Journal of Civil Engineering Research 2015, 5(4): 83-89
DOI: 10.5923/j.jce.20150504.02

Effect of High Peak Ground Acceleration on the Liquefaction Behaviour of Subsoil and Impact on the Environment

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Abstract Although liquefaction of soil is a function of soil condition but the effect of Peak Ground Acceleration (PGA) is obvious. A total of ten boreholes were selected in the Mohammadpur, Dhaka, Bangladesh for the study. Liquefaction potential at three different levels (3, 6 and 10 m) and for three different PGA of 0.15 g, 0.30 g and 0.47 g was estimated. Liquefaction maps were drawn by using Arc GIS software and the vulnerability due to liquefaction was categorized into three different names as liquefiable, marginally liquefiable and non-liquefiable. By analyzing the liquefaction maps a risk assessment of the study area has been done in this research. The liquefaction maps reveal a bird's eye view of the whole research project. High PGA value results in a high susceptibility to liquefaction. For a PGA of 0.47g the study areas are highly vulnerable in case of liquefaction at all levels. Although Mohammadpur as well as Dhaka is in the earthquake zone 2 with zone coefficient of 0.15 but it could be in danger if high PGA occurs. So it is of great concern. High PGA values should be taken into consideration during designing any structure in the study area and existing design should be modified as PGA is a dominant factor. An Environmental Impact Assessment (EIA) of the hazard due to liquefaction was also done which indicates that Strong ground shaking associated with a large earthquake on a nearby fault in the study area could trigger soil liquefaction and associated ground failures the impact of which would be significant.

Keywords PGA, Liquefaction Potential, SPT, Liquefaction Mapping, Risk Assessment, EIA

1. Introduction

Earthquake induced liquefaction is a prime research topic. An Earthquake can produce dynamic loading which cause increase in pore water pressure and decrease in effective stress of saturated cohesionless soils. In an extreme case the effective stress becomes zero and soil loses its strength completely causing liquefaction. Extensive research has been done throughout the years to reduce the liquefaction risk. Strong earthquakes can cause liquefaction and therewith ground failure in the form of sand boils, lateral spreading or subsidence [1]. A good number of studies have been performed by researchers throughout the world about liquefaction vulnerability mapping. In context to Bangladesh, several researches have been done but earthquake as well as liquefaction could be great threat for the country especially in the reclaimed residential area. Most of the reclaimed areas in Dhaka are being developed by filling dredged materials of river bed which are mostly silty sand. These reclaimed areas are susceptible to liquefaction if an earthquake of sufficient energy occurs [2]. Some researchers have used GIS mapping as a tool for assessment of Liquefaction hazard [3-7]. In this research, a risk assessment has been done using GIS map as GIS map can clearly reveal the high Peak Ground Acceleration (PGA) effect on subsoil. Liquefaction hazard maps are useful tools for identifying areas with high likelihood of liquefaction induced ground deformation, a major cause of damage in many earthquakes [8]. In this study, liquefaction hazard has been assessed for an area developed by land reclamation named Mohammadpur which is situated in capital city Dhaka of Bangladesh. Although some approaches and studies have been taken to assess the risk in case of an earthquake in Dhaka, an overpopulated city with lack of planning but the research about effect of high PGA on the behavior of subsoil liquefaction has not been done yet properly. This paper contains the prediction of liquefaction using 10 borehole data of Mohammadpur area, Dhaka, Bangladesh which will be used for future study for a large area. Earthquake ground damage hazards pose a significant risk to infrastructure, lifelines, buildings and life in urban areas. The ultimate objective of earthquake hazard and risk

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Published online at http://journal.sapub.org/jce

studies is to manage the risks posed by earthquake to the people and the built and natural environment [9]. Earthquake induced liquefaction hazard can cause devastating condition of the environment. So, an Environmental Impact Assessment (EIA) considering liquefaction susceptibility was also conducted for the study area.

2. Mechanism behind Liquefaction

Mechanism behind liquefaction phenomena can be described in a simple way. Soil is a combination of large amount of particles connected by inter-particular contact forces. When dynamic load produced by earthquake shaking acts on the soil particle then loosely-packed soil particles wants to come together. But pore water in the soil doesn't get the sufficient time to squeezed out and get trapped preventing the soil particles from approaching together. By this way increased water pressure reduces the contact forces between the individual soil particles causing softening and weakening. In the extreme case the soil particles lose contact with each other and this low strength soil behaves more like a liquid than a solid. This phenomenon is called liquefaction. This can be shown by diagrammatic way. Figure 1 shows the soil grains and contact forces between grains.

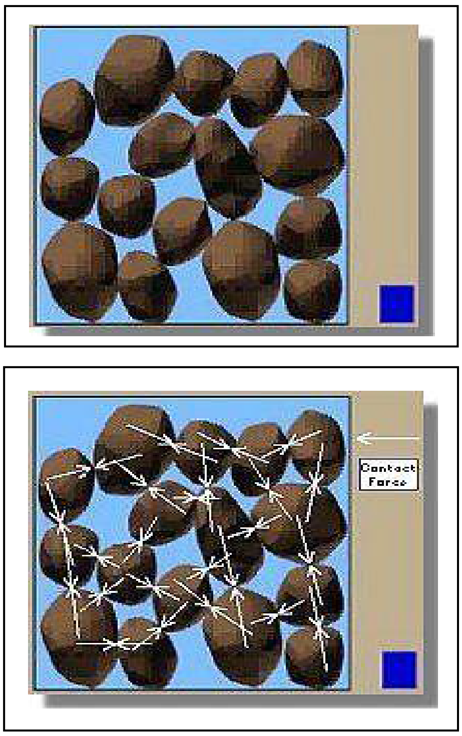

Figure 1. Soil grains in a soil deposit, white arrows showing contact forces between soils

The height of the blue column to the right represents the level of pore pressure in the soil while the white arrows represents the contact forces between individual soil grains which are strong when the pore pressure is low and vice versa. Dynamic loading like earthquake increases the pore pressure and contact forces becomes lower. At a stage contact forces within soil becomes zero and liquefaction occurs.

3. Study Area and Borehole Location

As it would be very costly to make sufficient number of boreholes in the study area, authors took initiative to find the parameters for calculating liquefaction potential from existing borehole reports of Mohammadpur, Dhaka. A total of ten boreholes were selected for the study. The locations were Jonota Hospital, PC Culture Housing, Badsah Foysal Institute, Nobody Housing Society, Geneva Camp, Japan Garden City, Mohammadpur Girl's College, Bangladesh University, Chanmiya Hosuing and Mohammadi Hosuing Ltd. Table 1 shows the latitudes and longitudes of the boreholes.

Table 1. Latitudes and Longitudes of Boreholes

Location	Latitude	Longitude
Jonota Hospital	23° 46' 22.2096"	90° 22' 12.8568"
Bangladesh University	23° 45' 42.2382"	90° 22' 2.6682"
Geneva camp	23° 46' 6.3552"	90° 21' 54.4536"
P C Culture Housing	23° 46' 5.124"	90° 21' 6.8034"
Badsah- Faisal Institute	23° 46' 20.4954"	90° 21' 40.5462"
Mohammadpur Girls College	23° 45' 43.9662"	90° 21' 38.8332"
Japan Garden city	23° 45' 54.705"	90° 21' 27.1866"
Nobody Housing	23° 46' 2.4054"	90° 21' 25.8624"
Chadmia Housing Mosjid	23° 45' 33.444"	90° 21' 30.2286"
Mohammadi Housing Society	23° 46' 6.3552"	90° 21' 54.4536"

4. Research Methodology

There are various methods available for calculating liquefaction potential. To estimate liquefaction potential one must determine the factor safety. The liquefaction potential of a sand deposit is evaluated in terms of factor of safety F_L as per Simplified Procedure is given by

$$F_L = \frac{\text{Cyclic Strength}}{\text{Cyclic Shear Stress}} \tag{1}$$

If $F_L \leq 1$, liquefaction is said to occur otherwise liquefaction does not occur. However in this research the factor of safety was classified into three categories to understand the effect of vulnerability due to liquefaction. These are liquefiable, marginally liquefiable and non-liquefiable for a factor of safety $F_L < 1$, $F_L = 1\text{-}1.2$ and $F_L > 1.2$ respectively.

On the basis of the large earthquake in China, the criterion of identifying sandy deposits as being susceptible to liquefaction was presented in the form of code requirement. Through some numerical manipulation Ishihara proposed an equation for calculating cyclic shear strength based on corrected SPT value N_1 as in [10].

Chinese criterion can be expressed as

Cyclic Strength (CS) = $(9.5N_{1(C)} + 0.466N^2_{1(C)})/1000$ (2)

Correction for fines content, F_C was done using defined formula. If more than 5% fines are seen to exist in the soil, the measured N_1 value should be increased using following equation.

For $5\% < F_C < 20\%$

$$\Delta N1 = 0.5*(Fc-5) \quad (3)$$

For $F_C > 20\%$

$$\Delta N1 = 7.5 \quad (4)$$

$$N2 = N1 + \Delta N1 \quad (5)$$

Correction for plasticity index was also done. If the plasticity index (I_P) of the fines is found to be greater than 10, further correction must be made for the cyclic strength.

$$R = \frac{Ip - 10}{45} + 1 \quad (6)$$

Where, R is resistance cyclic strength of soil at a given depth and I_P is plasticity index.

So, finally corrected SPT value,

$$N1(C) = N2*R \quad (7)$$

Cyclic shear stress was determined by Seed-Idriss simplified procedure as in [11]

$$CSR = \frac{\tau_{ave}}{\sigma'_v} = 0.65\frac{a_{max}}{g} r_d \frac{\sigma_v}{\sigma'_v} \quad (8)$$

Where, g is the acceleration due to gravity, r_d represents stress reduction coefficient (r_d = 1.0 for rock), a_{max} is Peak Ground Acceleration (PGA), σ_V is total overburden stress at the depth (z) in question, σ'_V is initial effective overburden stress at the same depth. The value of r_d can be determined by method given by Youd and Idriss as in [12]

$$r_d = 1.0 - 0.00765z \text{ for } z \le 9.15m \quad (9)$$

$$r_d = 1.174 - 0.0267z \text{ for } 9.15m \le z \le 23m \quad (10)$$

Recommended equation by Robertson and Wride as in [13] was used,

$$r_d = 0.744 - 0.008z \text{ for } 23m < z < 30m \quad (11)$$

Recommended equation by Youd and Idriss as in [12] was also used.

$$r_d = 0.5 \text{ for } z > 30m \quad (12)$$

5. Liquefaction Susceptibility Estimation

To evaluate the susceptibility whether liquefaction will occur or not the required data were extracted from borehole report. SPT N-value, water content(w%), unit weight (γ), saturated unit weight (γ_{sat}), ground water table location, plasticity Index (I_P), Fineness Content(F_C), size corresponding to 50% finer in grain size distribution curve and soil type etc. were taken. An example of data extraction is shown in Table 2. Following the research methodology the factor of safety was calculated and assessed. For example, the liquefaction susceptibility of borehole #10 is shown in Table 3.

Table 2. Geotechnical Data for Liquefaction Estimation

Location	ID	Depth (m)	N-value	w%	γ (kN/m³)	γ_{sat} (kN/m³)	GWT (m)	I_P	F_C	D_{50}	Soil Type
Mohammadi Housing Society	10	3.0	6	31.04	23.95	30.95	1.5	9.0	100	0.09	Grey medium stiff clayey Silt
		6.0	28					10	32	0.08	Light brown medium dense to dense silty fine Sand
		10.0	37					9.0	72	0.09	Grey medium stiff clayey Silt

Table 3. Evaluation Process of Liquefaction Phenomena

Location	ID	Depth (m)	PGA	Factor of Safety	Comment
Mohammadi Housing Society	10	3.0	0.15g	1.63	No Liquefaction
			0.30g	0.817	Liquefaction
			0.47g	0.521	Liquefaction
		6.0	0.15g	8.6	No Liquefaction
			.30g	4.31	No Liquefaction
			.47g	2.75	No Liquefaction
		10.0	0.15g	1.08	Marginally Liquefaction
			0.30g	0.70	Liquefaction
			0.47g	0.78	Liquefaction

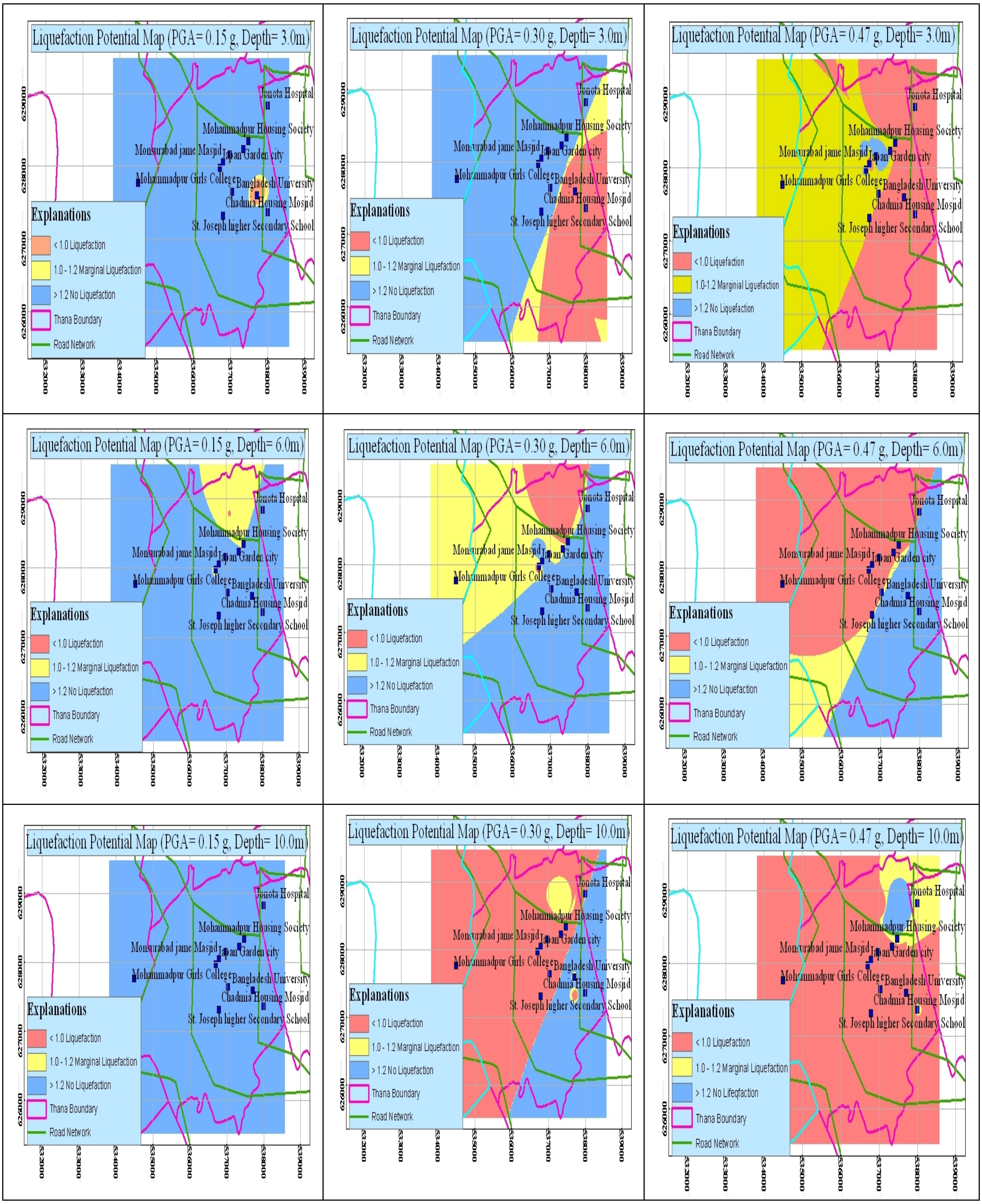

Figure 2. Liquefaction Potential Map of the Study Area

6. Liquefaction Vulnerability Mapping and Risk Assessment

Liquefaction hazard maps are useful tools for identifying areas with a high likelihood of liquefaction-induced ground deformation. Information about areas with a high likelihood of ground deformation can be used for effective regional earthquake hazard planning and mitigation [8].

In the last decade, with the advances in computer technologies, geographic information systems (GIS) are frequently used to produce hazard maps. For the study area, liquefaction potential maps were created by means of Arc GIS software. For this purpose, factors of safety were calculated at different depth intervals (i.e. 3, 6, and 10 m below the ground surface). For this process, it should be noted that the geological setting and ground water level were also considered. Different liquefaction potential maps were established by repeating the same procedure for each acceleration level (i.e. 0.15g, 0.30g and 0.47g). Three factors of safety definitions described in pervious section were used in the stage of the creation of liquefaction potential maps. These maps are illustrated in Figure 2.

The liquefaction potential mapping for the study area has been generated by using mapping software Arc GIS 10. After reviewing the topography of the Mohammadpur area and the borehole reports, 10 specific bore locations was chosen for the study. Different important parameters like SPT, D_{50}, Fineness content, Plasticity index, soil type, unit weight, ground water level etc. were extracted from the borehole reports.

6.1. Risk Assessment Using Liquefaction Map

Using Chinese criterion given by Ishihara, The value of the liquefaction potential of the soil at 3, 6 and 10 meter was calculated for varying Peak Ground Acceleration (PGA) of 0.15, 0.30 and 0.47g. The PGA has been selected based on historical earthquake occurrence and associated ground acceleration in and around Dhaka. Besides, the calculations were justified by readily available liquefaction estimation HTML software. For a clear understanding the liquefaction susceptibility of the soil has been divided into three categories. These are liquefiable, marginally liquefiable and non-liquefiable for a factor of safety F_L <1, F_L = 1-1.2 and F_L > 1.2 respectively. The liquefiable, marginally liquefiable and non liquefiable areas are shown by pink, yellow and green color respectively. As a bird's eye view of the whole project the 9 maps clearly indicates that the liquefaction potential as well as susceptibility to liquefaction hazards enhances due to an increment of ground acceleration. Although fineness content and soil type are the factors influencing liquefaction phenomena but high Peak ground acceleration will be a dominant factor in case of liquefaction after an earthquake in these areas of Mohammadpur.

At 3 m level, considering a magnitude of 0.15 g ground acceleration the study area are not vulnerable to liquefaction hazards except some portions in Bangladesh University area may liquefy. But, with 0.30 g the liquefaction susceptibility increases and some areas show a marginal vulnerability to liquefaction. With a magnitude of 0.47 g ground acceleration, the areas are highly susceptible to liquefaction and which is very clear from the map. Although some portions of Japan Garden City of Mohammadpur are still out of danger due soil strength.

At 6 meter level, for 0.15g ground acceleration except some marginally liquefiable area, the rest portions are out of danger in a case of liquefaction. For a ground acceleration of 0.30 g the map clearly indicates that the areas which were marginally liquefiable due to 0.15g are now liquefiable due to 0.30g. Moreover, for 0.47 g liquefiable area as well as liquefaction vulnerability increases.

At 10 m level and for PGA of 0.15 g, no areas are liquefiable and soil condition in this layer is highly of research interest because it is out of danger. As Dhaka is lying in seismic zone 2 with zone coefficient 0.15, the soil layer in this depth can be said to be strong in case of liquefaction. On the contrary, approximately 3/4th of the study areas are liquefiable with a PGA of 0.30 g. Moreover, Maximum areas are in danger with high liquefaction vulnerability at 10 m level. So, it can be said that, the ground acceleration is the dominant factor in case of liquefaction in the study area.

7. Environmental Impact Assessment Considering Liquefaction Vulnerability

An Environmental Impact Assessment (EIA) for the study area has been carried out to assess the impact of vulnerability upon the environment.

7.1. Threshold of Significance

a) Expose people or structures to potential and substantial adverse effects, including the risk of loss, injury, or death involving:
   i. Rupture of a known earthquake fault
   ii. Earthquake Fault Zoning Map issued by the National Geologist for the area or based on other substantial evidence of a known fault.
   iii. Strong seismic ground shaking.
   iv. Seismic-related ground failure, including liquefaction.

b) Result in substantial soil erosion or the loss of topsoil.

c) Be located on a geologic unit or soil that is unstable, or that would become unstable as a result of the project, and potentially result in on or off-site landslide, lateral spreading, subsidence, liquefaction or collapse.

7.2. Project Impacts and Mitigation Measures

7.2.1. Impact of Fault Rupture

As noted, the Project site is not located within Earthquake Fault Zones and the potential for fault rupture is considered to be low. Therefore, Project impacts related to fault rupture would be **less than significant** and no mitigation measures are required.

7.2.2. Impact of Strong Seismic Ground Shaking

The Project site is located in a Seismic Zone-2. Additionally, the Project site would follow the Bangladesh National Building Code (BNBC) Code Section 2.5.4 of Chapter-2 of Part-6. During the service life of the Project, the experience of at least one earthquake may produce potentially damaging ground shaking. In recent years, Earthquake vulnerability is a great concern in Bangladesh. If any such violent earthquake creates a high PGA then it will be hazards for the study area as high proportion of the areas are liquefiable. However, the project applicant would be required to design and construct the project in conformance to the most recently adopted BNBC design parameters for seismic design. Therefore, conformance with current BNBC requirements, as well as the RAJUK(Authority in Bangladesh which gives approval of structural design) seismic design requirements would reduce the potential for structures on the project site to sustain damage during an earthquake event, and project impacts related to ground shaking would be **less than significant** and no mitigation measures are required.

7.2.3. Liquefaction and Soil Instabilities

Impact: Geotechnical investigation on the project site indicates that the liquefaction potential as well as susceptibility to liquefaction hazards enhances due to an increment of ground acceleration. Although, Fineness content and soil type are the factors influencing liquefaction phenomena but high Peak ground acceleration will be a dominant factor in case of liquefaction after an earthquake in these areas of Mohammadpur.

In general, the potential for soil liquefaction is low where dense fill, topsoil and/or alluvium are less than approximately three to four feet thick and these "unsuitable" bearing materials would be excavated and replaced with well-compacted engineered fill. However, portions of the project site contain areas of fill and topsoil/alluvium up to seven feet in depth located from 1½ feet to greater than ten feet below the ground surface areas. Groundwater was encountered at depths ranging between 2½ to 8½ feet below the ground surface. The sandy fill and topsoil/alluvium materials are generally characterized as loose to medium dense. During the late spring or early summer, the local groundwater level is likely to rise and the lower portions of the loose to medium dense sandy fill and topsoil/alluvium layers may become saturated. Strong ground shaking associated with a large earthquake on a nearby fault could trigger soil liquefaction and associated ground failures. Ground failures associated with soil liquefaction include post-liquefaction reconsolidation, lateral spreading, and loss of bearing support. Impacts would be **significant**.

Soil erosion/loss of topsoil may occur during grading and earthwork on the project site. Geotechnical investigation recommends removal of unsuitable bearing materials from the project site where new improvements or new fills are planned and replaced with well compacted engineered fill. Unsuitable materials include loose or disturbed soils, undocumented fills and contaminated soils. As noted, undocumented fill and loose topsoil/alluvium are located on the project site with approximate depth maximums of seven feet and ten feet below the grounds surface. Therefore, removal of these soils may cause a **significant** impact.

Mitigation Measure: Prior to issuance of building permits and grading activities, a design level geotechnical report shall be prepared and all recommendations in the report shall be adhered. The design-level geotechnical report shall evaluate the potential for localized liquefaction by performing supplemental subsurface exploration to evaluate the thickness, in place density, fines content of the underlying loose to medium soil and gradation, laboratory testing, and engineering analysis.

Implementation should be carried out for all recommendations contained within the geotechnical reports, including those pertaining to site preparation, excavation, fill placement and compaction; foundations; concrete slabs-on grade; pavement design; lateral earth pressures and resistance; and surface drainage control.

The final grading, drainage, foundation plans and specifications shall be prepared and/or reviewed and approved by a Registered Geotechnical Engineer and Registered Engineering Geologist. In addition, upon completion of construction activities, the project applicant shall provide a final statement indicating whether the work was performed in accordance with project plans and specifications and with the recommendations of the Registered Geotechnical Engineer and Registered Engineering Geologist.

7.3. Level of Significance after Mitigation

Implementation of the mitigation measures listed above and compliance with applicable regulations would reduce all project impacts related to geology and soils to a **less-than-significant** level.

8. Conclusions

Although three PGA values of 0.15 g, 0.30 g and 0.47 g have been selected based on research on historical earthquakes and fault zones adjacent to Dhaka but Mohammadpur as well as Dhaka lying in seismic zone 2 with a zone coefficient of 0.15. Findings of this research indicate that, study areas are nearly safe with a PGA of 0.15 g but vulnerable in case of occurrence of a high PGA. In recent years, Earthquake vulnerability is a great concern in Bangladesh. If any such violent earthquake creates a high PGA then it will be hazards for the study area as high proportion of the areas are liquefiable. EIA study of the study area suggests that strong ground shaking causing high PGA in the nearby fault to Mohammadpur as well as Dhaka could cause subsoil to liquefy. This study discerns that earthquake could cause great threat to living body in Dhaka and its environment. So it high time to prepare an effective liquefaction map and design criteria for foundation for this city. Moreover, large scale assessment of earthquake and liquefaction vulnerability in Dhaka city should be started as soon as possible otherwise this overpopulated and unplanned city will face severe damage in case of a large earthquake with sufficient energy.

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