelter demand (capacitated accessibility), which is derived using network analysis of geospatial techniques. The weights of the criteria were expert opinion based. The combination of the criteria scores for each space gives a certain comparative value, which shows the relative rank. This index value also represents how suitable the spaces are to be used during emergency. Only 10.7% out of 410 open spaces in Kathmandu Metropolitan City were highly suitable. This enabled an efficient way to identify underserved areas in the urban city. They explicitly state that the selection of criteria can be customized to fit the needs and context of the application. It is also stated that the result is dependent on the distribution of population during the time of the study and with time it might need to be updated to be representative of reality.

2.3.3. Open Spaces for Enhancing Seismic Resilience of the Cities

Koren and Rus (2019) performed a systematic review of scientific literature to assess the role of open spaces for enhancing resilience in urban area. It is observed that there is still a gap on scientific study relating open spaces contributing towards urban resilience and most studies are related to the resilience of the structural aspects. A relation between climate change and resilience was also found where green open spaces help to reduce climate change impacts and therefore, which in turn reduces other risks and exposures. How much open spaces can contribute to urban resilience depends on specific characteristics of each space and different characteristics are required for different hazards and different communities. There is a lack of quantitative studies on open space usage in urban resilience and they suggested a conceptual model for assessment of such usage. The criteria include size, distribution, redundancy, road networks, connectivity and accessibility indicators, and nearness of facilities.

Zhao et al. (2017) indicated existing open spaces of the city can be used for emergency shelters thus resulting in effective response and quick recovery. The research first examines what conditions of the building force a potential evacuee to decide when to evacuate. It is also dependent on how different people perceive threats, like loss of services. This enables a forecasting method to be developed that can determine time-varying demand for shelters. To avoid shortage of shelter capacity they should be built keeping the maximum demand in mind. A subsequent model then determines which open spaces are in fact converted to shelter spaces and this is done in parallel with the time varying demand, thus reducing the cost of unnecessary shelter construction. Consequently, an allocation model is run that determines which community will head to a certain shelter location. This ensures the least distance is travelled by communities as a whole but without causing overcrowding in any shelter. The problem of location-allocation was solved by a novel Cross Entropy-Line Sampling Algorithm. The implementation requires large volumes of time varying data at high resolution, such as construction material of each building, which building is damaged and to what degree, is the damage same in all floors, the number of residents of each flat, the time when a service is lost for each flat, previous records of what causes the evacuees to flee to shelters, what proportion does not go to shelters, the path taken by evacuees, etc. The data are available in the context of Bangladesh.

2.3.4. Data requirements for automated assessments

Software like HAZUS Earthquake, SELENA, and EaRL (Earthquake Risk, Loss and Lifecycle Analysis) are used to determine the earthquake damage to buildings and then the loss resulting from such damage. But all necessary data are not available and it requires high computational power to run especially for high density urban areas like Dhaka Metropolitan Area (A. et al., 2006; Chou et al., 2013; Elkady & Lignos, 2020). There are essentially four basic steps to define loss. First, building data is needed (e.g., number of floors, floor area, asset in each flat, rebuilding cost, etc.). Then comes information regarding the structure (i.e., structural-and non-structural elements), the structural response to seismic shaking including Engineering Demand Parameter at specific building height. This has to be fed by highly accurate seismic data, which in itself is often varying in nature in academic papers for Bangladesh (T. Al-Hussaini et al., 2017; T. M. Al-Hussaini et al., 2015; Carlton et al., 2018; I. N. Chowdhury, 2016; B. Hossain & Hossain, 2020; Manzur & Noor, 2006; M. Rahman, 2019; M. Z. Rahman et al., 2017). Other requirements include population model data like occupancy rate and its variation with respect to time, the damage fragility curves that are developed for local building typologies, the repair time, creation of secondary hazards like fire, etc. Needless to state that such a study would be well beyond the scope in this research.

2.4 Summary

This chapter reflects on the key themes that should be considered for planning and designing open spaces shelters and the lessons learnt from post-disaster response and recovery after the earthquakes in the recent past. Despite being located near the seismically active zones, and having high building and population density, Dhaka Metropolitan Area does not have many open spaces to address the post-disaster response and recovery needs. The few open spaces that do exist are neither well managed nor ready to serve as emergency response sites in times of need. Thus, it is critical to determine the location and size of open spaces in Dhaka Metropolitan Area. This information enables emergency managers to choose the best locations to carry out emergency activities (De Alwis Pitts & So, 2015). A safe and easily accessible route, with good connectivity is required so that the shelter can be used effectively by both displaced people and response groups (Carmona, 2021). The site that is close to the community, social services, and other necessary facilities has shown to be more efficient in meeting the needs of the displaced population (Rimal & Lal, 2021). But there is no study to date that gives a plan on how to use open spaces to address earthquake response in Dhaka Metropolitan Area. Nor is there any study that guides on which open spaces will be able to attract potential evacuees and which do not have the necessary features for effective shelter placement. It has created the necessity to find a ranking of open space in Dhaka based on shelter including size, distribution, networks and connectivity and utility services and facilities. In the next chapters, suitability assessment of the available open spaces in Dhaka Metropolitan Area will be carried out which will eventually form the basis for further works on developing an open space management system to respond to post-earthquake scenario in Dhaka Metropolitan Area.

Chapter 3:
Suitability Assessment of Public Open Spaces

3.1 General

One of the primary strategies in improving the state of preparedness and disaster response is the identification and provision of suitable emergency shelter sites before the disaster occurs (Chandler, 2007; Tai et al., 2010). Earthquake, being a rapid onset and inherently unpredictable hazard, poses greater preparedness challenges for the emergency response planners as the lead time for preemptive evacuation is non-existent and planning for emergency shelter management requires a collaborative and coordinated approach, which is time consuming (Wright, 2010). The situation is further compounded in densely populated urban areas, like Dhaka City, the capital of Bangladesh.

With rapid urbanization and population growth over the past 40 years, the ill-planned establishments of the built environment resulted in high vulnerability to earthquakes for Dhaka City (Khan, 2000). The city is positioned among the twenty most vulnerable cities of the world in the earthquake disaster risk index (PreventionWeb, 2010). Adding to that, seismicity data also backs the notion that Dhaka City might experience earthquakes in the future (Islam et al., 2010).

In 2009, Comprehensive Disaster Management Program (CDMP) carried out a seismic risk assessment study with the help of the Asian Disaster Preparedness Center (ADPC). The study considered four earthquake scenarios, where each scenario was assigned a maximum possible earthquake. The study was conducted around 2009 and used the population statistics for 2009. The scenario of a 7.5 Mw earthquake in Madhupur Fault at a depth of 10 km from the surface and the dip angle is 45 degrees was used for this study (CDMP, 2009b). Around 23% of the building will collapse and 49% will be moderately damaged according to its results.

With the 2015 Gorkha Earthquake as the provocation, the Government of Bangladesh along with the UN Resident Coordinator under the United Nations Development Assistance Framework focused on preparedness for a large scale earthquake in 2019. The study is called "Contingency Plan for Earthquake Response in Major Urban Centres - Scale-Up 2019". The CDMP data was statistically projected to make it suitable for 2019 and as this data is more updated it was used here.

It showed that a large number of distressed population would be seeking shelter support in the aftermath of earthquake near Dhaka. Although only about 12.2% of the country's population live in Dhaka Metropolitan Area, but their activities contribute about 36% towards the Bangladesh's gross domestic product (GDP) (Muzzini & Aparicio, 2013).

Therefore, emergency response and recovery plans are essential and must be developed for seismic risk management of the metropolitan area. Emergency shelter placement planning and preparation are recognized as the most important components of earthquake contingency planning in an urban context (Humanitarian Charter, 2011). In an emergency, open space plays an important role in providing shelter facilities for people affected by disaster. Documented responses to earthquakes from around the world show that presence of open spaces contributes to improve recovery after an earthquake (Godschalk, 2003). A great number of post-earthquake rescue and rehabilitation efforts in the past have been found to utilize open spaces to operate response and recovery programs. Bryant and Allan, (2013) showed the importance and use of open spaces in Kobe Earthquake 1995. Manandhar *et al.* (2017) revealed that open space played an important role in Kathmandu Earthquake 2015. Saxena (2016) goes on to summarize the crucial role of open space in disaster management especially in post disaster period. A number of research has been carried out in different parts of the world for developing a sustainable open space management system for increasing resilience (Anhorn & Khazai, 2015; Bryant & Allan, 2013; Chou et al., 2013; Jayakody et al., 2016; Lahoti et al., 2019; Reja, 2012a; Shrestha, Sliuzas, et al., 2018; Soltani et al., 2014; Unal & Uslu, 2016).

Therefore, urban open spaces are essential resources for emergency response and recovery operations during and after an earthquake. Researchers like Reja (2012) have observed that open spaces in Dhaka Metropolitan Area too, could be useful for rescue and recovery for an effective post-earthquake emergency crisis management. However, rapid growth in Dhaka increased the need for more and larger open spaces to accommodate the large population, and on the other hand, the supply of open spaces have been reduced through utilizing the spaces for construction (Hackenbroch, 2012). In Dhaka Metropolitan Area, the Botanical Garden, Suhrawardy Udyan and Ramna Park are the three major green patches. Apart from those, other noticeable patches include the National Parliament Bhaban, Chandrima Park, Bahadur Shah Park, the National Zoo, etc. But these collectively represent a tiny proportion of the city, which is fairly inadequate in terms of the population and green space ratio (Byomkesh et al., 2012). This illustrates the importance to document the existing open spaces of all sizes including green spaces. The information can serve as an important planning tool to the emergency planners and responders in improving preparedness for timely and effective post-earthquake crisis management.

Detailed plans incorporating the use of open spaces for establishing emergency shelters in the existing urban setting does not exist. Neither has a detailed study been conducted at a large scale addressing urban open space management for emergency response purposes in Dhaka. At the same time, it is important to note that not all open spaces have the same features to be used as an emergency shelter (E. L. French et al., 2019). This is where suitability analysis comes in, which basically means ranking the existing open spaces based on the characteristics, which would make them useful for post disaster sheltering and contribute towards recovery. This portion of the research aims at conducting a comprehensive study to identify and categorize the existing open spaces in Dhaka Metropolitan Area.

3.2 Materials and Methods

The objective here is to assess the suitability of existing open spaces in serving as emergency shelter establishment sites in the immediate aftermath of an earthquake incident in Dhaka Metropolitan Area. The open spaces were mapped and then their relative suitability were evaluated.

It is necessary to first identify the existing open spaces, given that such data for the entire metropolitan area were not found. However, definition of open space had to be specified first. United States Environmental Protection Agency (EPA) defines open space as any open piece of land that is undeveloped and has no built structures, and is accessible to the public, usually for recreational purposes. This includes parks, playgrounds, public seating areas, community gardens, etc. This definition along with another condition was followed as the exclusionary criteria. The spaces those have possibility for future constructions of built structures were not considered, especially if it seemed to be privately owned for obvious reasons.

3.2.1 Open space identification and mapping

With the definition in mind, visual inspection was carried out in Google Earth Pro. When spaces that satisfied the criteria were found, they were digitized as polygons. Oftentimes the identified open spaces were cross checked with OpenStreet Maps, Google Maps and Google Street View to increase confidence. After multiple searches, a map of the footprints of all the existing open spaces was obtained. This spatially referenced map was exported as a KML file from Google Earth Pro to ArcGIS 10.5. Later it was converted to a shapefile.

3.2.2 Suitability

Evaluation of open space quality in serving as emergency shelter site, provides the basis for developing optimal and sustainable emergency shelter management plan (Indriasari et al., 2010). In order to analyze the suitability of open spaces for potential shelter sites several standards are promptly considered. Da Silva (2007) stressed upon considering both the perspectives of shelter occupants and emergency planners while evaluating shelter site quality. Emergency planners focuses upon resource availability and implementation while individual shelter seeking personnel seeks for better accessibility and space availability while choosing an optimum shelter location.

Several studies have been conducted on the principles of selecting sites for emergency shelters. Relevant in this regard, the China Earthquake Administration identified specifications for post-earthquake emergency shelters and specific directions on their construction strategy. Johnson (2007) has shown in his study a comprehensive framework for planning temporary shelters before any disaster. Liu et al.(2011) gives direction about choosing sites for emergency shelters. These studies provide valuable knowledge in the selection of sites for emergency shelters as well as the standards needed to be complied with, but fail to focus on choosing from many possibilities, or do not provide any method for creating a hierarchy of choices.

A set of suitability criteria/indicators are needed in order to compare each open space. Anhorn and Khazai (2015) integrated the capacity, accessibility, and quality information of each open space through the Comprehensive Open Space Suitability Index (COSI) for Kathmandu Metropolitan City. Since COSI is appropriate in determining the relative suitability of open spaces a modified version of it (Table 3.1) has been applied for this study. This modification is based on their recommendation to make it more suitable for local context. As such, experts (in Table 3.2) have selected the given weights and scores below. It is based on their consensus and experiences.

Table 3.1 Modified comprehensive open space suitability index (COSI) for Dhaka Metropolitan Area, adapted from Anhorn and Khazai (2015).

Indicator	Preference class	Score
Area/size of the open space (weight 60 %)	14000 m^2 or more	1.0
	below 14000 m^2 but above 8100 m^2	0.4
	less than or equal to 8100 m^2	0.1
Distance from Primary Road (weight 5 %)	within 250 m	1.0
	within 251 to 500m	0.8
	distance >500m	0.6
Number of Access Roads (weight 10 %)	3 or more	1.0
	2	0.7
	1	0.6
Distance from Fire Station (weight 10 %)	within 1000 m	1.0
	1001 to 2000m	0.7
	>2000m	0.5
Hospital service availability (weight 5 %)	within 500 m	1.0
	within 501 to 700m	0.8
	>700m	0.6
Highest Flood level (weight 10 %)	Low or no flood	1.0
	Moderate to High flood	0.4

Table 3.2 List of experts that have been consulted during the study.

Sl#	Name	Designation	Organization/Unit
1.	Lt Gen Md Akbar Hossain, SBP, SUP (BAR), afwc, psc, G+, PhD	Commandant	National Defense College
2.	Maj Gen Md Wahid-Uz-Zaman, BSP, ndc, aowc, psc, te	Commandant	Military Institute Science and Technology
3.	Prof Dr. Md Zillur Rahman	Co- Supervisor	University of Dhaka
4.	Brig Gen Akhter Shahid, SUP, ndc, psc, G+	Commander	HQ 6 Air Defense Artillery Brigade
5.	Brig Gen Tamjidul Haque Chowdhury, SGP, ndc, afwc, psc	Commander	HQ 86 Signal Brigade
6.	Brig Gen Mohammad Amirul Islam, psc	Chief Engineer	DNCC
7.	Brig Gen H M Mosihur Rahman, SGP, SPP, ndc, afwc, psc	DG Ops and Plan	Armed Forces Division
8.	Lt Col Muhammad Tanvirul Islam, SPP, psc, G+, Artillery	Commanding Officer	25 Air Defense Artillery Regiment
9.	Lt Col Md Atikul Islam, psc, Artillery	Commanding Officer	5 Air Defense Artillery Regiment
10.	Lt Col Zillur Rahman	Director Ops and Plan	Fire and Civil Defense
11.	Lt Col Jeenia Haque, psc, Signals	Staff Officer Ops and Plan	Armed Forces Division
12.	Saleh Ahmed	Chief Engineer	DSCC
13.	Kazi Mohammad Hasan	CEO	Cantonment Board, Dhaka
14.	Maj Istak	GE (Army), Mirpur	Military Engineer Services, Mirpur
15.	Maj Ahmed Ashequl Arefin	GSO-2 (Coord)	National Defense College

Given that the greater the size of the open space, the more people can be accommodated within it. Therefore, the size of the open space is considered as the most important suitability indicator. The population density and the lack of open spaces also contributed towards that decision. Also, without area, even if the site has all the other features, it does not benefit the evacuees much.

Open spaces with area beyond 14,000 m^2 represent an ideal space for potential sheltering space, whereas 8100 m^2 is acceptable, since it is able to accommodate around 3,500 people (i.e. around 850 families). But, areas below that are quite small considering Dhaka Metropolitan Area's population. The areas were calculated in ArcGIS using "Calculate Geometry" option.

It was shown that 79,055 people would be the immediate casualty (CDMP, 2009b); (GFDRR & EMI, 2014). Moreover, it is normal that a certain portion of the affected population would seek shelter elsewhere. Considering all these, the 2019 study showed that 44,76,128 people would seek shelter.

Then the population of each service area has been spatially disaggregated through multiplying population density with the area of each service catchment. The service areas are delineated based on the shortest displacement from each open space. There are as many service areas as there are open spaces. The population of the service areas are dependent not only of size of the area assigned to each open space but also on the population density of the ward that the service area is predominantly intersected upon. This ensures much more realistic calculations of shelter demand, which will be utilized later.

While the capacity of individual site influences its usability for the defined purpose, people seeking shelter also relies upon some sort of suitable networks (e.g., road) to access available shelter areas within a certain time (Tai et al., 2010). Accessibility is measured through number of access roads along with distance from primary road. Higher number of access roads means the population can take the easiest/shortest route to the site, and is expected to reduce their travel time and thus improve connectivity (X. Chen & Zhan, 2014). In Dhaka Metropolitan Area, primary roads must maintain certain width. Therefore, when building collapse does happen to fall on the road, there are greater chances of primary roads still maintaining traffic flows, as compared to secondary and tertiary roads, whose size is often unregulated or the roads may even be dilapidated (A. Chen et al., 2002; Imran & Hossain, 2016; Jahan et al., 2011).

Furthermore, the closer sites are to hospitals and fire stations, quicker service can be expected, whether that be medical attention or emergency rescue (M. S. Hossain et al., 2020, 2021; Schultz et al., 1996; Zhi-Yong, 1987). Therefore, these criteria have been considered as well.

Since Bangladesh is a flood prone country, its the Dhaka Metropolitan Area by virtue of being surrounded in all sides by four rivers also tends to flood. Therefore, it is logical to consider the level of flood risk. A simple way to determine the intensity of floods that may happen at a certain point is to consider the highest flood level at that site. For Dhaka that is the 1998 flood. Since that flood have been studied and mapped by previous researchers like Barua and van Ast (2011), it was chosen to use their result (Figure 3.1). The green color in the Figure 3.1 shows flood free zones, the lighter shade of blue represents shallow flood depth, and darker blue indicates deeper flood. The flood free zone along with F0 zone has been taken as low or no flood in Table 3.1. F1 and F2 zones represent moderate flood and F3 and F4 represent high flood zones.

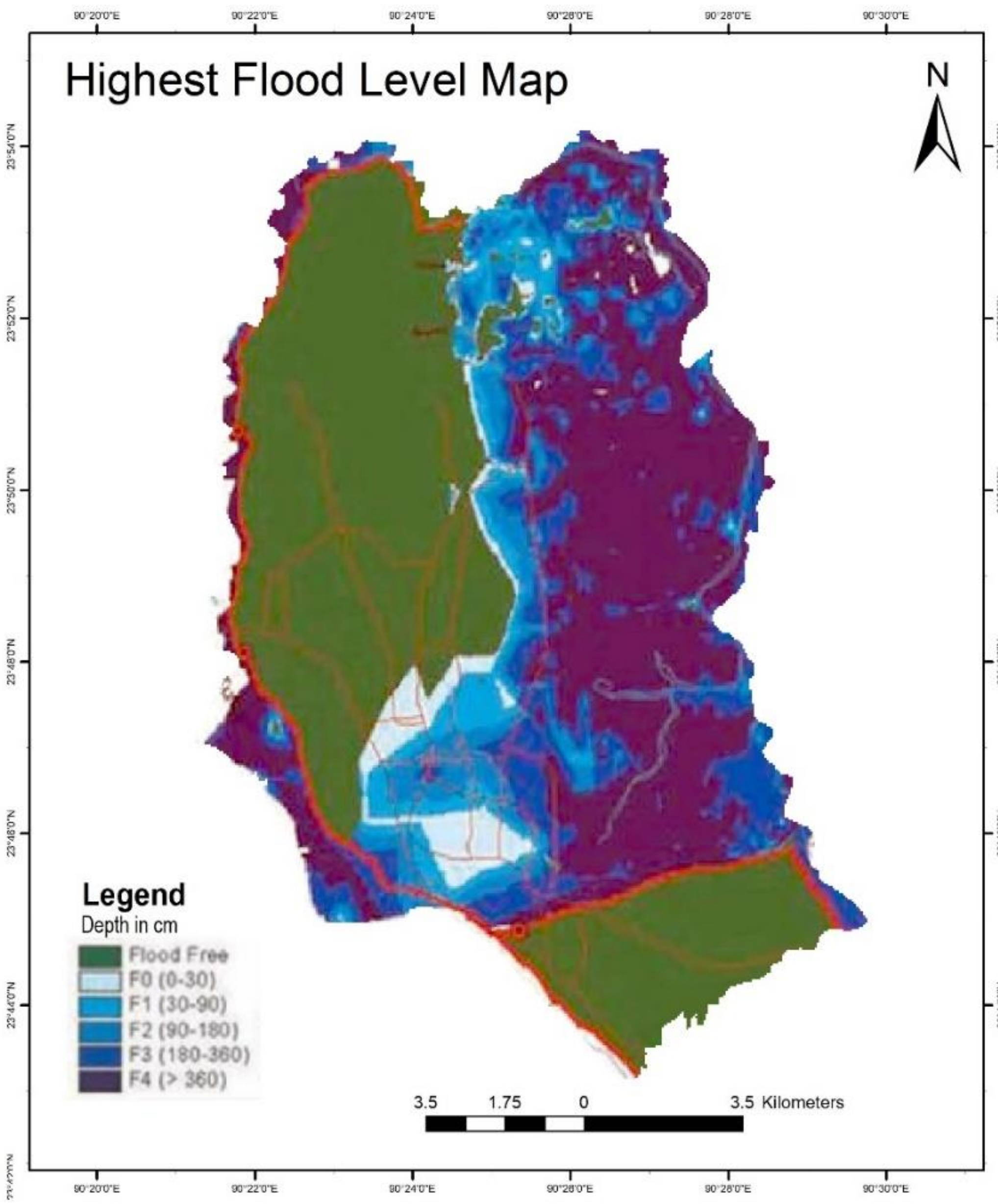


Figure 3.1 The 1998 inundation map of Dhaka adapted from Barua and van Ast (2011).

Finally, each indicator (I) is multiplied with its respective weight (W) and the values are summed. This is then multiplied with the population pressure. It is the number of people that can be accommodated in each shelter (PopCapacity) divided by the total population of that specific catchment (PopCatchment).

$\mathrm{COSI} = \frac{PopCapacity\ i}{PopCatchment\ i} \sum_{n=1}^{n} (\mathrm{Wi} * \mathrm{Ii} + \mathrm{Wi} + 1 * \mathrm{Ii} + 1 + \mathrm{Wi}{+}2 * \mathrm{Ii} + 2 + \mathrm{Wn} * \mathrm{In})$ (Anhorn & Khazai, 2015)

To determine accommodation capacity of each open space, considerations have been made on the covered/required living space per displaced person. As per the standard measurements found in temporary sheltering guidelines, covered floor area per person in universal terms is 3.5 m^2. The dimension allows safe separation, privacy between different age groups and sexes and provide safe, livable, and optimum living condition for medium term to even long term stay in shelters. But, in the immediate aftermath of a disaster, area of less than 3.5 m^2 /person may be adequate to save lives through the provision of adequate short-term shelter to largest number of displaced populations (Humanitarian Charter, 2011). It is obvious that the standards can be adjusted to local conditions. Furthermore, this study (section 5.3) found that 2.3m^2 per person would be ideal in the case of Dhaka Metropolitan Area. So this value has been utilized for space calculation here.

Although other relevant factors exist that affect the suitability of open spaces, they could not be included for this study. Anhorn and Khazai, (2015) considered secondary hazards at the site. For Dhaka, this could be fire outbreak (after quakes) and water logging. However, no such literature exists that studied the fire hazard of open spaces or their proximity to gas mains. Water logging data exists but is not publicly available from the city corporations. Therefore, open source highest flood level data has been used instead. In latter portions of this chapter some long-term shelter sites are identified. Liquefaction data is needed to ensure that these sites will remain safe in the long term, such as during after shocks. At the same time, it was not possible to carry out liquefaction tests due to temporal and financial constraints for all 1197 sites and so this parameter was not used at this stage of the research.

Unfortunately, no map or data of noise pollution could be found that covers the city or even a large portion of it. Although crime is an important factor in post disaster recovery, no data of crime rate for different wards in Dhaka were found either. Existing studies are based on point source observations, usually near hospitals, schools or road crossings (S. C. Chowdhury et al., 2010). Data resolution by Dey et al. (2004) is too coarse to be used as a pollution parameter. To find the type of water supply and electrical connection field visits are required, but could not be undertaken either.

3.3 Results and Discussion

The research intended to find the suitability of the identified open spaces in the study area for sheltering after earthquake using a modified form of the Comprehensive Open Space Suitability Index (COSI). In this regard, data and information have been collected and analyzed on suitability parameters pertaining to three criteria, namely, quality, capacity, and accessibility. Finally, a comprehensive suitability value has been derived for each candidate open space. Based on the comprehensive value, the open spaces in the study area have been classified or ranked as highly suitable, moderately suitable, and less suitable to develop shelter placement in the aftermath of a disaster.

The Comprehensive Open Space Suitability Index is a mathematical representation of how suitable an open space is to be used as an emergency shelter. The higher the index value means higher suitability. The classified the values are set such that values over 0.81 are considered to suitable, values between and equal to 0.81 and 0.31 have moderate suitability and those less than 0.31 have poor suitability. The scores of each open spaces are given in Figure 3.2. Each dot represents the centroid point of each open space (shown in Fig 3.4). In order to be able to perform the required calculations in ArcGIS, each open space polygon was taken as a point situated at respective centroids. These points carried the same information as the polygons (like area value of the polygons were not altered). All the polygons themselves are given in Fig 3.4.

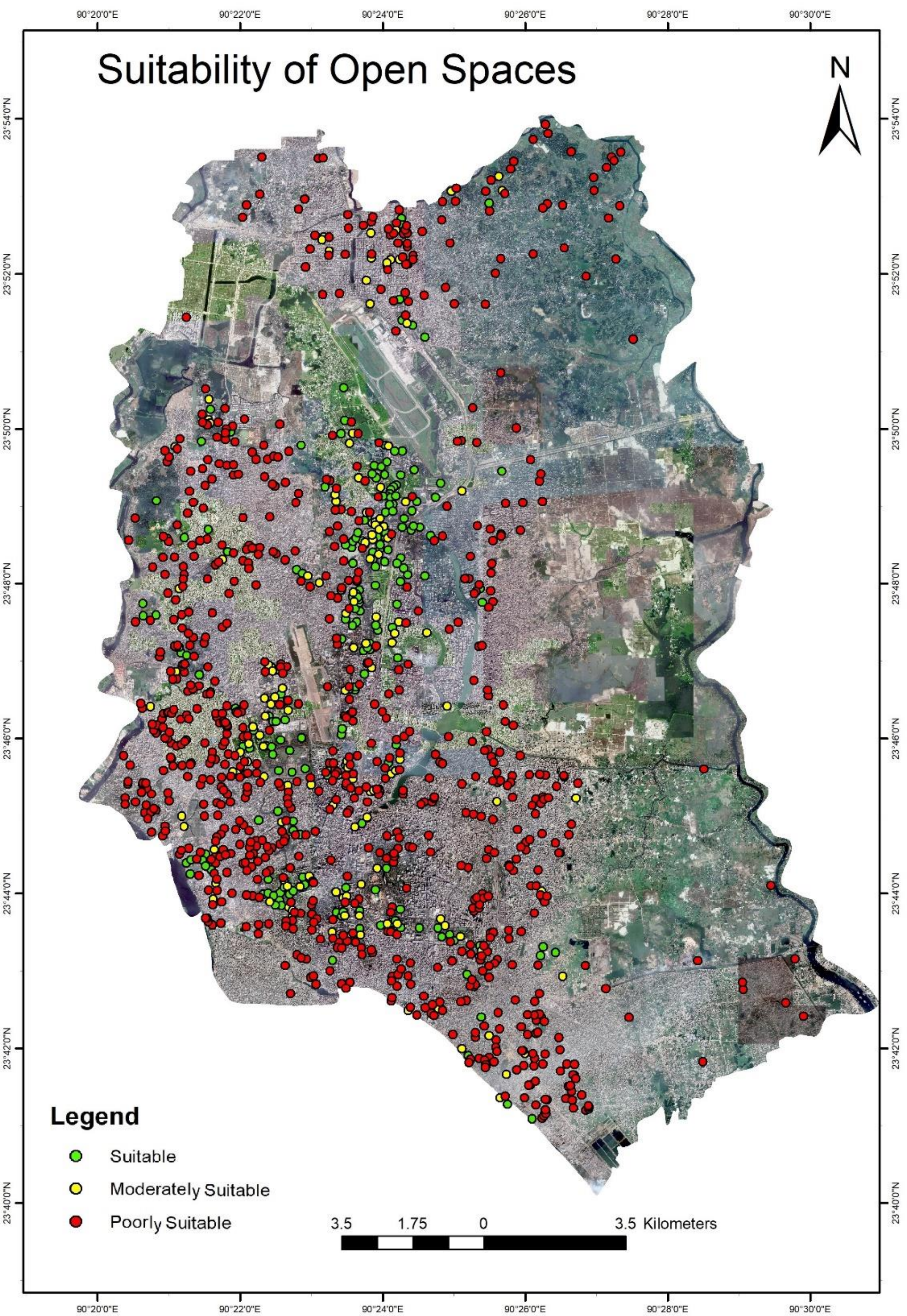


Figure 3.2 This map the Comprehensive Open Space Suitability Index scores for each of the 1197 open spaces in Dhaka Metropolitan Area . The base map is taken from Google Earth.

Considering all the suitability parameters, 217 open spaces falls within the suitable category. However, 151 of candidate open spaces signifies relatively fair (or moderate) suitability for temporary shelter establishment. Majority of the open spaces scores poor (Table 3.3). Open spaces from the lowest ranking category are the least suitable for establishing temporary shelters in the aftermath of earthquake incident in the study area and around 829 open spaces falls within this category. Through closer investigation, it became obvious that the primary restriction was the lack of area in each open space.

Table 3.3: Summary of comprehensive open space suitability scores for all open spaces.

Value range	Number of open spaces	Percent	Suitability status
Less than 0.31	829	70	Poorly suitability
Greater than or equal to 0.31 to 0.81	151	12	Moderately suitability
Greater than 0.81	217	18	Suitable
Total	1197	100	

Since the capacity of each open space was determined along with the total number of people in the catchment of each open space needed to serve, a simple arithmetic subtraction reveals whether each open space can accommodate the shelter seeking population in their individual catchment (also known as service area). The population difference summary reveals some interesting characteristics. 442 open spaces have the ability to accommodate more people even after providing shelter to the shelter seeking population in their respective catchments (Table 3.4).

However, 755 open spaces cannot provide sufficient space for the shelter seeking population in their respective catchments. This means 32,78,211 people in the catchments of those 755 open spaces will be left unaccommodated. If it is assumed that people who are unaccommodated can and will travel to the 442 open spaces (which have the capacity of taking in more people) then the total number of unaccommodated people comes down to about 15,70,125. However, this is an unlikely scenario due to distance and other constrains that will be present in the aftermath an earthquake in a place like Dhaka. The spatial distribution is given in Figure 3.3. All the dots (except for the green colored ones) indicate that the open space cannot accommodate the entire shelter seeking population in its catchment. Yellow colored ones indicate that the population left unaccommodated is less than 2000, whereas the red ones indicate that the unaccommodated population is more than 2000.

Table 3.4: Summary of open space accommodation capacity.

Population difference	Number of open spaces	Aggregate value	Status
Positive	442	(+)17,08,086	Can serve more people
Negative	755	(-)32,78,211	People left unaccommodated
Total	1197	(-)15,70,125	Total people left unaccommodated even if people travel to sites that could serve more people.

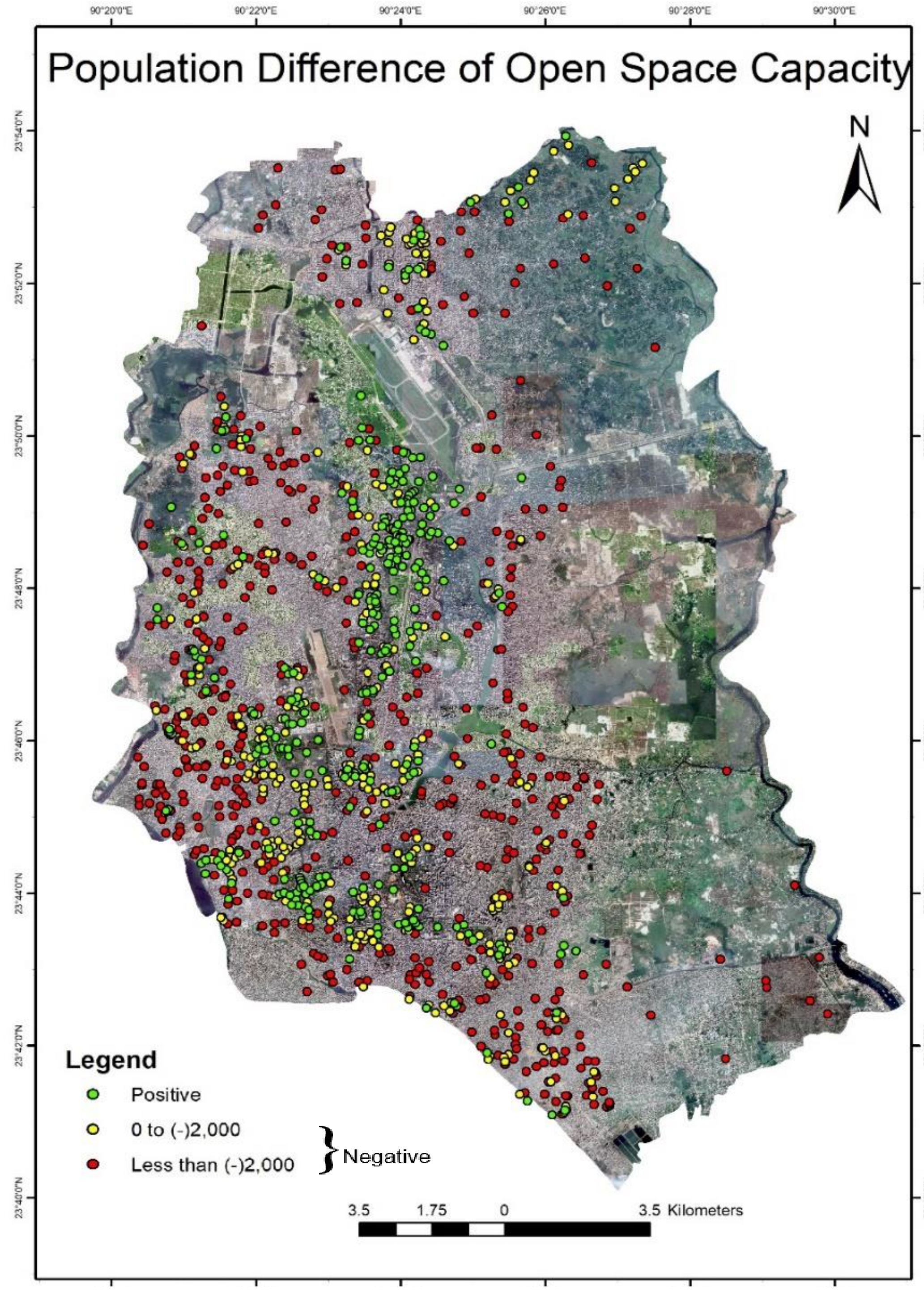


Figure 3.3 The map shows the difference of the population that can be accommodated into each open space (according ideal standard of 2.3 m^2/person considered for Dhaka).

At this stage, indicators, which were used to find the COSI will be discussed. As can be noticed from the weight distribution, area of the open spaces has been prioritized the most. This is because all other indicators are secondary, depending on the availability of space. If portion of the shelter seeking population cannot find the space in their designated open space, then there is no point on having good road access to that open space.

The result of visually identified open spaces in Dhaka Metropolitan Area is given in Fig 3.4. 1197 individual open spaces were identified and mapped within the boundary. These represent a combined area of 10290175.5 m^2. This accounts for only 0.67% of the total land area of the entire metropolitan. Caution was taken to only include sites that matched the assumed definition of open space for this study. Therefore, even though some spaces like, cemeteries, agricultural land, etc. are technically open spaces but they had to be excluded either because of social norms or because they were unfit for consideration of potential shelter. At the same time, it is noteworthy to be reminded of the exclusionary criteria of land (especially those privately owned) which had the potential of future development into built structures, given at the beginning of the study.

As such many spaces in the eastern and western flank of the city were not taken. Obviously these can and will have to be used in the immediate after math of a disaster, but including them in the study would mean that any future reader would think that the accommodation capacity in Dhaka Metropolitan Area is quite good, whereas given the past record of rapid urbanization, in reality it may be that many of such spaces are no longer available leading to adhoc actions during disasters which is exactly what emergency planners want to avoid. Nonetheless, when a population of over 15 lacs will not be able to find shelter, these empty places within Purbachal, Jolshiri and western parts of Uttara will be a good location to place shelters. In addition to parks, stadiums and any green spaces intentionally left open the empty plots can be used as temporary shelters.

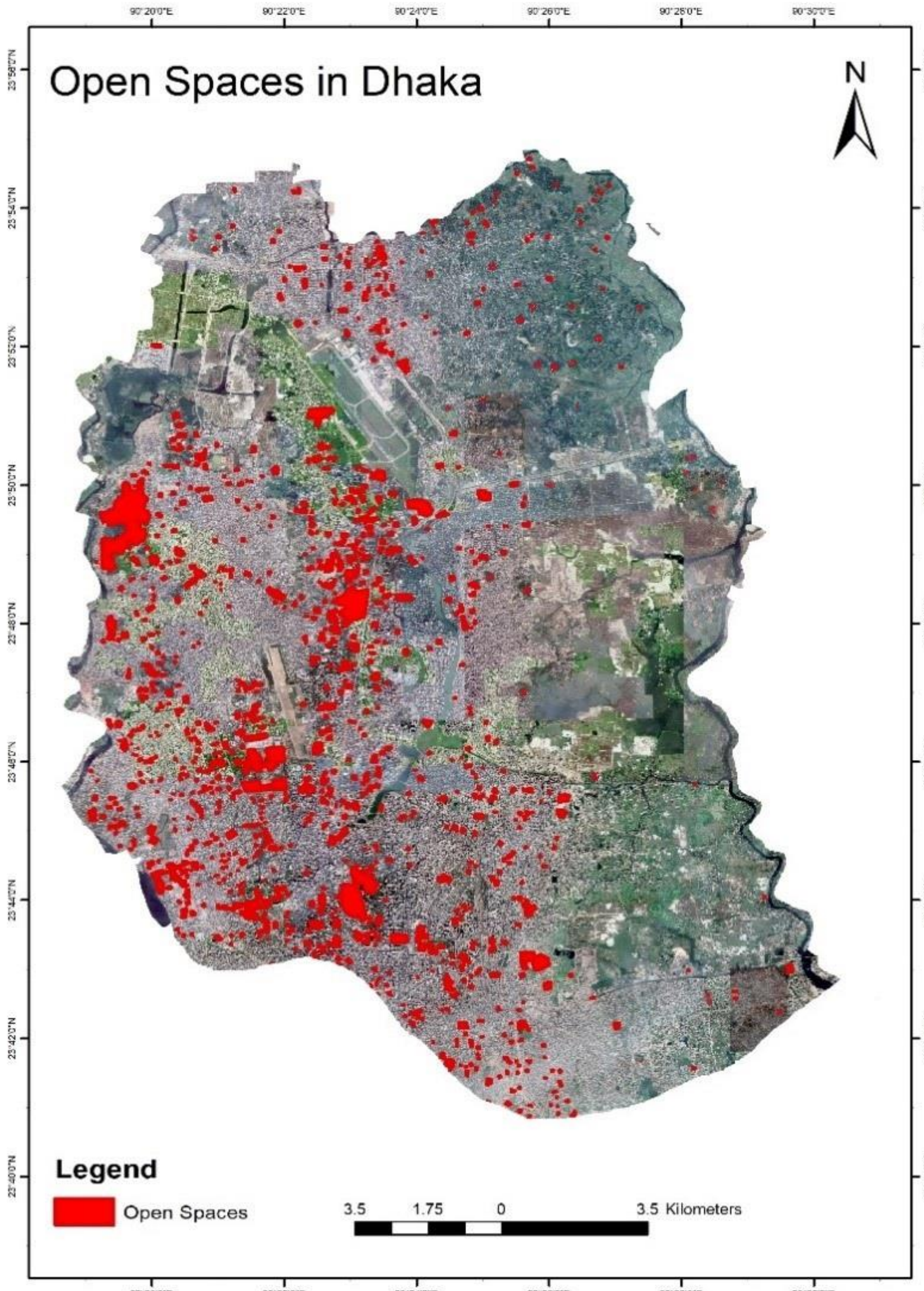


Figure 3.4 The map shows the spatial distribution of the open spaces within Dhaka Metropolitan Area that have been identified to serve as potential shelter sites. It includes all potential open spaces, from small scale to large scale. It is the centroid of these spaces that all other maps display. A zoomed in view is available in the map given in Appendix: A2.

After mapping of the spaces, the catchment/service areas of each open space were found (Fig 3.5).

This is based on the logic that the population closest to the open space will travel to that open space if need arises. The population of each catchment is representative of each ward's population density.

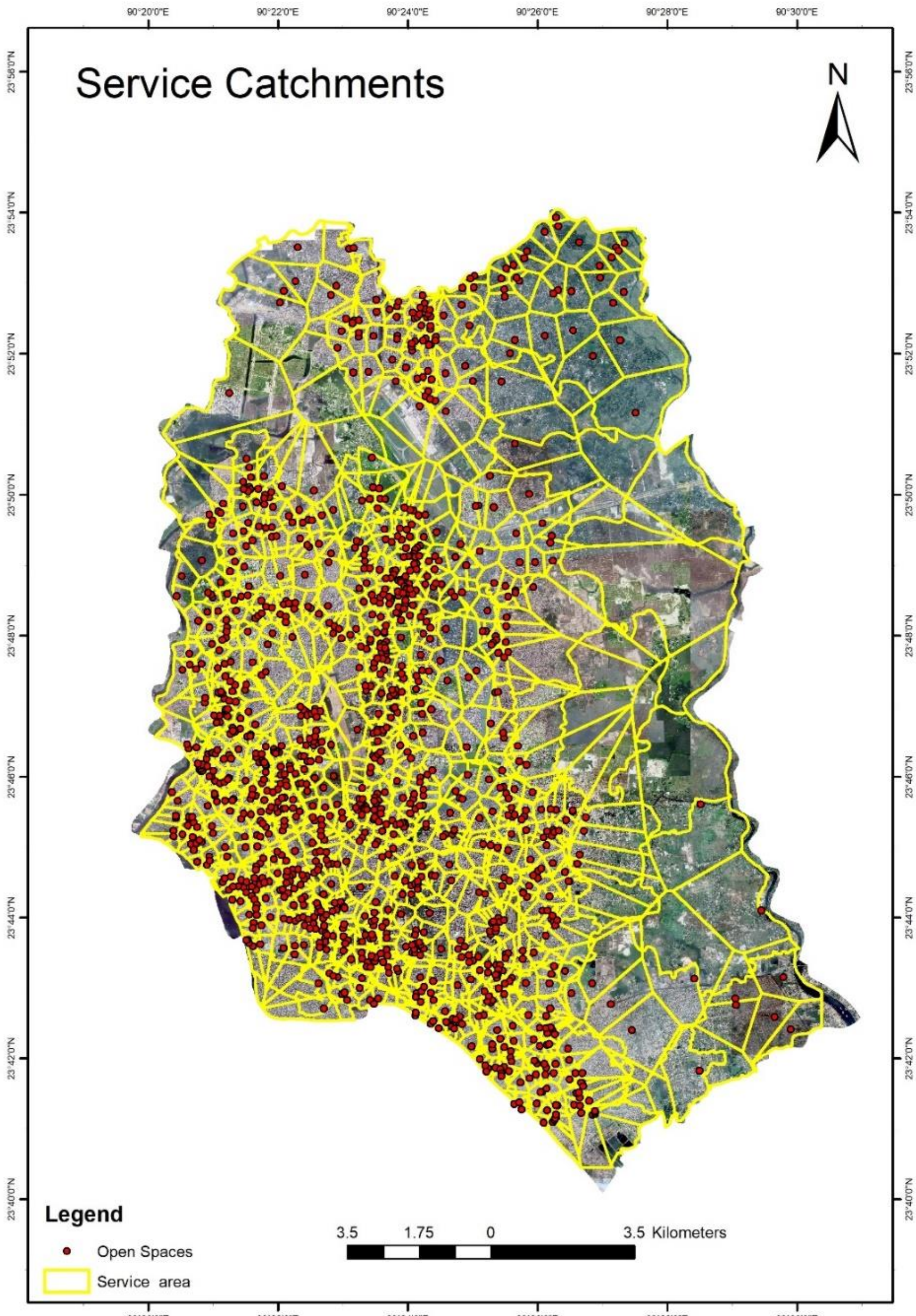


Figure 3.5 The yellow marked areas are the service catchment or service area of each open space. Since there are 1197 open spaces so there are 1197 service catchments.

Accessibility to the shelters forms an essential indicator of suitability since without proper accessibility the population cannot avail the facilities located at the open space. This was proven time and time again in past disasters (section 2.3). Distance from primary road and number of access road leading to each open space have been considered (Table 3.5 and Fig. 3.6). In the immediate aftermath of an earthquake incident, the first priority is to conduct search & rescue and evacuation activities within the least possible time. While planning for the emergency shelter placement sites, it is therefore important to consider the convenient routes to and from the open spaces. Most open spaces were found to be more than 500 m away from the main roads. It must be pointed out that in this context, primary roads mean the same as main roads. Sometimes they are referred to zilla roads or national highways (depending on the agency who names them).

A significant number of open spaces are quite close to the main roads as well. On the other hand, an overwhelming majority of the open spaces had 2 access roads, and a very few had 1 access road. Greater number of access roads means easier access for the surrounding population in addition to working as back up in case one road is blocked due to surface rupture or building collapse, another can be used to access the open space. Most of Dhaka Metropolitan Area's open spaces good to moderate accessibility. Appropriate and accessible road linkage is one of the important factors indicating accessibility. The roads or the transportation network serve as the potential gateway to emergency sheltering spaces. Enhanced connectedness of spaces with road network leads to better serviceability of a particular open space.

Table 3.5: Showing the summary of accessibility Indicators

Distance from primary roads	No. of open spaces	Number of access roads	No. of open spaces
Close (<250 m)	412	More than 3	218
Moderately far (250 to 500 m)	227	2	915
Very far (>500 m)	508	1	64
Total	1197	Total	1197

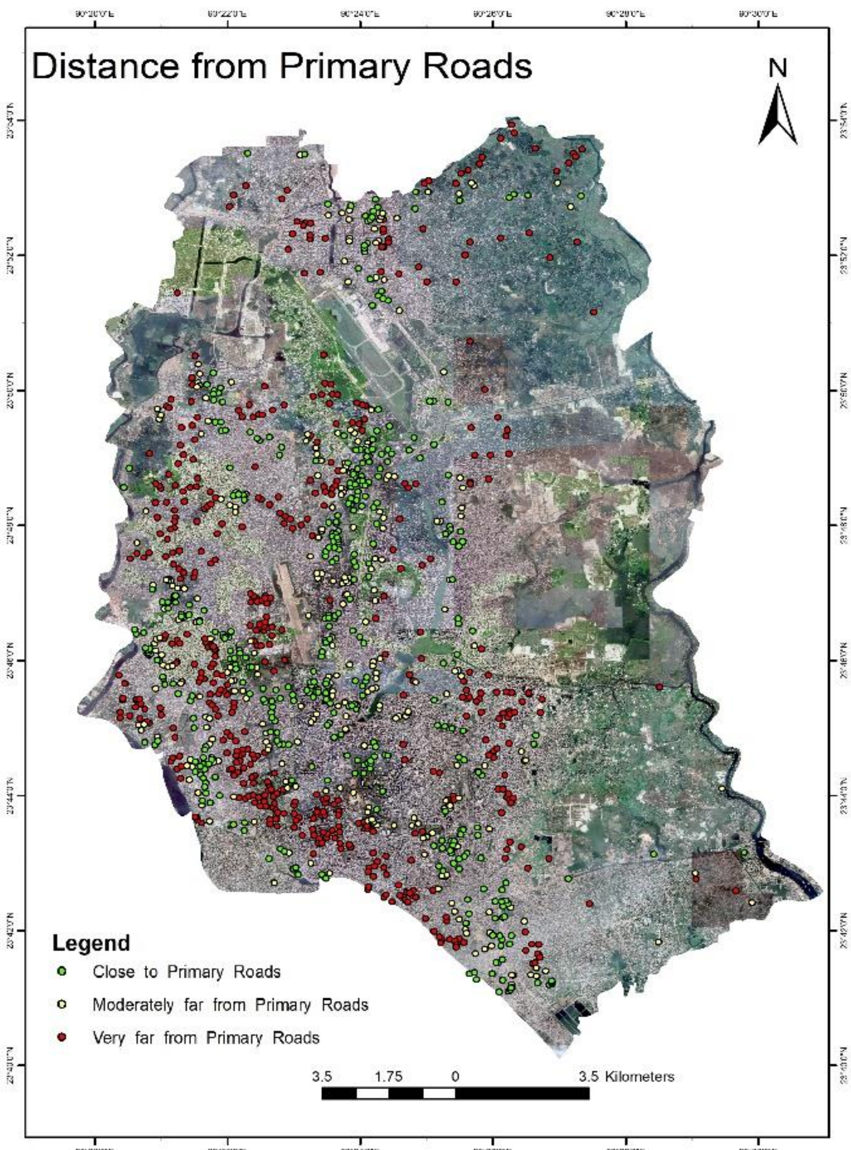


Figure 3.6 The map shows the open spaces with color coding. The colors indicate how far away they are from the nearest primary roads. Red dots mean most of the open spaces are more than 500 m away from primary roads.

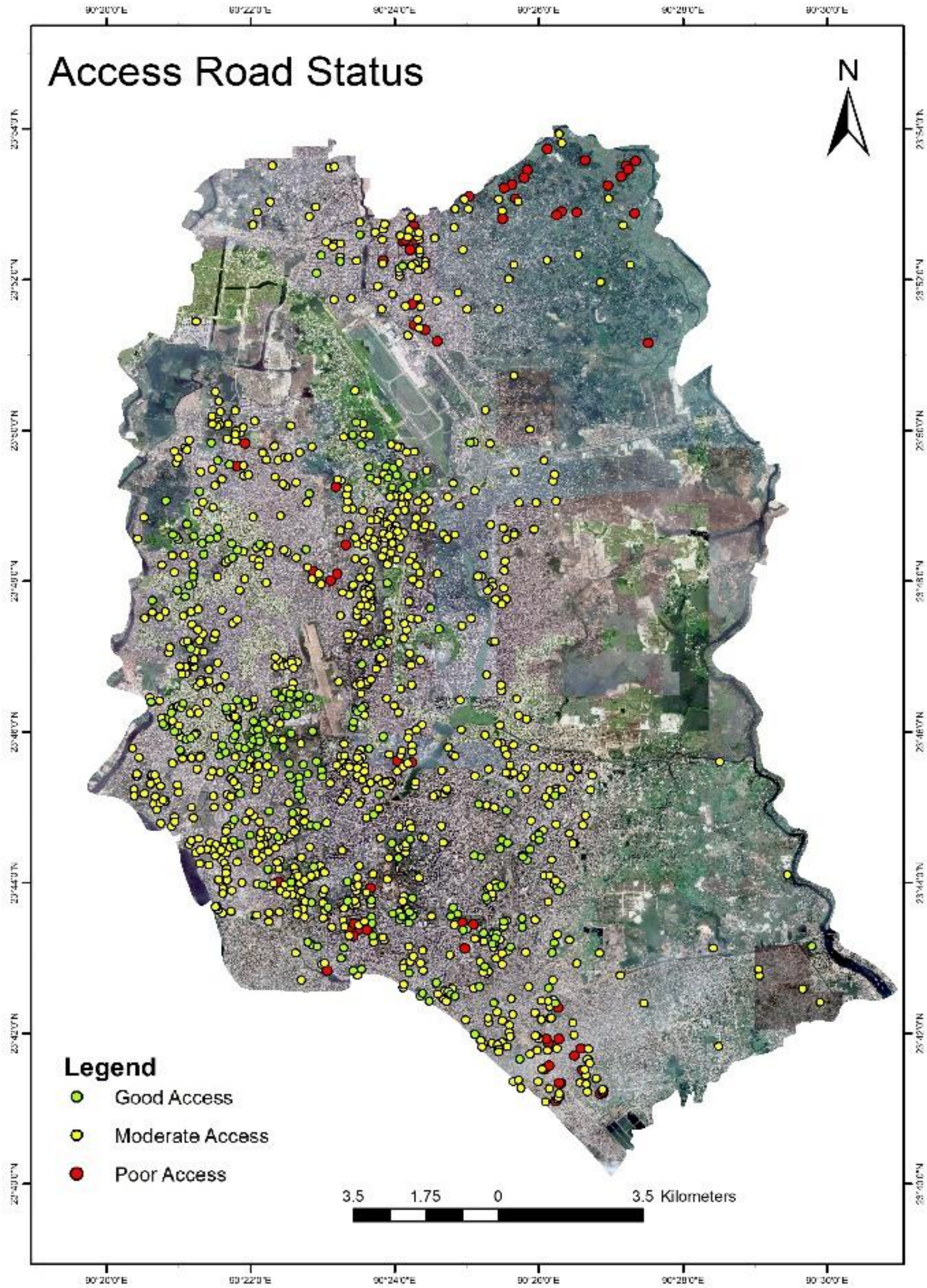


Figure 3.7 The map shows access road status of the open spaces.

Since Fire Service and Civil Defence is responsible (primary responders) for emergencies and rescue, the location of open space from fire stations where Fire Service and Civil Defence personnel are housed were considered. 21 Fire stations were successfully mapped (Figure 3.8).

Their locations were taken from resources like Google maps and other open-source repositories since government approved data could not be found at a single source. It is easily noticeable that

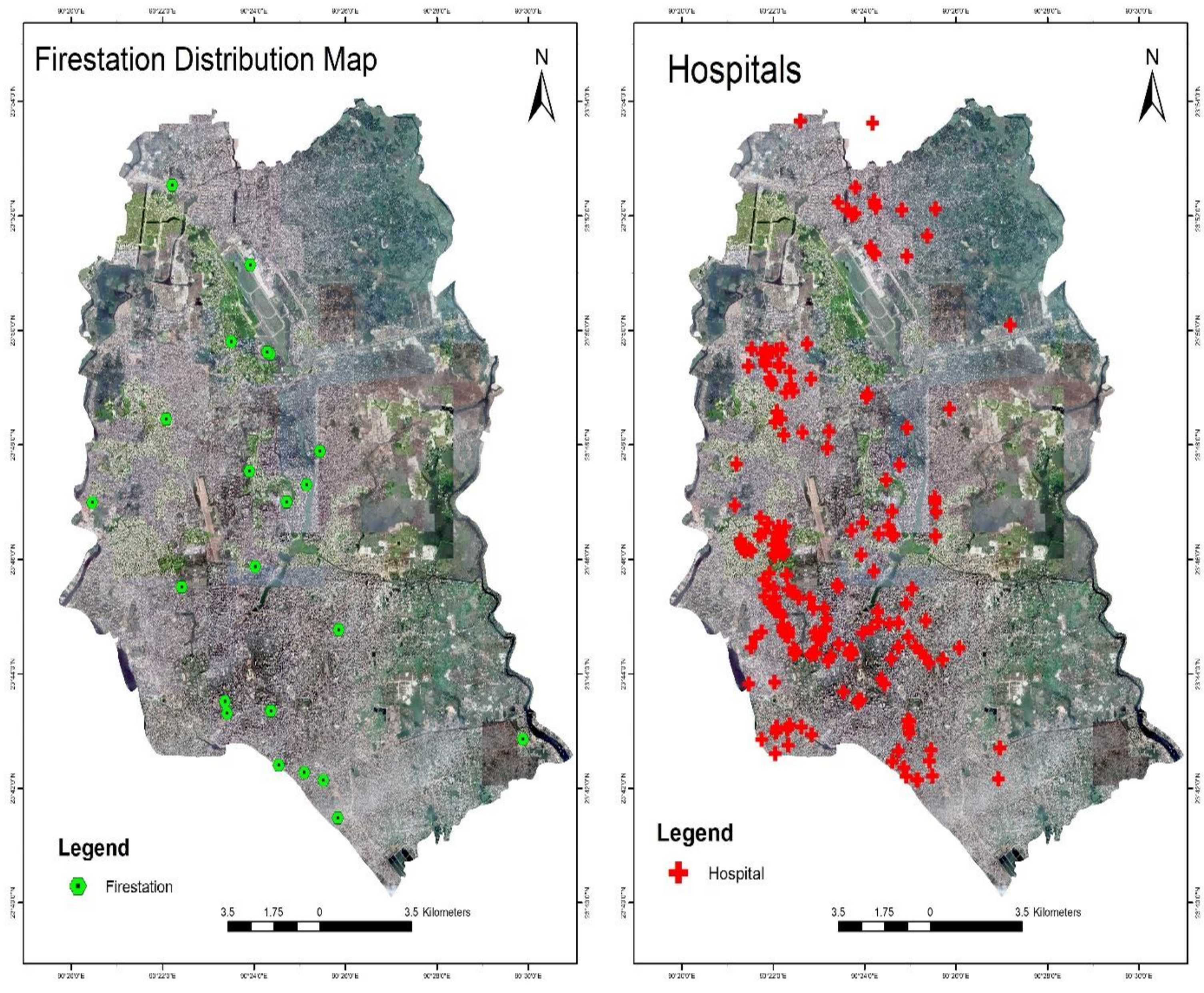


Figure 3.8 The figure on the left shows the various location of the fire station in Dhaka. On the right is the hospital map.

their quantity is not enough. Heavily populated areas in the north and west have only a few stations.

Similar techniques were used to map hospitals (Figure 3.8). 216 hospitals were found within Dhaka Metropolitan Area. Since most hospitals are privately owned in Dhaka, they were developed keeping the quantity of population they serve in mind. Therefore, their distribution naturally follows the population density. Hospitals provide healthcare and in post-earthquake scenario they are deem crucial resources. Most hospitals in Dhaka Metropolitan Area may not have an adequate earthquake contingency or continuity plan, so it is crucial that they develop one so that they are able to better serve the people (Tanim & Urmi, 2014).

The research has identified the open spaces in the study area that are suitable for sheltering. Establishing temporary shelters in the identified well suitable sites will ensure service provision to the maximum number of distressed populations with better quality and accessibility within the shortest possible time. Again, the areas identified as poor suitability may exhibit inadequate facilitation, low quality as well as impeded accessibility that may eventually lead to reduced efficiency of emergency response initiatives.

It is well known that in post-earthquake scenario, shelter requirement ranges from immediate to long term (Bolin, 1993; Bolin & Stanford, 1991; Li et al., 2017). Even in Kobe earthquake in 1995, the last shelter was closed down after many months (Japan Times, 2000). Given the vulnerability context of Dhaka Metropolitan Area, it would be better to prepare some sites for those people who require long term sheltering. Given that people will begin to move out of the shelters as time progresses and recovery activities move ahead, so the population volume requiring long term shelter facilities will be lower than those seeking temporary shelter. Nonetheless, it can be expected that long term shelters will be necessary. Large areas can fit more people and at the same time accommodate different facilities required to help them sustain during their long stay. Closeness to facilities and to the evacuees' home is also seen as a positive factor. Given that, based on such requirements a classification of suitability has already been performed so it is only logical to select the open spaces which are highly suitable, for usage in the long term sheltering (Figure 3.9 and Appendix: A3).

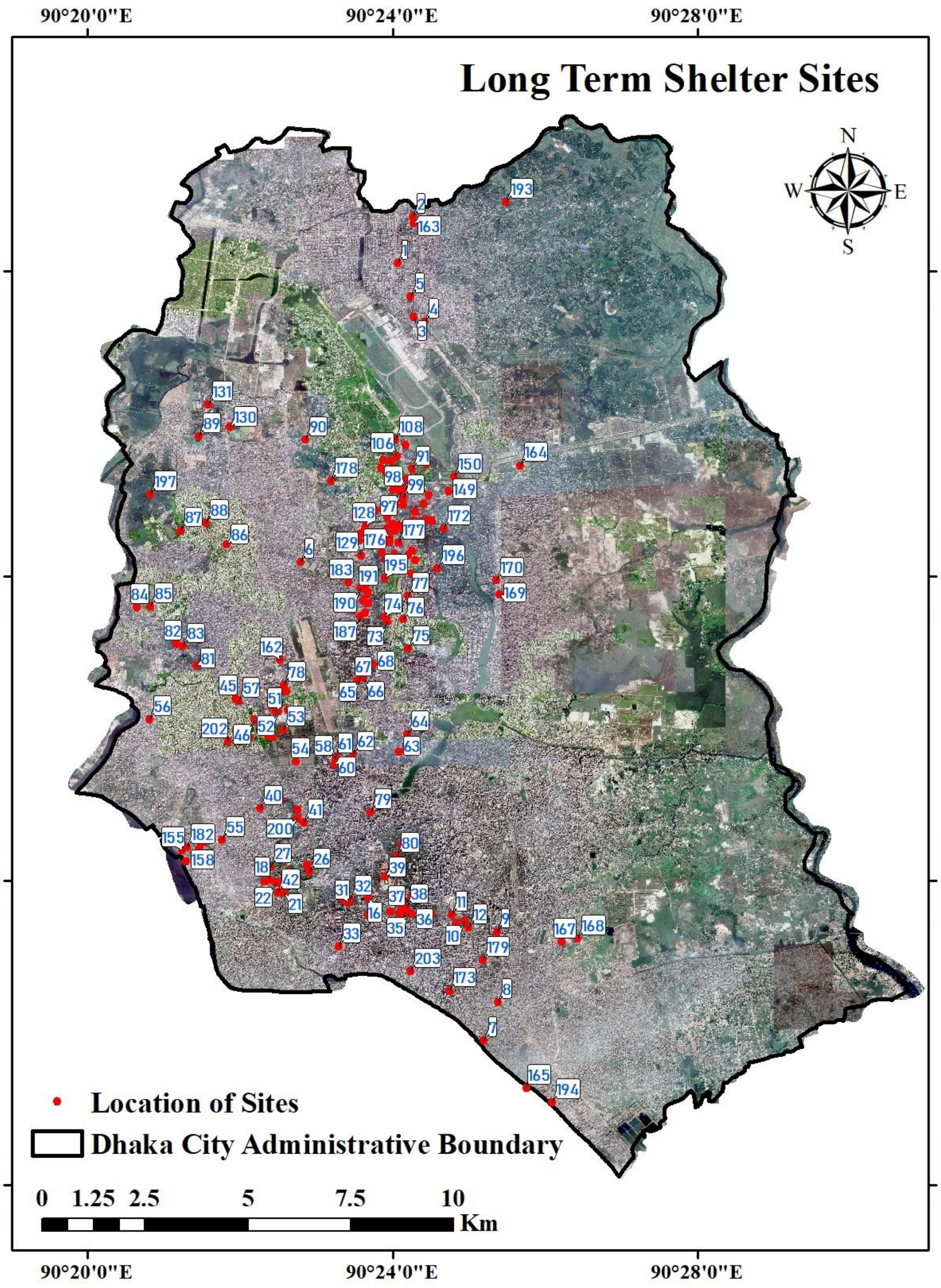


Figure 3.9 The map shows suggested long term shelter sites, with corresponding shelter ID. The names of these shelters are given in A3.

In A3 the latitude and longitude can be used to find the open spaces in maps. Not all the open spaces had names available in google maps. When that was the case, the site was named after the area/road/landmark nearest to it. It is important to note that 217 sites were identified as suitable, however, some of them are not appropriate for long term usage for obvious reasons of security, key point functionality or necessity during rehabilitation process. These include several spaces around the national parliament, airport, prime minister's office, various country's high commission, high court. As such, they are not considered in this list.

It should not be interpreted that the rest of the sites are not unfit for post-earthquake usage. Rather, what is meant is that these sites are expected to be specifically better when it comes to long term sheltering. In order to utilize the other sites, at their current conditions one way is to consider them for short to medium term shelter, and as places where people can take first aid, use for evacuation or for gathering in the immediate after math of the earthquake, and as center for food and relief distribution etc.

3.4 Summary

In this study, around 18% of the sites suitable. Whereas 12 % of the open spaces qualified as relatively moderately suitable for temporary shelter establishment, but majority (around 70%) of the open spaces scores poor. 442 open spaces have the ability to accommodate more people who may come beyond their respective population catchments. However, 32,78,211 people from the rest of the 755 sites cannot get space in their designated open space. While the sites with good scores are expected to perform best as sheltering sites, the rest of the sites may also be used according to requirements that may arise. 217 long term shelter placement sites have also been identified at this part of the study. For those 15,70,125 people that cannot be accommodated into identified shelters, the open and safe places in Uttara, Purchal and Jolshiri can be utilized. A portion of this population may also seek shelter in their relatives' house or evacuate from Dhaka entirely. Although, transferring people from heavily urbanized areas in the immediate aftermath of an earthquake remains a challenge. This is definitely an area that further research can explore to arrive at concrete conclusions.

Although a set of criteria was used to arrive at this, area of the open spaces were the main reason behind such results, and this was due to the weight distribution of the indicators. The logic is if there is no space to accommodate the people what use is the close fire station or good accessibility. Obviously, other factors like accessibility, closeness to essential services and hazards played a role in determining the index score, and hence the name Comprehensive Open Space Suitability Index.

However, the lack of building footprint, floor number and floor-space data has prevented a deeper network analysis, which not only would have provided more representative accessibility scores but would also make the suitability scores more meaningful. It is noteworthy that the 2019 study those results have been used here (owing to the lack of any other data) made a statistical projection from 2009 data. This assumed that the trends present in 2009 continued through 2019. This may not be completely accurate, and requires new seismic risk assessments including in depth building surveys to verify. Such a study could show how much risk has Dhaka accumulated in the last decade and is definitely a future recommendation.

The information derived from the research work will help to establish a comprehensive methodology to evaluate suitability of open spaces to serve as emergency shelter sites in a post-earthquake urban context. The resultant Comprehensive Open Space Suitability Index (COSI) database will provide extensive assistance to emergency planners and disaster managers in identifying optimum areas for placing emergency shelter camps in the immediate aftermath of an earthquake incident and thus improve response efficiency by reducing the response time. Authentic and reliable information on site suitability will help avoid confusion among emergency responders and policy level personnel in making decisions for emergency relief and mass care in a post disaster situation. Prepositioning of necessary items, adequate contingency planning, advanced collaboration of potential responders can be conducted at site specific level, which will help improve cost-efficiency and time effectiveness of emergency response operations in post disaster situation. Again, the identified areas with low suitability can be provided with improved services and facilities to improve their capacity in service provision. Besides that, hotspots of potentially unserved populated areas can be identified from the spatial representation of coverage. Moreover, the generated information from this study is expected to serve as a key to develop improved contingency planning for earthquake in the study area, which will eventually strengthen the overall earthquake response preparedness of the entire area and help reduce human casualties, sufferings, and economic loss in case of an earthquake incident. In the future, inclusion of field-based data of all the 1197 sites is expected to further improve the results of this study.

Chapter 4:
Seismic Hazard Analysis of Selected Open Spaces

4.1 Background

Liquefaction-induced ground failure can cause significant casualties and loss of properties (Chao et al., 2010; Hossain et al., 2020a; Ku et al., 2004; Lee et al., 2007; Sassa and Takagawa, 2019; Seed and Idriss, 1967). Even if the sites are not carrying any built structures, any significant amount of liquefaction will prevent the site from being used a post-disaster shelter. It occurs when a cohesionless saturated or partially saturated soil substantially loses strength and stiffness due to shaking during an earthquake and soils behaves like a liquid. In Bangladesh, most of the subsurface lithology is characterized by unconsolidated, sandy, and clayey floodplain sediments. In the alluvial deposits of Bangladesh, following the Srimangal Earthquake in 1918, the Great Indian Earthquake in 1897, and the Bengal Earthquake in 1885, the evidence of widespread liquefaction was documented (Hossain et al., 2020b; Middlemiss, 1885; Oldham, 1899; Stuart, 1920). Given that the study focuses on post-earthquake sheltering, and has identified suitable sites for that purpose, if those sites were to be vulnerable to liquefaction then the results would be rendered moot. So, studying the liquefaction potential of the open spaces is essential. But detailed in situ tests (e.g., Standard Penetration Test (SPT), P-S logging, Cone Penetration Test (CPT) data) or soil laboratory tests (e.g., cyclic triaxial test) for all of the selected sites for long-term shelter identified in chapter 3 are out of the scope of this study due to obvious time and financial constraints.

Therefore, initially, liquefaction potential for these sites was evaluated considering the general geomorphological classes according to Kotoda et al. 1988 and Matsuoka et al. 2019. And the geomorphological classes (Figure **4.1**) of the sites were identified from (Kamal and Midorikawa, 2004)

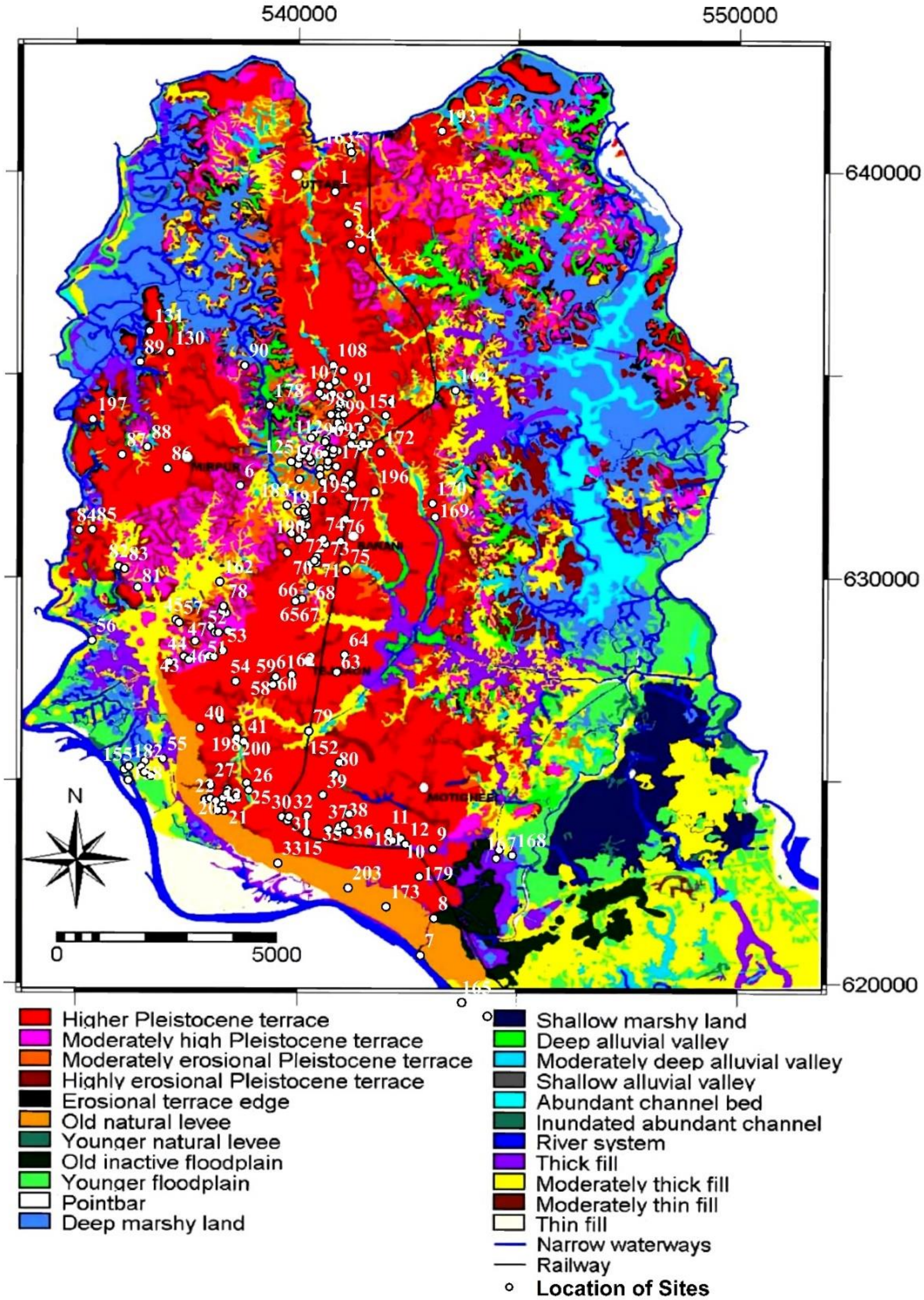


Figure 4.1 **Location of 203 selected sites on the detailed geomorphological map by Kamal & Midorikawa, 2004**.

Throughout the 203 selected sites (given in Appendix: A4) total of seven different geomorphological classes have been found, namely, Higher Pleistocene Terrace, Moderately High Pleistocene Terrace, Erosional Terrace Edge, Moderately Thick Fill, Thick Fill, Old Natural Levee and Younger Floodplain. Among them, most of the sites are in the Higher Pleistocene Terrace, which is made up of a thick layer of reddish to yellowish-brown, medium stiff to stiff silty clay, which has one of the lowest liquefaction potential areas even in a large earthquake. Moderately high Pleistocene Terrace and Erosional Terrace Edge also have low liquefaction potential. Old natural levees have high liquefaction potential, and the other three classes, particularly artificial fills, have very high liquefaction during a moderate to major earthquake (Kotoda et al., 1988; Matsuoka et al., 2019).

This generalized liquefaction analysis revealed that out of the 203 sites, 37 have high liquefaction possibility. Since it is based on a generalization methodology, more details need to be studied to find the extent that the sites may liquefy. These sites are given in the Appendix: A5. However, based on COSI scores and the lowest liquefaction potential values (obtained for generalized study), the rest of the 166 sites can be considered relatively better. Still, it is preferable to conduct a detailed test to be confirmed. Owing to the tests' costs, time requirements, and labor engagement, only eight sites were selected for further study (detailed seismic hazard including liquefaction potential investigation). The eight sites were selected as a case study with the intention of being relatively spread out over Dhaka Metropolitan Area. Since boring and hammering are required, so ease of conducting the tests and the possibility of getting permissions also played a role in site selection. The eight sites are given in Figure 4.2.

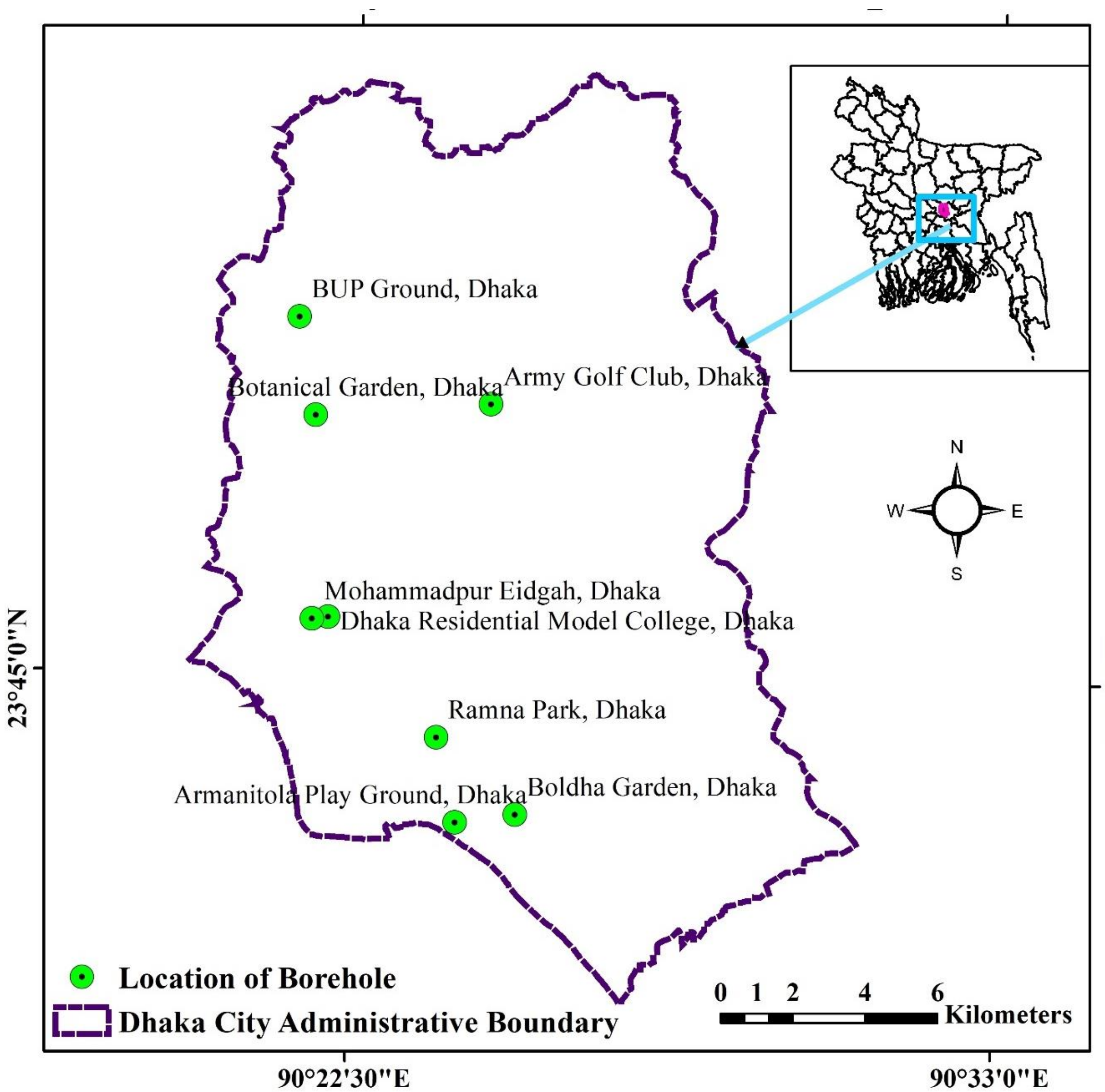


Figure 4.2 The location of the selected eight open spaces in Dhaka Metropolitan Area where boreholes have been drilled for detailed liquefaction hazard assessment.

For liquefaction potential evaluation, seismic hazard assessment and site response studies are prerequisites. Therefore, probabilistic seismic hazard assessment and site response are conducted for these selected eight spaces to calculate liquefaction in a detailed manner.

Throughout this section, the name of the eight sites has been used interchangeably with the borehole (BH) ID. They are **BH-1** (Army Golf Club), **BH-2** (Bangladesh University of

Professionals Ground), **BH-3** (Residential Model College), **BH-4** (Mohammadpur Eidgah), **BH-5** (Botanical Garden), **BH-6** (Baldha Garden), **BH-7** (Ramna Park), **BH-8** (Armanitola Playground).

4.2 Probabilistic Seismic Hazard Assessment (PSHA)

PSHA deals with the exceedance probability of various ground motion levels over a specific timeframe. This method was first proposed by Cornell (1968). All potential sources, along with their seismicity parameters and respective computational sources-to-site distances are amalgamated to estimate ground motion parameters. In the parameter estimation process, consideration of all possible GMPEs is also a common practice. The final product of this process is a hazard curve developed from ground motion intensity and annual exceedance rate or a uniform hazard spectrum for a definite annual exceedance rate (McGuire, 2001).

4.2.1 Materials and Method

The benefit of PSHA is mainly for accounting the most of the uncertainties (source, magnitude, time, intensity, etc.) involved with seismic hazards (Kramer, 1996). Baker (2013) has summarized the activities associated with PSHA in 5 generalized steps based on the procedure of Cornell (1968). These steps are as follows:

Step-1: Identification of Possible Earthquake Sources

Step-2: Identification of Magnitude

Step-3: Source to Site Distance Identification

Step-4: Employment of Appropriate Ground Motion Prediction Equation (GMPE)

Step-5: Combination of All Information

This particular hazard assessment study considered all of the procedures stated above that are appropriate to PSHA and integrated them according to the study's flexibility.

4.2.1.1 Source Model

Through a literature review combined with internationally accessible catalogs from renowned authorities in this field, special attention has been paid to geodesy, active tectonic structures, and geodynamic characteristics of the study regions when considering seismogenic sources applicable to Bangladesh. Seismic sources taken for this research contains

a) Gridded Seismicity or Background Seismicity Source,

b) Linear Source,

c) Areal Source.

Background Seismicity Source

The earthquake catalog provides essential information to quantify risk regardless of the approach, as recurrence relation is derived from the catalog. Unfortunately, Bangladesh does not possess regular documentation of earthquakes in Bangladesh and its adjoining tectonic region. In compensation, earthquake catalog prepared from all renowned international sources was adopted from Samm-A (2020) where instrumental earthquake records are taken from USGS online catalog, GCMT-Global Centroid Moment Tensor, ISC-GEM, NEIC catalog. For historical earthquakes, Samm-A (2020) considered the published works of Alam & Dominey-Howes (2016), Ambraseys and Douglas (2004) and Szeliga et al. (2010). These records had a geographical limit of 300 km surrounding Dhaka city. The earthquake events are sorted in chronological order, free of any redundancy. The catalog is standardized in a single unit of measurement, Moment magnitude (Mw), using the globally accepted conversion equation of Scordili (2006).

Parameters of truncated Gutenberg-Richter model for the declustered catalog is estimated considering the lower extreme magnitude value at 4.5 Mw and respective completeness period of each catalog using the following equation.

$$log_{10}\lambda_{\mathrm{m}} = \mathrm{a} - \mathrm{bm}; \quad (4.1)$$

$$\lambda_{\mathrm{m}} = 10^{a} 10^{-bm}$$

λm denotes the number of earthquakes with a higher value than lower extreme magnitude m per year. a and b denotes seismic coefficients. These coefficients represent the gross earthquake rate in an area and the correlative ratio of small to large earthquake events. For the background seismicity model, a uniform value of b parameter is employed separately for the entire study area for shallow and deep seismicity. In this model, the b values of the declustered catalog are calculated with the maximum-likelihood method of seismic parameter estimation by Weichart (1980) for earthquakes ranging from 4.5 to 7.5 Mw, with special attention given to different completeness times for different magnitude ranges of those catalogs. The calculated b value is 0.85. The activity rate is smoothed using kernel estimation.

Linear source

Significant earthquakes are commonly related to active faults, and in seismic hazard assessment, such active faults are termed linear seismic sources. The majority number of crustal faults within Bangladesh is not fully recognized or acknowledged based on their extent and slip characteristics. Paleo-seismological trenching and seismicity studies help infer faults' geologic slip rates. Linear sources are characterized from Samm-A (2020).

For each linear source, two types of seismicity models have been applied, namely the Gutenberg–Richter recurrence models and the characteristic seismicity model with equal weighting (1.0, 1.0) and probability (0.5, 0.5) except the Dauki. **Areal source**

Delineation of the areal seismic source demands unvarying and homogeneous seismicity within the unit zone. Baker (2013) assumes that each point of the areal source has equal potential to create a future earthquake. Based on the changes of seismicity in case of magnitude and focal depth distributed along the study area, and consideration of events in the comprehensive declustered catalog around geological structures, published literature dealing with a similar concept to this study, ten areal source zones are considered for this study from Samm-A (2020). Parameters of truncated Gutenberg-Richter model for three different declustered catalog is estimated considering the lower extreme magnitude value at 4.5 Mw and respective completeness period for each zone assessed by the method of Tinti & Mulargia (1985) of each catalog using following equation

$$\lambda_m = \lambda_0 \frac{e^{-\beta(\mathrm{m_w} - \mathrm{m_0})}}{e^{-\beta(\mathrm{m_u} - \mathrm{m_0})}} \quad (4.2)$$

In this model, the λ , a, b values of the catalog is calculated with the maximum-likelihood method of seismic parameter estimation by Weichart (1980) for greater than Mw 4.5, with special attention given to different completeness period for different magnitude bins with an equal interval of those catalogs. The regional maximum magnitude of all areal sources has been estimated from Kijko and Singh's (2011) Mmax program in MATLAB.

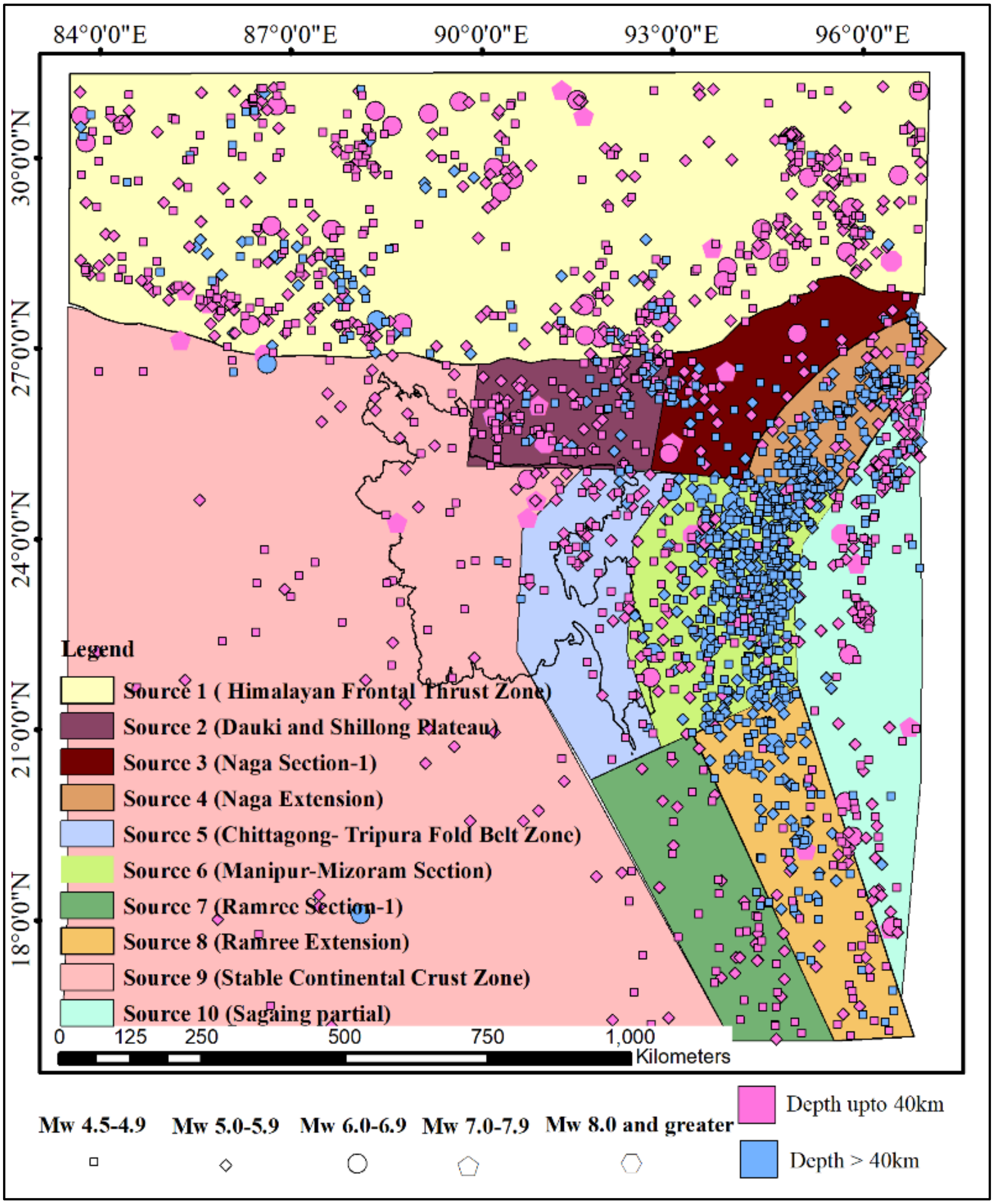


Figure 4.3 Areal sources (shallow crustal and subduction) considered for this study, taken from Samm-A (2020).

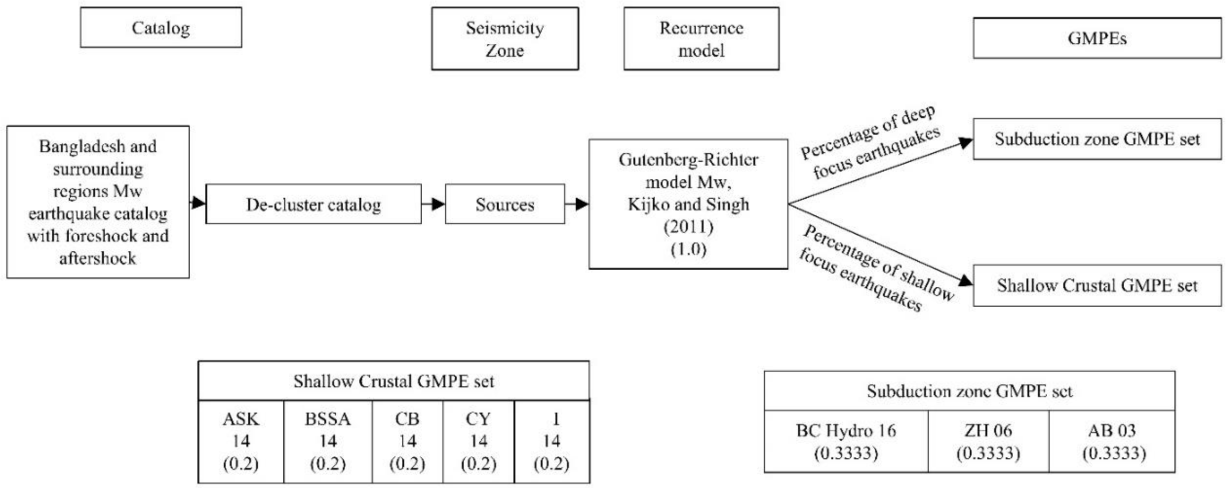


Figure 4.4 Logic tree combination for areal (shallow crustal and subduction) source model. Shallow crustal set includes GMPEs of Abrahamson, Silva and Kamai (2014) [ASK 14], Idriss (2014) [I 14], Campbell and Bozorgnia (2014) [CB 14], Boore, Stewart, Seyhan and Atkinson (2014) [BSSA 14], Chiou and Youngs (2014) [CY 14]. Subduction zone GMPE set includes Abrahamson et al. (2016) [BC Hydro16], Atkinson and Boore (2003) [AB03], and Zhao et al. (2006) [ZH06].

Table 4.1 Seismicity parameters and GMPE combination for different areal sources

Source name	a-value	b-value	λ	Mu	Uncertainty in Mu	Computed slip rate	Shallow EQ (%)	GMPE (Shallow crustal , Subduction)
Himalayan Frontal Thrust	4.21	0.76	14.13	9.00	0.5	10.7	85	(85,15)
Dauki	4.37	0.95	3.55	8.98	1.0	6.37	74	(74,26)
Naga section	3.46	0.79	1.95	7.95	0.6	1.85	58	(58,42)
Naga Extension	3.96	0.82	4.50	7.21	0.3	1.71	20	(20,80)
Chittagong-Tripura section	3.71	0.86	1.94	7.08	0.3	0.28	90	(90,10)

Mizoram-Manipur section	4.55	0.87	11.82	8.85	0.2	17.2	17	(17,83)
Ramree section 1	4.30	1.02	1.55	9.30*	0.7	1.57	93	(93,07)
Ramree-extention	4.37	0.92	4.72	8.18	0.6	2.14	33	(33,67)
Sagaing	3.49	0.72	4.00	8.45	0.5	6.85	78	(78,22)
Stable Continental crust	3.05	0.65	2.75	8.49	0.5	1.14	95	(95,05)

4.2.1.2 GMPE Selection

2 sets of Ground Motion Prediction Equations (GMPEs) are applied for this study. First set contains combination of 5 established GMPEs for shallow crustal earthquakes formulated in 2008 utilizing five global data sets of ground motions under the NGA-west program of PEER. The first set has been assigned for shallow crustal earthquake sources (Linear sources). Logic tree weights for this set is assigned conserving the similarity of weight assignment to this first set with Petersen et al. (2014) and Rahman et al. (2020).

The second set of GMPEs is the combination equations formulated by of Atkinson and Boore (2003) who used globally extensive ground motion information set of interface and intraslab sections of subduction zone, Abrahamson et al. (2016) who employed similar dataset as Atkinson and Boore (2003) and the third equation is of Zhao et al. (2006). They also considered earthquakes with similar but for Japanese dataset instead of global data set.

Apart from the linear sources, the other two sources are assigned GMPEs using combination of these two sets. Background seismicity has been assigned with 50-50 weighting for each set to avoid bias. Areal sources (subduction and shallow crustal zone) are given combined weighting with these two sets based on the depth distribution of the catalog. Each source is given weight according to the statistical distribution of shallow and deep earthquake.

4.2.1.3 Seismic Hazard Computation

To estimate seismic hazard on the basis of computed seismicity parameters, a final computation procedure has been carried out in the seismic hazard module R-CRISIS version 18.4.2 (Ordaz et al., 2017) due to its lucrative features. The module at a time allows the combination of different source models, seismicity models, attenuation models through logic tree structure, and computation at a large number of sites according to users' demand.

The hazard value wasassessed for all the selected GMPEs and all the 3 seismogenic sources separately. Later they are combined using the logic tree structure where equal weighting has been assigned to all the sources. Final hazard for the 8 selected sites are obtained.

4.2.1.4 Result and Discussion

After computation in the R-CRISIS version 18.4.2 (Ordaz & Salgado-Gálvez, 2017), uniform hazard spectra have been developed utilizing the PGA and SA values at 0.02s, 0.05s, 0.1s, 2.0s, 0.3s, 0.5s, 1.0s, 2.0s, 3.0s for the 8 sites of the study at 2%, 5% and 10% exceedance probability in 50 years timeframe at 0.05 critical damping factor (Figure 4.5). The PGA and SA values at 0.02s, 0.05s, 0.1s, 2.0s, 0.3s, 0.5s, 1.0s, 2.0s, 3.0 for 8 specific sites of study at 10% and 2% exceedance probability in 50 years timeframe at 0.05 critical damping factor are in Table 4.2. UHS of the sites shows highest SA values in 0.1s spectral period and lowest value in longer spectral period (3s) which implies that structures with 0.1s natural frequency are at greater risk. All the sites show less than 0.15g PGA value for 10% probability of exceedance in 50 years. BUP ground and Mohammadpur Eidgah have the lowest values of the 8 sites for all spectral periods. Boldha Garden has slightly higher values than the rest of the sites. The Uniform Hazard Spectra provide a guidance for choosing the sites as long term shelters.

Table 4.2 Intensity (g) for different spectral period at 10% probability of exceedance in 50 years

	Intensity (g)							
Spectral period(s)	BH-01	BH-02	BH-03	BH-04	BH-05	BH-06	BH-07	BH-08
0.010	0.142	0.137	0.141	0.141	0.138	0.147	0.144	0.146
0.020	0.147	0.143	0.147	0.147	0.143	0.153	0.150	0.152
0.050	0.198	0.192	0.198	0.198	0.192	0.207	0.202	0.205
0.100	0.31	0.301	0.310	0.310	0.301	0.324	0.316	0.321
0.200	0.305	0.296	0.304	0.304	0.296	0.317	0.309	0.314
0.300	0.253	0.245	0.251	0.251	0.244	0.262	0.255	0.259
0.500	0.181	0.177	0.180	0.180	0.176	0.186	0.182	0.184
1.000	0.0937	0.0915	0.093	0.093	0.091	0.095	0.094	0.095
2.000	0.0412	0.0404	0.041	0.041	0.040	0.042	0.041	0.041
3.000	0.0242	0.0238	0.024	0.024	0.024	0.024	0.024	0.024

Table 4.3 Intensity (g) for different spectral period at 2% probability of exceedance in 50 years

	Intensity (g)							
Spectral period(s)	BH-01	BH-02	BH-03	BH-04	BH-05	BH-06	BH-07	BH-08
0.010	0.313	0.307	0.314	0.314	0.308	0.325	0.318	0.322
0.020	0.327	0.32	0.328	0.328	0.321	0.340	0.332	0.337
0.050	0.446	0.436	0.448	0.448	0.438	0.466	0.455	0.462
0.100	0.712	0.697	0.715	0.715	0.699	0.742	0.725	0.737
0.200	0.722	0.707	0.724	0.724	0.709	0.749	0.733	0.743
0.300	0.597	0.586	0.598	0.598	0.587	0.616	0.604	0.612
0.500	0.428	0.42	0.428	0.428	0.421	0.441	0.433	0.438
1.000	0.223	0.218	0.222	0.222	0.218	0.228	0.224	0.227
2.000	0.0986	0.097	0.098	0.098	0.097	0.100	0.0989	0.100
3.000	0.0599	0.059	0.0595	0.0595	0.059	0.061	0.0599	0.060

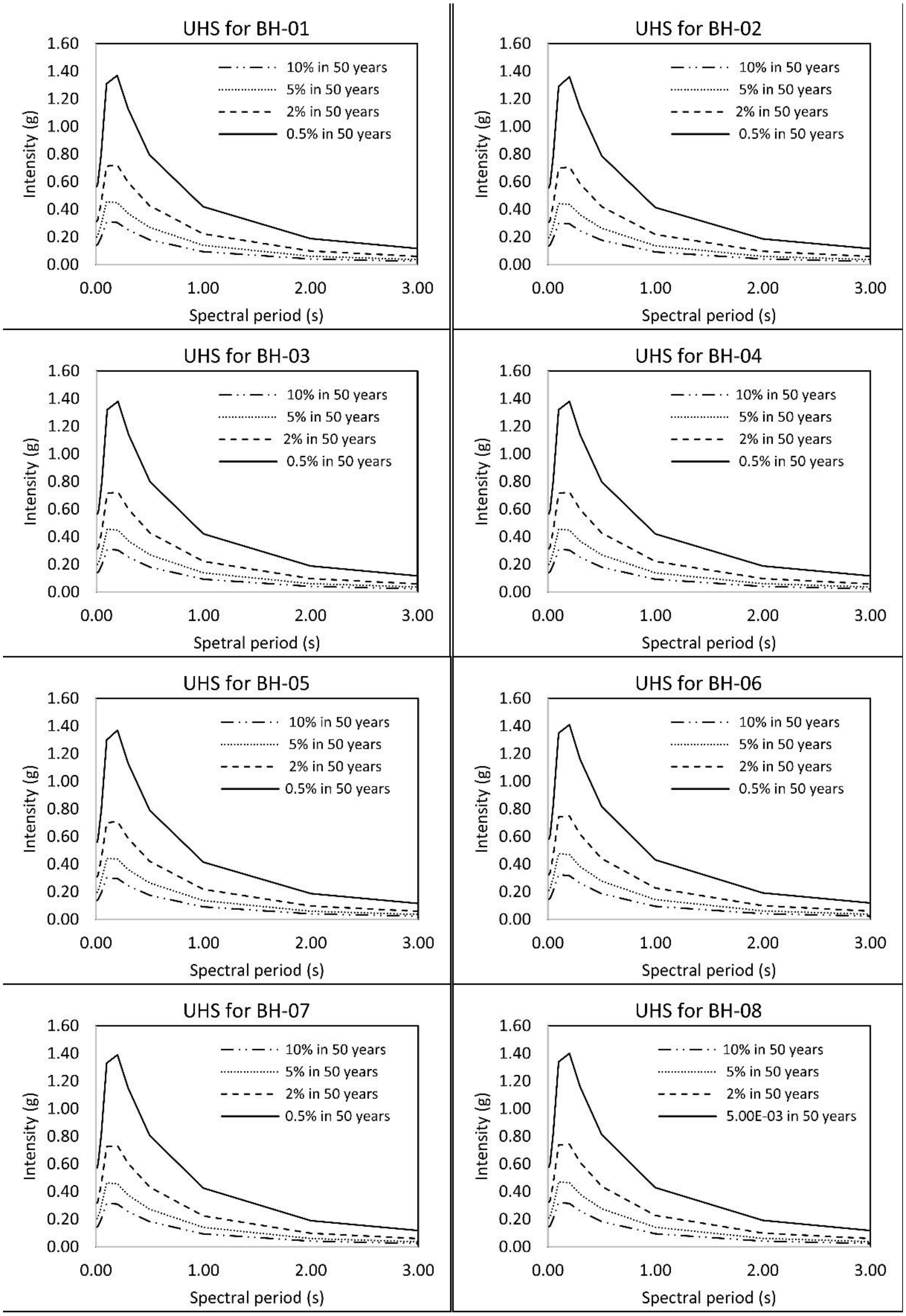


Figure 4.5 Uniform Hazard Spectra for the eight selected sites.

4.3 One-Dimensional (1D) Seismic Site Response Analysis

Seismic motions generate from the fracture point of fault and travel through the bedrock to reach the site of interest. The overlying local soil of that site modifies the characteristics of seismic motion that moves across the soil strata to reach the ground surface. Due to this, motion will act as amplified or de-amplified version to the ground surface. When motion reaches the ground surface it creates vibrations in the surfaces and structures. This vibration is the cause for failure of structures and for liquefaction, or even landslides. Therefore, ground motion amplification in soil deposits is important when assessing earthquake risk (Naik & Choudhury, 2013).

In site response analysis, free-field soil deposits response of ground motion is calculated. Site response analysis is performed by three processes; one dimensional, two dimensional and three dimensional. One dimensional mainly use for the flat site, where two dimensional is used for slope, embankments, retaining wall and tunnel, and three dimensional for complex soil structure, dams in small canary and multi structures. 1D site response analysis is the most widely used one. 1D site response analysis was performed by using two methods. One method is frequency-domain equivalent linear analysis using SHAKE200 developed by Schnabel (1972) and time-domain nonlinear analysis work with hysteric soil models. For the time-domain model, several programs like DeepSoil, D-MOD_2, OpenSeeS, ABAQUS and LS_DYNA are being used (Bolisetti etal., 2018).

Since the behavior of soil is nonlinear so certain modifications were need to make linear approach for estimating ground response. The equivalent-linear approach is that modified site response approach that gives a better result. Schnabel (1972) explained in their paper the actual hysteresis behavior of cyclic loading of soil. In the equivalent linear approximation, equivalent shear modulus (G) and damping ratio (ξ) are mainly required data. Schnabel (1972) established a computer-based program named SHAKE for equivalent-linear approximation based on equivalent linear refraction theory and is now widely used.

For this study, one dimensional time-domain nonlinear site response analysis will be conducted to determine the surface ground motion. The nonlinear analysis uses the hysteresis stress-strain relations of soil and showed that the result that is more practical than equivalent linear analysis. Both nonlinear and equivalent-linear analysis is recommended if the input peak acceleration value is greater than 0.2g. Evaluating past works, Yoshida et al. (2002) showed that shear stress leads to overestimation of peak acceleration in equivalent linear than nonlinear analysis. He also summarized that underrated high frequency response leads to underestimation of peak acceleration in weak shaking for equivalent linear. After that Stewart and Kwok (2008) investigated other method of site response and found that the response varies in short periods mostly but matches with long periods. Recently Kim and Hashash (2013) and Kaklamanos et al. (2013) both examined that nonlinear and equivalent has differences in large strains. In the study, they found that for short periods peak strains of equivalent linear is less than 0.1% and for nonlinear greater than 0.4%. But for long periods both analyses produce similar acceleration responses. So, for all these reasons nonlinear site response analysis is being chosen.

The main aim of this study is to determine site response for the selected open spaces considering earthquake around Bangladesh. Site response for both direct use of time histories and matched time histories will be determined.

4.3.1 Soil properties and shear wave velocity

Shear wave velocity of the soil was collected from eight boreholes. The boreholes data are collected from direct PS logging and Standard Penetration Test (SPT) N values.

Dhaka Metropolitan Area is situated top of Bengal Basin consists of Pleistocene and recent Holocene terrace. The Pleistocene deposits is the oldest exposed sedimentary rock. It is unconformably underlain and overlain by Dupitila formulation (Kabir et al., 2011). The shear wave velocity of this Pleistocene terrace is higher than the Holocene alluvium floodplains. The shear wave velocity profiles are given below (Fig 4.6). Though there are several uncertainties about shear wave velocity profile due uncertain position of bedrock under sedimentary deposits.

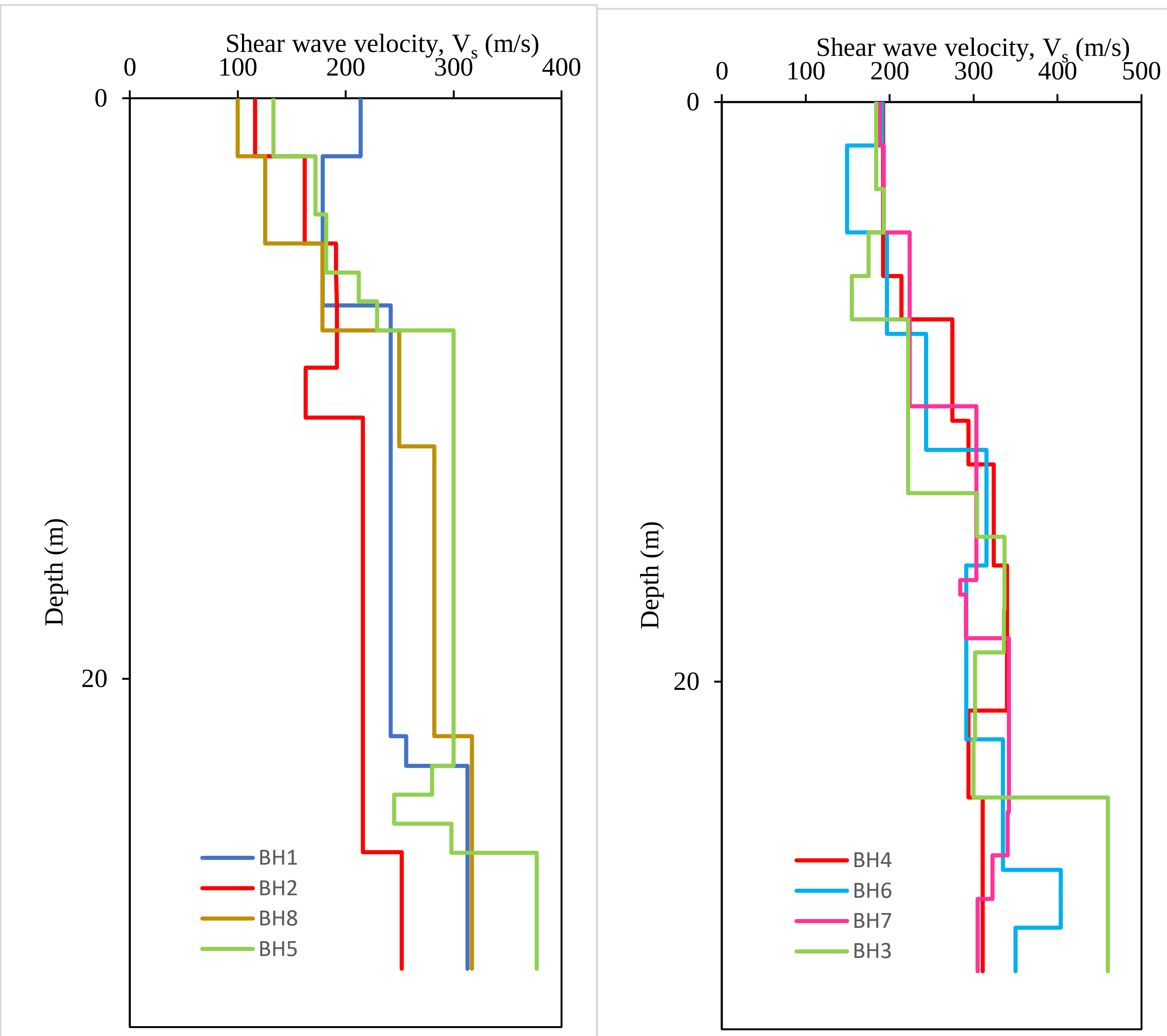


Figure 4.6 Shear wave velocity profile for 8 boreholes up to 30m depth.

4.3.2 Shear modulus reduction and material damping curves

It is important to measure shear modulus and soil material damping curves in site response analysis. Shear modulus of soil is estimated using field tests from the seismic downhole tests. Reduction of shear modulus and damping ratio are determined from cyclic soil behavior. Cyclic soil behavior is characterized by laboratory tests (Asakereh & Tajabadiur, 2018).

In the majority of the study of nonlinear analysis, these both curves use predict the baseline curves based on soil type, stress conditions etc. (Rathje et al., 2010). Several models are developed by many researchers considering different shear strains for different soils types. The widely used curves for categorizing dynamic soil behavior are represented by Vucetic & Dobry (1991), Seed & Idriss (1970), Sun et al. (1988), Darendeli (2001), Zhang et al. (2008), Zefeng et al. (2017).

In this study, fitting shear modulus reduction curve and damping ratio, Darendeli (2001) references are being used. The empirical model of Darendali (2001) is most used because it the most intelligible research for determining the variability of soft soil nonlinear properties. This model predicts the baseline for damping ratio and reduction of modulus curves based on soil over-consolidation ratio, number of loading cycles and plasticity index. Darendali (2001) assumed by his model that at a given strain level damping and modulus reduction curves were normally distributed. To fit the Darendali (2001) curves, over consolidation ratio for clayey soil is given 2, and for sand 1; earth pressure for clayey soil 0.83 and for sand 0.2 and plasticity index selected for clay is 30 soil has no plasticity so for sand PI is zero. The Figure 4.7 shows the damping ratio curve and shear modulus reduction curve together.

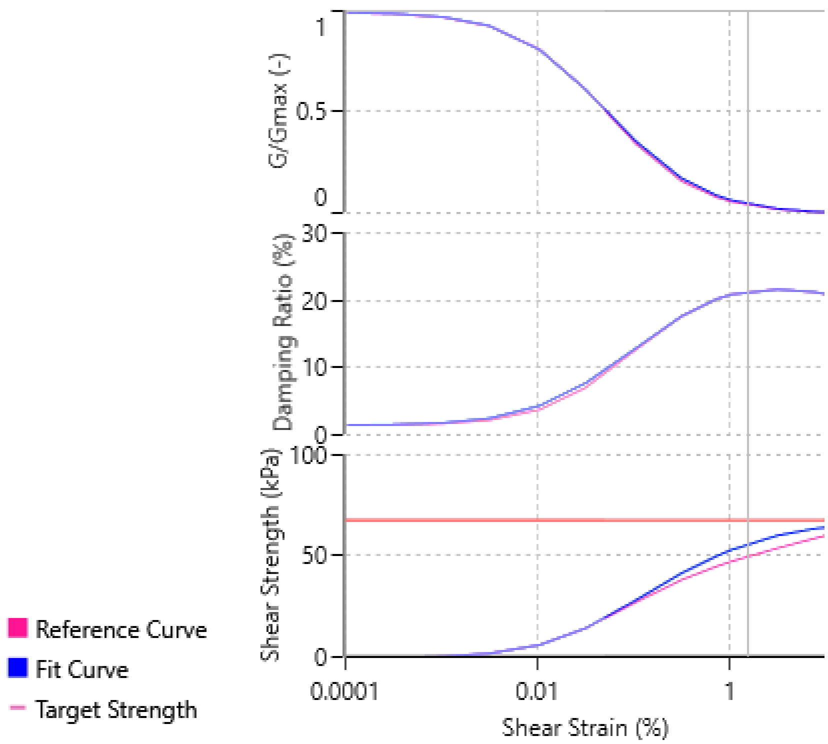


Figure 4.7 Shear modulus reduction curve and damping ratio for clayey soil of BH-1 at first 4m depth.

4.3.3 Uniform hazard spectrum at bedrock

In site response analysis, the earthquake time histories are collected from different seismometer stations. Every station collects earthquake time histories when earthquake occurred. These stations have different shear wave velocities of the sites and some stations collect surface time histories of earthquake ground motion that are mainly amplified version, not the original bedrock motion. The surface geology of Dhaka Metropolitan Area and other places have some differences. Both types of data were used; the original time histories and match the station time histories with the bedrock uniform hazard spectrum at bedrock that is measured from probabilistic seismic hazard assessment.

The uniform hazard spectrum (UHS) is generated for bedrock condition where Vs=760 m/s for Dhaka. As Dhaka is relatively small so there are no significant changes among the different location in uniform hazard spectrum. Figure 4.8 & 4.9 show the UHS for different probability of exceedance.

Table 4.4 Tabular form of the selected 3 types UHS for borehole 8.

Time (s) / Name	0.01	0.02	0.1	0.2	1	2	3
Intensity (g) for exc. probability of 10% in 50 years	0.142	0.147	0.31	0.305	0.094	0.041	0.024
Intensity (g) for design basis earthquake (BNBC, 2021)	0.21	0.218	0.47	0.48	0.148	0.065	0.039
Intensity (g) for exc. probability of 2% in 50 years	0.32	0.34	0.74	0.74	0.24	0.1	0.06

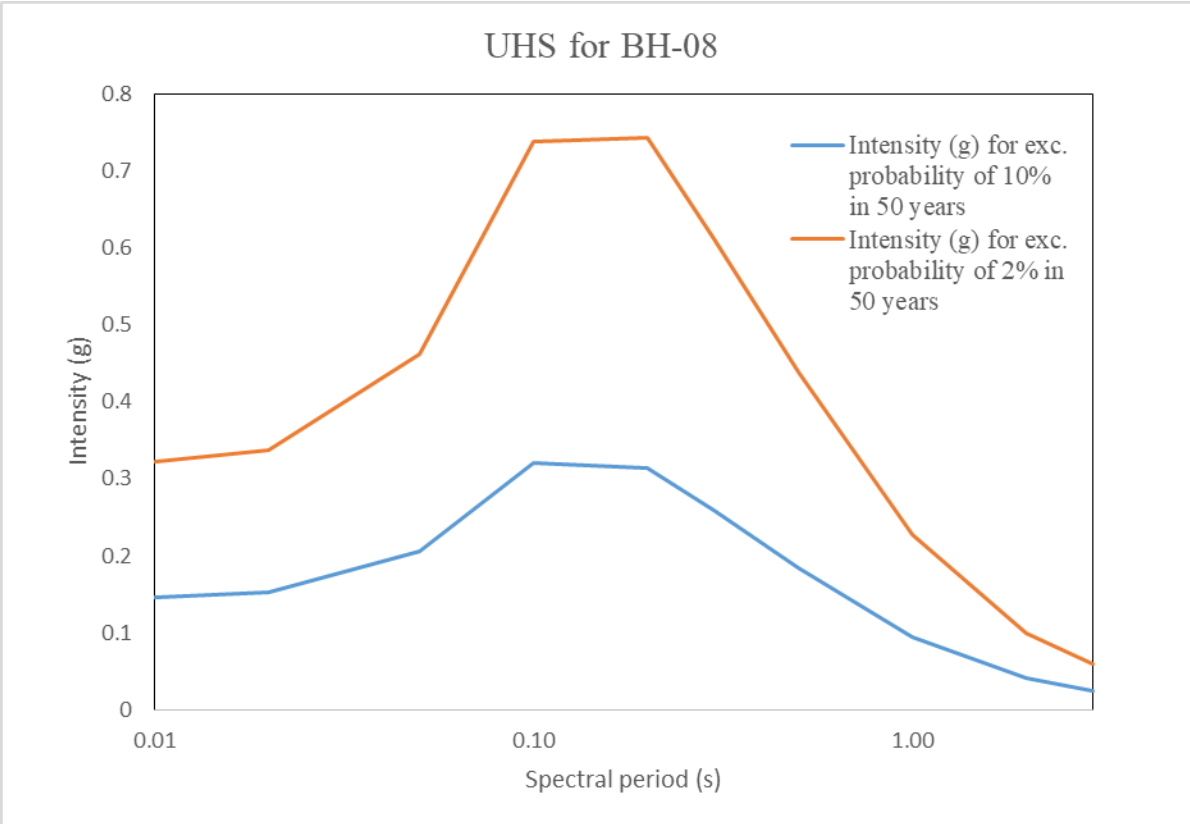


Figure 4.8 Uniform Hazard Spectrum (bedrock) at 10% and 2% probability of exceedance in 50 years for borehole 8.

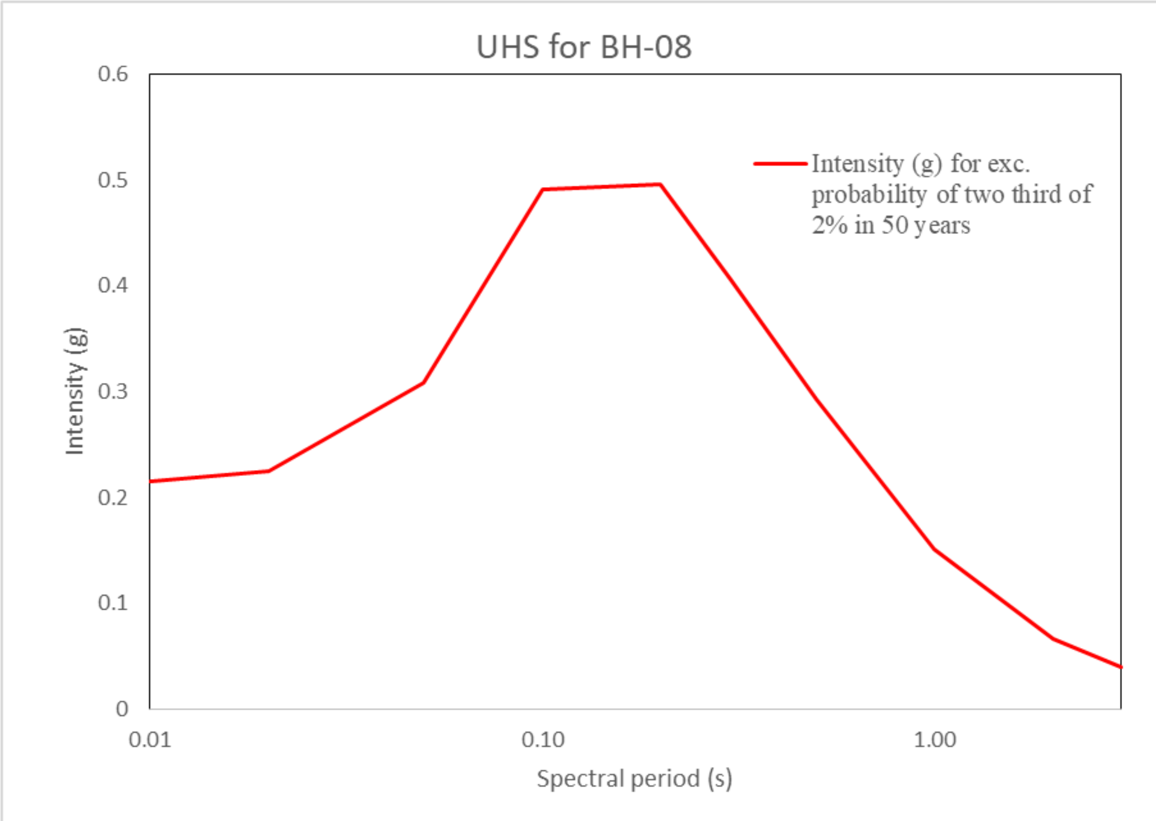


Figure 4.9 Uniform Hazard Spectrum (bedrock) at two third of 2% probability of exceedance in 50 years or design basis UHS at bedrock for borehole 8.

4.3.4 Input earthquake acceleration time history

The input earthquake time histories are selected for seismic site response analysis to fit a target response spectrum. Strong earthquake acceleration time histories are needed for more accurate results. Hence, the seismic sources around Bangladesh are far from Dhaka and in the last 100 years, no strong earthquake occurred that were more than 7 magnitude. So, earthquake that happened in near source are collected from near stations in this study. Total 7 earthquakes around Bangladesh are selected for site response.

The earthquake acceleration time histories are collected from Center for Engineering Strong motion Data (CESMD) which is a cooperative effort CGS (California Geological Survey). From this database, 17 earthquake time histories near Bangladesh-India border, India-Burma border and

Northeast India are selected. The time histories of selected earthquakes are being collected for both rock and site geology stations. The details of the selected station and time histories are given in Table 4.5 and spectral accelerations (SA) of the selected time histories are given in Figure 4.8 and 4.9.

Table 4.5 Information about the selected time histories of selected earthquakes are given. The time histories are downloaded from CESMED database.

	Earthquake name	Year	Station name	Magnitude	Hypocentral Distance (km)	Site Geology	Depth	PGA (g)
1	North East (NE), India	1986	Ummulong (ummu)	4.5	40.8	Rock	43	0.3
2			Dauki (dauk)		50.9	Soil		0.35
3	India-Burma Border	1987	Nongpoh (nonp)	5.9	248.2	Rock	49	0.18
4			Laisong (lang)		102.3	Soil		0.21
5	India-Burma Border	1988	Shillong (shil)	7.2	340.8	Rock	90	0.3
6			Umsning		343.8	Rock		0.41
7			Bokajan (bok)		189.9	Soil		0.44
8		1988	Shillong (Shill)	5.8	110	Rock	15	0.36

9	India Bangladesh Border		Dauki (dauk)		80.5	Soil		0.27
10			Mawphlang (mawp)		94.7	Rock		0.16
11	India-Burma Border	1990	Laisong (lang)	6.1	233.5	Soil	119	0.28
12			Ummulong (ummu)		342.9	Rock		0.5
13	India-Burma Border	1995	Diphu (dipu)	6.4	245.6	Soil	117	0.48
14			Khliehriat (khli)		323.2	Rock		0.21
15	India-Burma Border	1997	Shillong (shill)	5.6	90.1	Rock	34	0.34
16			Jellalpur (jella)		41.9	Soil		0.42
17			Ummulong (ummu)		78.4	Rock		0.31

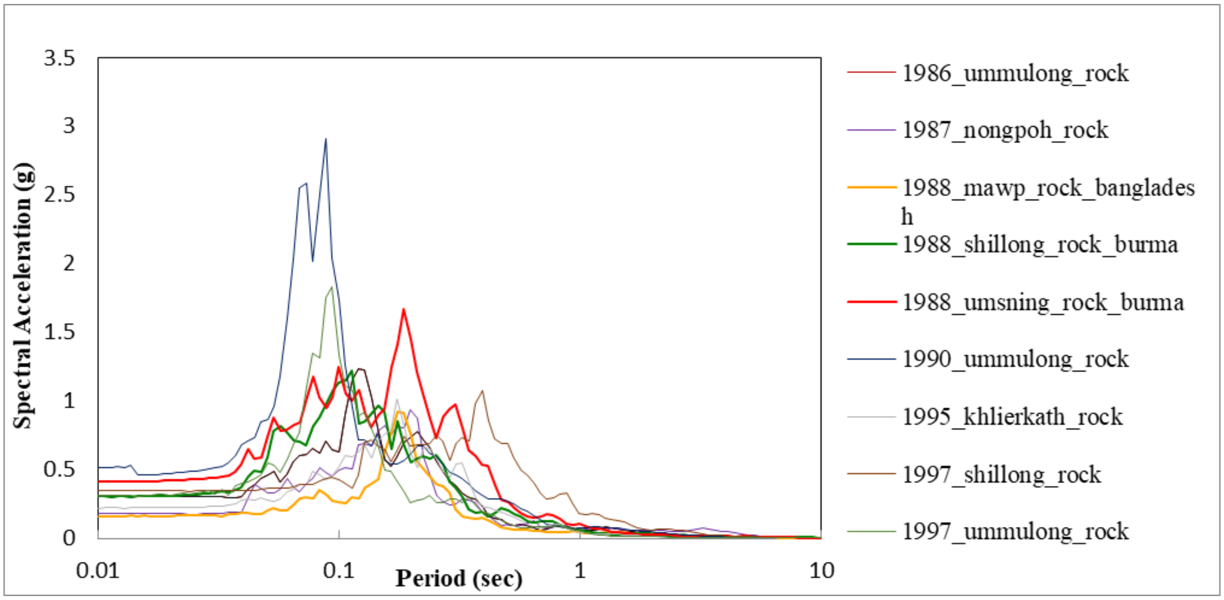


Figure 4.10 Spectral acceleration for rock site station of the selected earthquakes time histories

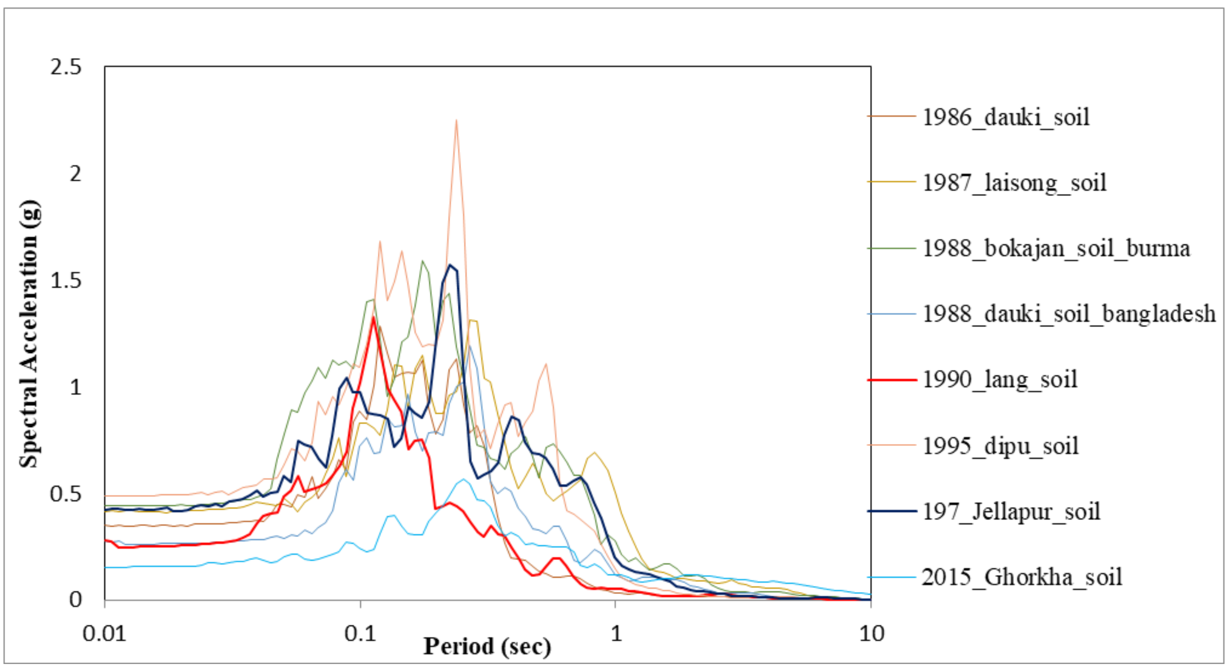


Figure 4.11 **Spectral acceleration for soil site station of the selected earthquakes time histories**

4.3.5 Spectral matching with target spectrum

As explained above, earthquake acceleration time histories are matched with uniformed hazard spectrum to determine that the time histories are bedrock motion and not from the surface. In spectral matching, the actual acceleration time histories are matched with target spectrum (UHS at bed rock) and prepared with consistent target spectrum time history to continue further. The spectral matching is executed using Seismomatch 2022 eddition. The 18-time histories have been matched with 10% probability of exceedance in 50 years. The matched SA with UHS are given in Figure 4.12.

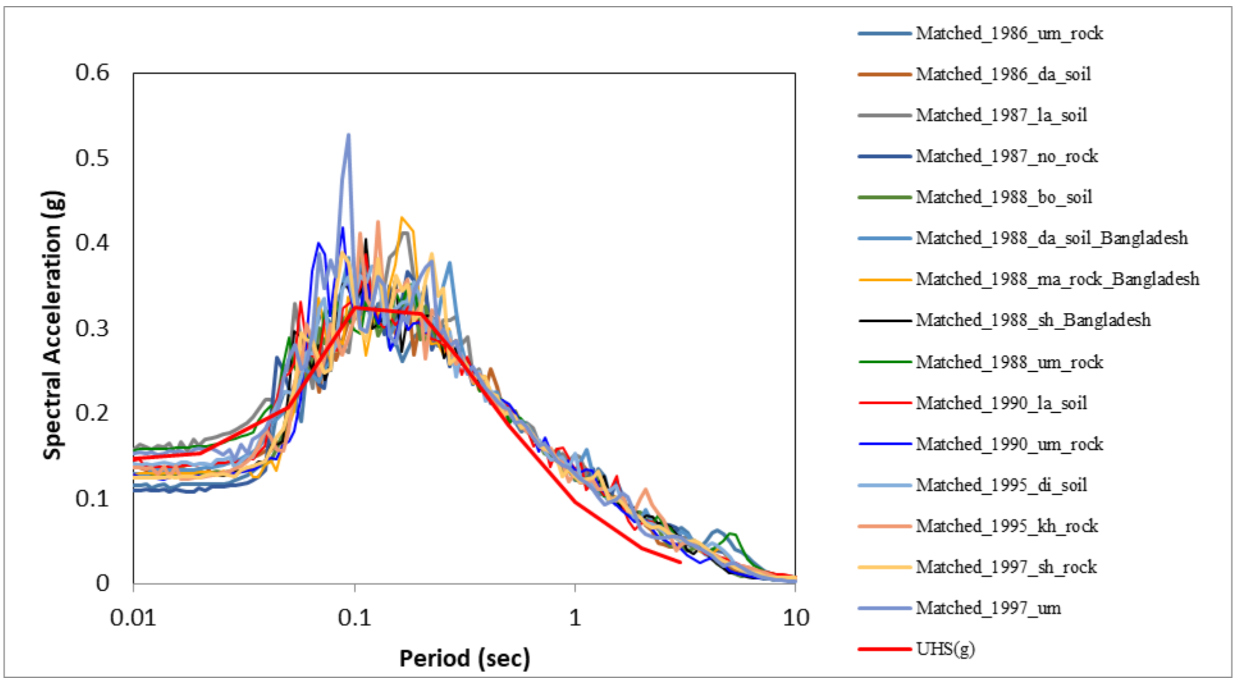


Figure 4.12 Matched time histories for borehole 1 with respect to UHS of 10% probability of exceedance in 50 years

4.3.6 Computing one-dimensional surface site response analysis

In this study, nonlinear response analysis is performed in DEEPSOILv7 developed by Hashash (2017). In DEEPSOIL along with nonlinear, equivalent linear and linear response analysis can be determined. In DEEPSOIL, several soil constitutive models are available like the MKZ developed by (Matasović & Vucetic, 1993) with pressure dependent and the General Quadratic/Hyperbolic (GQ/H) model with masing criteria (Groholski et al., 2015). In computer program, there are also several model for reference fit curves for shear modulus reduction and damping ratio curves. The model introduces shear strength failure while the model still tries to become flexible with small strain soil behavior. This model work with modified KZ model for comparative analysis. In a quadratic model, these linear boundaries are joined together in a continuous curve because these two linear lines intersect in a common reference shear strain. As for primary soil model, the GQ/H model is used in the thesis. The GQ/H model is used here because it is the best fit for clayey and sandy soils and it's updated. To fit the model, shear modulus reduction damping curves of references are used. The fitted dynamic soil curves are used in the further model to complete the analysis.

After preparing all the soil properties and constitutive model, the soil profiles will be analyzed with the earthquake time histories and estimate the site response spectrum at the different level depths of soil according to the soil profile.

4.3.7 Result and Discussions

In this study, nonlinear response analysis for both rock and soil station recorded time histories are used separately and spectral response graphs are estimated. Again, the selected time histories are matched with UHS at bedrock for Dhaka city and responses estimated for both rock matched and soil matched time histories.

The uniform hazard spectrum at bedrock for selected open spaces display that PGA value is around 0.14g and peak acceleration is 0.31g at 0.1s. The graph shows higher acceleration in short period and lower acceleration in long period. But the site response spectrums show different result for all the selected boreholes. They also present different results in terms of rock and soil-based time histories, and matched time histories with UHSs. The response spectrum for the boreholes for direct rock and soil station recorded time histories are given below.

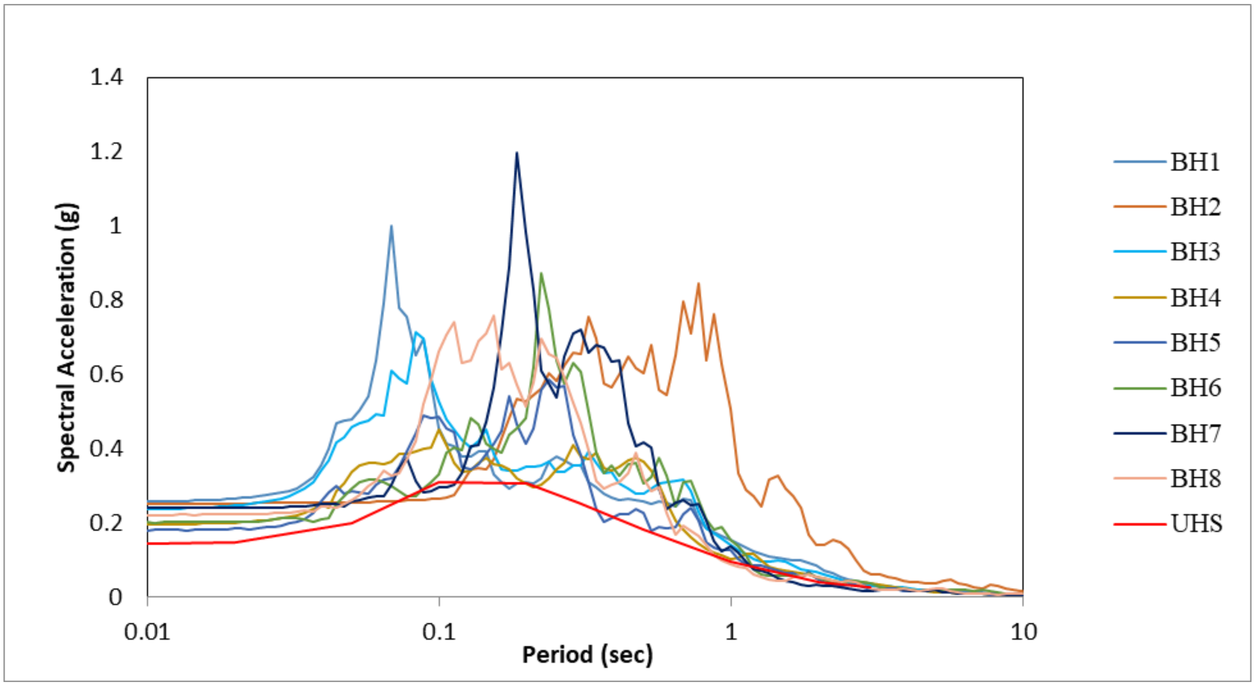


Figure 4.13 Spectral Responses of all boreholes in term of original rock site station recorded data

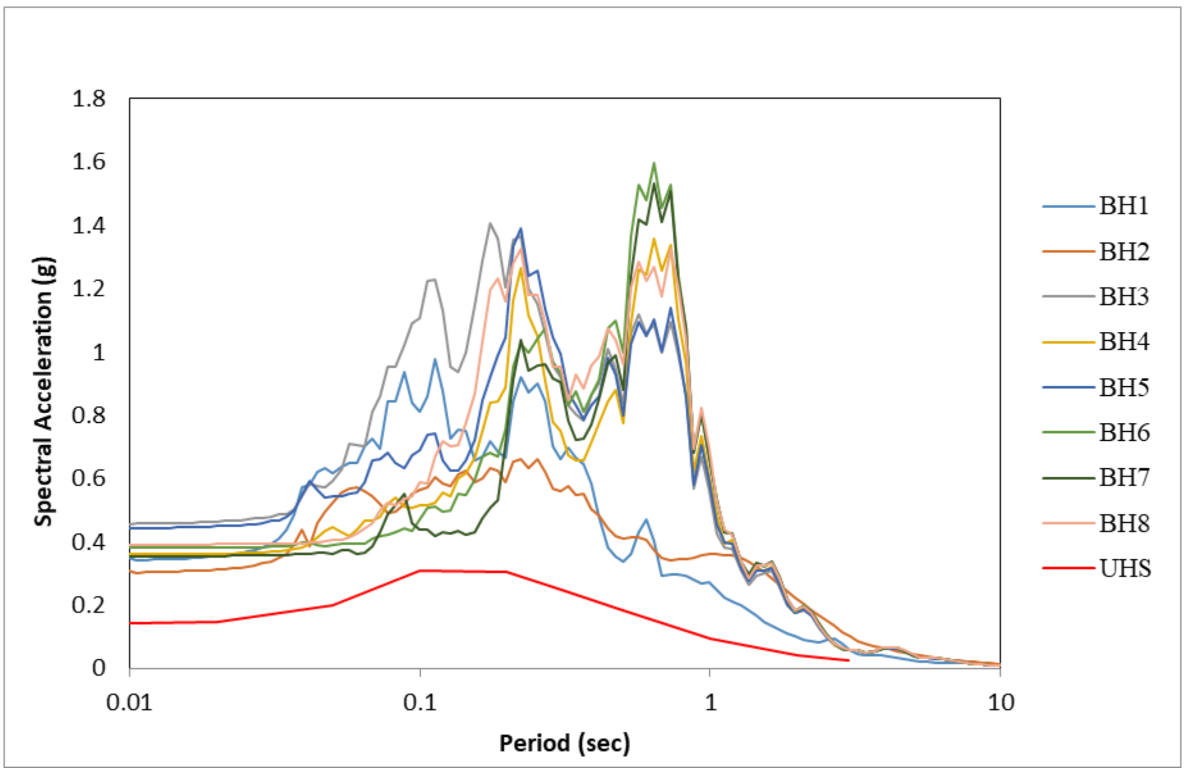


Figure 4.14 Spectral Responses of all boreholes in term of original soil site station recorded data

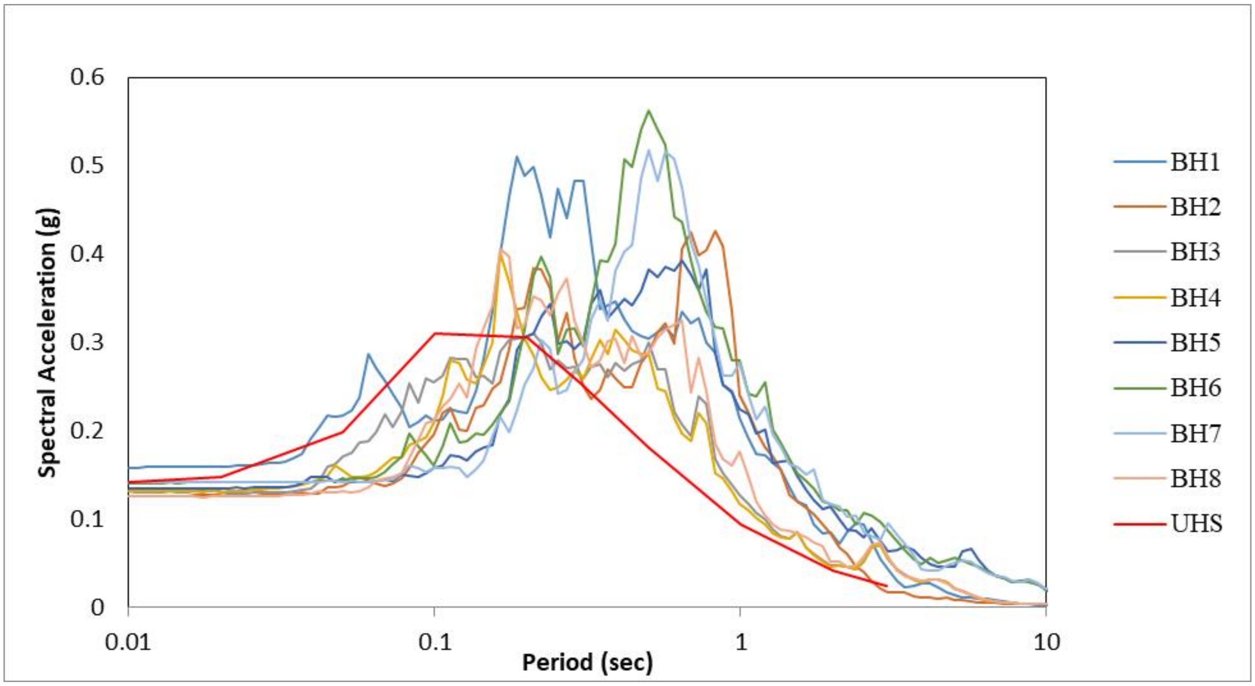


Figure 4.15 Spectral Responses of all boreholes in term of matched time histories soil site station recorded data with 10% probability of exceedance.

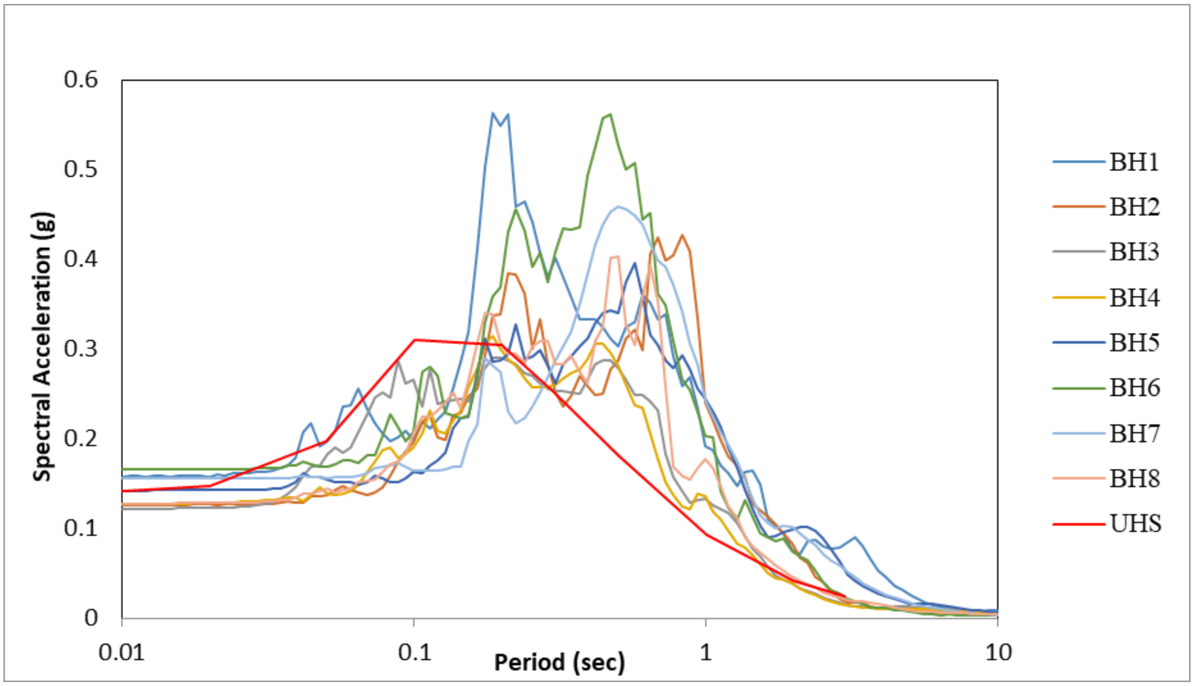


Figure 4.16 Spectral Responses of all boreholes in term of matched time histories rock site station recorded data with 10% probability of exceedance.

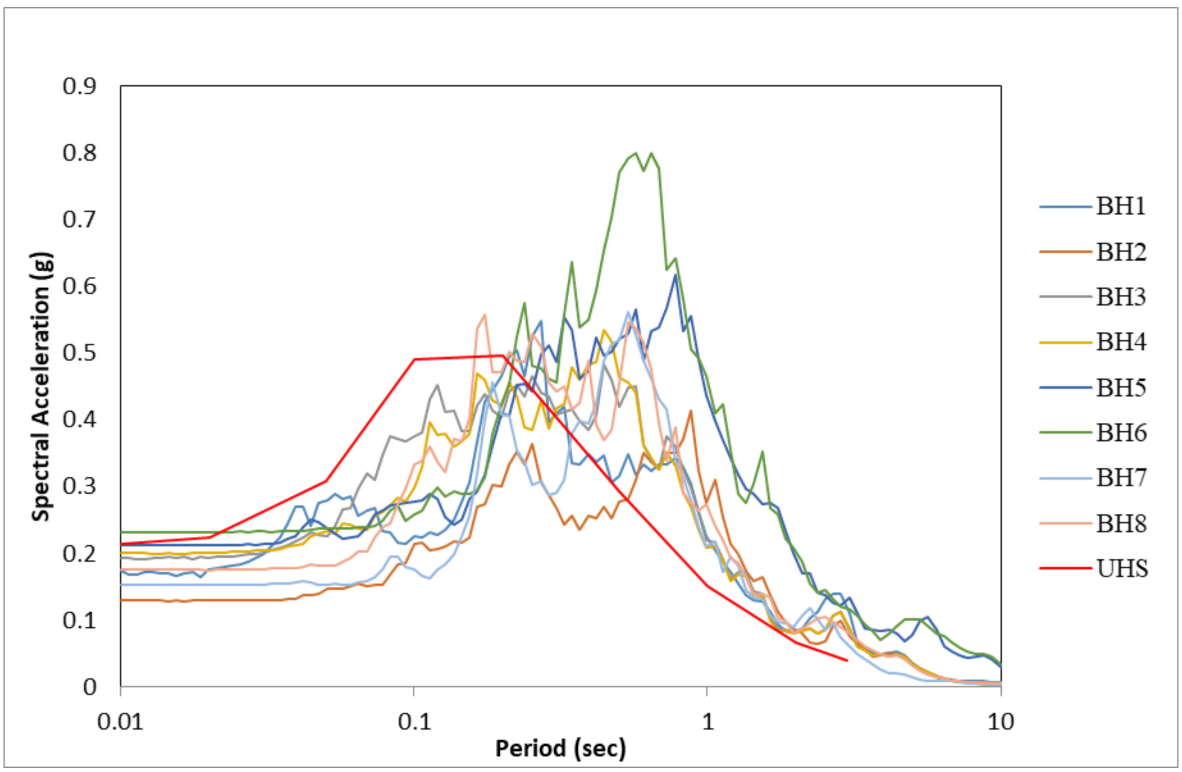


Figure 4.17 Spectral Responses of all boreholes in term of matched time histories soil site station recorded data with design basis earthquake spectrum.

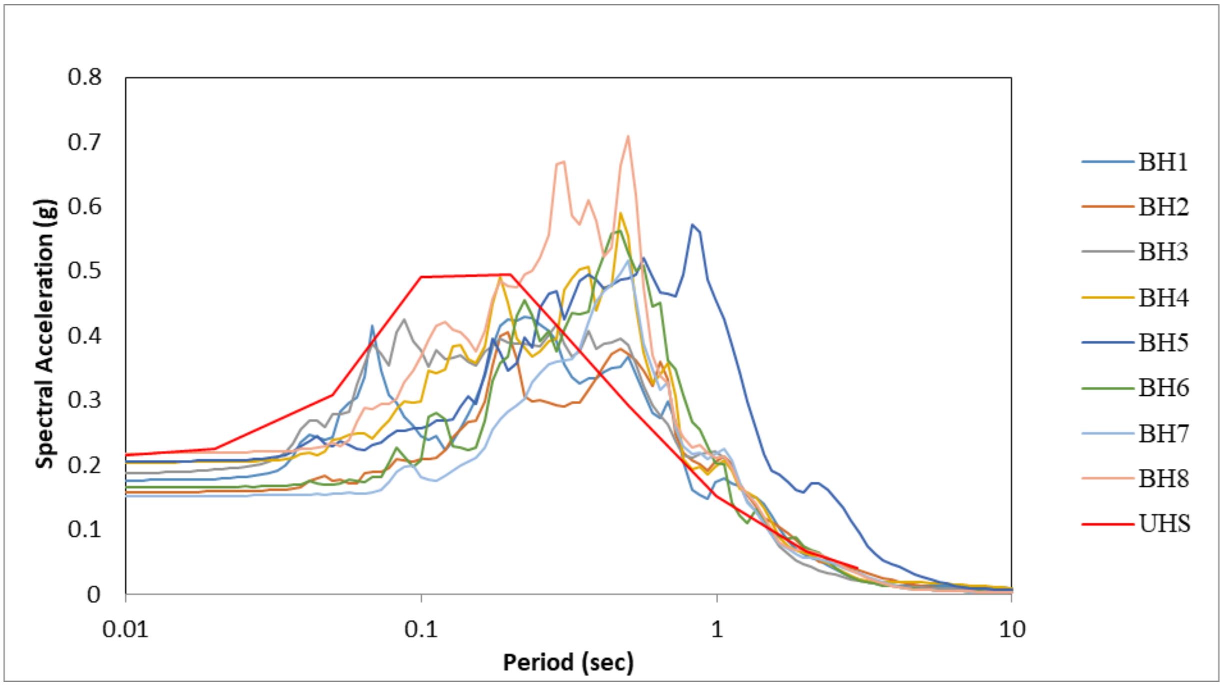


Figure 4.18 Spectral Responses of all boreholes in term of matched time histories rock site station recorded data with design basis earthquake spectrum.

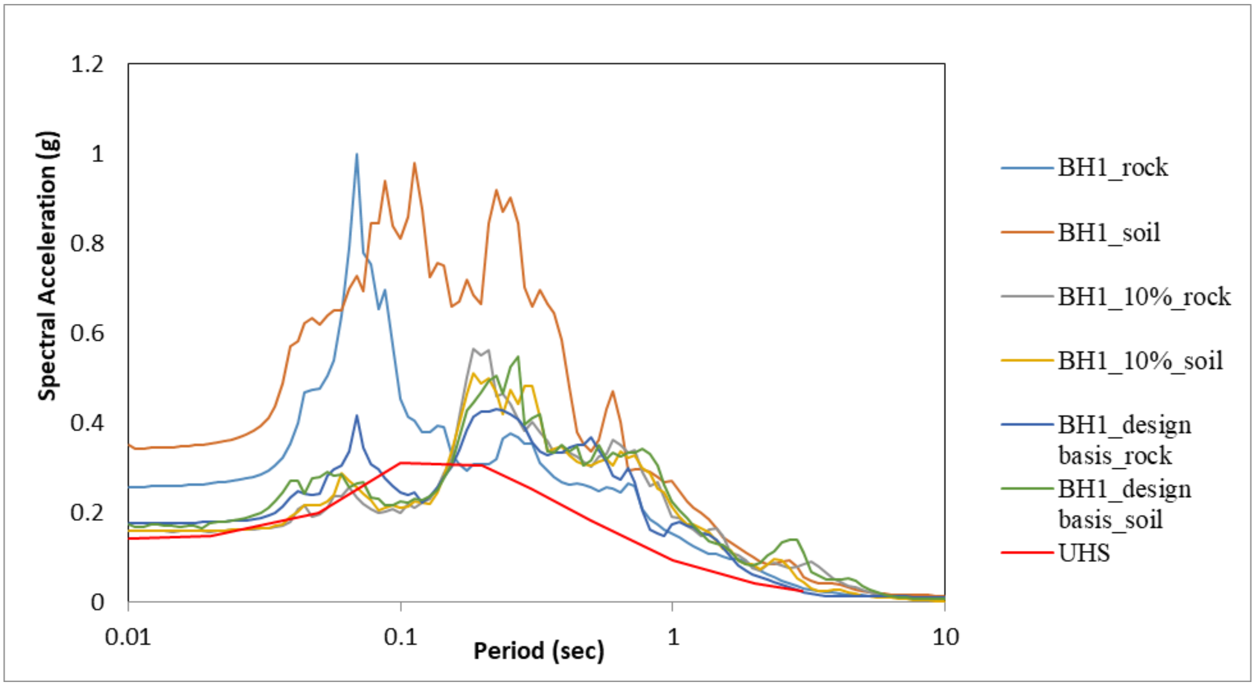


Figure 4.19 All the response spectra for borehole 1

All the response spectra are estimated for the selected time histories presented in Table 4.4 for the 30m depths soil column. The results present de-amplification in short period and amplification of acceleration in long period.

The Figure 4.13 to 4.19 represents the response spectra for 8 boreholes for three type of earthquake time histories. Figure 4.13 and 4.14 showed response for original or direct use earthquakes time histories collected from the site. Then, the figure 4.15 and 4.16 show responses for matched time histories with UHS for 10% probability of exceedance in 50 years for both stations recorded time histories. The Figure no 4.17 and 4.18 represent the response considering design basis earthquake from BNBC, matched with collected raw time histories of both record station. The final figure 4.19 shows the all response for borehole 1. Except borehole 1 and 8, other borehole response has de-amplification of acceleration short period and amplification of acceleration in long period. The borehole 1 and 8 has their maximum amplification in short period at 0.06s and 0.1s respectively. The Figure 4.14 shows de-amplification of acceleration in short period and amplification in long period for soil site record station. All the boreholes show similar results of amplification and de-amplification (Figure 4.14). From Figure 4.13 and 4.14, for soil site station time histories have higher response than the rock site station responses.

For matched time histories, for 10% probability of exceedance in 50 years showed that all the responses have de-amplified acceleration in short period and amplified acceleration in long period (Figure 4.15 & 4.16). For rock station matched time histories BH 6 has maximum response spectra than the other boreholes (Fig 4.16) and PGA for all borehole varies from 0.12g to 0.16g. Again, for soil station matched time histories, borehole 1 has maximum response spectra than the other boreholes (Figure 4.15) and PGA varies from 0.13g to 0.16g. For design basis earthquake matched time histories show similar result to the 10% probability of exceedance (BNBC, 2021). The responses are de-amplified in short and amplified in long period (Fig 4.17 and 4.18). The soil station record of BH6 has maximum response than other boreholes (Fig 4.17). But for rock station record BH8 has maximum response than other boreholes. However, borehole 5 represents long amplification in long period than others.

The response spectrum for matched ground motion with respect to uniform hazard spectrum shows that the response is near to the bedrock motion. For, 10% probability to exceedance, BH1, BH6, BH7 has higher PGA value and response than UHS for rock station recording (Fig 4.16). On the other hand, for soil station, only BH1 has high PGA and response than UHS (Fig 4.15). For design basis matched time histories all the responses are lower than the design basis of UHS. But for the matched time histories, the response spectrum is equally de-amplified till 0.1 s. When UHS is 0.2s the acceleration is in peak status. So, from all the response spectrums for both original and matched time histories of rock and soil site stations all the sites represent similar response pattern.

The Figure 4.19 illustrates all the response for borehole1 as an example. From the graph, borehole 1 has maximum response for original soil site station recorded time histories. For matched time histories, the surface responses decreased than original response.

The result of site response analysis presents amplified or de-amplified response spectrum for any area. The nonlinear behavior of soil causes this amplification and de-amplification of acceleration. In this research, site responses are estimated for soft sediments of Pleistocene and Holocene deposits using nonlinear and equivalent linear processes. From the result, it is observed that the nonlinear response spectrum shifted toward long period with maximum acceleration. The soil characteristics of Dhaka is sandy and clayey soil, that makes the estimated response spectrum shift towards the longer period. Again, as for the NEHRP site amplification factor, for 30m depth soil, the response amplified both in short and long period (Dobry et al., 2000). As for Dhaka's soil, at

30m depth, the response spectra are de-amplified in short period and amplified in long period. All the graph in result section represents that for 30m depth soil profile has maximum acceleration in longer period at around 1s. According to Dobry et al. (2000), the nonlinear property of soil behaves like amplification in long period and de-amplification in short period. For this difference dynamic properties of soil are mainly responsible.

As a seismically active region, report of Middlemiss (1885) mentioned that Mw =6.9 magnitude earthquake that occurred in 1885 (known as the Bengal earthquake) did not cause any serious damage in Dhaka city. The epicenter of that earthquake was near 50 km around but still did not damage seriously as near-source earthquake. The effect was little compared to the 100 km distance from the other events. This is happed because of the soft and clayey soil of Dhaka. Again, a report of Stuart, (1926) stated that the 1918 Srimangal earthquake with 7.1 magnitude didn't produce any damage to the city though the epicenter was 150 km away from the city. The reason behind this no damage or little damage in these two earthquakes was the deep sedimentary soil of Pleistocene and Holocene deposits. According to the research of Singh et al. (2016), the sedimentary deposit thickness of early Cretaceous, increases around 3 to 17 km across the south of Madhupur Terrence. The crystalline baserock has much lower depth than Dhaka city, that is why the region around this Eocene zone faced more damage during the 1885 earthquake.

Dhaka city is confined with Pleistocene Terrence and Holocene deposits and many high rise and low-rise building are being constructed on these areas. It is observed that, as the response spectrum has higher acceleration values in the long period, it leads to damage of tall buildings than low-rise buildings. The high-rise building has its own resonance during earthquake which has long period. So, when an earthquake occurs, buildings experience high acceleration in long period due to soft soil above the bedrock. This long period acceleration will be matched with high-rise buildings' own vibration and make the shaking resonant and finally the buildings may collapse. In Dhaka, the number of tall buildings is increasing because the modern concept is vertical development when horizontal development is not possible. Hence, the number of high-rise buildings may be the reason of huge post-earthquake losses. Therefore, open spaces can help during response and recovery. In the open spaces, people can take immediate shelter during the disaster or even take long term shelter in recovery period. This section mainly dealt with feasibility about this selected 8 sites. From the result, Ramna Park has the lowest responses and is the safest, but the others are also relatively safe.

In summary, it can be concluded, that surface responses of the selected open spaces illustrate de-amplification of acceleration in the short period and amplified acceleration in the long period. The characteristics and properties of soft clayey and sandy soil control this type of spectra. Such results do not mean much on their own, since the 8 sites are empty and without any structures. However, they are essential for the detailed calculations done in the next chapter.

4.4 Liquefaction Potential Evaluation using Deterministic, Probabilistic, and Artificial Neural Network Approach

There are hardly any scientific studies for liquefaction as a seismic hazard before 1964, although numerous historical cases of liquefaction of soils during earthquakes were described by many early researchers and observers of the earthquake phenomenon (Richter, 1958), was one of them. But after the Japan Nigata and the Great Alaska earthquakes of 1964, after observing and understanding their destructive effects, geoscientists, geotechnical engineers, and researchers in the related field started detailed studies on liquefaction events (Farazi et al., 2018), (H Bolton Seed & Lee, 1966), (H. B. Seed & Idriss, 1971) and (Whitman, 1971) started working on this topic. (H. B. Seed & Idriss, 1971) developed a simplified procedure for liquefaction evaluation and is known as the pioneer of liquefaction studies. (Iwasaki et al., 1978), (Iwasaki et al., 1982) comes with an index to calculate the severity of liquefaction, called the Liquefaction Potential Index. Initially, liquefaction potential assessment was based on the SPT method, (Robertson & Wride, 1998)evaluates liquefaction potential from the CPT method and told it gives more accurate results than the SPT method and in 2000, (Andrus & Stokoe, 2000; M. Z. Rahman & Siddiqua, 2017a) comes with shear wave velocity method to analysis liquefaction potential where it is difficult to do SPT and CPT. In NCEER workshops, the simplified procedure was revised and updated (Youd et al., 2001). These are basically the deterministic approach to liquefaction analysis. Besides this,

Numerous researchers have also established SPT, shear wave velocity (V_S) and CPT-based probabilistic correlations for the initiation of liquefaction in sands and silty sands, including (Christian & Swiger, 1975); (Boulanger, 2010); (Moss et al., 2006); (Liao & Lum, 1998); (Youd & Noble, 1997); (Juang et al., 2002a); (Toprak et al., 1999); (Cetin et al., 2002); (Cetin et al., 2004); (Cetin et al., 2018); (Idriss & Boulanger, 2008, 2014).

A deterministic technique uses the factor of safety to compute soil liquefaction and predicts when it will happen if the factor of safety, which is the reciprocal of the ratio of cyclic resistance to cyclic stress (CRR/CSR), is less than or equal to one. Although it is the simplest and most often used method for evaluating liquefaction, there are some major uncertainties in the several variables that are involved in this deterministic method, making it occasionally less reliable. A method of assessing the cumulative impacts of uncertainties is provided by reliability calculations, which also offer a logical framework for selecting safety precautions that are appropriate for the level of uncertainty and the potential consequences of failure. Therefore, a probabilistic evaluation of the liquefaction potential may be carried out as an addition to or an alternative to the deterministic assessment, in which the liquefaction potential is evaluated in terms of the liquefaction probability. The outcomes of such a probabilistic evaluation of the possibility for liquefaction may help engineers make better choices.

However, in the current study, limit state function (LSF), a variation of the performance function (Seed & Idriss, 1971b, 1982) was taken into consideration together with artificial neural network (ANN) models based on (Juang et al., 2000, 2002b, 2003b). The disadvantages of the simplified technique have been significantly minimized by this mechanical way of determining LSF. These flaws mostly stem from the limit state curves' reliance on engineering judgment and from the insufficient analysis of all potential interactions between various types of soil and load characteristics. The ANN models are very beneficial for researching multivariate nonlinear relationships in particular. A thorough examination of the ANN approach is not possible given the limitations of this study. In (Eberhart et al., 1990; Flood & Kartam, 1994; Hammerstrom, 1993a, 1993b; Krogh, 2008; Lippmann, 1987; Rumelhart et al., 1986, 1988) and other publications, the basic architecture of ANN has been thoroughly studied.

ANN models have a number of benefits, including the availability of multiple training algorithms, the capacity to detect all potential interactions between predictor variables, and the capacity to detect complex nonlinear relationships between independent and dependent variables without the need for extensive formal statistical training ((Flood & Kartam, 1994; Hammerstrom, 1993a; Krogh, 2008; Tu, 1996). Numerous research has demonstrated the usefulness of ANN approaches in categorizing scenarios of field performance (Agrawal et al., 1997; Ali & Najjar, 1998; Goh, 1994, 1995, 1996; Juang et al., 2000, 2001, 2003b; Juang & Chen, 1999). As a result, this study makes use of a more effective, reliable, and optimistic methodology to evaluate the soils' resistance to liquefaction in eight specific open places.

Furthermore, differences in LPI of the same location from V_S and SPT-N data have also been found in many studies (Ateş et al., 2014; Fahim et al., 2022; Rahman & Siddiqua, 2017b; Rahman & Siddiqua, 2016). These discrepancies can be brought on by built-in uncertainty in the SPT-N and VS data retrieval processes. Estimating SPT-N is unclear because different SPT equipment components have varying levels of energy efficiency (Mayne et al., 2009). And the competence, knowledge, and ability of the person conducting the test, the kind of casing used in the borehole, the kind of measuring device utilized, etc. are all uncertainties in determining VS. Additionally, the accuracy of the tests, the kind of soil, the particles concentration, and the tests themselves all have an impact. Therefore, to make the study more reliable both standard penetration test blow count (SPT-N) and V_S data in all locations were used in the LPI calculation and then the findings were compared for an accurate liquefaction potential evaluation. Both SPT and V_S data were employed in all three approaches except the probabilistic approach where only SPT data were used according to Cetin et al. 2018.

4.4.1 Materials and Methods

The main aim of this paper is to carry out a liquefaction hazard assessment for some open spaces in Dhaka. This will be done considering an Earthquake Magnitude of 7.5 and PGA of 0.15g. For this assessment, 8 boreholes have been constructed in 8 different open spaces.

4.4.1.1 Database establishment

The V_s and SPT-N data from eight (8) boreholes along with relevant geotechnical information like sand, silt, clay percentage, grain size, lithology, plasticity index, and ground water label were used to evaluate the soil liquefaction resistance of the selected open spaces. In order to determine the liquefaction indicator (LI) function and points of the limit state function, the artificial neural network (ANN) needs the SPT-N and Vs data of the locations where the historical data of liquefaction and non-liquefaction instances are available (LSF). Fear & McRoberts (1995) gathered the majority of the SPT-N data for the historical examples of liquefaction and non-liquefaction. They later detailed their findings in Idriss & Boulanger (2010). The Vs information was gathered by Andrus et al. (1999a). A total of 225 SPT instances and 225 Vs cases from 26 earthquakes across 70 locations identified by Andrus et al. (1999b) were employed after being screened according to the ANN model application requirements of used parameters as specified in Juang et al. (2000).

4.4.1.2 Estimation of Liquefaction Potential Index

For liquefaction hazard assessment first comes the need to calculate the Liquefaction Potential Index, which is considered a sole parameter to quantify the severity of liquefaction. (Iwasaki et al., 1978), (Iwasaki et al., 1982) proposed the equation for Liquefaction potential index is a combination of depth, the thickness of the layers in a soil column which has the susceptibility of liquefaction, and the indicator of liquefaction occurrence (safety factor or probability of liquefaction). According to (Luna & Frost, 1998a) this index can predict the consequences of liquefaction like surface manifestations of liquefaction, liquefaction damage, or failure potential of a liquefaction-prone area.

Calculating the Liquefaction Potential Index, which is thought of as the only metric to evaluate the severity of liquefaction, is necessary for liquefaction hazard assessment initially. Iwasaki et al., (1978) and Iwasaki et al., (1982) provided the equation for the LPI, which combines depth, the thickness of the strata in a soil column that is susceptible to liquefaction, and the liquefaction occurrence indicator. The results of liquefaction, such as surface manifestations of liquefaction, liquefaction damage, or the failure potential of a liquefaction-prone location, may be predicted using this index, claim Luna & Frost (1998a). Since no damages from soil liquefaction have been observed at depths more than 20 m, the impacts are only felt there (Dixit et al., 2012). Below is presented the LPI equation:

$$\text{LPI}= \int_0^{20} F(z)W(z)\,dz \tag{4.3}$$

$$F(z) = \begin{cases} 1 - Fs, & Fs < 1.0 \\ 0, & Fs \geq 1.0 \end{cases} \tag{4.4}$$

$$W(z) = \begin{cases} 10 - 0.5z, & z < 20m \\ 0, & z > 20m \end{cases} \tag{4.5}$$

where z is the depth (generally from 0 to 20 m) from the ground surface in meters, F(z) is the severity of liquefaction, W(z) is the weighting factor that gives more importance to the layers closer to the ground surface by following a linear trend and dz is the differential depth increment. The severity function, F(z) is a key component that is a function of the factor of safety. Factor of safety is basically used in deterministic approach. However, according to (Li et al., 2006), in the probabilistic approach F(z) may be derived from the probability of liquefaction.

Since the risk of liquefaction is regarded low if PL is lower than 0.35 and, in this situation, the liquefaction-induced ground failure may be insignificant, Li et al., (2006) assumed threshold probability of 0.35 as the boundary between liquefaction/non-liquefaction.

Table 4.6 Classification of liquefaction potential index used in different studies

LPI	(Iwasaki et al., 1982)	(Luna and Frost, 1998b)	(Chung and Rogers, 2011; Kang et al., 2014)	Present Study
0	Not likely	Little to none	None	Very low
0<LPI ≤ 5	-	Minor	Little to none	Low
5<LPI ≤ 15	-	Moderate	Moderate	High
LPI> 15	Severe	Major	Severe	Very high

4.4.1.3 Estimation of Probability of Liquefaction

A new set of probabilistic seismic soil liquefaction triggering relationships is presented (Cetin et al., 2018), on the back analyses of standard penetration test liquefaction triggering case histories, which are fully documented in (Cetin et al., 2018).

Table 4.7 Liquefaction occurrence likelihood based on calculated probability (Caroline J. Chen and Juang, 2000)

Probability	Class	Description (Likelihood of Liquefaction)
0.85< PL	5	Almost Certain that it will liquefy
0.65 ≤ PL< 0.85	4	Very likely
0.35 ≤ PL< 0.65	3	Liquefaction/ non-liquefaction is equally likely
0.15 ≤ PL< 0.35	2	Unlikely
PL< 0.15	1	Almost certain that it will not liquefy

4.4.1.4 Estimation of Cyclic Stress Ratio

The cyclic stress ratio (CSR) measures the seismic loading on a soil layer of level ground. (Seed & Idriss, 1971a) formulated the following equation to calculate the CSR:

$$\boldsymbol{CSR_{\sigma'_v,M_w} = 0.65.\frac{\sigma_v}{\sigma'_v}.a_{max}.r_d} \tag{4.6}$$

where, a_{max} = peak horizontal ground acceleration and g = gravitational acceleration; r_d = stress reduction co-efficient that works for the elasticity of the soil column. The average values of ; r_d given in that chart can be estimated using the following equation (Juang et al., 2017):

$$r_d = \begin{cases} 1.000 - 0.00765z, & z \leq 9.15 \text{ m} \\ 1.174 - 0.00267z, & 9.15 < z \leq 23 \text{ m} \\ 0.744 - 0.008z, & 23 < z \leq 30 \text{ m} \\ \text{and } 0.5, & z \geq 30 \text{ m} \end{cases} \qquad [4.12]$$

For ease of computation, , Youd et al. (2001) used the following equation for the calculation of r_d:

$$r_d = \frac{1.000-0.4113z^{0.5}+0.04052z+0.0017532z^{1.5}}{1.000-0.4177z^{0.5}+0.05729z-0.006205z^{1.5}+0.001210z^2} \qquad [4.13]$$

Cetin and Seed (2004) comes with an updated version of the term r_d. The updated and modified equation of r_d is following:

$$r_d(d, M_w, a_{max}, V_{s,12m}) = \frac{\left[1+\frac{(-23.013 - 2.949.a_{max}+ 0.999.M_w+ 0.0525.V_{s,12m})}{16.258+ 0.201.e^{(0.341.(-d+0.0785.V_{s,12m}+7.586)}}\right]}{\left[1+\frac{(-23.013 - 2.949.a_{max}+ 0.999.M_w+ 0.0525.V_{s,12m})}{16.258+ 0.201.e^{(0.341.(0.0785.V_{s,12m}+7.586)}}\right]} \pm \sigma_{\varepsilon_{r_d}} \qquad [4.14]$$

For, d < 12 m (_40 ft): $\sigma_{\varepsilon_{r_d}}(d) = d^{.850}.0.198$ [4.14a]

and d ≥ 12 m (_40 ft): $\sigma_{\varepsilon_{r_d}}(d) = 12^{.850}.0.198$ [4.14b]

4.4.1.5 Estimation of cyclic resistance ratio (CRR)

The resistance of the soil to cyclic loading or stress that is applied by seismic shaking to change the condition of the soil is known as the CRR. Data from many in-situ tests, including the standard SPT, CPT, V_S and Becker penetration test (BPT), may be used to calculate the CSR. (Youd et al., 2001)

Deterministic Approach:

In 1971 (Seed & Idriss, 1971a) give the equation of CRR from the SPT-N which is later updated by (Youd et al., 2001). The equation is following:

$$\text{CRR} = \frac{1}{34-N_{1,60cs}} + \frac{N_{1,60cs}}{135} + \frac{50}{(N_{1,60cs}+45)^2} - \frac{1}{200} \qquad [4.15]$$

where, $N_{1,60cs}$ = a + b$N_{1,60}$ [4.16]

a and b are the line fitting parameters that depend on the fine content (FC) of soils that can be calculated by the following functions:

$$a = \begin{cases} 0, & FC \leq 5\% \\ e^{[1.76-(190/FC^2)]}, & 5\% < FC < 35\,\% \\ and\ \ 5, & FC \geq 35\% \end{cases} \qquad [4.16a]$$

$$b = \begin{cases} 1, & FC \leq 5\% \\ [0.99\ +\ (FC^2/1000)], & 5\% < FC < 35\,\% \\ and\ \ 1.2, & FC \geq 35\% \end{cases} \qquad [4.16b]$$

For Shear Wave velocity, v_s

$$\text{CRR} = 0.02\,(\frac{v_{s1}}{100})^2 + 2.8\,(\frac{1}{v_{s1}^{*} - v_{s1}} - \frac{1}{v_{s1}}) \qquad [4.17]$$

v_{s1} = overburden stress corrected V_S. The value of it is calculated from the following equation,

$$v_{s1} = v_s(100/\sigma_v')^{0.25}$$ [4.17a]

v_{s1}^* is the limited upper value of v_{s1} for the liquefaction occurrence.

Another empirical equation for easily calculating CRR from shear wave velocity and for all content of fineness (FC) of soil is following,

$$\text{CRR} = p[\frac{v_{s1}}{100}]^4 - [\frac{1}{q - v_{s1}}]$$ [4.18]

Here,

$$p = 0.013 + (0.001/15)(FC - 5)$$ [4.18a]

$$q = 225 - \frac{2}{3}(FC - 5)$$ [4.18b]

Probabilistic Approach:

Cetin et al. (2018) equation of calculating CRR from standard penetration test blow count (SPT-N) is given below:

$$CRR(N_{1,60}, M_w, \sigma'_v, FC, P_L) = \exp[-\frac{(N_{1,60}.(1+\theta_1.FC) - \theta_2.\ln(M_w) - \theta_3.\ln\left(\frac{\sigma'_v}{P_a}\right) + \theta_4.FC + \sigma_\varepsilon.\Phi^{-1}(P_L)}{\theta_5}]$$ [4.19]

where $\Phi^{-1}(P_L)$ is the opposite of a standard cumulative normal distribution, where the mean and standard deviation are both equal to one. $N_{1,60}$ is the corrected Standard Penetration Test blow count value which is normalized for the reference effective overburden stress (1 atmospheric pressure =101.03 kPa). It is calculated from the following equation:

$$N_{1,60} = N_m C_N C_B C_R C_E C_S$$ [4.19a]

where, N_m denotes SPT-N for each depth, C_N is effective overburden pressure, $(101.03/\sigma'_v)^{0.5}$, C_R = correction factor for rod length, C_E = correction of hammer energy ratio (ER), C_S = sampler correction, C_B = correction factor for borehole diameter.

ANN Approach:

In this investigation, the suggested methods from Juang et al. (2000) and Juang et al. (2002b) for computing CRR from LSFs generated using the SPT-N and Vs (Figure. 4.20). The LI function (Eq. 4.20) is a multidimensional, very nonlinear function in general. A three-layer neural network model may be used to create it:

$$LI = f_T \left[B_0 + \sum_{k=1}^{n} \{W_k f_T (B_{Hk} + \sum_{i=0}^{m} W_{ik} P_i)\}\right] \quad (4.20)$$

The LI function is then used to provide a search mechanism for finding points on the limit state's surface. Thirdly, the resulting points together define the LSF. Finally, utilizing these produced data points, ANN models were trained for both datasets (SPT-N and Vs) to estimate the CRR for the chosen open areas. Conceptually, the LI function of the SPT-N and Vs data may assume, respectively, the following ANN model forms (Juang et al., 2000, 2002b)

$$LI_{SPT} = f\,((N_1)_{60}, FCI, \sigma'_v, R_p, S_L) \quad (4.21)$$

$$LI_{Vs} = f\,(V_{s1}, FCI, CSR_{7.5}) \quad (4.22)$$

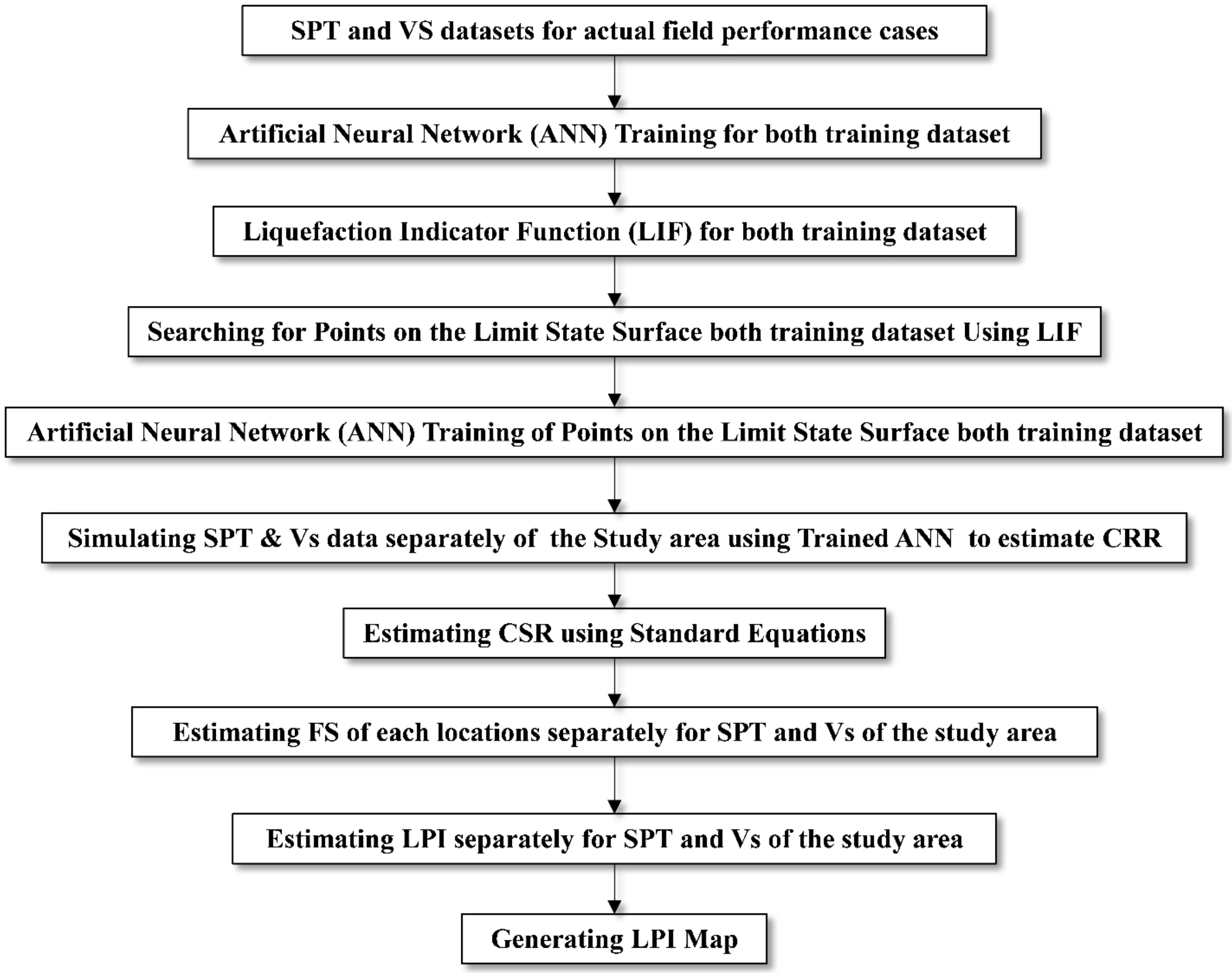


Figure 4.20 Flowchart showing the workflow of calculating LPI based on ANN approach

The limit state in this study is defined by the crucial CSR = CRR = *f* (indices of soil properties). The LSF, theoretically depicted in Figure. 4.21, is defined based on a reliable yet straightforward approach (Juang et al., 2000) A data point on the multidimensional surface of the limit state is created from each successful search. Once sufficient data points have been collected, an LSF is defined through CRR= *f* (indices of soil properties) since CRR = CSR7.5 or critical CRR determines the limit state boundary surface by its definition. Figure. 4.22 provides an illustration of the specified search algorithm.

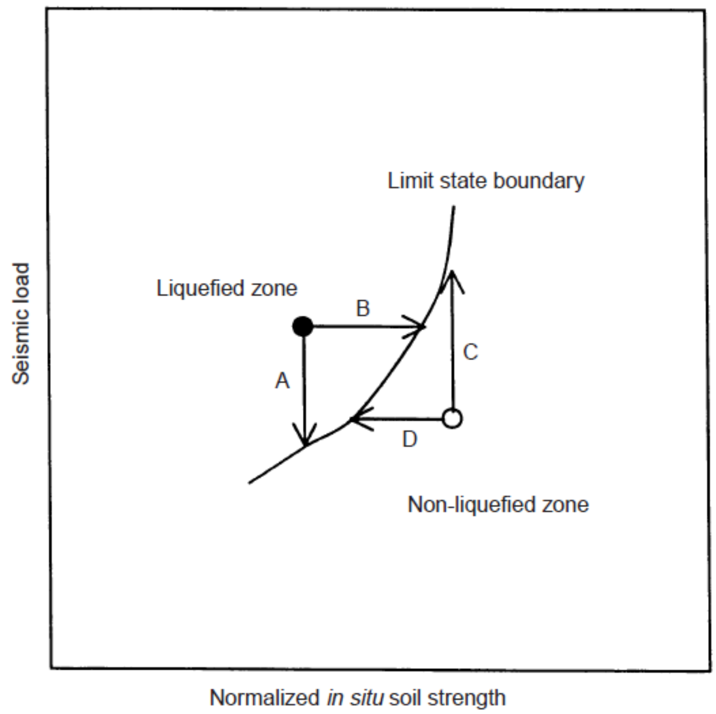


Figure 4.21 Conceptual model of the mechanism to search limit state boundary (after (Juang et al., 2000, 2002b))

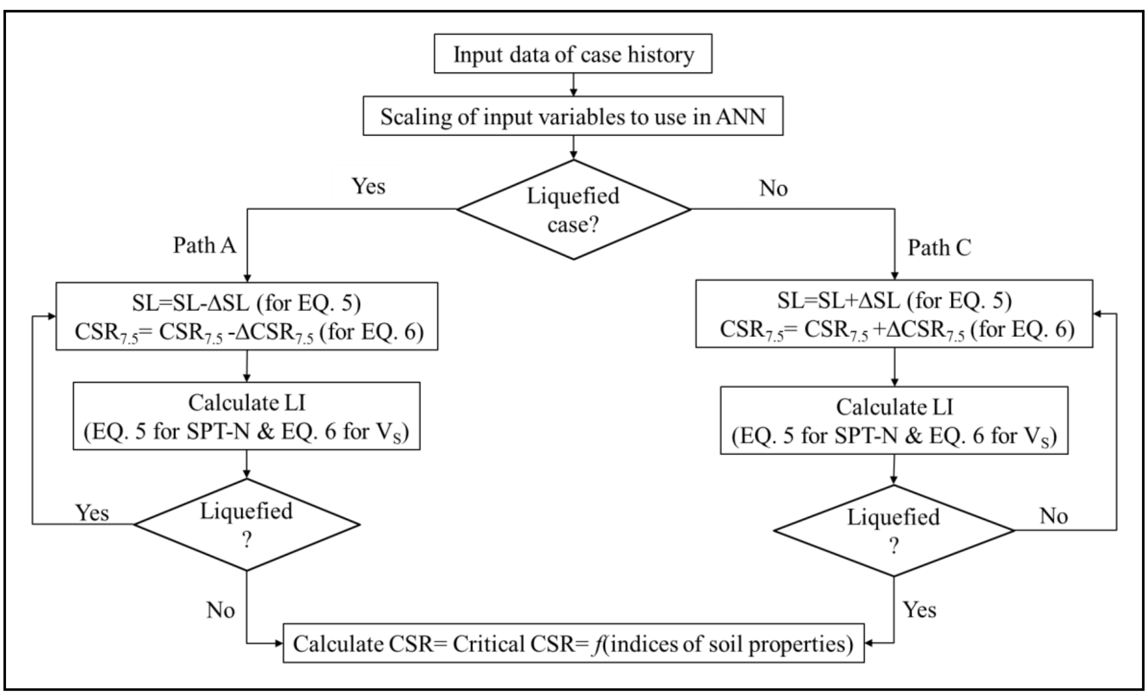


Figure 4.22 Searching mechanism of critical cyclic stress ratio (CSR) (after (Juang et al., 2002b, 2000))

It is possible to generate the connection weights and biases needed for CRR estimation by training the boundary surface points created by the aforementioned approach with a feed-forward, three-layer neural network:

$$\mathrm{CRR} = f_T \left[B_0 + \sum_{k=1}^{n} \{W_k f_T (B_{Hk} + \sum_{i=0}^{m} W_{ik} P_i)\}\right] \quad (4.23)$$

The following ANN model forms, respectively, are conceptualized as the LSF from the SPT-N and Vs data (Juang et al., 2002b, 2000):

$$CRR_{SPT} = f\,((N_1)_{60}, FCI, \sigma'_v, R_p) \quad (4.24)$$

$$CRR_{Vs} = f\,(V_{s1}, FCI) \quad (4.25)$$

The Neural Network Toolbox of MATLAB was used to implement all the requirements of the ANN model for training for LI and LSFs, respectively, as shown in Tables 4.8 and 4.9. (Beale et al., 2017)

Table 4.8 ANN model specifications for both LI and LSF

Network Type	Training Function (both hidden and output layers)	Transfer Function	Adaption Learning Function	Performance Function
Feed-forward Backpropagation	Levenberg-Marquardt (TRAINLM)	Hyperbolic Tangent Sigmoid (tansig)	Gradient descent with momentum (LEARNGDM)	Mean squared error (MSE)

Table 4.9 Numbers of layers and hidden neurons in ANN models

	LI_{SPT}	LI_{Vs}	CRR_{SPT}	CRR_{Vs}
Number of layers	3	3	3	3
Number of hidden neurons	8	6	5	4

4.4.2 Result and Discussion

This portion of the study dealt with the liquefaction hazard assessment for eight open spaces in the Dhaka Metropolitan Area. These open spaces are far away from each other. The locations are given Figure 4.2. For hazard assessment, liquefaction potential of those areas has been evaluated by both deterministic and probabilistic approaches. The deterministic approach is basically factor of safety-based analysis, whereas the probabilistic approach is the likelihood of liquefaction or probability-based. And the ANN approach is more robust of the three and bound to generate more realistic results by establishing precise nonlinear relationships. All the equations are described in the methodology section. A scenario of an earthquake 7.5 magnitude and PGA 0.15 g was considered. The LPI values of those areas were calculated. As the areas are far away from each other it was not possible to generate a contour or classification map of LPI. The prepared maps that show the individual LPI values of those individual open spaces for both SPT and V_S in all three approaches are shown in Figure. 4.23 to 4.27.

Table 4.10 The LPI values of each borehole based on SPT-N and Vs for a Mw 7.5 earthquake with a 0.15 g PGA.

Location	Lat	Long	GWT (m)	SPT			Vs	
				LPI from ANN	LPI from FS	LPI from PL	LPI from ANN	LPI from FS
Army Golf Club, Dhaka	23.81808	90.41166	1.4	4.73	2.49	4.07	0.00	0.00
BUP Ground, Dhaka	23.83908	90.35922	2.13	0.39	1.83	2.16	1.30	3.20
Dhaka Residential Model College, Dhaka	23.76426	90.3684	2.44	1.49	2.16	3.36	0.00	1.45
Mohammadpur Eidgah, Dhaka	23.76375	90.3641	2.44	0.38	0.00	0.00	0.00	0.00
Botanical Garden, Dhaka	23.81464	90.3641	2.44	1.11	1.75	3.67	0.00	0.00
Boldha Garden, Dhaka	23.71562	90.42014	3.66	0.56	0.96	2.41	0.00	0.00
Ramna Park, Dhaka	23.73453	90.39842	3.35	0.37	1.71	2.16	0.00	0.00
Armanitola Play Ground, Dhaka	23.71341	90.40385	3.66	0.00	0.37	2.46	1.12	1.43

The results (Table. 4.10) have revealed very low (<5) liquefaction potential in a scenario earthquake of 7.5 magnitude and PGA 0.15g for all locations, all datasets and all approaches indicating higher suitability for shelter construction.

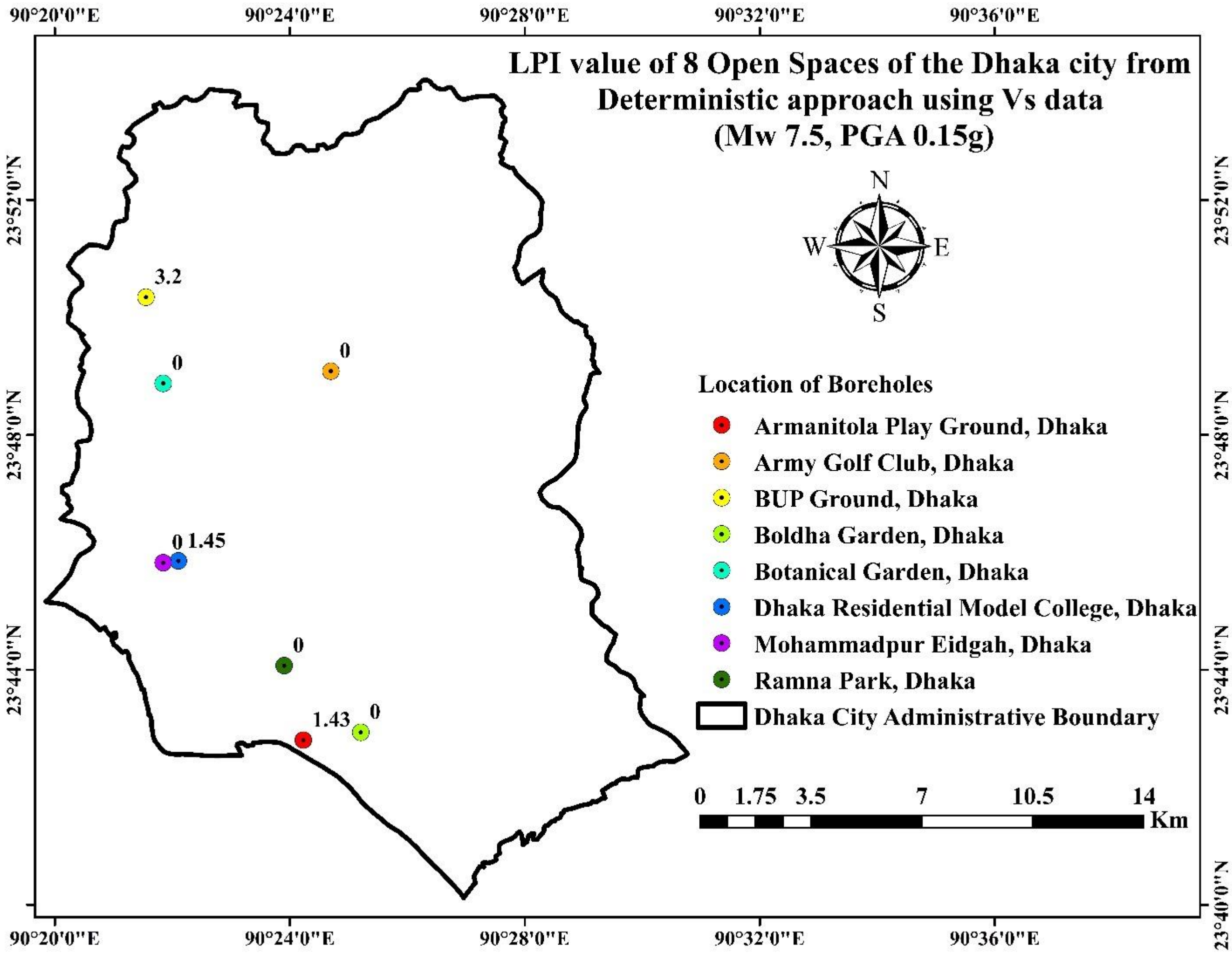


Figure 4.23 Map Showing LPI value of Eight Open Spaces of the Dhaka considering Mw 7.5, PGA 0.15g, in-situ ground water depth in a deterministic approach using V_S data.

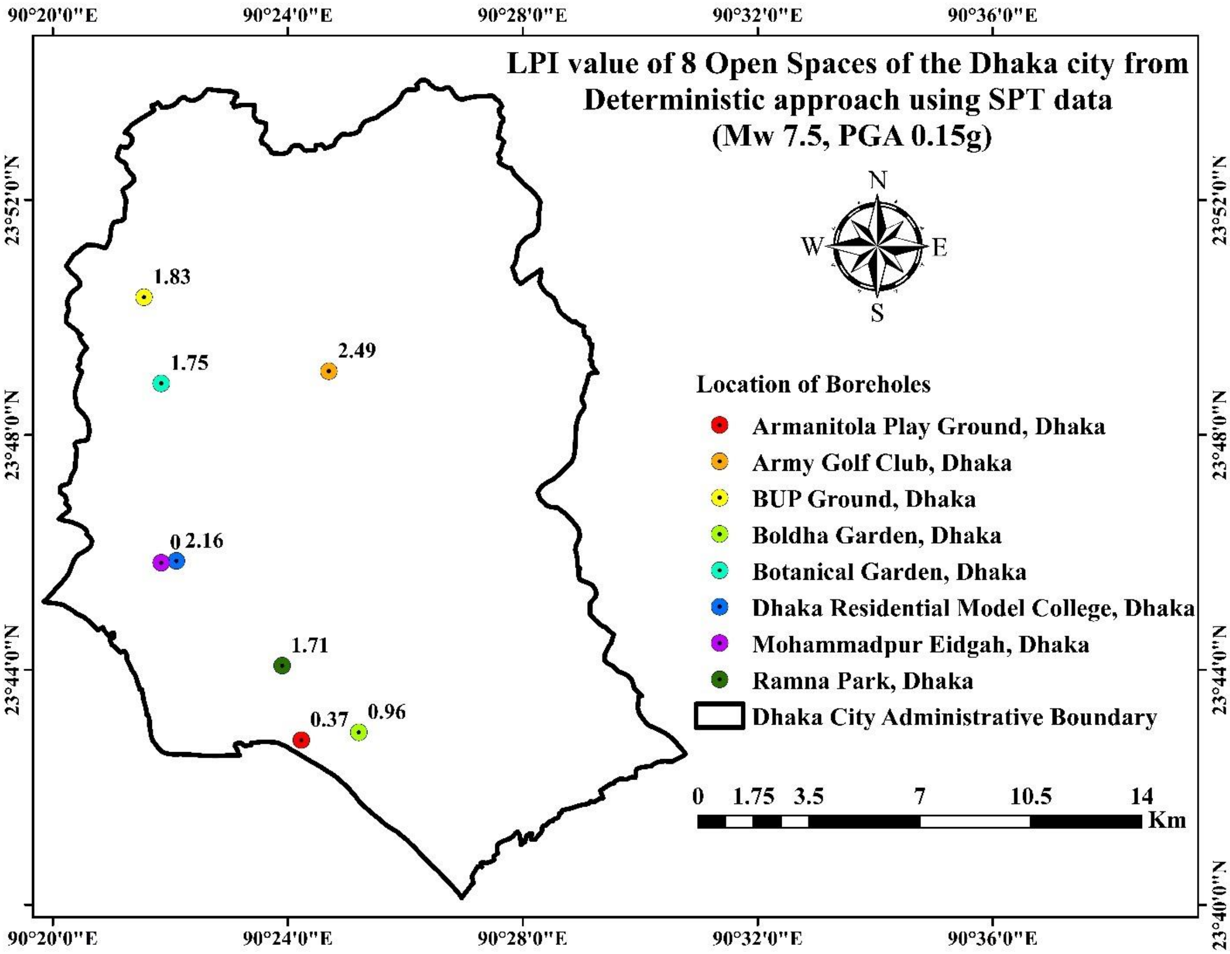


Figure 4.24 Map Showing LPI value of Eight Open Spaces of the Dhaka considering Mw 7.5, PGA 0.15g, in-situ ground water depth in a deterministic approach using SPT data.

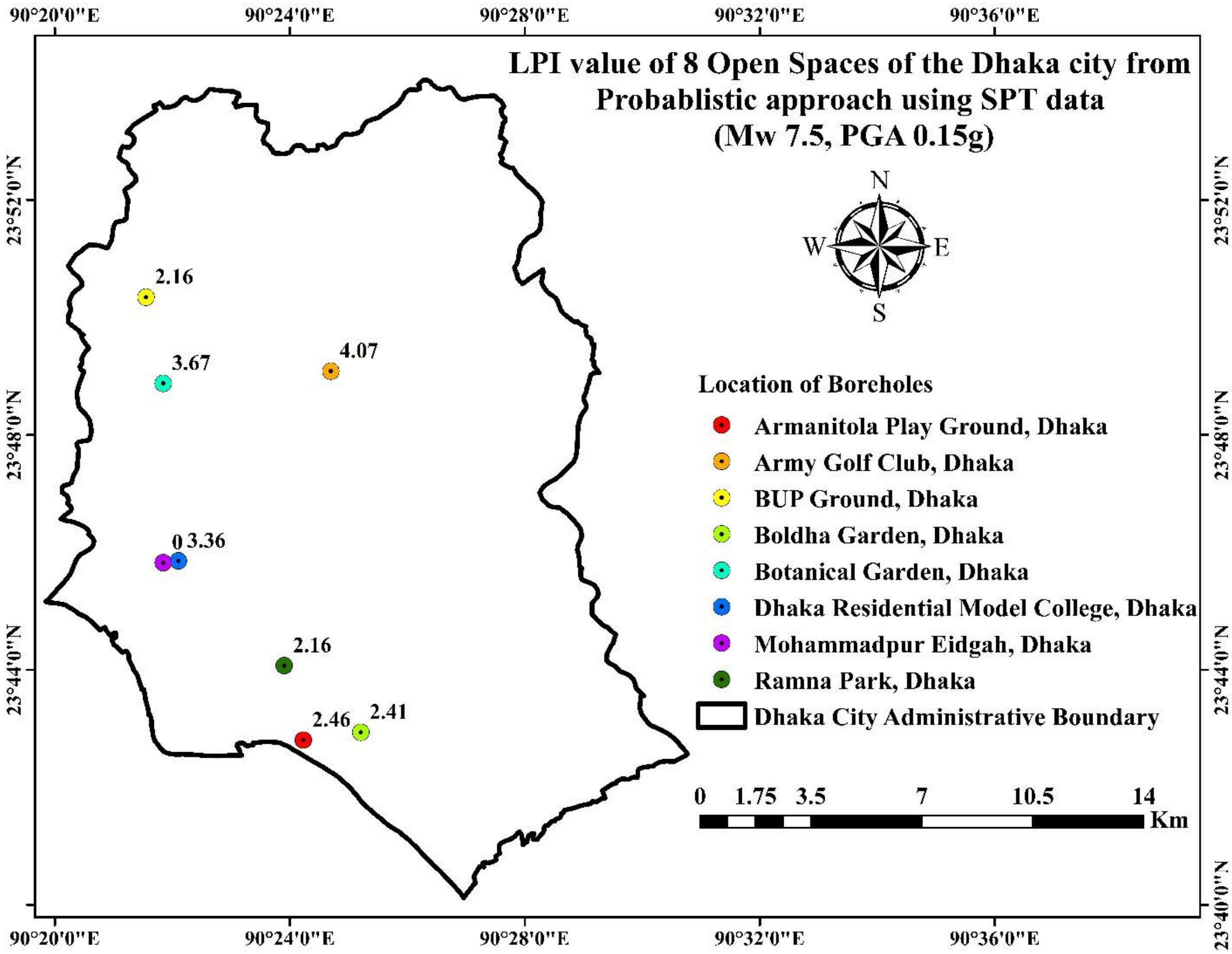


Figure 4.25 Map Showing LPI value of Eight Open Spaces of the Dhaka considering Mw 7.5, PGA 0.15g, in-situ ground water depth in a probabilistic approach using SPT data.

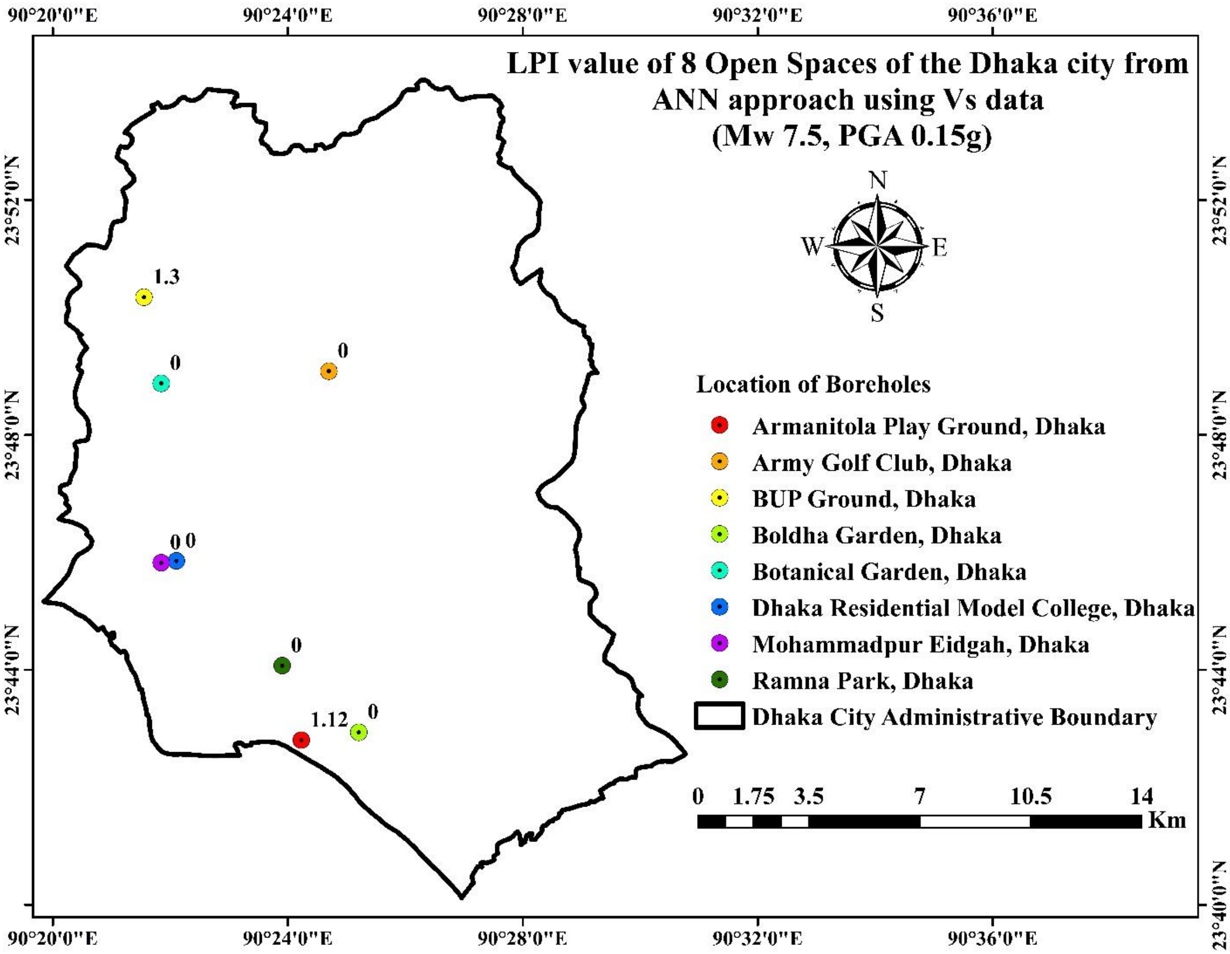


Figure 4.26 Map Showing LPI value of Eight Open Spaces of the Dhaka considering Mw 7.5, PGA 0.15g, in-situ ground water depth in a ANN approach using V_S data.

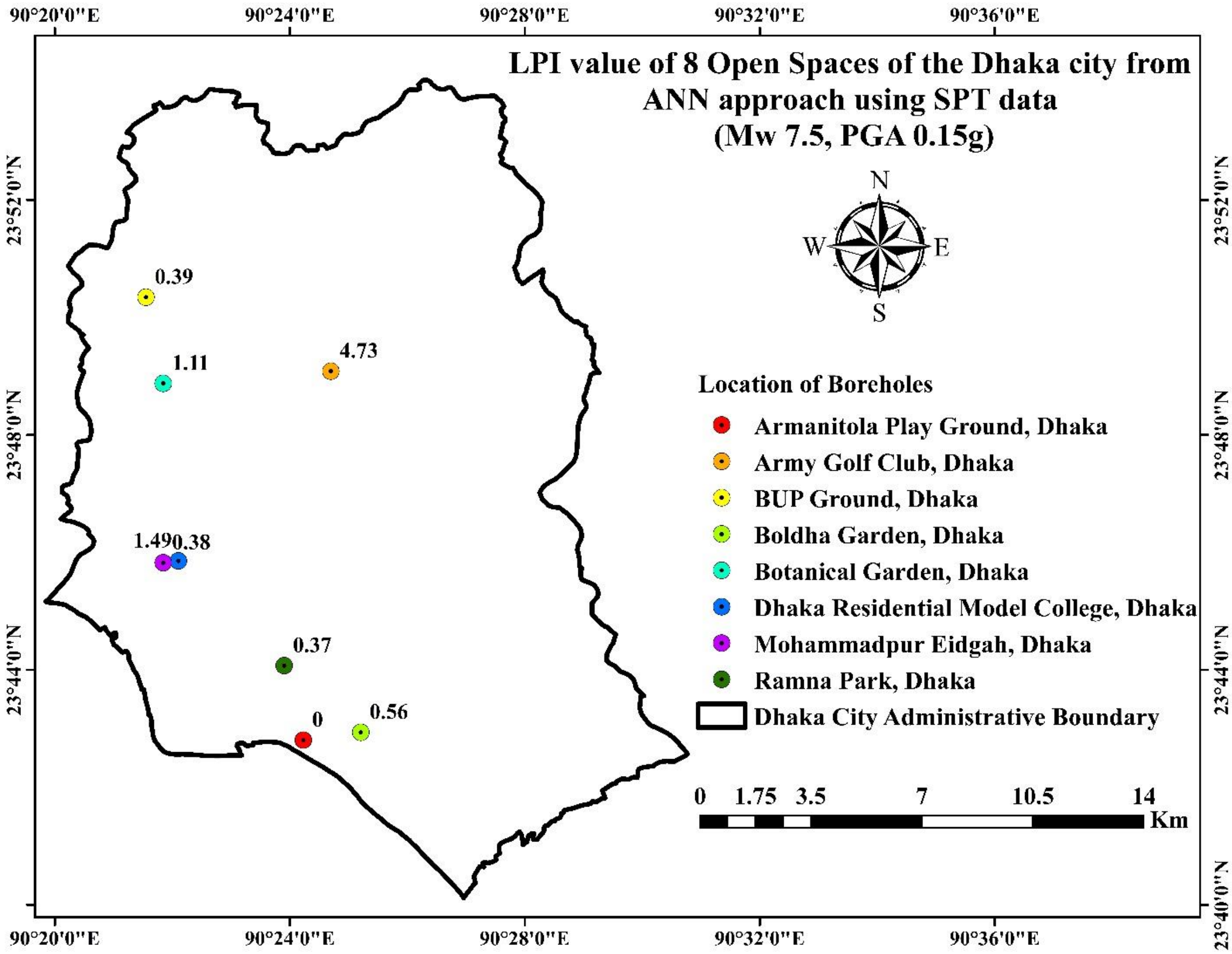


Figure 4.27 Map Showing LPI value of Eight Open Spaces of the Dhaka considering Mw 7.5, PGA 0.15g, in-situ groundwater depth in ANN approach using SPT data.

Liquefaction hazard assessment is very important to understand any possible impact after an earthquake. Open spaces are vital places after an earthquake as these are used for evacuation, emergency operation centers or shelters. But if these areas undergo liquefaction the response and recovery work will be severely hampered. In this study, liquefaction hazard has been assessed in 8 selected sites with deterministic, probabilistic and ANN approaches. The results have revealed very low liquefaction potential at all these sites for a scenario earthquake of 7.5 magnitude and 0.15g PGA. The upper reddish clay of the Higher Holocene Terrace is the primary reason for the low liquefaction potential in those sites.

4.4.3 Summary

Based on innate characteristics 203 sites were thought to be appropriate for long-term sheltering. However, it must be determined whether these sites will lose their effectiveness as a result of the earthquake's impacts, specifically liquefaction. Due to time and budgetary limitations, detailed tests cannot be done at all of the locations. Therefore, eight sites were chosen as case studies as they have the lowest risk (found from generalized liquefaction analysis) and highest COSI scores.

Seismic hazard assessment and site response analysis are necessary to evaluate the potential for liquefaction. The hazard assessment and response analysis of the eight locations were done using the PS logging, and shear wave velocity. In PSHA, PGA for these sites has been calculated which was used in 1-D Seismic Site Response Analysis that measured the response spectrum for the surface ground of the selected sites. But it did not provide any information regarding the resistance of these sites to liquefaction. The liquefaction potential is measured using the simplified procedure-based liquefaction potential index or LPI using the PGA value derived from PSHA. In this study, three different approaches were utilized, namely, the deterministic approach, the probabilistic approach, and the ANN approach. Two different types of data were employed in the LPI calculation. According to previous studies, using both SPT-N and V_S data is highly advised. To confirm the reliability of the study, all three of the most popular and trustworthy methods for calculating LPI, especially ANN, were used. The results have revealed very low (less than 5) liquefaction potential in a scenario earthquake of 7.5 magnitude from the Madhupur Fault, with PGA 0.15g (from PSHA), for all eight locations, all datasets, and all approaches. That indicates the high suitability of the sites for long-term shelter placement consideration.

Chapter 5:
Post-disaster Open Space Shelter Model for Dhaka Metropolitan Area

5.1 Background

It is better to be prepared than to wait for a disaster to occur, and it is also necessary to have plans for the people who survive the disaster. For that, there is a need to strengthen disaster management capabilities, and the first step towards that is disaster preparedness for urban areas, starting with identifying potential open spaces where people can be safely take refuge during and after a disaster.

One of the critical strategies for improving disaster preparedness is the identification and provision of suitable areas for emergency shelters prior to any disaster so that the response is planned and adequate. This is especially concerning in urban settings, where the availability of such areas is limited and there is an ever-increasing need for risk-sensitive land use planning. That is why it is crucial to understand the quality and quantity of possible shelter locations in the planning phase prior to the occurrence of any disaster. Moreover, in order to be used as humanitarian shelters in the event of a disaster, these open spaces must meet a set of specific criteria. The criteria for open spaces to be used in the wake of a disaster vary. Knowing the specific criteria for identifying open spaces for humanitarian purposes will aid in categorizing open spaces capable of functioning well during emergencies, thereby strengthening emergency preparedness in those areas and providing the public, government entities, and partner organizations with a pre-identified spaces for better response (Rimal & Lal, 2021). All these have been done and discussed in chapter 3 and the methodology used in chapter 4 allows to fully ensure identified sites are safe for long term shelter consideration.

Proper planning regarding open spaces' use as shelter site in post-disaster scenario can assist the public, authorities, and other humanitarian groups in responding promptly and efficiently in the aftermath of any disaster (Jones et al., 2014). In case of earthquakes, open space shelters play vital role in different phases of emergency management cycle as shown in table 5.1.

Table 5.1 Role of open space shelters in emergency management cycle (Wei et al., 2020)

Region	Emergency management cycle			
	Preparedness	Response	Mitigation	Recovery
Istanbul, Turkey			✓	
Umbria Region, Italy			✓	
Christchurch, New Zealand				✓
Mehuin & Dichato, Chile				✓
Tokyo and Kobe, Japan	✓		✓	
Concepción, Chile		✓		✓
San Francisco, U.S.	✓	✓	✓	✓

The various vulnerabilities, needs, and capacities of affected groups must be recognized and considered in the planning and design of a standard open space shelter (French, 2017). They need to meet the requirement for emergency food, WASH (water, sanitation and hygiene) services, and emergency evacuation sites (Rimal & Lal, 2021). The Sphere Project has provided the standards and general guidelines that can be used in most emergency response scenarios, as well as provisions for strategic planning and settlement planning that cover living space, construction, and environment for emergency shelters (Anhorn & Khazai, 2015). The foundation of the Sphere guideline is based on the Humanitarian Charter. The Humanitarian Charter acknowledges that all affected people in a crisis have the right to receive assistance and protection of their lives, that in turn, requires all the basic conditions for life are met with dignity. The standards can be adjusted to meet local needs. The Sphere addresses the standards in the four key response sectors–

1. Water Supply, Sanitation and Hygiene Promotion (WASH)
2. Food Security and Nutrition
3. Shelter and Settlement
4. Health (Sphere, 2018)

Therefore, open space shelter management should be planned in accordance with standards, criteria, and guidelines developed for emergency responders and humanitarian groups based on post-disaster assessments of previous disasters (Rimal & Lal, 2021).

5.2 The Cluster Approach to Post-Disaster Emergency Management

The cluster approach is a set of structures, processes, principles and commitments to coordinate humanitarian action when a national government requests international support. Its goal is to improve the humanitarian community's organization and accountability to disaster victims. It is used to coordinate humanitarian aid. At the global level, humanitarian organizations have agreed to lead particular clusters, and at the country level, a cluster structure for humanitarian responses has been created. Cluster leadership ideally replicates global arrangements at the country level, and clusters are frequently co-led by government and/or co-chaired by NGO partners. The cluster system was created to address inadequacies in international humanitarian response accountability. It distributes responsibility for service delivery (health, housing, etc.) across several cluster lead agencies, so no single agency is responsible for the entire response. The Humanitarian Coordinator has overall responsibility for coordination and delivery in each country (HC) (Lee & Low, 2006; Mister, 2006; Parmar et al., 2007; Steets et al., 2010).

Clusters are groups of UN and non-UN humanitarian organizations working in each of the major humanitarian fields (water, health, shelter, logistics, etc.). They are selected by the Inter-Agency Standing Committee (IASC) and have specific coordination responsibilities. After the earthquake in Pakistan in 2005, the Cluster Approach was used for the first time. There have been two appraisals since then. The first, completed in 2007, was mostly concerned with implementation. In 2010, the second looked at how clusters contributed to bettering humanitarian aid. The Cluster Approach was refined and improved in the context of the 'Transformative Agenda' following the 2010 report.

There are 11 clusters in the world (Figure 5.1). In response to a specific emergency, the same clusters might be triggered on a national and sometimes subnational level. One or two United Nations agencies, or a United Nations agency and an international NGO, lead each global cluster. Clusters are usually co-led by a UN agency and an NGO at the country level. Cluster leaders must be prepared to assist affected persons where other groups are unable to (IASC, 2020; Mister, 2006; Steets et al., 2010; Stoddard et al., 2007).

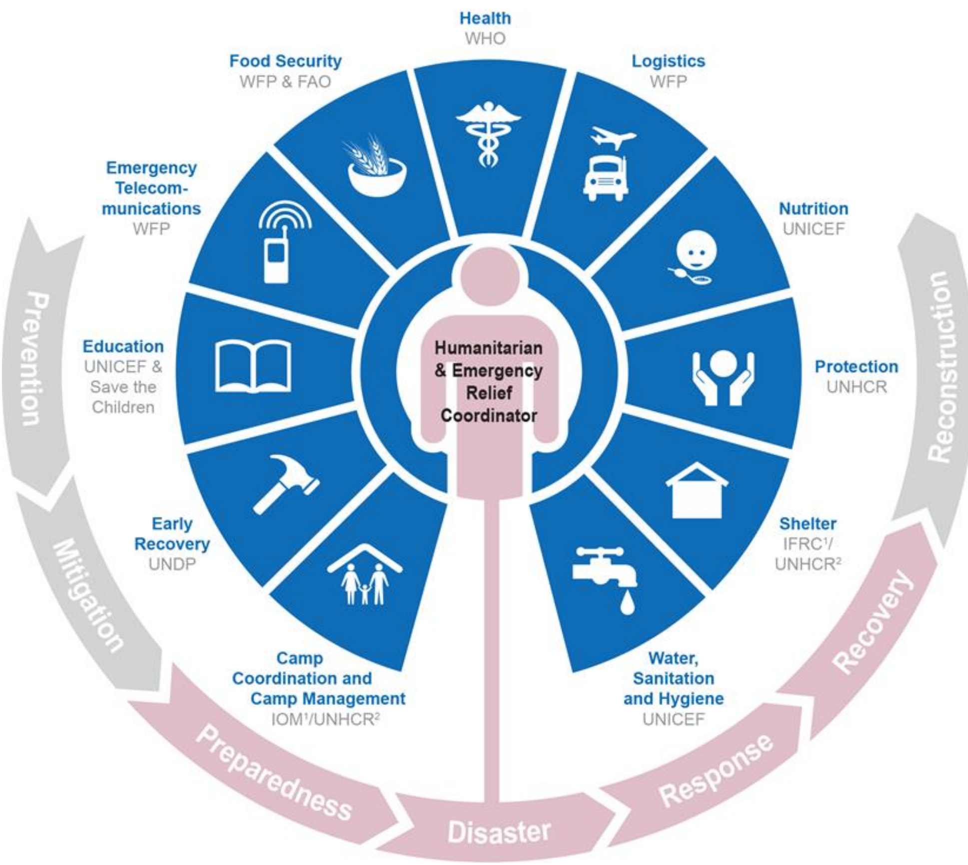


Figure 5.1 Globally Agreed 11 clusters for humanitarian emergency response (IASC, 2020)

Both humanitarian emergencies caused by conflicts and those caused by disasters can benefit from a Cluster Approach. The Approach strives to improve system-wide preparedness, ensure fast access to vital resources and expertise, and focus technical capabilities. It:

(1) Improves accountability and openness. Its techniques increase resource allocation transparency, build leadership, and emphasize on operational performance, all of which contribute to increased responsibility.

(2) Provides more predictability. Sector and theme responsibilities are clarified, and institutional processes at the national and international levels add clarity to areas that aren't covered otherwise.

(3) Collaboration with national and local governments. The principal duty-bearers are government officials. Humanitarian actors actively engage with the distressed population, support them and take over operational delivery, coordination, monitoring, protection and assistance.

(4) Involvement of affected groups. Humanitarian actors must hold themselves accountable to the people they help. They must, at the very least, consult and engage with the people they help. Affected communities contribute to the development of the best solutions to the problems they confront.

(5) More effective lobbying. Advocacy carries more weight when clusters, individually or collectively, speak with one voice on topics of common concern, and do so in collaboration with affected groups that are not generally heard.

(6) Strategic and operational planning in collaboration. Formal coordination methods within and across clusters increase efficiency and effectiveness (IASC, 2020; Steets et al., 2010; Stoddard et al., 2007).

In Bangladesh, the cluster approach has also been adopted in the "National Earthquake Contingency Plan" having 9 clusters in total. These are (CDMP, 2009):

- Cluster 1 - Emergency Operations- Overall Command and Coordination
- Cluster 2 - Emergency Operations- Search, Rescue and Evacuation
- Cluster 3 - Health
- Cluster 4 - Relief Services (Food, Nutrition and other Relief)
- Cluster 5 - Shelter
- Cluster 6 - Water Supply, Sanitation and Hygiene

- Cluster 7 - Restoration of Urban Services
- Cluster 8 - Transportation (road, rail, air, water way, sea)
- Cluster 9 - Security, and Welfare

In emergency situation, Cluster 1 will seek to develop a framework for coordinated response activities by putting together a well-coordinated mechanism to mitigate the effects of probable earthquakes. It will be led by Department of Disaster Management and National Emergency Operation Center (NEOC). Cluster 2 will develop an effective plan for emergency services (Search, Rescue, and Evacuation, First Aid, and Fire Safety, among others) by ensuring inter-agency coordination at the national level, increasing the capacity of concerned agencies, and developing national guidelines based on international practice under the leadership of Fire Service and Civil Defense (FSCD). Cluster 3 aims to reduce human casualties by establishing an effective medical first response system in high-risk areas, improving emergency medical care through the development of Hospital Preparedness plans, increasing capacity for establishing a well-organized mass casualty treatment system, and developing an epidemic surveillance system to prevent epidemic outbreaks during the post-earthquake period. This cluster will be led by Directorate General of Health Services (DGHS) with support during emergency response phase from office of Civil Surgeon, Armed Forces Division (AFD), FSCD, NGOs, Cyclone Preparedness Program (CPP), Hospital and Clinic Authorities, District Hospitals, Local Governments etc. Cluster 4 will assess damage and needs in order to identify external requirements, as well as ensure the provision of essential facilities for displaced people following emergencies, secure food and nutrition, logistic supply to displaced people based on need assessments, and efficient coordination with UN agencies, international and local NGOs, and donor agencies to supplement government welfare assistance. These activities will be led by Ministry of Disaster Management and Relief. Cluster 5 is assigned to provide temporary shelter for displaced people following disaster events such as earthquakes and to provide basic facilities to them. Cluster 6 will ensure rapid restoration of water supply for safe drinking water and sanitation management during earthquake disasters; Cluster 7 will identify critical public facilities vulnerable to earthquakes and strengthen them to a higher level of safety; enact spatial planning and land use control for earthquake vulnerability reduction; and build control and ensure compliance with Building Code practices; Cluster 8 will identify vulnerabilities of transportation systems and strengthen them to a higher level of safety; and Cluster 9 is responsible for maintaining law and order during catastrophes such as earthquakes (CDMP, 2009).

Table 5.2 The Cluster Approach with the lead agencies and the global partners as was given in the Dhaka Earthquake Contingency Plan of 2009 (CDMP, 2009).

Functional Clusters	Lead agency	Global Cluster Partners
Emergency Operations Cluster 1 – Overall Command and Coordination	DDM, MoDMR (National EOC)	UNOCHA, UNRC
Emergency Operations Cluster 2 – Search, Rescue and Evacuation	FSCD, Ministry of Home Affairs	IFRC
Restoration of Urban Services Cluster	City Corporations, Ministry of Local Government & Rural Development	UNDP
Health Cluster	Directorate General of Health Services, Ministry of Health and Family Welfare	WHO
Relief Services (Food, Nutrition and other Relief) Cluster	Directorate of Relief and Rehabilitation	UNICEF, IFRC, WFP
Security and Welfare Cluster	Bangladesh Police	UNHCR/OHCHR/UNICEF
Shelter (Including Camp Management) Cluster	DDM, MoDMR	IFRC/UNHCR/IOM
Water Supply, Sanitation and Hygiene Cluster	City Corporations, Ministry of Local Government and Rural Development	UNICEF
Transport (Road, Rail, Air, Sea) Cluster	BRTA, CAAB, BR, CPA	UNDP, WFP

Cluster 5 is assigned for Shelter Management (including putting up temporary shelter), which is one of the most crucial and urgent necessities during the early phase of the emergency. This coincides with the focus of our research. During an emergency, this cluster will be led by the Department of Disaster Management (DDM), with the Ministry of Disaster Management and Relief as the responsible ministry. The main task is to set up temporary shelter and basic essential facilities for displaced people so that they can live in the shelters (CDMP, 2009).

Earthquake, being a rapid onset and inherently unpredictable natural disaster, poses greater response and preparedness challenges for the emergency response planners as the lead time for preemptive evacuation is non-existent. So, pre-disaster planning for emergency shelter placement for a collaborative and coordinated response in the disaster aftermath is critical. A well-judged and adequately distributed emergency shelter placement strategy is essential for ensuring that these Cluster 5 tasks are completed in such a timely manner after an earthquake. For an overcrowded city like Dhaka, it is critical to locate existing open spaces. In order to tackle a severe earthquake in the future, the focus of this chapter will be proposing guidelines for preparing and prepositioning resources to carry out Cluster 5 activities in a timely and efficient manner.

5.3 Open Space Shelter Model Considerations

People's perceptions of risk are influenced by a range of factors both during and after a disaster. As emergency needs are superseded by shelter needs, these factors change over time. Near open spaces, the availability of infrastructure and services such as electricity, restrooms, and clean drinking water becomes vital (Shrestha, Romão, et al., 2018). Pre-identifying suitable open spaces and establishing shelter services aid in their use as a temporary meeting point immediately following earthquakes or any other disaster. They can be utilized for urgent care of those in need, as well as for foreign assistance management, which is critical for any local emergency management (Rimal & Lal, 2021).

Water, sanitation, food, and health are all linked to the right to adequate shelter (Sphere, 2018). Shelter needs are divided into –

1. Short term (during or immediately after an earthquake) or
2. Long term

In the aftermath of the 1995 Kobe earthquake, it was seen that *average* accommodation time in temporary shelters were 8.5 months as post-disaster recovery activities were being carried out (Liedtke, 2020b). If a high-magnitude earthquake does occur near Dhaka, such long term shelters might be required to support response and recovery activities. In chapter 3, some suitable open spaces were located for long-term shelter establishment. The open space shelter model proposed in this chapter is meant to be planning aid for providing long term shelter needs after an earthquake. The considerations are based on literature review and expert opinions (table 3.2) will be discussed in the following subsections.

5.3.1 Shelter

The foundation for a well-planned and coordinated shelter response is identifying requirements and then generating appropriate response choices. Each affected household will need sufficient space for performing their basic domestic activities and to live with dignity. That is why the open space shelter's space capacity for each individual must be determined, and appropriate shelter planning, as well as the plan of essential services, must be adequately executed and documented. The site's area should be large enough to allow for proper separation of living units, and the site's capacity should be determined based on that (Rimal & Lal, 2021). Standard of covered living area for affected population of urban settings living in shelter conditions is 3.5 m^2 per person to carry out their domestic activities (Sphere, 2018). It should be considered while determining the sheltering capacity of the open spaces. However, in a city of high population density like Dhaka, it might not always be possible to maintain this standard and accommodate all affected people due to limited size and number of open spaces. Even though 3.5 m² per person is a very small space to live in, it can be extremely difficult to achieve even this space, under the densely populated urban context. Thus, the goal should be to provide assistance to as many people as possible even if it means providing less covered space per person. Covered living area per person can be adjusted based on evaluation of the field context because the benchmark should be appropriate to the needs of the stakeholders under a particular context. Figure 5.2 shows the sizes of the shelters allocated for families after disasters in comparison with the standard.

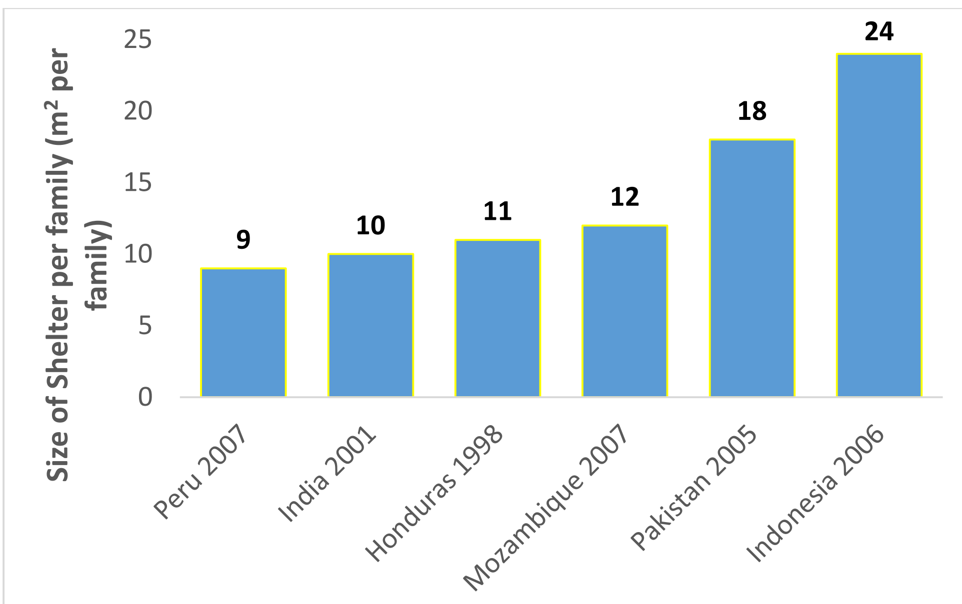


Figure 5.2 Comparison of shelter sizes for family accommodation (Ashmore, 2008)

The vertical axis in Figure 5.2 shows the shelter size provided for families in various shelter programs (horizontal axis). Each of these case studies were fully implemented within the first year of the disasters and accommodated at least 500 families. The average family sizes in these countries are about 4 to 7 members. Apart from Indonesia, most of the countries could not meet the standard for covered living space for their given household size. In Pakistan, the shelters could provide protection from the winter weather even though they were smaller than 3.5 m². After the 2008 conflict in Kivu, Congo, large number of people were displaced to Goma where they were supported with shelters. They were able to provide 2.25 m² covered living area per person which proved to be efficient in providing dignified accommodation (NRC, 2010). Even in India after Bhuj Earthquake, the small living space were considered adequate for accommodating the large households. Thus, the "one size fits all' approach is not able to account for the differences in needs of various individuals and regions (Ashmore, 2008). Considering these cases studies, in the context of densely populated Dhaka metropolitan area and the scarcity of open spaces, it is suggested that 2.3 m² (2.2 to 2.4 m² on average) covered living space per person should be appropriate in shelter camps. Taking this value instead of 3.5 m² means 15.3 lakh more people get to be accommodated in the existing open spaces. Within each tent, around 10 people can be accommodated in the demonstrated tent size of 4.8m by 4.8m dimension (see section 5.4). Under this calculation there will even be some space left between the two sides of the tent, whose benefits are discussed later.

Culturally and socially acceptable shelter options, construction techniques, and materials that are also environmentally sustainable should be adopted. Suitable shelter construction materials will be lightweight, having low thermal capacity, like – tarpaulin, plastic sheets etc. (Sphere, 2018). Since Bangladesh is frequently affected by other natural disasters like storms, nor'westers, cyclones etc., it is necessary to consider the strength of tent construction materials. To protect against rain and flooding, the tent materials should be water-proof.

In hot climates like that of Dhaka, internal floor-to-ceiling height should be 2 meters minimum. The floors of the shelter should be high enough so that floodwaters cannot enter the living area.

The shelter should have separate areas for cooking, healthcare facilities, sanitation, administration, storage, religious activities etc. In case of Dhaka, the cooking area should be shaded or covered and adjacent to the shelter area to reduce additional heating as the climate is warm and humid. Also there should be outlets to allows cooking gases and smokes to escape. Minimum one blanket and bedding per person will be required inside these tents. In the context of Dhaka, “safe for humans” insecticide-treated nets may be a used as the open spaces are infested with mosquitos and various insects (Sphere, 2018; The Daily Star, 2012).

5.3.2 Health and Nutrition Services

Significant impact may occur on the health and well-being of the affected people after an earthquake. During a crisis, the fundamental purpose of health response is to avoid and reduce excessive mortality and morbidity. Adequate planning and proper provision of services at post-disaster shelter facilities can protect the health, safety, and dignity of the affected persons. Insufficient health services, drainage, sanitation, water supply, or weather protection can significantly increase the risk of disease outbreak within a shelter site (Rimal & Lal, 2021). In urban setting, the scale of need can overwhelm the capacities to quickly provide assistance. At the same time, people at risk can vary based on time of the day when the earthquake occurs. Triage mechanisms are appropriate under such circumstances when immediate attention will be given to those who needs quick treatment and stabilization. Minimum standards of providing healthcare services are linked with other rights like WASH, food and shelter. So, it is necessary to apply all these standards at the same time for open space shelter management (Sphere, 2018). For providing adequate emergency healthcare services, the shelter must have a functional healthcare unit reflecting the emergency and long-term needs of the affected people.

Based on the author's knowledge about Dhaka Metropolitan Area's context and reviewed literature, the following suggestions regarding healthcare services are noteworthy –

1. There should be an operational plan for the shelter's healthcare providing systems that clearly states the roles and responsibilities of the health service providers. It should place a functional committee consisting of local healthcare providers headed by professionals and experts.
2. The shelter warehouse must store first aid materials and equipment as well as items related to reproductive health, enough to meet the needs of the people living in the catchment area. The expiration and storage of these materials should be monitored and maintained at routine basis.
3. It needs to be ensured that the healthcare workforce (health service providers like doctors, nurses, psychological care givers and support staff) in terms of number and profile in the catchment area of the open space shelter is enough to meet the population and service requirements. The workforce should be capable of all types of emergency services, ranging from first aid and pediatrics to invasive surgical care and childbirth, if required.
4. The local markets and pharmacies should have enough supply of required approved drugs and the nearby hospitals should have necessary life-saving equipment that can be retrieved, if necessary, in the aftermath of an earthquake. This includes considerations for various gender, age groups and persons with disabilities as well.
5. There should be vector-borne disease control mechanisms in the open space shelter.

The shelter-seeking people will require emergency food for survival. There should be necessary provision for adequate and nutritious food stored to tackle the early recovery phase for the population of the shelter catchment. Needs of people of different age groups, especially infants and mothers should be given proper consideration. But these facilities at the shelter will be managed and provided by cluster groups 3 (Health) and 4 (Relief Services) of the "National Earthquake Contingency Plan" of Bangladesh.

5.3.3 WASH Services

People who are affected by crises are more vulnerable to diarrheal and infectious diseases, which can cause illness and death. Risk of these diseases are higher where sanitation, water and hygiene services are not adequate. After Kobe earthquake, elderly people and other vulnerable population were adversely affected due to insufficient sanitary facilities (Liedtke, 2020b). That is why it is essential for the open space shelter to have proper WASH facilities. In order to provide that, the key actions documented by the Sphere should be followed, such as (Sphere, 2018) –

1. Identification and prepositioning of accessible piped water supplies or surface water sources, according required amount of water. For instance- large tanks should be established for storing and providing drinking water (daily 2.5 liters/ person).
2. Identification of the necessary hygiene items needed by the affected community considering the different needs of various gender, age groups and people with disabilities.
3. Establishing excreta management facilities considering the surroundings to avoid contamination of resources and environment, as well as cultural habits (e.g., access to running water in toilets). The toilets should be constructed using most suitable technical options, keeping in mind the needs of women, children, elderly and persons with disabilities.
4. Setting up a solid waste management and drainage system as necessary for the shelter inhabitants, and pre-positioning cleaning materials and equipment.

5. Making sure the required items and equipment are available in the surrounding areas and stocking minimal number of items at the shelter in case of emergency.

However, these facilities should be maintained and monitored by the cluster 6 (Water Supply, Sanitation and Hygiene) of the “National Earthquake Contingency Plan” of Bangladesh. The minimum quantities of essential WASH items are listed in table 5.2.

Table 5.2: Standards for WASH facilities (Sphere, 2018; UNHCR, 2022a)

Item	Quantity Required
Water (drinking and domestic usage)	15 liters per person per day
Soap	250 grams per person per month (extra 250 grams for women)
Disposable sanitary pads	15 per month per person
Shared toilets	1 per 20 people
Shower	1 per 50 people
Water tap stand	1 per 80 people

The toilets should not be placed less than 6 meters and more than 50 meters away from the shelter in order to prevent odor and pests. The distance from bottom of pit to water table should be at least 1.5 meter while the refuse disposals should be placed less than 100 meters from dwellings (DFID, 2010). It will be required to provide separate toilet and bathing areas for men and women. Water sources should not be more than 200 meters from the inhabitants (UNHCR, 2022a). It should be made sure that sanitary facilities and drinking water supplies are pre-positioned in all the open spaces to provide support during the emergency.

5.3.4 Other Emergency Infrastructures and Service Utilities

People benefit tremendously from the availability of electricity (Shrestha, Romão, et al., 2018). For safety and security concerns, enough light should be provided in and around the shelter site. Existing structures on the site should be safe and compliant with national construction requirements (Rimal & Lal, 2021). So, there should be sufficient and safe energy supply to provide lighting, ventilation and other basic facilities (Sphere, 2018). There should be backup measures like solar panels, generator, lights, candles, lamps etc. in case of power failure. Fuel and other energy sources will be required for power generation and cooking. The shelter should have fire safety measures and fire-fighting equipment considering that fires are the most common secondary hazard following an earthquake (Sphere, 2018; Wei et al., 2020). It should be considered that gap is required between structures to prevent spread in case of fire (UNHCR, 2022a). There should be functional emergency communication services at or near the open space shelter with redundancy measures to prevent their failure at times of crises.

5.3.5 Security and Cultural Considerations

Security at the shelter means availability of a living environment that is secure and safe in order to provide the shelter-seeking people with privacy and dignity during their stay. It is important that the shelter is culturally and socially acceptable. In the crowded shelters, privacy is a major concern (Liedtke, 2020b). Thus, it is recommended that men and women have separate tents and toilet and bathing facilities due to gender sensitivity. However, in case the need for shelter exists for longer than 2-3 months, tents can be organized for family accommodation. Unaccompanied children, vulnerable women, elderly and persons with disabilities can be at great risk of harassment, exploitation and in some cases, trafficking in the shelter environment if proper protection is not available at the shelter. There are possibilities of rising conflict and disorder due to limited ration, assistance and living space (UNHCR, 2022b). Therefore, it will be necessary to appoint appropriate *non-military* personnel for the protection of the shelter inhabitants and maintain law and order. This responsibility will be undertaken by the respondents appointed under cluster 9 (Security, and Welfare) of the “National Earthquake Contingency Plan” of Bangladesh. Separate prayer areas for people of different religions are also their basic human right. Thus, considerations should be given to –

1. Women’s privacy needs
2. Religious and cultural needs
3. Needs of the elderly and people with disabilities
4. Safety of children and women.

5.3.6 Operation and Maintenance

The open space shelter's operation mechanism is something that defines how successful the recovery would be. So it must be clear so that the facility can be used promptly in an emergency (Rimal & Lal, 2021). Localized standards are suggested in this research but the exact steps and standard operating procedures require further research to be determined properly and are out of the scope of this study. It is suggested that an National emergency operation center should be maintained from where the shelter activities will be coordinated.

Each shelter site shall also have registration, administration and coordination tents where the people will first arrive, register their information, seek for assistance. There shall be provisions where the emergency supplies will be stored. The overall management of this unit will be carried out by representatives of DDM and MoDMR. The various cluster representatives will also coordinate relevant activities from this unit.

Coordination with logistics supply is also done here. The tent construction materials or shelter kits should be accessible to use in case of an emergency, possibly stored at a warehouse near the open space. Because collecting a large amount of construction materials immediately after an earthquake may not be possible. Most of the identified open spaces does not have pre-constructed structures nearby to be used as warehouse. Thus, attempts can be taken to implement this consideration in the suitable open spaces. Routine tests and maintenance works should be carried out at the open space shelter for the guarantee of its serviceability when in need. In the aftermath of the disaster, it will also be necessary to monitor and evaluate the shelter's performance to understand the varying needs and challenges (Pitts & So, 2015). That is why a well-documented plan should be made to operate and maintain the facilities, services and utilities effectively at the shelter (Sphere, 2018). Since such a plan requires the intense stakeholder engagement which is more appropriate for ministries, making such a plan was out of the scope of this study. However, the suggestions floated here may be utilized when such an initiative is taken.

5.3.7 Shelter Activation and Staffing

In the pre-disaster phase the DDM will responsible for ensuring preparedness of first responder organizations for effective management of response activities in partnership with other stakeholder agencies.

Usually it is the contingency plan that defines the activation and the government is then follow protocols to declare it. The shelter management activities will be led by DDM and MoDMR. According to "National Earthquake Contingency Plan" of Bangladesh, the activation and staffing of shelters will be determined after rapid risk assessment following the disaster (CDMP, 2009). But the primary suggestion of this study is safe site selection and establishing localised standards for various shelter aspects before the earthquake strikes. Preparation for activating the shelters should be undertaken much before the earthquake occurs. The excution of the shelter activities and dissemination of roles and responsibilities of the personnels will be assigned by cluster lead. The required personnels may be:

- National Disaster Coordinators
- Shelter manager (administrative)
- Cluster representatives (Health personnel, FSCD personnel, City corporation representatives, Bangladesh police etc.)
- Security personnel
- Cooks
- Storekeeper and food service personnel
- Cleaners, plumbers and maintenance personnel
- Support personnel

The exact number and roles of such personnel can be investigated in further research works.

5.4 Open Space Shelter Model Design and Validation

In order to demonstrate the feasibility of such open space shelters, a shelter model has been proposed in this section. The selected location was a playground opposite of Bangladesh University of Professionals (BUP Playground). It is easily accessible from the roads in its east and west sides. It had suitable value based on the COSI and seismic hazard assessment. The proposed shelter will have all the facilities discussed in the previous section. The plan-view of the proposed model in shown in Figure 5.3.

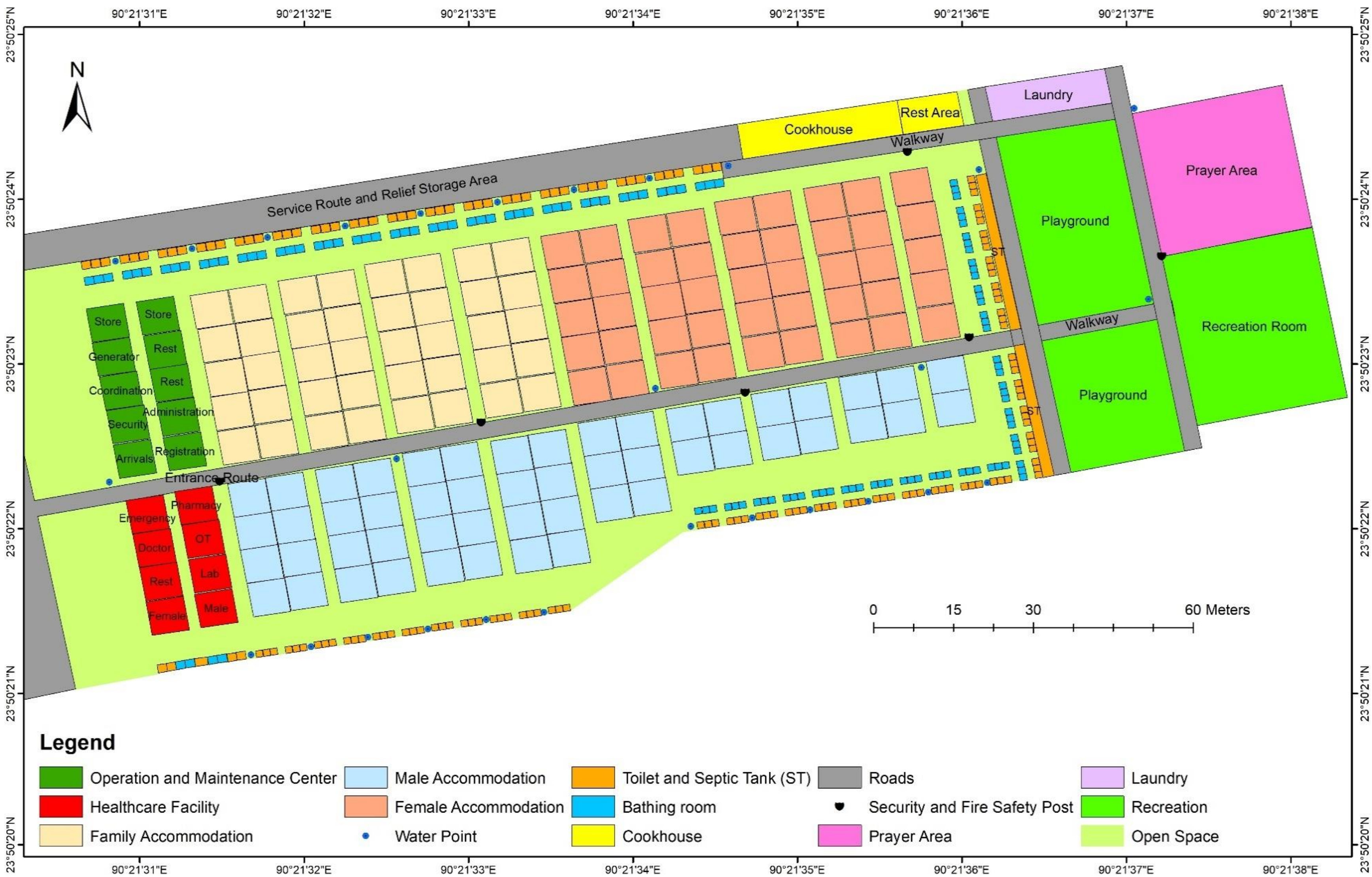


Figure 5.3 Plan View of Open Space Shelter Model on BUP Playground

Figure 5.4 (a) Shows the wide entry way to the shelter. (b) Depicts the bird's eye (drone) view of the field demonstration of the open space shelter model.

A field demonstration (Figure 5.4) of the hypothetical shelter model was carried out to validate the feasibility of such an open space shelter. The horizontal line (Fig 5.4 b) in the middle actually represents the entrance road inside the shelter site shown in figure 5.3. The tents on the left are the field demonstration of the various units shown in figures 5.5 and 5.6. The vertical row of tents (in the middle) are the actual living quarters. Due to the lack of tents available this could not be replicated as much as was shown in figure 5.3.

The open space shelter will have the following facilities-

Operation and Maintenance Center: It will be a separate unit comprising of arrivals and registration area, administration and coordination tents, tents for accommodating the management personnel, power generation room and tents for storing emergency supplies for the shelter inhabitants (Figure 5.5). Representatives of various clusters will coordinate their activities from this unit.

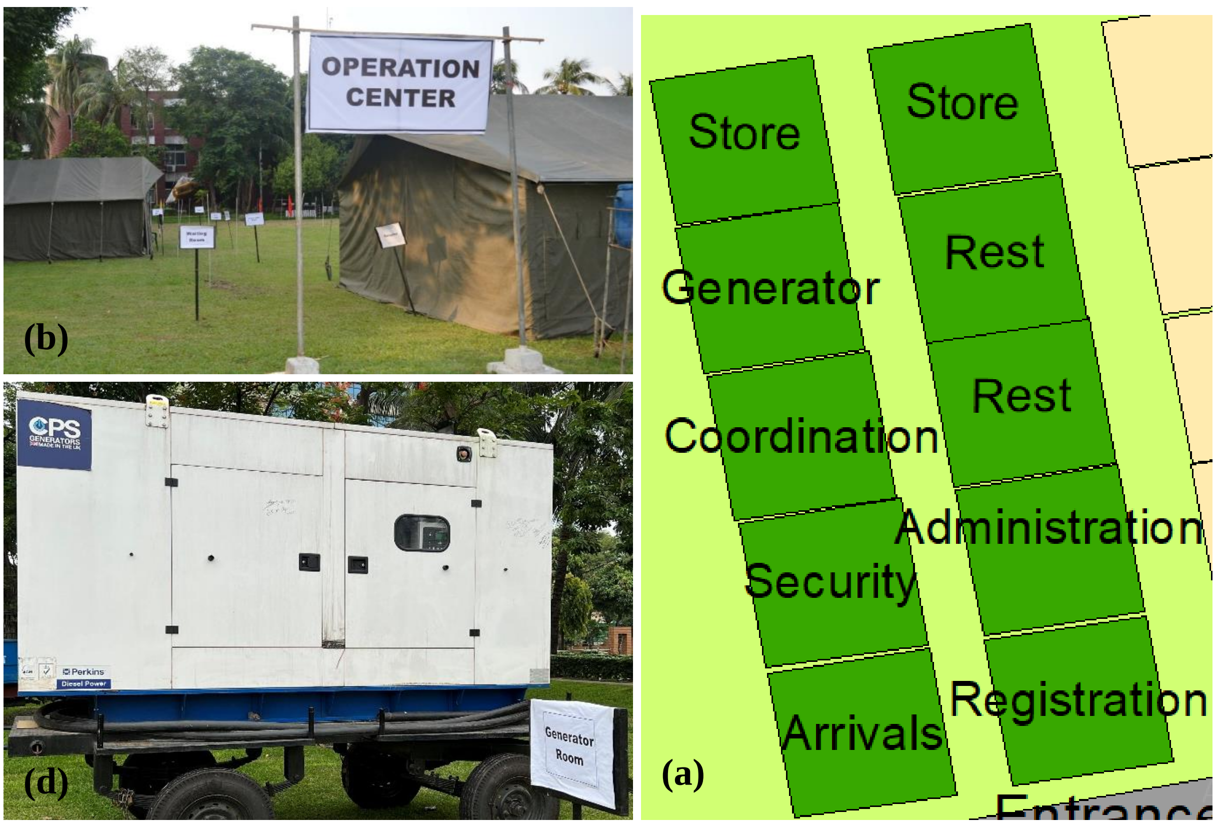


Figure 5.5 Operation and Maintenance Center – (a) field view, (b) plan view and (c) power generation room

Healthcare Facility: This unit (Figure 5.6) will have separate tents for emergency, operative procedures and lab facilities. Emergency and necessary drugs will be stored at the pharmacy. There will be separate tents for male and female patient accommodation. The doctor and other staff will be accommodated in a tent within this unit. This unit will be coordinated and lead by Directorate

General of Health Services (DGHS). When the healthcare need decreases some of these tents may be used for temporary shelter purposes if required.

Figure 5.6 Field Hospital – (a) and (b) field view, (c) plan view and (d) 8-bed ward

Shelter Accommodation: The tents (Fig 5.7) in this proposed model are 16×16 ft^2 (approximately 24 m^2) in area and there will be 5 feet gap in between tents. Based on our established standards, each tent will be able to accommodate 10-12 person. There will be separate accommodation areas for male and female inhabitants. However, based on needs and circumstances, separate tents for family may be provided.

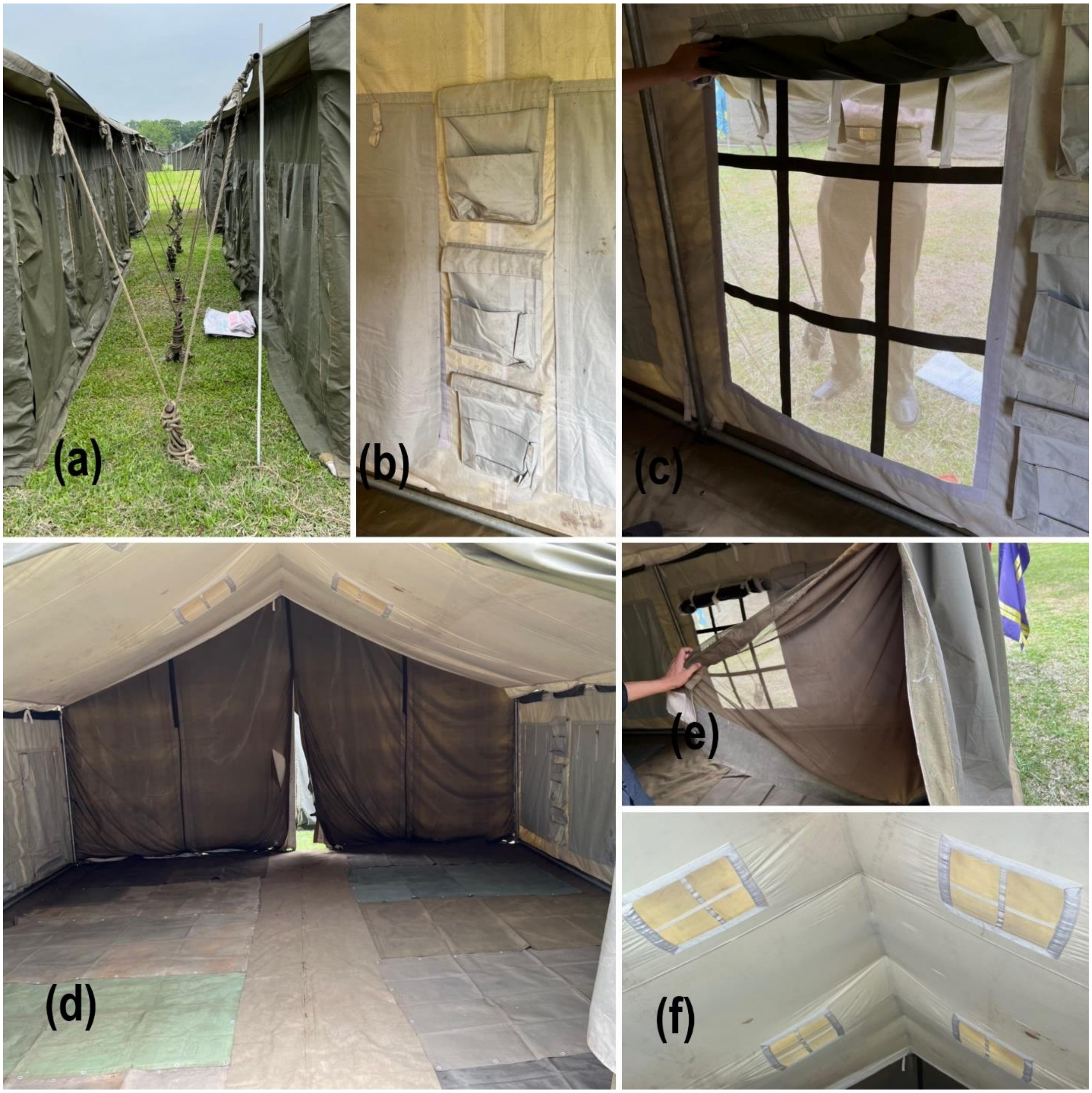


Figure 5.7 Shelter accommodation tents - (a) 5 feet gap between tents; (b) storage pockets for inhabitants inside the tents; (c) side ventilation window; (d) inside view of the tents; (e) mosquito net and water-proof layers of the tents; (f) heat protectant layer and roof ventilation

Water Points: There will be 28 well distributed water points (Fig 5.8) in accordance with global standards and fire safety protocol. These points should be able to provide the requirement of safe drinking water for the shelter inhabitants.

Figure 5.8 Drinking water distribution point

Figure 5.9 (a) Male toilets, (b) female toilets and (c) inside view of the model toilets

Toilets and Septic Tanks: The toilets (Figure 5.9) for female inhabitants and families will be 5×5 ft² and 4×4 ft² for that of males. The septic tanks will be established at the rear end of the shelter camp.

Bathing Rooms: The bathrooms for female (and families) and male inhabitants will be 5×5 ft² and 4×4 feet, respectively, according to the Sphere Guidelines.

Figure 5.10 (a) Entrance to the Cookhouse, (b) food distribution area, (c) food preparation area, and (d) food storage area

Cook House: A pre-constructed structure (Figure 5.10) will be used as cook house including separate sections for emergency food storage, food preparation and cooking, and food distribution area. The food supplies and distribution will be managed by cluster 4 (relief services). There will be a resting area for the cluster representatives working here.

Figure 5.11 (a) Firefighting vehicle, (b) model security and fire safety post, and (c) firefighting equipment

Security and Fire Safety Posts: There will be 5 security posts (Figure 5.11) along the entrance route at regular intervals that will contain firefighting equipment and one near the cookhouse. These posts will be occupied by personnel designated from cluster 9 (security and welfare). Obviously, the number will vary according to the size of the open space and sheltering population.

Prayer Area: A designated space (Figure 5.12) male and female occupants will be provided for prayer, so that people are able to practice their religion.

Figure 5.12 (a) Separate prayer rooms for male and (b) female shelter occupants

Recreation: A recreation room will consist of various indoor games. Apart from that there will be two designated open spaces for outdoor games. Figure 5.13 shows the recreation facilities inside the shelter camp.

Figure 5.13 (a) Recreation room and (b) playground area

Roads and Open Spaces: For the ease of movement and relief distribution, there will be an entrance route and walkways of 10 feet width in and around the shelter camp. The service route will be used by cluster representatives and shelter managers to preposition and store relief goods. There will be 2 m gap in between each row of tents for ventilation and movement. The toilets will be situated at least 6 m away from the inhabiting tents.

Other Facilities: There will be provision for laundry facilities. Utility services like electricity, fuel, lighting etc are also required (Figure 5.14). and will be established by local government bodies with support from utility agencies.

Figure 5.14 Light post

5.5 Summary

In this chapter, various literature on standards of emergency shelters and case studies in other countries for seismic hazards were reviewed. The "National Earthquake Contingency Plan" of Bangladesh follows the Cluster Approach and one of these clusters is "Shelter" management. Based on the literature and circumstances of Dhaka, some parameters were identified to consider before, during and after establishing a long-term open space shelter which includes- shelter facilities, health and nutrition services, WASH services, other emergency infrastructures and service utilities, security and cultural considerations, and operation and maintenance of the shelter.

The standard covered living space per person proposed for post-disaster shelters in Dhaka Metropolitan area is 2.3 m^2 (2.2 to 2.4 m^2 on average) while the average shelter dimensions were suggested to be 4.8m by 4.8m to provide shelter to around 10 people. Considering the climate and culture of Dhaka, the shelter materials should be lightweight, waterproof, have low thermal capacity, proper ventilation system, safe insecticide-treated nets and be environmentally sustainable. The areas for administrative activities, healthcare services, cooking, sanitation, storage, religious activities, recreation etc. should be separate. Standards of health and nutrition services, WASH facilities, safety and security, service facilities and utilities will be maintained in the shelter camp by the cluster representatives mentioned in the "The National Earthquake Contingency Plan" of Bangladesh. The lead agencies for shelter cluster, DDM and MoDMR will set in place a clear and concise shelter operation mechanism and maintenance system with adequately defined roles and responsibilities for the management personnel and cluster representatives. They will take necessary steps for shelter establishment and prepositioning of resources before disaster and conduct routine tests to ensure timely functionality of the shelter system, decide the activation of the shelter activities after the disaster and monitor the performance of the shelter to address the gaps and challenges.

A model open space shelter was proposed for BUP Playground according to the considerations identified in this study. This model was designed in a manner so that people in the catchment of this shelter can access it in time and utilize all the necessary life-saving facilities which should be prepositioned for their survival. Cultural and security considerations were given importance in this model. Meeting the basic needs with dignity and safety is also a basic right for people especially in the aftermath of an earthquake. This model was demonstrated on the actual ground to validate its feasibility and appropriateness. The following facilities were provided at the proposed shelter - operation and maintenance center, healthcare facility, shelter accommodation, water points, toilets and septic tanks, bathing rooms, cook house, security and fire safety posts, recreation, laundry facilities, utility services like electricity, fuel, lighting, roads and open spaces etc.

Through identification of the open space shelter considerations and demonstrating the localized standards of a model open space shelter, guideline for establishing shelters to tackle the emergency situation that may arise following an earthquake in the context of Dhaka city have been created. These guidelines can be used to establish a network of open space shelters in the suitable open spaces identified in the previous chapters.

Similar studies in other cities with high to moderate seismic risk in Bangladesh can also be carried out. Being able to develop a network of open space shelters and implementing these guidelines properly will bring about a major advancement in earthquake preparedness in the country.

Chapter 6:
Conclusion and Recommendation

6.1.1 Conclusion

Large earthquakes cause massive loss of lives, livelihoods, and damage to property. Given Bangladesh's location in the vicinity of seismic sources, it may experience large magnitude earthquake (Kamal, 2013). The capital city of the country, Dhaka is threatened by the risks of earthquake as well. The city is positioned among the twenty most vulnerable cities of the world in the earthquake disaster risk index (PreventionWeb, 2010). 36% of Bangladesh's GDP depends upon the activities of the people of Dhaka. Therefore, emergency response and recovery plans have to be developed for seismic risk management of the city.

Emergency shelter placement planning and preparation is recognized as an important component of earthquake contingency planning in an urban context (Humanitarian Charter, 2011). In an emergency, open space plays an important role in providing sheltering facilities for people affected by disaster. A great number of post-earthquake rescue and rehabilitation efforts in the past have been found in literature review to utilize open spaces to operate response and recovery programs.

The purpose of emergency sheltering is to provide required residence, security and dignity for earthquake inflicted population. Shelters need to be placed in appropriate sites where it is the most convenient for the earthquake victims to access in the immediate aftermath of disaster occurrence. Selection of sites has to be performed based on some specifically defined criteria on site characteristics. Without proper planning and strategical selection process, authorities may end up choosing potentially unsuitable or inappropriate places which may lead to resistance to site acceptance. A gap was identified that such identification of open spaces was not performed for

Dhaka. Moreover, this research also ranked the open spaces according to their facilities to support usage in the post-earthquake situation.

Existing open spaces in Dhaka Metropolitan Area was identified through visual identification from Google Earth Imagery. Thereafter suitability of the identified open spaces was analyzed. A Modified Comprehensive Open Space Suitability index for Dhaka adapted from Anhorn and Khazai (2015) used for Kathmandu Metropolitan City was utilized. All 1197 open spaces were ranked based on their inherent characteristics including size, nearness to fire station and hospitals, road accessibility and connectivity, and flood hazard risk. The 1197 open spaces represent a combined area of 10290175.5 m^2. This accounts for only 0.67% of the total land area of the entire metropolitan. Caution was taken to only include sites that matched the assumed definition of open space for this study. Therefore, even though some spaces like, cemeteries, agricultural land, etc. are technically open spaces but they had to be excluded either because of social norms or because they were unfit for consideration of potential shelter. At the same time, it is noteworthy to be reminded of the exclusionary criteria of land (especially those privately owned) which had the potential of future development into built structures.

Around 18% (217) sites were found to be suitable. Whereas 12 % (151) open spaces qualified as relatively moderately suitable for shelter establishment, but majority (around 70%, i.e. 829) open spaces scored poor. 442 open spaces have the ability to accommodate more people beyond their respective population catchment. However, 32,78,211 people from the rest of the 755 sites cannot get space in their designated open space. Even if they travel to other shelters still 15,70,125 people will be left unaccommodated. For them the empty places within Purbachal, Jolshiri and western parts of Uttara will be a good location to place shelters. In addition to designated parks and stadiums (which are already part of the identified open spaces) any private land left undeveloped (like the empty plots) can be used as temporary shelters. This will reduce the number of unaccommodated people. However, this may lead to new challenges like pre-positioning resources in undeveloped zones, shelter security and transportation of displaced populations. So future research can be done regarding such issues.

Size played the most important role in these calculations, since without space people cannot get accommodation and without accommodation even good accessibility, connectedness, nearness to facilities do not matter.

Literature review showed that beyond immediate needs, some spaces are required for long term sheltering purpose. As such 203 sites classed as suitable open spaces were recommended (excluding 14 sites out of 217 sites for security and Key Point Installation consideration).

Although 203 sites have the inherent characteristics to make them suitable for long term sheltering, it needs to be investigated whether the sites themselves will be rendered ineffective due to the effects of the earthquake, namely liquefaction. Due to financial and time constrains detailed study cannot be conducted at all the sites, so generalized liquefaction study is done to select the sites with the lowest hazard along with highest COSI scores. This generalized liquefaction revealed that out of the 203 sites 37 has high to very high liquefaction possibility. So from the remaining 166 sites, 8 sites are selected as case study. They are- Army Golf Club, Bangladesh University of Professionals ground, Residential Model College, Mohammadpur Eidgah, Botanical Garden, Baldha Garden, Ramna Park and Armanitola Playground.

To assess the detailed liquefaction potential, seismic hazard assessment and site response analysis are the prerequisites. From the SPT-N value, PS logging and shear wave velocities of the 8 sites, the hazard assessment and response analysis were conducted. Some soil general properties like unit weight density, effective vertical pressure are determined from the numerical formulas. The most important input is earthquake time histories with which site response will be determined. As input earthquake time histories, surrounding earthquakes of Bangladesh, India and Myanmar are selected.

From the seismic hazard assessment and site response analysis, it observed that in site response the nonlinear soil behaved as de-amplified in short and amplified in the long period. It is observed that, as the response spectrum has higher acceleration values in the long period. The study shows the sites have similar responses as with bedrock response and does not have very high values. Meaning they are safe for selection as suitable for long-term sheltering in regards to seismic shaking. The results obtained are then used to calculate liquefaction. The limitations of this portion of the study are the unavailability of recent database about time histories of the surrounding earthquakes of Bangladesh. Shear wave velocity data from more than 30m (or bedrock) is also difficult to find.

The potential of liquefaction is measured using the simplified procedure-based liquefaction potential index or LPI value. In this study, three different approaches were utilized, namely, deterministic approach (factor of safety), probabilistic approach (probability of liquefaction), and artificial neural network (ANN) approach. Two different types of data were employed in LPI calculation. From previous studies it has been found that employing both standard penetration test blow count (SPT-N) and shear wave velocity (VS) data is highly recommended and all the three most used and most reliable approaches in LPI calculation were used and compared to ensure the reliability of the study. The results have revealed very low (less than 5) liquefaction potential in a scenario earthquake of 7.5 magnitude from Madhupur Fault, with PGA 0.15g for all 8 locations, all datasets and all approaches. This indicates high suitability of the sites for long term shelter placement consideration.

However, liquefaction hazard is not the only consideration when it comes to long term shelter sites. Standards need to be established in order to ensure that during long term usage no problems arise for the shelter seekers. The Sphere Guidelines provide a foundation for such standards. However, they need to be adjusted to local context, needs and preferences. Since the Bangladesh Earthquake Contingency Plan follows the cluster approach, so only the factors related to emergency shelters from Shelter Cluster were in the scope of this study. The standard covered living space per person proposed for post-disaster shelters in Dhaka Metropolitan area is 2.3 m^2 (2.2 to 2.4 m^2 on average) while the average shelter dimensions were suggested to be 4.8m by 4.8m to provide shelter to around 10 people. Other localized standards include- shelter (made using lightweight, waterproof and environmentally sustainable shelter materials having low thermal capacity, proper ventilation system, safe insecticide-treated nets etc.); separate spaces for administrative activities, healthcare services, cooking, sanitation, storage, religious activities, recreation etc.; health facilities (although part of health cluster, but some ideas were floated as necessary- operational plan with defined roles, prepositioning of staff, medicine and equipment, disease control mechanism, addressing mental health issues etc.); WASH facilities (although part of WASH cluster some responsibilities do coincide like placement of toilets not less than 6m or more than 50m from tents, 15 litre water per person per day, minimum 1 shower per 50 people etc.); emergency infrastructure (like generators, solar lighting requirements, firefighting equipment pre-positioned); security (placement of non-military security personnel in maintaining order in the camp, well lit access roads to WASH facilities, separate spaces according to gender); cultural adequacy (prayer space, recreational scope to boost mental health etc.); operation and maintenance (coordination room for all agencies, updating mechanisms, administration for proper maintenance of the camp, registration of all shelter seekers so that information can be added to database, assignment of appropriate roles etc.) were all considered. With clearly defined duties and responsibilities for the management staff and cluster members, the lead agencies for the shelter cluster, DDM and MoDMR, will put in place an structure for operating and maintaining shelters. Details of such operating mechanisms along with staffing requirements can be explored in further research. Much of these should be defined in Contingency Plans, to avoid haphazard decision making. They will take the necessary actions for shelter establishment and resource prepositioning before disaster, perform routine tests to ensure timely system functionality, activate the shelter activities when instructed by government, and monitor the shelter's performance to address any gaps and difficulties during the response and recovery phase. The research aimed to find the standards required in the context of Dhaka Metropolitan Area to make the shelters useful and safe for the displaced population. Developing step by step procedures or instructions would be useful but is beyond the scope and time frame of this research. Nonetheless, this remains an important area to explore during future works. Finally, an ideal shelter model was planned for the Bangladesh University of Professionals Playground and demonstrated with the support of Armed Forces Division to verify the standards that were developed for Dhaka. The components of the proposed shelter model were - operation and maintenance center, healthcare facility, shelter accommodation, water points, toilets and septic tanks, bathing rooms, cook house, security and fire safety posts, recreation, laundry facilities, utility services like electricity, fuel, lighting, roads and open spaces etc. Experts were present and consented to the standards, design and placement.

Finally, it can be concluded that a methodology for comprehensive for management of open spaces was developed so as to be prepared for efficient response to earthquakes and so a quick recovery can be achieved in Dhaka.

6.1.2 Recommendations

Following recommendations can be adopted for implementing the findings of this research regarding development of Open Space Management System in Bangladesh.

1. The open spaces were simply identified visually from open source satellite imagery, some of which are outdated. Detailed field visit to each site to ground truth and to determine future development potential, presence of hazards, electrical, gas, water supply lines should be done. These can then be incorporated into the selection criteria. Some areas like old Dhaka store hazardous materials in residential buildings. Only though surveys can such things be identified and then through appropriate criteria can included in the selection process. Obviously, sites near to such phenomenon will be less suitable.
2. Large scale building survey based seismic risk assessment should be performed. This was last done in 2009. The data obtained and the results found should be made open source, so that researchers like myself can get more realistic data about displaced people, disaggregated into wards. The cantonment area should be included in this study as well and the data can then be anonymized to preserve secrecy. Another alternative can be they perform their own assessment and publish the data as they see fit. But being in the dark will not be wise, especially since post-disaster effects spill over to neighboring wards.
3. This study should be repeated for multiple scenarios of magnitude, depth, distance and faults. Moreover, creating a day night variation contingency plan will be much more effective since there is a great difference in population in some wards which is related to time of occurrence of earthquake, such as residential vs industrial zones. Replicating similar studies for other cities having high to moderate seismic risk is also required. Along

with that detailed Standard Operating Procedures for each cluster should be developed and updated regularly.

4. Preservation of the open spaces identified here (ex-post field verification) through appropriate legal instruments at policy level. Provision of keeping easily accessible and sufficiently large open spaces in housings like Bashundhara should be mandated and not kept optional. In projects like Bashundhara, Jolshiri and Uttara there are spaces which are privately owned but are empty. For the people who cannot get accommodation into identified shelters this could be a place for temporary shelters. However, it will require further research to find any problems with those places, like accessibility. Another option for those people may be evacuating outside Dhaka.
5. Investments should be made in the field of seismic risk reduction for innovating low cost and highly effective construction solutions for future buildings, since many become disinterested in the high cost of adherence to the building code. Awareness generation of the simple but not yet adapted techniques of building construction is necessary.
6. Institutional coordination mechanism according to specific scenarios should be developed and practiced. AFD has already done exercises like that in the field of civilian-military and military-military coordination. However, for other ministries and institutions the level of preparation is probably not as much as it could be.
7. Conducting detailed liquefaction potential investigation for all the selected sites for shelter establishment. Generation of water logging data for different scenario is required (especially considering that climate change is intensifying rainfall and highest possible water levels are often broken like the case of Sunamganj in 2022).

8. Prepositioning shelter kits and other emergency items for their easy access in the aftermath of any disaster. Preparing the open spaces for temporary shelter establishment by constructing necessary infrastructures and service facilities in and around them. Giving volunteer training for installing tents, first aid and humanitarian emergency management facilities in the shelter site. Also, given the recent foreign currency conservation attempts it may be best to manufacture the tents (of varying diversity) in Bangladesh that are suited to local needs.
9. Decentralize education, healthcare and other facilities which will reduce Dhaka's population, because no amount of emergency planning will be enough for a very large earthquake impact.

References

A., K. C., V., W. R., & T., H. W. (2006). HAZUS Earthquake Loss Estimation Methods. *Natural Hazards Review*, *7*(2), 45–59. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(45)

Abrahamson, N. A., Silva, W. J., & Kamai, R. (2014). Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra*, *30*(3), 1025–1055. https://doi.org/10.1193/070913EQS198M

Abrahamson, N., Gregor, N., & Addo, K. (2016). BC hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra*, *32*(1), 23–44. https://doi.org/10.1193/051712EQS188MR

Ahmed, B., Hasan, R., & Maniruzzaman, K. M. (2014). Urban morphological change analysis of Dhaka city, Bangladesh, using space syntax. *ISPRS International Journal of Geo-Information*, *3*(4), 1412–1444.

Ahmed, M. S., & Morita, H. (2018). An analysis of housing structures' earthquake vulnerability in two parts of Dhaka city. *Sustainability*, *10*(4), 1106.

Akason, J. B., Ólafsson, S., & Sigbjörnsson, R. (2006). Phases of Earthquake Experience: A Case Study of the June 2000 South Iceland Earthquakes. *Risk Analysis*, *26*(5), 1235–1246. https://doi.org/10.1111/j.1539-6924.2006.00811.x

Al-Hussaini, T., Chakraborty, S., Chowdhury, I. N., Vaccari, F., Romanelli, F., Magrin, A., & Panza, G. F. (2017). Neo-Deterministic seismic hazard assessment research programs for Bangladesh. *Proc. International Conference on Disaster Risk Mitigation Sept*, 23–24.

Al-Hussaini, T. M., Chowdhury, I. N., & Noman, M. N. (2015). Seismic hazard assessment for Bangladesh-old and new perspectives. *First International Conference on Advances in Civil Infrastructure and Construction Materials*, 841–856.

Alam, E., & Dominey-Howes, D. (2016). A catalogue of earthquakes between 810BC and 2012 for the Bay of Bengal. *Natural Hazards*, *81*(3), 2031–2102. https://doi.org/10.1007/s11069-016-2174-7

Ambraseys, N. N., & Douglas, J. (2004). Magnitude calibration of north Indian earthquakes. *Geophysical Journal International*, *159*(1), 165–206. https://doi.org/10.1111/j.1365-246X.2004.02323.x

Anhorn, J., & Khazai, B. (2015). Open space suitability analysis for emergency shelter after an earthquake. *Natural Hazards and Earth System Sciences*, *15*, 789–803. https://doi.org/10.5194/nhess-15-789-2015

Asakereh, A., & Tajabadiur, M. (2018). Local Site Effects on Seismic Ground Response under Various Earthquakes. *AUTJournal of Civil Engineerng*, *2*(2), 227–240. https://doi.org/10.22060/ajce.2018.13696.5253

Ashmore, J. (2008). *Shelter Projects 2008*. http://shelterprojects.org/shelterprojects2008/ref/UN_Habitat_shelter_projects_2008.pdf

Aten, J. D., Smith, W. R., Davis, E. B., Van Tongeren, D. R., Hook, J. N., Davis, D. E., Shannonhouse, L., DeBlaere, C., Ranter, J., O'Grady, K., & Hill, P. C. (2019). The psychological study of religion and spirituality in a disaster context: A systematic review. *Psychological Trauma: Theory, Research, Practice, and Policy*, *11*(6), 597–613. https://doi.org/10.1037/tra0000431

Atkinson, G. M., & Boore, D. M. (2003). Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions. *Bulletin of the Seismological Society of America*, *93*(4), 1703–1729. https://doi.org/10.1785/0120020156

Barua, S., & van Ast, J. A. (2011). Towards interactive flood management in Dhaka, Bangladesh. *Water Policy*, *13*(5), 693–716. https://doi.org/10.2166/wp.2011.020

BBS. (2011). *Population & Housing Census*. https://doi.org/10.1007/BF00175563

BNBC. (2021). *Bangladesh Building Code* (Issue 2).

Bolin, R. (1993). Post-earthquake shelter and housing: Research findings and policy implications. In *Monograph 5: Socioeconomic impacts* (pp. 107–131).

Bolin, R., & Stanford, L. (1991). Shelter, housing and recovery: A comparison of US disasters. *Disasters*, *15*(1), 24–34.

Bolisetti, C., Whittaker, A. S., & Coleman, J. L. (2018). Linear and nonlinear soil-structure interaction analysis of buildings and safety-related nuclear structures. *Soil Dynamics and Earthquake Engineering*, *107*(January), 218–233. https://doi.org/10.1016/j.soildyn.2018.01.026

Boore, D. M., Stewart, J. P., Seyhan, E., & Atkinson, G. M. (2014). NGA-West2 Equations for predicting PGA, PGV, and 5%-damped PSA from shallow crustal earthquakes. *Earthquake Spectra*, *30*, 1057–1085.

Britannica, E. of E. (2021). *Mexico City earthquake of 1985 | History, Facts, & Response | Britannica*.

Bryant, M., & Allan, P. (2013). Open Space Innovation in Earthquake Affected Cities. In

Approaches to Disaster Management - Examining the Implications of Hazards, Emergencies and Disasters (pp. 183–204).

Byomkesh, T., Nakagoshi, N., & Dewan, A. M. (2012). Urbanization and green space dynamics in Greater Dhaka, Bangladesh. *Landscape and Ecological Engineering*, *8*(1), 45–58. https://doi.org/10.1007/s11355-010-0147-7

Campbell, K. W., & Bozorgnia, Y. (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. *Earthquake Spectra*, *30*(3), 1087–1114. https://doi.org/10.1193/062913EQS175M

Carlton, B. D., Skurtveit, E., Bohloli, B., Atakan, K., Dondzila, E., & Kaynia, A. M. (2018). Probabilistic seismic hazard analysis for offshore Bangladesh including fault sources. In *Geotechnical Earthquake Engineering and Soil Dynamics V: Seismic Hazard Analysis, Earthquake Ground Motions, and Regional-Scale Assessment* (pp. 154–163). American Society of Civil Engineers Reston, VA.

Carmona, M. (2021). *Public places urban spaces : the dimensions of urban design*. https://www.routledge.com/Public-Places-Urban-Spaces-The-Dimensions-of-Urban-Design/Carmona/p/book/9781138067783

CDMP. (2009a). *Earthquake Risk Assessment for Dhaka, Chittagong and Sylhet City Corporation Area*.

CDMP. (2009b). *Seismic hazard and vulnerability assessment of Dhaka, Chittagong and Sylhet city corporation areas. Final report, Comprehensive Disaster Management Programme (CDMP).*

Chan, Y. F., Alagappan, K., Gandhi, A., Donovan, C., Tewari, M., & Zaets, S. B. (2006). Disaster management following the chi-chi earthquake in Taiwan. *Prehospital and Disaster Medicine*, *21*(3), 196–202. https://doi.org/10.1017/S1049023X00003678

Chandler, P. J. (2007). *Environmental factors influencing the siting of temporary housing in Orleans Parish*.

Chen, A., Yang, H., Lo, H. K., & Tang, W. H. (2002). Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B: Methodological*, *36*(3), 225–252. https://doi.org/10.1016/S0191-2615(00)00048-5

Chen, X., & Zhan, F. B. (2014). Agent-based modeling and simulation of urban evacuation: relative effectiveness of simultaneous and staged evacuation strategies. In *Agent-Based Modeling and Simulation* (pp. 78–96). Palgrave Macmillan UK. https://doi.org/10.1057/9781137453648_6

Chiou, B. S. J., & Youngs, R. R. (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra, 30*(3), 1117–1153. https://doi.org/10.1193/072813EQS219M

Chou, J., Ou, Y., Cheng, M.-Y., & Lee, C.-M. (2013). Emergency shelter capacity estimation by earthquake damage analysis. *Natural Hazards*. https://doi.org/10.1007/s11069-012-0461-5

Chowdhury, I. N. (2016). *Neo-deterministic studies for seismic hazard assessment of Bangladesh*.

Chowdhury, S. C., Razzaque, M. M., Helali, M. M., & Bodén, H. (2010). Assessment of noise pollution in Dhaka city. *17th International Congress on Sound and Vibration, Cairo, Egypt, 2010-07-18-2010-07-22*.

Da Silva, J. (2007). Quality and standards in post-disaster shelter. *Structural Engineer*, *85*(14), 25–32.

Darendali, M. Ba. (2001). Development of a new family of normalized modulus reduction and material damping curves. *The University of Texas at Austin, Austin*.

Darendeli, M. (2001). *Development of New Family of Normalized Modulus Reduction and Material Damping Curves*.

De Alwis Pitts, D. A., & So, E. (2015). Enhanced Change Detection Index for Disaster Response, 4 Recovery Assessment and Monitoring of Accessibility and Open Spaces (Camp Sites). *International Journal of Applied Earth Observation and Geoinformation*.

Dey, A. R., Kabir, N., & Effroymson, D. (2004). Noise pollution in Dhaka: current situation and suggestions for action. *Work for a Better Bangladesh, Dhaka*.

DFID. (2010). *Shelter after disaster: strategies for transitional settlement and reconstruction*.

CDMP. (2009). *National Earthquake Contingency Plan*.

Earthquake Engineering Research Institute. (2006, February 28). *The Kashmir earthquake of October 8, 2005: Impacts in Pakistan - Pakistan* . ReliefWeb. https://reliefweb.int/report/pakistan/kashmir-earthquake-october-8-2005-impacts-pakistan

Elkady, A., & Lignos, D. G. (2020). EaRL—Software for Earthquake Risk, Loss and Lifecycle Analysis. *SoftwareX*, *12*, 100607. https://doi.org/10.1016/j.softx.2020.100607

EPA. (n.d.). *What is Open Space/Green Space?*

Félix, D., Branco, J., & Feio, A. (2013a). *Improving Sustainability and Cultural Integration in Post-Disaster Temporary Housing*.

Félix, D., Branco, J. M., & Feio, A. (2013b). Temporary housing after disasters: A state of the art survey. *Habitat International*, *40*, 136–141. https://doi.org/https://doi.org/10.1016/j.habitatint.2013.03.006

French, E. (2017). *Designing Public Open Space to Support Seismic Resilience: A Systematic Review*.

French, E. L. (2017). *Designing Public Open Space to Support Seismic Resilience: A Systematic Review*. The University of Guelph.

French, E. L., Birchall, S. J., Landman, K., & Brown, R. D. (2019). Designing public open space to support seismic resilience: A systematic review. *International Journal of Disaster Risk Reduction*, *34*, 1–10. https://doi.org/10.1016/j.ijdrr.2018.11.001

Gao, H. (2020). The Power of the Square: Public Spaces and Popular Mobilization after the Wenchuan Earthquake. *Journal of Chinese Political Science*, *25*(1), 89–111. https://doi.org/10.1007/S11366-019-09643-W/FIGURES/4

Gardner, J. K., & Knopoff, L. (1974). Is the sequence of earthquake in southern California, with aftershocks removed, Poissonian? *Bulletin of the Seismological Society of America*, *64*(5), 1363–1367. https://doi.org/10.2307/1779766

GFDRR, & EMI. (2014). *Dhaka Profile and Earthquake Risk Atlas*.

Gianisa, A., & Le De, L. (2018). The role of religious beliefs and practices in disaster. *Disaster Prevention and Management*, *27*(1), 74–86. https://doi.org/10.1108/DPM-10-2017-0238

Girard, T., Brink, S., & Anhorn, J. (2015). *Shelter response and vulnerability of displaced populations in the April 25, 2015 Nepal Earthquake* . http://eq.nitc.gov.np/

Godschalk, D. R. (2003). Urban hazard mitigation: creating resilient cities. *Natural Hazards Review*, *4*(3), 136–143.

Groholski, D. R., Hashash, Y. M. A., Musgrove, M., Harmon, J., & Kim, B. (2015). Evaluation of 1-D Non-linear Site Response Analysis using a General Quadratic/Hyperbolic Strength-Controlled Constitutive Model. *6ICEGE: 6th International Conference on Earthquake Geotechnical Engineering*, *November*.

Hackenbroch, K. (2012). *The Spatiality of Livelihoods – Negotiations of Access to Public Space in Dhaka, Bangladesh* (p. 396). Franz Steiner Verlag. https://doi.org/DOI

Hadafi, F., & Fallahi, A. (2010). Temporary housing respond to disasters in developing countries-case study: Iran-Ardabil and Lorestan Province Earthquakes. *World Academy of Science, Engineering and Technology*, *66*(42), 1536–1542.

Hanks, T. C., & Kanamori, H. (1979). *A moment magnitude scale*. *84*(9), 2348–2350.

Hashash, Y. M. A. (2017). *DEEPSOIL 7.0 User Manual*.

Hirano, S. (2012). *Learning from the Urban Transitional Shelter Response in Haiti*. https://ressources.fondation-uved.fr/Cours_CRAterre/media/haiti-shelter-response.pdf

History. (2016). 1985 Mexico City earthquake. *A&E Television Networks*, *April 1986*, 1–15.

Horwich, G. (2000). Economic lessons of the Kobe earthquake. *Economic Development and Cultural Change*, *48*(3), 521–542.

Hossain, B., & Hossain, S. S. (2020). Probabilistic estimation of seismic parameters for Bangladesh. *Arabian Journal of Geosciences*, *13*(6), 1–7.

Hossain, M. S., Chaitanya, K., Bhattacharya, Y., Numada, M., Kamal, A. S. M. M., & Meguro, K.

(2021). Integration of smart watch and geographic information system (GIS) to identify post-earthquake critical rescue area part. II. Analytical evaluation of the system. *Progress in Disaster Science*, *9*, 100132. https://doi.org/10.1016/j.pdisas.2020.100132

Hossain, M. S., Gadagamma, C. K., Bhattacharya, Y., Numada, M., Morimura, N., & Meguro, K. (2020). Integration of smart watch and Geographic Information System (GIS) to identify post-earthquake critical rescue area part. I. Development of the system. *Progress in Disaster Science*, *7*, 100116. https://doi.org/10.1016/j.pdisas.2020.100116

Hosseini, M., Izadkhah, Y. O., & Pir-Ata, P. (2008, October). Lessons Learnt from Shelter Actions and Reconstruction of Bam after the Destructive Earthquake of December 26, 2003. *The 14th World Conference on Earthquake Engineering*. https://www.iitk.ac.in/nicee/wcee/article/14_01-1048.PDF

Humanitarian Charter. (2011). The Sphere Project. In *Response* (Vol. 1).

IASC. (2010). *Response to The Humanitarian Crisis in Haiti: Achievements, challenges and lessons to be learned*. *January*, 1–44.

IASC. (2020). Cluster Approach (IASC). In *UNHCR Emergency Handbook*. https://emergency.unhcr.org/entry/61190/cluster-approach-iasc

Idriss, I. M. (2014). An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. *Earthquake Spectra*, *30*, 11555–1177.

Imran, M., & Hossain, M. I. (2016). A Brief Study on Capacity Loss at Major Dhaka City Roads. *International Journal of Transportation Engineering and Technology*, *2*(1), 1.

Indriasari, V., Mahmud, A. R., Ahmad, N., & Shariff, A. R. M. (2010). Maximal service area problem for optimal siting of emergency facilities. *International Journal of Geographical Information Science*, *24*(2), 213–230. https://doi.org/10.1080/13658810802549162

Islam, A. B. M. S., Arabia, S., Ahmad, S. I., & Al-hussaini, T. (2010). *Effect of Isolation on Buildings in Dhaka*. *May 2016*.

Islam, N. (1999). *Urbanisation, migration and development in Bangladesh: recent trends and emerging issues*. Centre for Policy Dialogue.

Jahan, I., Ansary, M. A., Ara, S., & Islam, I. (2011). Assessing social vulnerability to earthquake hazard in Old Dhaka, Bangladesh. *Asian Journal of Environment and Disaster Management (AJEDM)*, *3*(3), 285–300.

Japan Times. (2000). *Kobe closes last quake shelter*.

Jayakody, R., Amaratunga, D., & Haigh, R. (2016). *The use of public open spaces for disaster resilient urban cities*. IIIRR.

Johnson, C. (2007). *Strategic planning for post-disaster temporary housing*. *31*(4), 435–458.

Jones, S., Oven, K., Manyena, B., & Aryal, K. (2014). Governance struggles and policy processes in disaster risk reduction: A case study from Nepal. *Geoforum*, *57*, 78–90. https://doi.org/10.1016/J.GEOFORUM.2014.07.011

Kabir, A. S. M. S., Hossain, D., & Abdullah, R. (2011). 2-D Electrical Imaging in Some Geotechnical Investigation of Madhupur 2-D Electrical Imaging in Some Geotechnical Investigation of Madhupur Clays , Bangladesh. *JOURNAL GEOLOGICAL SOCIETY OF INDIA*, *77*(August 2015), 73–81. https://doi.org/10.1007/s12594-011-0009-4

Kaklamanos, J., Bradley, B. A., Thompson, E. M., & Baise, L. G. (2013). Critical parameters affecting bias and variability in site-response analyses using KiK-net downhole array data. *Bulletin of the Seismological Society of America*, *103*(3), 1733–1749. https://doi.org/10.1785/0120120166

Kamal, A. S. M. M. (2013). Earthquake Risk and Reduction Approaches in Bangladesh. In R. Shaw, F. Mallick, & A. Islam (Eds.), *Urban Risk Reduction Approaches in Bangladesh* (pp. 103–130). Springer. https://doi.org/10.1007/978-4-431-54252-0_11

Khan, N. I. (2000). Temporal mapping and spatial analysis of land transformation due to urbanization and its impact on surface water system: A case from Dhaka metropolitan area, Bangladesh. *Int. Arch. Photogramm. Remote Sens*, *33*, 598–605.

Khazai, B., Eeri, M., & Hausler, E. (2005). Intermediate Shelters in Bam and Permanent Shelter Reconstruction in Villages Following the 2003 Bam, Iran, Earthquake. *Earthquake Spectra*, *21*(1). https://doi.org/10.1193/1.2098907

Knopoff, L. (1996). Earthquake prediction: the scientific challenge. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(9), 3719.

Koren, D., & Rus, K. (2019). The Potential of Open Space for Enhancing Urban Seismic Resilience: A literature Review. *Sustainability*, *11*(21), 5942. https://doi.org/10.3390/su11215942

Kroll, C. A., Landis, J. D., Shen, Q., & Stryker, S. (1991). *Economic impacts of the Loma Prieta earthquake: a focus on small business*.

Lahoti, S., Kefi, M., Lahoti, A., & Saito, O. (2019). Mapping methodology of public urban green spaces using GIS: An example of Nagpur City, India. *Sustainability (Switzerland)*, *11*, 1–23.

https://doi.org/10.3390/su10022166

Lee, V. J., & Low, E. (2006). Coordination and resource maximization during disaster relief efforts. *Prehospital Disast Med*, *21*(SUPPL.1), s8. https://doi.org/10.1017/s1049023x00015818

Li, H., Zhao, L., Huang, R., & Hu, Q. (2017). Hierarchical earthquake shelter planning in urban areas: A case for Shanghai in China. *International Journal of Disaster Risk Reduction*, *22*, 431–446.

Liedtke, F. H. (2020a). *Enhancing Urban Resilience After the 1995 Kobe Earthquake* (pp. 167–180). https://doi.org/10.14361/9783839450185-009

Liedtke, F. H. (2020b). Enhancing Urban Resilience After the 1995 Kobe Earthquake: Parks and Open Spaces as a Multi-Functional Resource. In *Urban Resilience in a Global Context* (pp. 167–180). https://doi.org/10.14361/9783839450185-009

Lingling, J., Jiexiu, W., & Lianyou, L. (2008). Technical Assistance Consultant's Report; Providing Emergency Response to Wenchuan Earthquake. In *ADB Technical Assistance Consultant's Report Project* (Issue December).

Liu, Q., Ruan, X., & Shi, P. (2011). Selection of emergency shelter sites for seismic disasters in mountainous regions : Lessons from the 2008 Wenchuan Ms 8 . 0 Earthquake , China. *Journal of Asian Earth Sciences*, *40*(4), 926–934. https://doi.org/10.1016/j.jseaes.2010.07.014

Manandhar, M. Das, Varughese, G., Howitt, A. M., & Kelly, E. (2017). *Disaster preparedness and response during political transition in Nepal: Assessing civil and military roles in the aftermath of the 2015 earthquakes*.

Manzur, T., & Noor, M. A. (2006). Displacement Based Fragility Curves for RCC Frame Structures in Context of Dhaka, Bangladesh. *Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference*, 84–98.

Margesson, R., & Taft-Morales, M. (2010). *Haiti Earthquake: Crisis and Response* . www.crs.govR41023.c11173008

Matasović, N., & Vucetic, M. (1993). Cyclic characterization of liquefiable sands. *Journal of Geotechnical Engineering*, *119*(1), 4279. https://doi.org/10.1061/(ASCE)0733-9410(1995)121:1(102)

Mister, R. (2006). Natural disasters—Humanitarian coordination among international agencies: Experience from Pakistan and the tsunami. *Refugee Survey Quarterly*, *25*(4), 122–128. https://doi.org/10.1093/rsq/hdi0179

Montejano-Castillo, M., & Moreno-Villanueva, M. (2016). The adaptability of public space in Mexico City after an earthquake: A Preliminary classification. *International Journal of Safety and Security Engineering*, *6*(2), 104–113. https://doi.org/10.2495/SAFE-V6-N2-104-113

Morshed, N., Yorke, C., & Zhang, Q. (2017). Urban Expansion Pattern and Land Use Dynamics in Dhaka, 1989–2014. *The Professional Geographer*, *69*(3), 396–411. https://doi.org/10.1080/00330124.2016.1268058

Murao, O., Ichiko, T., & Nakabayashi, I. (2004, August). Evaluation of Building Reconstruction Process in Chi-Chi Area Based on A GIS-Database after the 1999 Chi-Chi Earthquake, Taiwan. *13th World Conference on Earthquake Engineering*. https://www.iitk.ac.in/nicee/wcee/article/13_174.pdf

Muzzini, E., & Aparicio, G. (2013). *Bangladesh: The path to middle-income status from an urban perspective*. World Bank Publications.

Naik, N. P., & Choudhury, D. (2013). Site Specific Ground Response Analysis for Typical Sites in Panjim City , Goa. *Proceedings of Indian Geotechnical Conference, November 2014*, 1–10.

NRC. (2010). Urban Shelter Guidelines. In *Shelter Center*. http://shelterprojects.org/files/NRC-urban-shelterguidelines_23-11-10_compressed.pdf

Okuyama, Y. (2004). Modeling spatial economic impacts of an earthquake: Input-output approaches. *Disaster Prevention and Management: An International Journal*.

Oldham, R. D. (1899). *Report on the Great Earthquake of 12th June 1897. Mem. Geol. Surv. India 29.*

Ordaz, M., & Salgado-Gálvez, M. A. (2017). *R-CRISIS Validation and Verification Document. Technical Report. Mexico City, Mexico.*

Orme, W. A. (1986). Thousands Still Homeless 1 Year After Mexico Quake. *The Washington Post*, A01. https://www.washingtonpost.com/wp-srv/inatl/longterm/mexico/stories/860920.htm

Orr, B. (2007). *Kobe : Disaster Response and Adaptation*.

Pacific, A. (2016). *Nepal 2015 / earthquake*.

Parmar, S., Lobb, A., Purdin, S., & McDonnell, S. (2007). Enhancing Collaboration during Humanitarian Response: An Interim Report from Stakeholders Survey. *Prehospital and Disaster Medicine*, *22*(5), 414–417. https://doi.org/10.1017/S1049023X00005136

Perrucci, D. V, & Baroud, H. (2018). Improving Community Resilience through Post-Disaster Temporary Housing Optimization. *Proceedings of the Probabilistic Safety Assessment and Management PSAM*, *14*.

PreventionWeb. (2010). *Disaster Risks and Risk Mitigation in Dhaka*.

Qazi, U. (2010). Pakistan: Implementing people-centred reconstruction in urban and rural areas . In *Building Back Better: Delivering people-centred housing reconstruction at scale* (pp. 113–162). Practical Action Publishing Ltd. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.309.3363&rep=rep1&type=pdf#page=125

Rahman, M. (2019). *Probabilistic seismic hazard analysis with nonlinear site response and liquefaction potential evaluation for deep sedimentary deposits*. University of British Columbia.

Rahman, M. Z., & Siddiqua, S. (2017). Evaluation of liquefaction-resistance of soils using standard penetration test, cone penetration test, and shear-wave velocity data for Dhaka, Chittagong, and Sylhet cities in Bangladesh. *Environmental Earth Sciences*, *76*(5). https://doi.org/10.1007/s12665-017-6533-9

Rahman, M. Z., Siddiqua, S., & Kamal, A. S. M. M. (2015). Liquefaction hazard mapping by liquefaction potential index for Dhaka City, Bangladesh. *Engineering Geology*, *188*, 137–147. https://doi.org/10.1016/j.enggeo.2015.01.012

Rahman, M. Z., Siddiqua, S., & Kamal, A. S. M. M. (2017). Probabilistic seismic hazard analysis for Dhaka city, Bangladesh. *70th Canadian Geotechnical Conference*.

Rathje, E. M., Kottke, A. R., & Trent, W. L. (2010). Influence of Input Motion and Site Property Variabilities on Seismic Site Response Analysis. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(4), 607–619. https://doi.org/10.1061/(asce)gt.1943-5606.0000255

Ray, B. (2017). Response of a Resilient Community to Natural Disasters: The Gorkha Earthquake in Nepal, 2015. *The Professional Geographer*, *69*(4), 644–654. https://doi.org/10.1080/00330124.2017.1298452

Reja, M. Y. (2012a). *Investigating the role of open spaces and public buildings for earthquake vulnerability reduction in old Dhaka* (Issue November).

Reja, M. Y. (2012b). *Investigating the role of open spaces and public buildings for earthquake vulnerability reduction in old Dhaka*. Bangladesh University of Science and Technology.

Report, E. (2003). *Chi-Chi , Taiwan Earthquake*.

Rimal, A., & Lal, A. C. (2021). An Analysis on Open Spaces in Kathmandu Valley from Disaster Management Perspectives. *Proceedings of 10th IOE Graduate Conference*.

Saha, M. . (2011). Earthquake: emerging threat for Dhaka city. *Journal of Urban and Regional Planning*, 26–31.

Samm-A, A. (2020). *Probabilistic seismic hazard assessment of Bangladesh* [University of Dhaka]. https://doi.org/10.1785/0120180022

Sattar, M. A., Rahman, M. S., & Roy, S. (2014). *Green Global Foundation ©. 2571*.

Saxena, M. (2016). Role of Open Spaces in Disaster Management. *Conference: AGORA 2016*.

Saxena, M. R. (2016). Role of Open Spaces in Disaster Management. *School of Architecture and*

Planning. https://www.researchgate.net/publication/312661449

Schnabel, P. B. (1972). SHAKE: A computer program for earthquake response analysis of horizontally layered sites. *EERC Report 72-12*, *University of California*, *Berkeley*.

Schultz, C. H., Koenig, K. L., & Noji, E. K. (1996). A Medical Disaster Response to Reduce Immediate Mortality after an Earthquake. *New England Journal of Medicine*, *334*(7), 438–444. https://doi.org/10.1056/NEJM199602153340706

Scordilis, E. M. (2006). Empirical global relations converting MS and mb to moment magnitude. *Journal of Seismology*, *10*(2), 225–236. https://doi.org/10.1007/s10950-006-9012-4

Seed, H. B., & Idriss, I. M. (1970). Soil Moduli and Damping Factors for Dynamic Response Analyses. In *EARTHQUAKE ENGINEERING RESEARCH CENTER SOIL* (Issue December).

Shelter Cluster Nepal. (2015). *Nepal Earthquake Recovery Monitoring Assessment* (Issue November).

Shelter Projects. (2008). *Pakistan Earthquake Summary*.

Shrestha, S. R., Romão, X., Chapagain, N. K., Shrestha, S. R., Sliuzas, R., & Kuffer, M. (2018). *Open spaces and risk perception in post-earthquake Kathmandu city Cite this paper Related papers Revisit ing Kathmandu: Proceedings of an international symposium Open spaces and risk perception in post-earthquake Kathmandu city*. https://doi.org/10.1016/j.apgeog.2018.02.016

Shrestha, S. R., Sliuzas, R., & Kuffer, M. (2018). Open spaces and risk perception in post-earthquake Kathmandu city. *Applied Geography*, *93*, 81–91.

https://doi.org/10.1016/j.apgeog.2018.02.016

Soltani, A., & Ardalan, A. (2019). *Criteria for Site Selection of Temporary Shelters after Earthquakes : a Delphi Panel*. 1–12. https://doi.org/10.1371/currents.dis.07ae4415115b4b3d71f99ba8b304b807.Authors

Soltani, A., Ardalan, A., Boloorani, A. D., Haghdoost, A., & Hosseinzadeh-Attar, M. J. (2014). Site Selection Criteria for Sheltering after Earthquakes: A Systematic Review. *Plos Currents*. https://doi.org/10.1371/currents.dis.17ad1f98fb85be80785d0a81ced6a7a6

Sphere. (2018). *The Sphere Handbook* . https://handbook.spherestandards.org/en/sphere/#ch001

Steets, J., Binder, A., Krüger, S., Meier, C., Grünewald, F., de Geoffroy, V., Kauffmann, D., & Sokpoh, B. (2010). Cluster Approach Evaluation II Synthesis Report. *Www.Gppi.Net*. https://www.gppi.net/2010/04/01/cluster-approach-evaluation-ii-synthesis-report

Stepp, J. C. (1972). Analysis of Completeness of the Earthquake Sample in the Puget Sound Area and Its Effect on Statistical Estimates of Earthquake Hazard. *Proceedings of the Microzonation Conference. Seattle, WA*, 897–909.

Stewart, J. P., & Kwok, A. O. L. (2008). Nonlinear seismic ground response analysis: code usage protocols and verification against vertical array data. *Geotechnical Earthquake Engineering and Soil Dynamics IV*.

Stoddard, A., Harmer, A., Haver, K., Salomons, D., & Wheeler, V. (2007). Cluster Approach Evaluation. *ALNAP*. https://www.alnap.org/system/files/content/resource/files/main/erd-3641-full.pdf

Sukhwani, V., Napitupulu, H., Jingnan, D., Yamaji, M., & Shaw, R. (2021). Enhancing cultural adequacy in post-disaster temporary housing. *Progress in Disaster Science*, *11*, 100186. https://doi.org/10.1016/j.pdisas.2021.100186

Sun, J. I., Golesorkhi, G., & Seed, H. B. (1988). Dynamic Moduli and Damping Ratios for a Soft Clay. In *Journal of the Soil Mechanics and Foundations Division* (Vol. 97, Issue 1). https://doi.org/10.1061/jsfeaq.0001542

Szeliga, W., Hough, S., Martin, S., & Bilham, R. (2010). Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762. *Bulletin of the Seismological Society of America*, *100*(2), 570–584. https://doi.org/10.1785/0120080329

Tai, C., Lee, Y., & Lin, C. (2010). *Urban Disaster Prevention Shelter Location and Evacuation Behavior Analysis*. *7581*. https://doi.org/10.3130/jaabe.9.215

Tanim, P. S. H., & Urmi, S. A. (2014). Vulnerable Hospital function after a potential earthquake of Dhaka. *World Town Planning Day 2014*.

The Daily Star. (2012). Magic mosquito net . *The Daily Star*. https://www.thedailystar.net/news-detail-227552

The World Bank. (2020). *The World Bank Population Data*.

Tierney, K. J., & Gotlz, J. D. (1997). Emergency Response: Lessons Learned from the Kobe earthquake. *University of Delaware Disaster Research Center Preliminary Papers*, *260*.

Tinti, S., & Mulargia, F. (1985). An improved method for the analysis of the completeness of a seismic catalogue. *Lettere Al Nuovo Cimento Series 2*, *42*(1), 21–27. https://doi.org/10.1007/BF02739471

Unal, M., & Uslu, C. (2016). GIS-based accessibility analysis of urban emergency shelters: The case of Adana City. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *3rd International GeoAdvances Workshop*, *42*(2W1), 95–101. https://doi.org/10.5194/isprs-archives-XLII-2-W1-95-2016

UNECE. (2015). *The Geneva UN charter on sustainable housing*.

UNHCR. (2022a). *Camp planning standards (planned settlements)* . UNHCR Emergency Handbook. https://emergency.unhcr.org/entry/45581/camp-planning-standards-planned-settlements

UNHCR. (2022b). Shelter solutions. In *UNHCR Emergency Handbook*. https://emergency.unhcr.org/entry/57186?lang=en_US

Varyani, U. H. (2001). Lessons from Bhuj earthquake. In *Indian Concrete Journal* (Vol. 75, Issue 5, p. 305).

Vucetic, M., & Dobry, R. (1991). Effect of Soil Plasticity on Cyclic Response. *Journal of Geotechnical Engineering*, *117*(1), 89–107. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:1(89)

Wei, Y., Jin, L., Xu, M., Pan, S., Xu, Y., & Zhang, Y. (2020). Instructions for planning emergency shelters and open spaces in China: Lessons from global experiences and expertise. *International Journal of Disaster Risk Reduction*, *51*, 2212–4209. https://doi.org/10.1016/J.IJDRR.2020.101813

Weichart, D. H. (1980). Estimation of the Earthquake Recurrence Parameters for Unequal Observation Periods for Different Magnitudes. *Bulletin of the Seismological Society of America*, *70*(4), 1337–1346.

Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of The Seismological Society of America*, *84*(4), 974–1002.

World Bank & United Nations. (2010). *Natural hazards, unnatural disasters: the economics of effective prevention*.

Wright, K. C. (2010). *Post-earthquake sheltering needs ; how loss of structures and services affects decision making for evacuation*. *31*.

Yoshida, N., Kobayashi, S., Suetomi, I., & Miura, K. (2002). Equivalent linear method considering frequency dependent characteristics of stiffness and damping. *Soil Dynamics and Earthquake Engineering*, *22*(3), 205–222.

Youngs, R. R., & Coppersmith, K. J. (1985). Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. *Bulletin of the Seismological Society of America*, *75*(4), 939–954. https://doi.org/10.1016/0148-9062(86)90651-0

Zaman, M. A. Al, Shifty, S., Rakhine, N. J., & Aziz, M. A. (2018). *Earth Science & Climatic Change Earthquake Risks in Bangladesh and Evaluation of Awareness among the University Students*. *July*, 0–6. https://doi.org/10.4172/2157-7617.1000482

Zaveri, M. A. (2019). *Resource Scheduling for Postdisaster Management in IoT Environment*. *2019*.

Zefeng, Y., Jiao, Y., Junwei, L., & Bo, H. (2017). Shear Modulus Degradation Curves of Gravelly and Clayey Soils Based on KiK-Net In Situ Seismic Observations. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(9), 6017008.

https://doi.org/10.1061/(ASCE)GT.1943-5606.0001738

Zhang, J., Andrus, R., & Juang, C. H. (2008). Model Uncertainty in Normalized Shear Modulus and Damping Relationships. *Journal of Geotechnical and Geoenvironmental Engineering*, *134*. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:1(24)

Zhang, J., D., A. R., & Hsein, J. C. (2005). Normalized Shear Modulus and Material Damping Ratio Relationships. *Journal of Geotechnical and Geoenvironmental Engineering*, *131*(4), 453–464. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:4(453)

Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, *96*(3), 898–913. https://doi.org/10.1785/0120050122

Zhao, L., Li, H., Sun, Y., Huang, R., Hu, Q., Wang, J., & Gao, F. (2017). Planning Emergency Shelters for Urban Disaster Resilience: An Integrated Location-Allocation Modeling Approach. *Sustainability*, *9*(11), 2098. https://doi.org/10.3390/su9112098

Zhi-Yong, S. (1987). Medical support in the Tangshan earthquake: a review of the management of mass casualties and certain major injuries. *Journal of Trauma and Acute Care Surgery*, *27*(10), 1130–1135.

Appendix

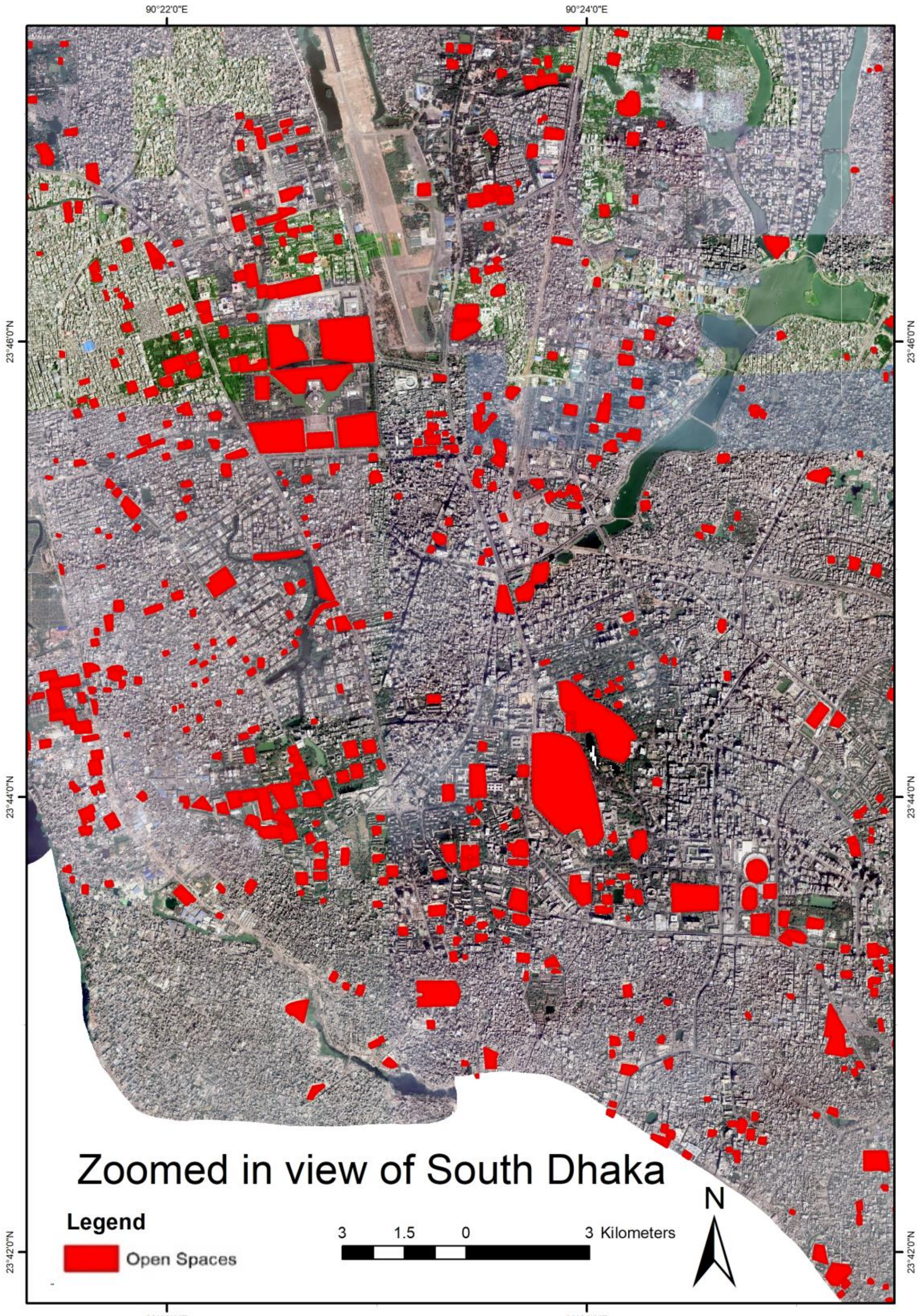
A1: The ward names and associated wardnumber in Dhaka Metropolitan Area.

Ward Number	Ward Name
Ward No-01	Biman Bandar
Ward No-02	Pallabi
Ward No-03	Pallabi
Ward No-04	Kafrul
Ward No-05	Pallabi
Ward No-06	Pallabi
Ward No-07	Mirpur
Ward No-08	Shah Ali
Ward No-09	Darus Salam
Ward No-10	Darus Salam
Ward No-11	Mirpur
Ward No-12	Mirpur
Ward No-13	Mirpur
Ward No-14	Kafrul
Ward No-15	Cantonment
Ward No-16	Kafrul
Ward No-17	Badda
Ward No-18	Gulshan
Ward No-19	Gulshan
Ward No-20	Tejgaon Ind. Area
Ward No-21	Badda
Ward No-22	Rampura
Ward No-23	Rampura
Ward No-24	Khilgaon
Ward No-25	Khilgaon
Ward No-26	Khilgaon
Ward No-27	Sabujbagh
Ward No-28	Sabujbagh
Ward No-29	Sabujbagh
Ward No-30	Sabujbagh
Ward No-31	Motijheel
Ward No-32	Motijheel
Ward No-33	Motijheel
Ward No-34	Motijheel
Ward No-35	Motijheel
Ward No-36	Paltan
Ward No-37	Tejgaon

Ward No-38	Tejgaon
Ward No-38	Tejgaon
Ward No-39	Tejgaon
Ward No-40	Sher-e-bangla Nagar
Ward No-40	Tejgaon
Ward No-41	Sher-e-bangla Nagar
Ward No-42	Mohammadpur
Ward No-43	Adabor
Ward No-44	Mohammadpur
Ward No-45	Mohammadpur
Ward No-46	Adabor
Ward No-46	Mohammadpur
Ward No-46	Hazaribagh
Ward No-47	Dhanmondi
Ward No-47	Mohammadpur
Ward No-48	Dhanmondi
Ward No-48	Hazaribagh
Ward No-49	Dhanmondi
Ward No-50	Kalabagan
Ward No-51	Kalabagan
Ward No-51	Mohammadpur
Ward No-52	New Market
Ward No-53	Ramna
Ward No-54	Ramna
Ward No-55	Ramna
Ward No-56	Lalbagh
Ward No-56	Shahbagh
Ward No-57	Shahbagh
Ward No-58	Hazaribagh
Ward No-59	Lalbagh
Ward No-60	Lalbagh
Ward No-61	Lalbagh
Ward No-62	Lalbagh
Ward No-63	Bangshal
Ward No-63	Chak Bazar
Ward No-64	Chak Bazar
Ward No-65	Chak Bazar
Ward No-66	Bangshal
Ward No-66	Chak Bazar
Ward No-67	Bangshal
Ward No-67	Chak Bazar
Ward No-68	Bangshal
Ward No-68	Kotwali

Ward No-69	Bangshal
Ward No-70	Bangshal
Ward No-71	Bangshal
Ward No-71	Kotwali
Ward No-72	Kotwali
Ward No-73	Kotwali
Ward No-74	Sutrapur
Ward No-75	Sutrapur
Ward No-76	Gendaria
Ward No-76	Jatrabari
Ward No-77	Sutrapur
Ward No-78	Sutrapur
Ward No-79	Sutrapur
Ward No-80	Gendaria
Ward No-80	Sutrapur
Ward No-81	Gendaria
Ward No-82	Gendaria
Ward No-83	Shyampur
Ward No-84	Jatrabari
Ward No-85	Jatrabari
Ward No-86	Jatrabari
Ward No-87	Shyampur
Ward No-88	Kadamtali
Ward No-89	Kadamtali
Ward No-90	Shyampur
Ward No-91	Lalbagh
Ward No-92	Lalbagh
Ward No-98 (Restricted)	Biman Bandar
Ward No-98 (Restricted)	Cantonment

A2: Zoomed in view of South Dhaka



A3: List of the names of open spaces from Fig. 3.9.

Site ID	Site Name	Latitude	Longitude
1	Azampur Government Primary School Playground	23.8683758943	90.4010104061
2	Sonali Bank Staff College Field, Sector 8, Utara	23.8785203389	90.4043122654
3	Armed Police Battalion Headquarters Grounds, Uttara	23.8566504757	90.4044777108
4	Ershal Colony (Civil Aviation) Playground	23.8555466928	90.4069533563
5	Uttara Sector 4 Park & Playground	23.8611817984	90.4039302442
6	Bangladesh Police Cricket Stadium, Kafrul	23.8030133098	90.3798459165
7	Milbarak Police Shooting Club Ground	23.6983986462	90.4199338047
8	Dhupkhola Field	23.7066592025	90.4229708613
9	Brothers' Union Club Field	23.7220804118	90.4227399063
10	Bangabhaban Garden-2	23.7244134637	90.4156489719
11	Mawlana Bhasani Stadium	23.7258787501	90.4129414524
12	Bangabhaban Garden-1	23.7231126395	90.4166320693
13	National Eidgah	23.7298737585	90.4040969482
14	Dhaka Univesity Central Field	23.7264668777	90.3994840094
15	BUET Field	23.7257539919	90.3945965472
16	Jagannath Hall Playground	23.7295209568	90.3946401640
17	Bir Uttam Anwar Hossain Darbar Hall Playground, Pilkhana	23.7331328227	90.3720107756
18	Shultan Ground,Pilkhana	23.7334198107	90.3731104320
19	BGB Parade Ground	23.7334486585	90.3759874341
20	ICT BN playground, Pilkhana	23.7318298216	90.3758006043
21	Kriraboard Field, Pilkhana	23.7306801130	90.3762373705
22	West Nandi Para Field	23.7328264881	90.3744526076
23	Pilkhana Field	23.7331349020	90.3781731645
24	Bangladesh-Kuwait Friendship Hall Field	23.7338958221	90.3790890221
25	Govt Laboratory High School Playground	23.7368132333	90.3812819813
26	Dhaka College Playground	23.7352124193	90.3817368729
27	Joysar Jame Mosque Field, Pilkhana	23.7363498057	90.3732248343
28	BGB 11 Battalion Field	23.7353701176	90.3771168751
29	Dhaka SHQ Garden, Pilkhana	23.7345753050	90.3768918381
30	Shaheed Sergeant Zahurul Haque Hall Playground	23.7292268363	90.3891185955
31	Salimullah Hall Playground	23.7283821187	90.3903485903
32	Salimullah Muslim Hall Garden	23.7292900846	90.3907253321
33	Lalbag Fort	23.7189238184	90.3882101831
34	Dr. Muhammed Shahidullah Hall Garden	23.7257968111	90.4016206137
35	Fazlul Huq Muslim Hall, Main Building Garden	23.7262277120	90.4034725885

36	Fazlul Huq Muslim Hall Playground	23.7259706467	90.4041141051
37	Curzon Hall Field Dhaka University	23.7270533925	90.4018604638
38	Department of Chemistry Garden, University of Dhaka	23.7274679872	90.4029349055
39	Suhrawardy Udyan	23.7341098567	90.3982599776
40	Abahani Field	23.7490539148	90.3709442543
41	Lt. Sheikh Jamal Cricket Academy Field	23.7460066755	90.3806151645
42	Shimanto 26 Café BGB Field	23.7307374053	90.3748462736
43	Mohammadpur Residential College Field	23.7649816535	90.3673119892
44	DRMC Playground	23.7645526347	90.3687974802
45	Shyamoli Park	23.7731697303	90.3655670531
46	Shaheed Suhrawardy Medical College and Hospital Garden	23.7684229142	90.3698021507
47	Sher-e-Bangla Agricultural University Fruit Garden	23.7714860742	90.3733779458
48	Sher-e-Bangla Nagar Staff Quarter Playground	23.7746464317	90.3767007377
49	Lal mat, Sher-E-Bangla Nagar	23.7750859259	90.3757399814
50	Banijjo Mela Field	23.7706446677	90.3771360263
51	Agricultural land, Sher-e-Bangla Agricultural University	23.7703342767	90.3742365610
52	Nursery Orchard, Sher-e-Bangla Agricultural University	23.7703091117	90.3750207049
53	Chandrima Uddyan	23.7663194756	90.3760198183
54	National Parliament	23.7594279737	90.3788160115
55	Tallabag Open Space, Rayer Bazaar	23.7422370323	90.3626314136
56	Shahed Bashar Road Field, Cantonment	23.7685760757	90.3468200082
57	Govt. Jamila Aynul Andho School & College Garden, Shyamoli	23.7725659316	90.3662315558
58	SRDI Garden-2	23.7599006997	90.3874738053
59	SRDI Garden	23.7594600876	90.3878301392
60	Sher-E-Bangla Nagar Park	23.7586594282	90.3871357765
61	Sheltech Momena Garden, Monipuripara 2 No. Gate Road	23.7604207444	90.3877577017
62	Khalek Sarani Women's Hostel Garden	23.7608776050	90.3913164343
63	Government Printing Press Garden, Begunbari	23.7614646742	90.4013436963
64	Dhaka Polytechnic Institute Field	23.7652998378	90.4030993269
65	Bangladesh Air Force Shaheen English Medium College (SEMC) Field-2	23.7777477630	90.3928505295
66	Saudi Colony Playground-1	23.7777270407	90.3936140095
67	Bangladesh Air Force Shaheen English Medium College (SEMC) Field-1	23.7772128985	90.3921498301
68	BATB Playground	23.7806038184	90.3956733182
69	43 Engineers Field-1, Cantonment	23.7856327322	90.3955069386
70	43 Engineers Field-2, Cantonment	23.7858404051	90.3968825063
71	23 EB Mosque Field, Cantonment	23.7871339666	90.3969248053

72	43 Engineers Field-3, Cantonment	23.7863008342	90.3963740589
73	Army Playground, Shadheenata Sharani	23.7899338373	90.3988701429
74	Shadhinata Sharani Army Playground, Shahid Yusuf Road	23.7910580817	90.3983337822
75	T and T Playground, Banani	23.7840041173	90.4034100559
76	Baishakhi Park Banani	23.7905572214	90.4022290184
77	Banani Bidyaniketan Playground	23.7955179070	90.4032969993
78	Bangladesh Telecommunication Regulatory Commission (BTRC) Field	23.7761534836	90.3761283609
79	Hatirjheel Field Sonargaon Signal	23.7483229322	90.3951189930
80	Ramna Park	23.7387591171	90.4008635827
81	Gonomaddom Institute Soccer Field	23.7803781303	90.3570193191
82	Bangla College Campus Field	23.7850898022	90.3528040690
83	Kallyanpur Housing Play Ground 2	23.7845334652	90.3540879663
84	Golartek Playground	23.7931360088	90.3439678796
85	Mirpur Buddjibi Sahid Minar Car Parking	23.7932877796	90.3469586829
86	Sher e Bangla Cricket Stadium	23.8068518445	90.3636341409
87	Bangladesh Insulator Factory Field	23.8098990038	90.3535603857
88	Milk Vita Field, Mirpur 6	23.8116266780	90.3591518253
89	Defense Sevices Command and Staff College Park, Pallabi	23.8305664620	90.3575989031
90	Baguntila Playground Pallabi	23.8297387094	90.3808688380
91	BSD Mosque Field, Cantonment	23.8233305733	90.4041348679
92	AITSO Office Field, Cantonment	23.8212457208	90.4030856033
93	Cantonment Officer Mess Field-1	23.8208498468	90.4024759940
94	Cantonment Officer Mess Field-2	23.8202949870	90.4018495763
95	Cantonment Officer Mess Field-3	23.8193848603	90.4016028998
96	Cantonment Officer Mess Field-4	23.8188490742	90.4009968990
97	Cantonment Officer Mess Field-5	23.8185555623	90.4018732765
98	Cantonment Officer Mess Field-6	23.8188501435	90.4029663978
99	Shaheed Mannan Line Park-2, Cantonment	23.8170757178	90.4022890339
100	Shaheed Mannan Line Park-1, Cantonment	23.8169685546	90.4016078693
101	Cantonment Officer Mess Field	23.8187835151	90.4000444126
102	Army Static Signal Battalion Training Ground	23.8227491925	90.3984216294
103	Army Static Signal Battalion Training Ground	23.8235676704	90.3974276561
104	703 play ground, Shaheed Sharani	23.8253712538	90.3979672921
105	UN Transit Complex Field	23.8251032671	90.3996811510
106	BAF Kurmitola Cantonment Garden	23.8262108312	90.4009834602
107	BAF Shaheen College Kurmitola Field	23.8285331426	90.4027423076
108	BAF Officer's Mess Field, Kurmitola	23.8297728960	90.4005533720
109	CMH Field, Cantonemnt	23.8143941485	90.3963546401

110	CMH Field, Cantonemnt	23.8135674009	90.3956802083
111	Ananta Somore Garden, CMH	23.8133444814	90.3989416767
112	Trauma Center & Burn Unit Garden, CMH	23.8127040777	90.3987464261
113	Bijoy Keton, Cantonment	23.8113034384	90.3998029104
114	Bijoy Keton, Cantonment	23.8110205503	90.3997385057
115	187 Shaheed Bashar Road Field, Cantonment	23.8106176134	90.4007707095
116	Shahed Bashar Road Field, Cantonment	23.8106677803	90.4013279174
117	Shahed Bashar Road Field, Cantonment	23.8106811286	90.4017076874
118	Shahed Bashar Road Field, Cantonment	23.8100038090	90.4005148873
119	Army Central Masjid Field	23.8067246302	90.3976402559
120	Nirjhor Cantonment Field	23.8082711861	90.3956540512
121	Nirjhor Cantonment Field	23.8092010983	90.3951919713
122	Helmet Bhaban Garden	23.8073098553	90.3992722082
123	Army Central Mosque Parking Lot	23.8052593557	90.3976055845
124	Nirjhor Residential Area Field	23.8077077707	90.3927927634
125	Nirjhor Cantonment Field	23.8082989474	90.3912242168
126	Nirjhor Cantonment Public School & College Field	23.8091335882	90.3929733535
127	NCPSC Playground, Nirjhor, Cantonment	23.8098564158	90.3937232752
128	Nirjhor Cantonment Public School & College Field	23.8109588095	90.3941883429
129	Nirjhor Residential Area Ground (Army HQ)	23.8043897497	90.3930375606
130	National Defense College Field	23.8326839313	90.3643711502
131	BUP Field	23.8374559824	90.3597253978
132	Adamjee Cantonment College Field-1	23.7940876841	90.3947168146
133	Bihongo Officers Quarters Garden, Cantonment	23.7918333692	90.3939393290
134	Aziz Palli Field, Shaheed Sharani	23.7923679769	90.3912610217
135	Bangladesh Army Stadium	23.8055399752	90.4041617113
136	Army Stadium Playground	23.8043872075	90.4033042011
137	Naval Headquarter Playground	23.8033222197	90.4048244650
138	Army Head Quarter Admin Wing Playground	23.8047490973	90.4004457754
139	Sena Kunja Field	23.8036799632	90.3982690685
140	Engineer Brigade Football Ground, Cantonment	23.8114993339	90.4065937832
141	Seo Dex Field, DOHS Baridhara	23.8121350533	90.4086255747
142	Abhik Ground, DOHS Baridhara	23.8123333388	90.4071185979
143	Army Physical Training Playground, Banani	23.8140098222	90.4049662578
144	Officer Mess Field, Cantonemnt	23.8121299614	90.4044937538
145	Shaheed Ramiz Uddin Cantonment School Playground	23.8153952649	90.4005986111
146	Shaheed Ramiz Uddin Cantonment School Playground	23.8156451298	90.4022598845
147	Armed Forces Medical College Field	23.8176864802	90.4079191854
148	Central Ordnance Depot (COD) Garden	23.8157123823	90.4068367613

149	Army Golf Club Fitness Centre Field	23.8185773440	90.4122500371
150	Army Golf Club	23.8216481647	90.4134899044
151	Central Maintenance Transport Depot (CMTD) Canteen Field	23.8244807981	90.4073205670
152	24 Baily Road (Minister's House) Garden	23.7413314259	90.4018957416
153	Mandy Dental College Sadarghat	23.7417382693	90.3585831387
154	Tekkir Field, Sadarghat	23.7384271754	90.3599098399
155	Riverside Play Ground	23.7398728940	90.3540192057
156	Shikder Medical Ground	23.7404484858	90.3578197908
157	Z. H. Sikder Women's Medical College Mosque Ground	23.7392304792	90.3585159528
158	Hazaribag Field	23.7375071654	90.3549095044
159	Station Officers Mess-B Field, Cantonment	23.7880776345	90.3903391041
160	Ganabhaban Public Meeting Place	23.7650461077	90.3727698825
161	Ganabhaban Garden	23.7649046855	90.3740057272
162	Kollol Complex Field, Bou Bazar Road	23.7815820081	90.3752963017
163	Sonali Bank Officer's Quarter Field, Uttara Sector 8	23.8771721807	90.4046180672
164	Bashundhara Industrial Headquarters 1	23.8241586599	90.4278043824
165	Postogola Army Camp Field	23.6879076084	90.4291700911
166	Maniknagar Field	23.7218420182	90.4375052909
167	Wasa Saidabad Water Treatment Plant Ground	23.7199669275	90.4368337221
168	Gopalbag Field	23.7206335555	90.4404183558
169	Shahjadpur Playground, Baridhara	23.7959696460	90.4232574410
170	Royal Thai Embassy Garden	23.7989616987	90.4226947084
171	Banani Garden	23.8004007902	90.4040404774
172	Police Plaza Field, DOHS Baridhara	23.8103137967	90.4111568233
173	Bahadur Shah Park	23.7092260750	90.4123150113
174	Shahed Bashar Road Field, Cantonment	23.8110168380	90.4006122018
175	Army Head Quarter Tennis Ground	23.8100902988	90.3987228767
176	Army Multipurpose Complex Field	23.8083703518	90.3993936775
177	Bangladesh Army Headquarter Garden	23.8072295278	90.4012531767
178	Namapara Field, Cantonment	23.8208037397	90.3864614462
179	Balda Gardens	23.7159031431	90.4197163594
180	Birshreshtha Shohid Motiur Rahman Park	23.7239639841	90.4137770688
181	Osmani Uddyan	23.7259234594	90.4085499869
182	Mandy Dental College Playground	23.7405686779	90.3550599973
183	Bangladesh Navy College Playground	23.7985863960	90.3902642924
184	Kurmitola Pool Field	23.7985860370	90.3944822860
185	Dhaka Cantonment Board Office Garden	23.7958724868	90.3945294709
186	Adamjee Cantonment College Field-2	23.7945707938	90.3935344924
187	Shaheed Bir Uttam Lt. Anwar Girls' College Playground	23.7909956259	90.3928984861

188	Chief of the Army Staff's Palace Garden-1, Shaheed Sharani	23.7965552277	90.3944463543
189	Shikha Anirban, Shaheed Sharani	23.7978489536	90.3938016424
190	2 Shaheed Sharani Garden	23.7972669549	90.3929263797
191	Chief of the Army Staff's Palace Garden-2, Shaheed Sharani	23.7970809203	90.3941819289
192	Shaheed Sharani Basketball Court	23.8234367814	90.4004718813
193	Ambagan Field, Masterbari	23.8818657714	90.4248147056
194	Buriganga Eco-Park	23.6848308108	90.4348791973
195	Kurmitola Golf Club	23.7995772207	90.3982698384
196	Gulshan Lake Park	23.8016212315	90.4098407510
197	Botanical Garden	23.8177820962	90.3470446256
198	Kalabagan Cricket Ground	23.7488542374	90.3790863209
199	Dhanmondi 32 No. Lake	23.7510017168	90.3754509575
200	Dhanmondi 10 No. Lake	23.7468931465	90.3790843059
201	Armanitola Play Ground, Dhaka	23.7642620000	90.3684040000
202	Dhaka Residential Model College, Dhaka	23.7637470000	90.3640960000
203	Mohammadpur Eidgah, Dhaka	23.7134090000	90.4038500000

A4: Liquefaction potential of 203 selected sites based on geomorphology.

Site No.	Open Space Name	Geomorphology	Liquefaction Potential
1	Azampur Government Primary School Playground	Higher Pleistocene Terrace	Very low to none
2	Sonali Bank Staff College Field, Secctor 8, Utara	Higher Pleistocene Terrace	Very low to none
3	Armed Police Battalion Headquarters Grounds, Uttara	Higher Pleistocene Terrace	Very low to none
4	Ershal Colony (Civil Aviation) Playground	Higher Pleistocene Terrace	Very low to none
5	Uttara Sector 4 Park & Playground	Higher Pleistocene Terrace	Very low to none
6	Bangladesh Police Cricket Stadium, Kafrul	Moderately high Pleistocene Terrace	Low
7	Milbarak Police Shooting Club Ground	Old natural levee	High
8	Dhupkhola Field	Erosional Terrace Edge	Low
9	Brothers' Union Club Field	Thick fill	Very high
10	Bangabhaban Garden-2	Higher Pleistocene Terrace	Very low to none
11	Mawlana Bhasani Stadium	Higher Pleistocene Terrace	Very low to none
12	Bangabhaban Garden-1	Higher Pleistocene Terrace	Very low to none
13	National Eidgah	Higher Pleistocene Terrace	Very low to none
14	Dhaka Univesity Central Field	Higher Pleistocene Terrace	Very low to none
15	BUET Field	Higher Pleistocene Terrace	Very low to none
16	Jagannath Hall Playground	Higher Pleistocene Terrace	Very low to none
17	Bir Uttam Anwar Hossain Darbar Hall Playground, Pilkhana	Old natural levee	High
18	Shultan Ground,Pilkhana	Higher Pleistocene Terrace	Very low to none
19	BGB Parade Ground	Higher Pleistocene Terrace	Very low to none
20	ICT BN playground, Pilkhana	Higher Pleistocene Terrace	Very low to none
21	Kriraboard Field, Pilkhana	Higher Pleistocene Terrace	Very low to none
22	West Nandi Para Field	Higher Pleistocene Terrace	Very low to none
23	Pilkhana Field	Higher Pleistocene Terrace	Very low to none
24	Bangladesh-Kuwait Friendship Hall Field	Higher Pleistocene Terrace	Very low to none
25	Govt Laboratory High School Playground	Higher Pleistocene Terrace	Very low to none
26	Dhaka College Playground	Higher Pleistocene Terrace	Very low to none
27	Joysar Jame Mosque Field, Pilkhana	Highly erosional Pleistocene Terrace	Low

28	BGB 11 Battalion Field	Higher Pleistocene Terrace	Very low to none
29	Dhaka SHQ Garden, Pilkhana	Higher Pleistocene Terrace	Very low to none
30	Shaheed Sergeant Zahurul Haque Hall Playground	Higher Pleistocene Terrace	Very low to none
31	Salimullah Hall Playground	Higher Pleistocene Terrace	Very low to none
32	Salimullah Muslim Hall Garden	Higher Pleistocene Terrace	Very low to none
33	Lalbag Fort	Old natural levee	High
34	Dr. Muhammed Shahidullah Hall Garden	Higher Pleistocene Terrace	Very low to none
35	Fazlul Huq Muslim Hall, Main Building Garden	Higher Pleistocene Terrace	Very low to none
36	Fazlul Huq Muslim Hall Playground	Higher Pleistocene Terrace	Very low to none
37	Curzon Hall Field Dhaka University	Higher Pleistocene Terrace	Very low to none
38	Department of Chemistry Garden, University of Dhaka	Higher Pleistocene Terrace	Very low to none
39	Suhrawardy Udyan	Higher Pleistocene Terrace	Very low to none
40	Abahani	Higher Pleistocene Terrace	Very low to none
41	Lt. Sheikh Jamal Cricket Academy Field	Higher Pleistocene Terrace	Very low to none
42	Shimanto 26 Café BGB Field	Old natural levee	High
43	Mohammadpur Residential College Field	Moderately high Pleistocene Terrace	Low
44	DRMC Playground	Moderately high Pleistocene Terrace	Low
45	Shyamoli Park	Moderately thick fill	Very high
46	Shaheed Suhrawardy Medical College and Hospital Garden	Highly erosional Pleistocene Terrace	Low
47	Sher-e-Bangla Agricultural University Fruit Garden	Moderately high Pleistocene Terrace	Low
48	Sher-e-Bangla Nagar Staff Quarter Playground	Moderately high Pleistocene Terrace	Low
49	Lal mat, Sher-E-Bangla Nagar	Moderately high Pleistocene Terrace	Low
50	Banijjo Mela Field	Higher Pleistocene Terrace	Very low to none
51	Agricultural land, Sher-e-Bangla Agricultural University	Moderately high Pleistocene Terrace	Low
52	Nursery Orchard, Sher-e-Bangla Agricultural University	Moderately high Pleistocene Terrace	Low
53	Chandrima Uddyan	Higher Pleistocene Terrace	Very low to none
54	National Parliament	Higher Pleistocene Terrace	Very low to none

55	Tallabag Open Space, Rayer Bazaar	Thick fill	Very high
56	Shahed Bashar Road Field, Cantonment	Moderately thick fill	Very high
57	Govt. Jamila Aynul Andho School & College Garden, Shyamoli	Moderately thick fill	Very high
58	SRDI Garden-2	Higher Pleistocene Terrace	Very low to none
59	SRDI Garden	Higher Pleistocene Terrace	Very low to none
60	Sher-E-Bangla Nagar Park	Higher Pleistocene Terrace	Very low to none
61	Sheltech Momena Garden, Monipuripara 2 No. Gate Road	Higher Pleistocene Terrace	Very low to none
62	Khalek Sarani Women's Hostel Garden	Higher Pleistocene Terrace	Very low to none
63	Government Printing Press Garden, Begunbari	Higher Pleistocene Terrace	Very low to none
64	Dhaka Polytechnic Institute Field	Higher Pleistocene Terrace	Very low to none
65	Bangladesh Air Force Shaheen English Medium College (SEMC) Field-2	Higher Pleistocene Terrace	Very low to none
66	Saudi Colony Playground-1	Higher Pleistocene Terrace	Very low to none
67	Bangladesh Air Force Shaheen English Medium College (SEMC) Field-1	Higher Pleistocene Terrace	Very low to none
68	BATB Playground	Higher Pleistocene Terrace	Very low to none
69	43 Engineers Field-1	Higher Pleistocene Terrace	Very low to none
70	43 Engineers Field-2	Higher Pleistocene Terrace	Very low to none
71	23 EB Mosque Field, Cantonment	Higher Pleistocene Terrace	Very low to none
72	43 Engineers Field-3	Higher Pleistocene Terrace	Very low to none
73	Army Playground, Shadheenata Sharani	Higher Pleistocene Terrace	Very low to none
74	Shadhinata Sharani Army Playground, Shahid Yusuf Road	Higher Pleistocene Terrace	Very low to none
75	T and T Playground, Banani	Higher Pleistocene Terrace	Very low to none
76	Baishakhi Park Banani	Higher Pleistocene Terrace	Very low to none
77	Banani Bidyaniketan Playground	Higher Pleistocene Terrace	Very low to none
78	Bangladesh Telecommunication Regulatory Commission (BTRC) Field	Moderately high Pleistocene Terrace	Low
79	Hatirjheel Field Sonargaon Signal	Moderately thick fill	Very high
80	Ramna Park	Higher Pleistocene Terrace	Very low to none
81	Gonomaddom Institute Soccer Field	Moderately high Pleistocene Terrace	Low
82	Bangla College Campus Field	Moderately high Pleistocene Terrace	Low
83	Kallyanpur Housing Play Ground 2	Moderately high Pleistocene Terrace	Low

84	Golartek Playground	Higher Pleistocene Terrace	Very low to none
85	Mirpur Buddjibi Sahid Minar Car Parking	Higher Pleistocene Terrace	Very low to none
86	Sher e Bangla Cricket Stadium	Higher Pleistocene Terrace	Very low to none
87	Bangladesh Insulator Factory Field	Higher Pleistocene Terrace	Very low to none
88	Milk Vita Field, Mirpur 6	Higher Pleistocene Terrace	Very low to none
89	Defense Sevices Command and Staff College Park, Pallabi	Moderately erosional Pleistocene Terrace	Low
90	Baguntila Playground Pallabi	Moderately high Pleistocene Terrace	Low
91	BSD Mosque Field, Cantonment	Moderately thick fill	Very high
92	AITSO Office Field, Cantonment	Higher Pleistocene Terrace	Very low to none
93	Cantonment Officer Mess Field	Higher Pleistocene Terrace	Very low to none
94	Cantonment Officer Mess Field	Higher Pleistocene Terrace	Very low to none
95	Cantonment Officer Mess Field	Higher Pleistocene Terrace	Very low to none
96	Cantonment Officer Mess Field	Moderately erosional Pleistocene Terrace	Low
97	Cantonment Officer Mess Field	Higher Pleistocene Terrace	Very low to none
98	Cantonment Officer Mess Field	Higher Pleistocene Terrace	Very low to none
99	Shaheed Mannan Line Park-2, Cantonment	Higher Pleistocene Terrace	Very low to none
100	Shaheed Mannan Line Park-1, Cantonment	Higher Pleistocene Terrace	Very low to none
101	Cantonment Officer Mess Field	Moderately erosional Pleistocene Terrace	Low
102	Army Static Signal Battalion Training Ground	Higher Pleistocene Terrace	Very low to none
103	Army Static Signal Battalion Training Ground	Higher Pleistocene Terrace	Very low to none
104	703 play ground, Shaheed Sharani	Higher Pleistocene Terrace	Very low to none
105	UN Transit Complex Field	Higher Pleistocene Terrace	Very low to none
106	BAF Kurmitola Cantonment Garden	Higher Pleistocene Terrace	Very low to none
107	BAF Shaheen College Kurmitola Field	Higher Pleistocene Terrace	Very low to none
108	BAF Officer's Mess Field, Kurmitola	Higher Pleistocene Terrace	Very low to none
109	CMH Field, Cantonemnt	Moderately high Pleistocene Terrace	Low
110	CMH Field, Cantonemnt	Moderately high Pleistocene Terrace	Low
111	Ananta Somore Garden, CMH	Moderately high Pleistocene Terrace	Low

112	Trauma Center & Burn Unit Garden, CMH	Moderately high Pleistocene Terrace	Low
113	Bijoy Keton, Cantonment	Moderately high Pleistocene Terrace	Low
114	Bijoy Keton, Cantonment	Moderately high Pleistocene Terrace	Low
115	187 Shaheed Bashar Road Field, Cantonment	Moderately thick fill	Very high
116	Shahed Bashar Road Field, Cantonment	Higher Pleistocene Terrace	Very low to none
117	Shahed Bashar Road Field, Cantonment	Higher Pleistocene Terrace	Very low to none
118	Shahed Bashar Road Field, Cantonment	Moderately thick fill	Very high
119	Army Central Masjid Field	Moderately thick fill	Very high
120	Nirjhor Cantonment Field	Higher Pleistocene Terrace	Very low to none
121	Nirjhor Cantonment Field	Higher Pleistocene Terrace	Very low to none
122	Helmet Bhaban Garden	Moderately high Pleistocene Terrace	Low
123	Army Central Mosque Parking Lot	Moderately erosional Pleistocene Terrace	Low
124	Nirjhor Residential Area Field	Moderately thick fill	Very high
125	Nirjhor Cantonment Field	Moderately thick fill	Very high
126	Nirjhor Cantonment Public School & College Field	Highly erosional Pleistocene Terrace	Low
127	NCPSC Playground, Nirjhor, Cantonment	Highly erosional Pleistocene Terrace	Low
128	Nirjhor Cantonment Public School & College Field	Highly erosional Pleistocene Terrace	Low
129	Nirjhor Residential Area Ground (Army HQ)	Old natural levee	High
130	National Defense College Field	Higher Pleistocene Terrace	Very low to none
131	BUP Field	Higher Pleistocene Terrace	Very low to none
132	Adamjee Cantonment College Field-1	Higher Pleistocene Terrace	Very low to none
133	Bihongo Officers Quarters Garden, Cantonment	Higher Pleistocene Terrace	Very low to none
134	Aziz Palli Field, Shaheed Sharani	Higher Pleistocene Terrace	Very low to none
135	Bangladesh Army Stadium	Higher Pleistocene Terrace	Very low to none
136	Army Stadium Playground	Higher Pleistocene Terrace	Very low to none
137	Naval Headquarter Playground	Higher Pleistocene Terrace	Very low to none
138	Army Head Quarter Admin Wing Playground	Higher Pleistocene Terrace	Very low to none
139	Sena Kunja Field	Moderately thick fill	Very high

140	Engineer Brigade Football Ground, Cantonment	Moderately thick fill	Very high
141	Seo Dex Field, DOHS Baridhara	Higher Pleistocene Terrace	Very low to none
142	Abhik Ground, DOHS Baridhara	Higher Pleistocene Terrace	Very low to none
143	Army Physical Training Playground, Banani	Higher Pleistocene Terrace	Very low to none
144	Officer Mess Field, Cantonemnt	Higher Pleistocene Terrace	Very low to none
145	Shaheed Ramiz Uddin Cantonment School Playground	Moderately high Pleistocene Terrace	Low
146	Shaheed Ramiz Uddin Cantonment School Playground	Higher Pleistocene Terrace	Very low to none
147	Armed Forces Medical College Field	Higher Pleistocene Terrace	Very low to none
148	Central Ordnance Depot (COD) Garden	Higher Pleistocene Terrace	Very low to none
149	Army Golf Club Fitness Centre Field	Higher Pleistocene Terrace	Very low to none
150	Army Golf Club	Higher Pleistocene Terrace	Very low to none
151	Central Maintenance Transport Depot (CMTD) Canteen Field	Higher Pleistocene Terrace	Very low to none
152	24 Baily Road (Minister's House) Garden	Higher Pleistocene Terrace	Very low to none
153	Mandy Dental College Sadarghat	Moderately thick fill	Very high
154	Tekkir Field, Sadarghat	Moderately thick fill	Very high
155	Riverside Play Ground	Yonger floodplain	Very high
156	Shikder Medical Ground	Moderately thick fill	Very high
157	Z. H. Sikder Women's Medical College Mosque Ground	Moderately thick fill	Very high
158	Hazaribag Field	Higher Pleistocene Terrace	Very low to none
159	Station Officers Mess-B Field, Cantonment	Higher Pleistocene Terrace	Very low to none
160	Ganabhaban Public Meeting Place	Higher Pleistocene Terrace	Very low to none
161	Ganabhaban Garden	Higher Pleistocene Terrace	Very low to none
162	Kollol Complex Field, Bou Bazar Road	Moderately thick fill	Very high
163	Sonali Bank Officer's Quarter Field, Uttara Sector 8	Higher Pleistocene Terrace	Very low to none
164	Bashundhara Industrial Headquarters 1	Moderately deep Alluvial valley	High
165	Postogola Army Camp Field	Moderately thick fill	Very high
166	Maniknagar Field	Thick fill	Very high
167	Wasa Saidabad Water Treatment Plant Ground	Thick fill	Very high
168	Gopalbag Field	Thick fill	Very high

169	Shahjadpur Playground, Baridhara	Moderately high Pleistocene Terrace	Low
170	Royal Thai Embassy Garden	Higher Pleistocene Terrace	Very low to none
171	Banani Garden	Higher Pleistocene Terrace	Very low to none
172	Police Plaza Field, DOHS Baridhara	Higher Pleistocene Terrace	Very low to none
173	Bahadur Shah Park	Old natural levee	High
174	Shahed Bashar Road Field, Cantonment	Highly erosional Pleistocene Terrace	Low
175	Army Head Quarter Tennis Ground	Moderately erosional Pleistocene Terrace	Low
176	Army Multipurpose Complex Field	Moderately high Pleistocene Terrace	Low
177	Bangladesh Army Headquarter Garden	Higher Pleistocene Terrace	Very low to none
178	Namapara Field, Cantonment	Yonger floodplain	Very high
179	Balda Gardens	Higher Pleistocene Terrace	Very low to none
180	Birshreshtha Shohid Motiur Rahman Park	Higher Pleistocene Terrace	Very low to none
181	Osmani Uddyan	Higher Pleistocene Terrace	Very low to none
182	Mandy Dental College Playground	Moderately thick fill	Very high
183	Bangladesh Navy College Playground	Moderately thick fill	Very high
184	Kurmitola Pool Field	Higher Pleistocene Terrace	Very low to none
185	Dhaka Cantonment Board Office Garden	Higher Pleistocene Terrace	Very low to none
186	Adamjee Cantonment College Field-2	Moderately thick fill	Very high
187	Shaheed Bir Uttam Lt. Anwar Girls' College Playground	Higher Pleistocene Terrace	Very low to none
188	Chief of the Army Staff's Palace Garden-1, Shaheed Sharani	Higher Pleistocene Terrace	Very low to none
189	Shikha Anirban, Shaheed Sharani	Moderately thick fill	Very high
190	2 Shaheed Sharani Garden	Moderately thick fill	Very high
191	Chief of the Army Staff's Palace Garden-2, Shaheed Sharani	Higher Pleistocene Terrace	Very low to none
192	Shaheed Sharani Basketball Court	Higher Pleistocene Terrace	Very low to none
193	Ambagan Field, Masterbari	Higher Pleistocene Terrace	Very low to none
194	Buriganga Eco-Park	Moderately thick fill	Very high
195	Kurmitola Golf Club	Higher Pleistocene Terrace	Very low to none
196	Gulshan Lake Park	Higher Pleistocene Terrace	Very low to none
197	Botanical Garden	Higher Pleistocene Terrace	Very low to none
198	Kalabagan Cricket Ground	Higher Pleistocene Terrace	Very low to none
199	Dhanmondi 32 No. Lake	Higher Pleistocene Terrace	Very low to none

200	Dhanmondi 10 No. Lake	Higher Pleistocene Terrace	Very low to none
201	Armanitola Play Ground, Dhaka	Higher Pleistocene Terrace	Very low to none
202	Dhaka Residential Model College, Dhaka	Moderately high Pleistocene Terrace	Low
203	Mohammadpur Eidgah, Dhaka	Moderately high Pleistocene Terrace	Low

A5: 37 Sites with high liquefaction possibility, from generalized study.

ID	High Liquefaction Site Names
7	Milbarak Police Shooting Club Ground
9	Brothers' Union Club Field
17	Bir Uttam Anwar Hossain Darbar Hall Playground, Pilkhana
33	Lalbag Fort
42	Shimanto 26 Café BGB Field
45	Shyamoli Park
55	Tallabag Open Space, Rayer Bazaar
56	Shahed Bashar Road Field, Cantonment
57	Govt. Jamila Aynul Andho School & College Garden, Shyamoli
79	Hatirjheel Field Sonargaon Signal
91	BSD Mosque Field, Cantonment
115	187 Shaheed Bashar Road Field, Cantonment
118	Shahed Bashar Road Field, Cantonment
119	Army Central Masjid Field
124	Nirjhor Residential Area Field
125	Nirjhor Cantonment Field
129	Nirjhor Residential Area Ground (Army HQ)
139	Sena Kunja Field
140	Engineer Brigade Football Ground, Cantonment
153	Mandy Dental College Sadarghat
154	Tekkir Field, Sadarghat
155	Riverside Play Ground
156	Shikder Medical Ground
157	Z. H. Sikder Women's Medical College Mosque Ground
162	Kollol Complex Field, Bou Bazar Road
165	Postogola Army Camp Field
166	Maniknagar Field
167	Wasa Saidabad Water Treatment Plant Ground
168	Gopalbag Field
173	Bahadur Shah Park
178	Namapara Field, Cantonment
182	Mandy Dental College Playground
183	Bangladesh Navy College Playground
186	Adamjee Cantonment College Field-2
189	Shikha Anirban, Shaheed Sharani
190	2 number Shaheed Sharani Garden
194	Buriganga Eco-Park

Declaration

I, the undersigned, declare that the thesis titled "**Development of Open Space Management System to Response Scenario Earthquake in Dhaka Metropolitan Area**" is my original research work and has not been submitted anywhere else. The plagiarism report (attached at the end) indicated a similarity index of only 10% (ten percent).

A K M Aminul Haque
Ph.D. Student
Department of Disaster Science and Climate Resilience
University of Dhaka
Registration No.: 33/2017-2018

Similarity Index Report

Development of Open Space Management System to Response Scenario Earthquake in Dhaka Metropolitan Area

ORIGINALITY REPORT

10%
SIMILARITY INDEX

PRIMARY SOURCES

1	assets.researchsquare.com Internet	352 words — 1%
2	link.springer.com Internet	337 words — 1%
3	open.library.ubc.ca Internet	197 words — < 1%
4	lib.buet.ac.bd:8080 Internet	135 words — < 1%
5	rpcc.portal.gov.bd Internet	124 words — < 1%
6	nhess.copernicus.org Internet	103 words — < 1%
7	www.cdmp.org.bd Internet	90 words — < 1%
8	reliefweb.int Internet	86 words — < 1%
9	emi-megacities.org Internet	80 words — < 1%

05.09.2022

05/09/22