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LPI Based Earthquake Induced Soil Liquefaction Susceptibility Assessment at Probashi Palli Abasan Project Area, Tongi, Gazipur, Bangladesh

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Abstract

This study aims at evaluation of seismic soil liquefaction hazard potential at Probashi Palli Abasan Project area of Tongi, Gazipur, exploiting standard penetration test (SPT) data of 15 boreholes, following Simplified Procedure. Liquefaction potential index (LPI) of each borehole was determined and then cumulative frequency distribution of clustered LPI values of each surface geology unit was determined assuming cumulative frequency at LPI = 5 as the threshold value for liquefaction initiation. By means of geotechnical investigation two surface geological units—Holocene flood plain deposits, and Pleistocene terrace deposits were identified in the study area. We predicted that 14% and 24% area of zones topped by Pleistocene terrace deposits and zones topped by Holocene flood plain deposits, respectively, would exhibit surface manifestation of liquefaction as a result of 7 magnitude earthquake. The engendered hazard map also depicts site specific liquefaction intensity through LPI values of respective boreholes, and color index, which was delineated by mapping with ArcGIS software. Very low to low, and low to high liquefaction potential, respectively, was found in the areas covered by Pleistocene terrace deposits and Holocene flood plain deposits. LPI values of both units are such that sand boils could be generated where LPI > 5.

Keywords: Standard Penetration Test (SPT); Surface geology; Safety factor; Liquefaction potential index; Earthquake.

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1. Introduction

The liquefaction phenomenon provides an unsupportive environment to the built structures by altering previously solid ground into a liquefied softened condition [1].

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Rigorous studies on the phenomenon of liquefaction among geotechnical engineers were started after the Alaska and the Japan earthquakes of 1964, which included field evaluation of major earthquakes and laboratory studies, applying cyclic loading devices [2].

Rather than occurring randomly, the liquefaction phenomenon abides by some geological and hydrological conditions of subterranean soil deposits. According to Palacios et al. [1], potentially liquefiable areas generally lye within 15 m of the ground surface, where soils are dominantly cohesionless and granular, and simultaneously saturated by water. Another factor instrumental for this phenomenon to take place is the magnitude of ground shaking, which needs to be substantially strong for liquefying susceptible soils. Preferably, moderate to great earthquakes effectively trigger liquefaction, which commonly induce ground failure and deformation [1].

Seismic soil liquefaction potential can be assessed from standard penetration test (SPT) N values, using the Simplified Procedure of Seed and Idriss [3]. Factor of safety, F_L, against liquefaction can be determined through this method. Factor of safety > 1 for soil layer is generally assumed as non-potential for liquefaction whereas that of < 1 is stated as potential for the phenomenon to take place. As this method is not capable of further determining the surface effect of liquefaction, liquefaction potential index (LPI), proposed by Iwasaki et al. [4], is used to serve the purpose, in which the factor of safety values are also included for LPI calculation.

The juxtaposition of Bangladesh, as well the Bengal Basin, with the active Indian-Eurasian plate boundaries [5-10] (Fig. 1) has made this eastern portion of the Indian Plate as one of the highest vulnerable zones of the world for earthquake hazard [10]. In spite of this, holistic and comprehensive seismic risk assessment and provision plans are yet to be done [10]. Probashi Palli Abasan Project area at Pubail Union, Tongi, Gazipur is a newly proposed site for development of settlements for dwelling purpose, and other relevant infrastructures. This area is close to Dhaka and a high seismic risk zone. In this disquisition, seismic soil liquefaction potential of the study area was estimated using SPT borehole data, in terms of LPI, and later presented by a hazard map.

2. Geology and Seismotectonic Setting

Probashi Palli Abasan Project area is bounded approximately by latitudes from $23^o55'27.8472''$ N to $23^o55'31.386''$ N and longitudes from $90^o28'0.725''$ E to $90^o28'3.961''$ E from North to South, and by latitudes from $23^o55'27.8472''$ N to $23^o55'26.526''$ N and longitudes from $90^o28'0.725''$ E to from $90^o28'17.645''$ E from West to East. Total area is 0.21 sq. Km. It is in the Eastern periphery of Gazipur Sadar Thana, and broadly within Gazipur-Tongi region of Bangladesh that covers parts of Khilgaon and Kamaira village of Pubail Union (Fig. 1). The area is nearly 45 km by road from Dhaka.

The project area is located almost at the central part of Bangladesh and lies within Dhaka-Gazipur terrace, a part of Madhupur Tract [13]. The area comprises two surface geology units, i) pleistocene terraces and ii) flat flood plains (Fig. 2). The Pleistocene terraces (also locally called “Tila”) are lowly elevated compared to adjacent flat flood plains. The highest elevation of the terraces is 11.89 m, and lowest elevation within the flood plains is 7.01 m [13]. The terraces are surrounded by natural small channels (most appropriately Khal in local name) in a cross-cutting manner. They remain dry in the dry season and used for irrigation purpose but water flows through them during the wet season.

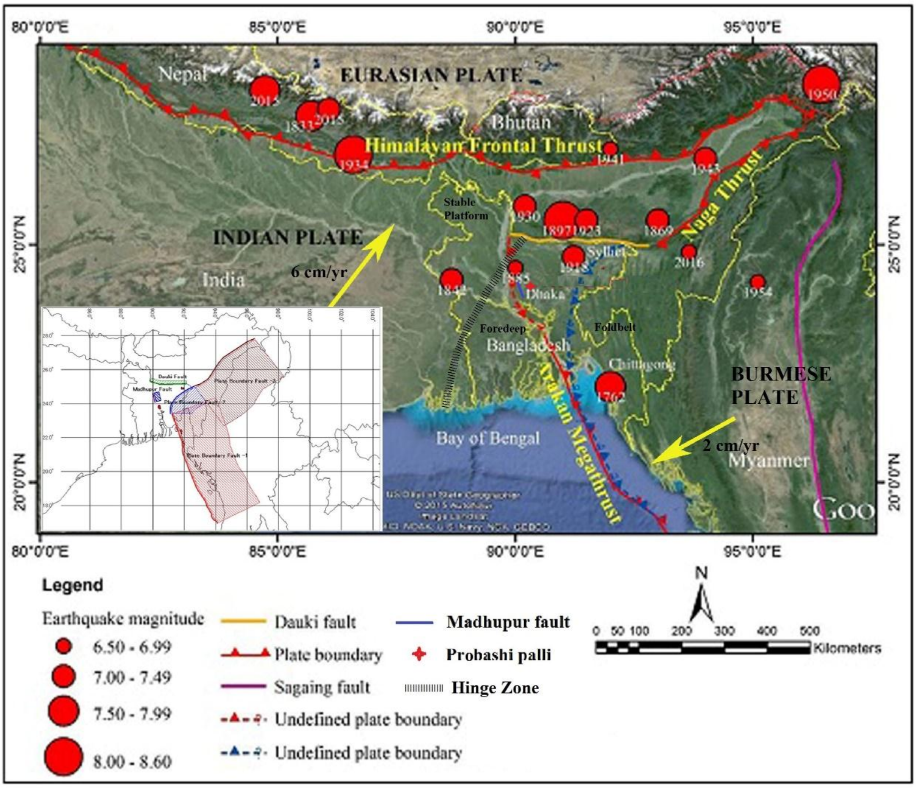

Fig. 1. Tectonic map of Bangladesh (reproduced from Rahman et al. [10]). The map represents all the major tectonic elements of Bangladesh, and plate boundaries and active faults in and around Bangladesh, alongside past and recent, from 1762 to 2016, earthquake locations and magnitudes. Scenario earthquake fault model [11] has been manifested on the lower-left corner of the map. Plate movement rates are from [12].

Kamal *et al.* [13] described the subsurface geology of the area dividing the subsurface geological materials into four lithofacies, which they termed “local units”, as presented in Table 1. They used 15 SPT borehole data, which are also basis for LPI calculation in this research. Geological evolution of the study area could be outlined from the surface and subsurface geology there.

The study area lies within the Bengal Basin that is situated at the eastern part of the Indian Plate (Fig. 1). Origin and sedimentation history of the basin is believed to be related to the orogenesis of the Himalayan ranges due to the northward collision of the Indian Plate with the Eurasian Plate [10]. Bangladesh covers most of the part of the Bengal Basin, and as a result of the convoluted interaction of the Indian, Eurasian, and Burmese plates, this country is bounded by plate boundary faults in the north and east, which are regarded seismically active and hence the main source of earthquakes in and around the country [9,10]. Fig. 1 represents these faults along with historical and recent earthquakes in Bangladesh and surroundings.

Table 1. Subsurface lithostratigrapjic units of Probashi Palli Dwelling Project area.

Age	Formation	Geotechnical units	Subsurface lithology units	Thickness (m)
Holocene	Alluvium	Unit 1	Lowland: Floodplain deposit: Grey to light grey fine grained sand. Local unconformity	1.5
		Unit 2	Backswamp and depression deposits: Grey, light grey, dark grey, black clay and silty clay with organic materials	3-7
Pleistocene	Madhupur Clay	Unit 3	Light brown to brick red mottled clay with some silt, organic materials and iron concretions. Light grey with patches of orange, brown, black color containing silt, organic materials and iron concretions.	20+
Plio-Pleistoce ne	DupiTila Sandstone Formation	Unit 4	Unconformity Massive sand: Yellowish brown very fine grained micaceous sand with silt and clay	3-7.5+

* Modified from [13]

The 1885 Bengal Earthquake of magnitude 7 (M_w) is most important for Dhaka for assessing seismic risk, and site characterization, as stated by Comprehensive Disaster Management Program (CDMP) [14]. The epicenter of this earthquake was almost 50 km northwest from the city.

It is believed that the Madhupur Fault, around 60 km northwest from Dhaka City, was the source of this seismic event [9]. Because of closeness of Probashi Palli to Dhaka, the Madhupur Fault is also crucial for seismic hazard assessment is this area. Hence, 18885 Bengal earthquake, caused by the Madhupur Fault, should be considered in this area to serve the purpose. According to the updated seismic zonation map of Bangladesh (Fig. 3) by BNBC [15], there are four major seismic zones in the country. The zonation was performed following peak horizontal ground acceleration (PGA) value distribution. These zones are Zone I, Zone II, Zone III and Zone IV, which have PGA values 0.12 g, 0.20 g, 0.28 g and 0.36 g, respectively. The study area is in the Zone II, where PGA value is 0.20 g.

3. Methodology

In this research, SPT N values and other geotechnical parameters of 15 borehole profiles up to 20 m, scattered throughout the surface geology units of Probashi Palli, were used for LPI calculation. Among these boreholes, 7 are located on the Pleistocene terrace deposits, and 8 of them are on the Holocene flood plain deposits. Geotechnical properties, i.e., grain size distribution and fines content (FC), plasticity index (PI) and liquid limit (LL) from Atterberg Limit test, water content (w_c), and wet and dry unit weight, of the soil samples of these boreholes were determined in the Engineering Geology laboratory of Department of Geology, University of Dhaka. Water table depth was measured manually by simple measuring tape. Table 2 summarizes borehole data and respective LPI values.

Liquefaction potential index (LPI), proposed by Iwasaki *et al*. [4], can predict the severity of seismic soil liquefaction. It is assumed that severity of liquefaction is proportional to the:

i) thickness of the liquefiable layer
ii) distance of the layer from the surface
iii) the factor of safety, when < 1.

So, the LPI is defined and calculated by the following formula:

$$LPI = \int_0^z F(z)W(z)d(z) \tag{1}$$

here, z is the distance of the layer from the ground surface, and F(z) is a function of factor of safety (F_L) against liquefaction.

$F(z) = 1 - F_L$ for $F_L < 1.0$

$F(z) = 0$ for $F_L \geq 1.0$

$W(z) = 10 - 0.5z$ for $z < 20$ m

$W(z) = 0$ for $z > 20$ m

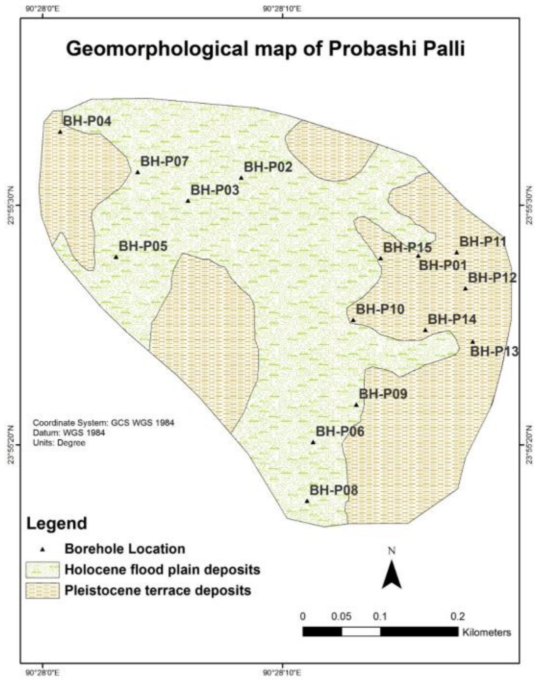

Fig. 2. Geomorphological map of Probashi Palli area illustrates surface geology units and SPT borehole positions.

For calibration of factor of safety against liquefaction (F_L), we used the updated Simplified Procedure of Youd *et al*. [16], which was originally proposed by Seed and Idriss [3]. According to the deterministic procedure of Youd *et al.* [14], factor of safety against liquefaction is defined as

$$F_L = (CRR_{7.5}/CSR)\ MSF \quad (2)$$

here, CRR is cyclic resistance ratio, implying the resistance offered by the soil layer during cyclic loading or the stress required to change the condition of a soil layer by an earthquake of magnitude 7.5 (M_w) in vice versa; CSR is cyclic stress ratio, which is a measure of both the cyclic stress generated by an earthquake and the cyclic stress required to liquefy a soil layer; and MSF is magnitude scaling factor that is used to adjust the effect of earthquake of any magnitude on CSR. The details of the procedures for determining these parameters have been listed elsewhere [16].

While calculating LPI, plasticity index (PI) and liquid limit (LL), and water content (w_c) of each soil profile were carefully examined. Soil layers with soil types other than non-plastic or low plasticity silts and/or silty clays with PI ≤ 12, LL ≤ 37, and w_c > 0.85. LL were regarded as non-potential for liquefaction phenomenon [17], and excluded from LPI calculation. Then, LPI values of each borehole were obtained by summing up the LPI values of individual SPT profiles.

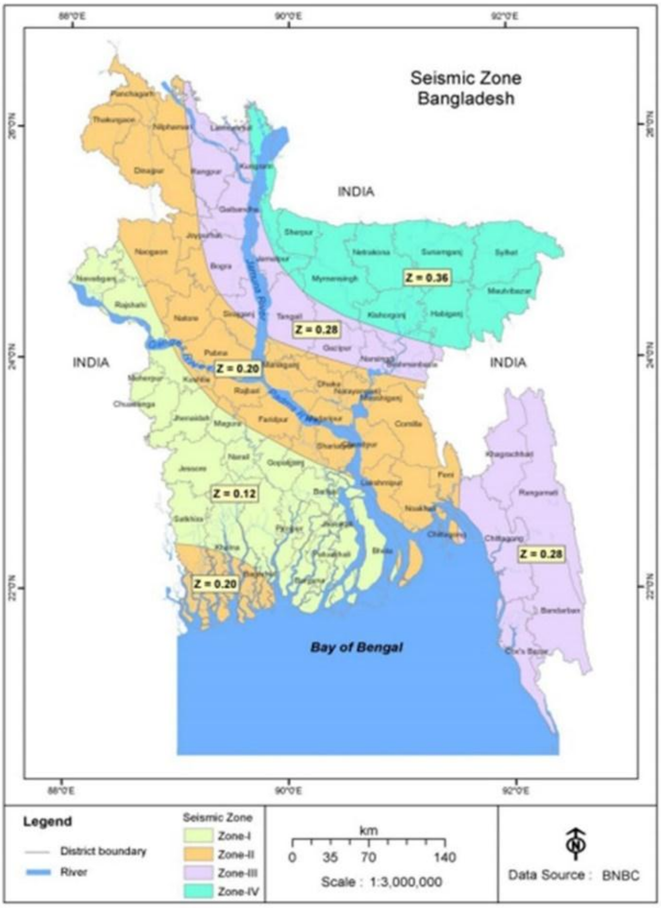

Fig. 3. Seismic zonation map of Bangladesh [15].

Table 2. LPI values of each SPT boreholes for a scenario earthquake of M_w = 7, and PGA = 0.20 g.

Borehole ID	Coordinates		Water Table (m)	Drilling depth (m)	Liquefaction potential index (LPI)
	Latitude (N)	Longitude (E)			Designed earthquake (M_w=7 and a_{max}=0.20 g)
BH-P01	23° 55´ 27.7896´´	90° 28´ 15.665´´	0.013	19.5	3.43
BH-P02	23° 55´ 31.152´´	90° 28´ 8.285´´	0.50	30.0	4.89
BH-P03	23° 55´ 30.1872´´	90° 28´ 6.064´´	1.00	19.5	2.10
BH-P04	23° 55´ 33.0708´´	90° 28´ 0.725´´	0.20	19.5	0.65
BH-P05	23° 55´ 27.8472´´	90° 28´ 3.061´´	0.40	19.5	2.60

Borehole ID	Coordinates		Water Table (m)	Drilling depth (m)	Liquefaction potential index (LPI)
	Latitude (N)	Longitude (E)			Designed earthquake (M_w=7 and a_{max}=0.20 g)
BH-P06	23° 55´ 20.1072´´	90° 28´ 11.284´´	0.70	30.0	8.75
BH-P07	23° 55´ 31.386´´	90° 28´ 3.961´´	0.60	19.5	2.58
BH-P08	23° 55´ 17.648´´	90° 28´ 11.028´´	1.00	19.5	3.54
BH-P09	23° 55´ 21.666´´	90° 28´ 13.084´´	0.20	19.5	2.43
BH-P10	23° 55´ 25.2084´´	90° 28´ 12.961´´	0.70	19.5	0.02
BH-P11	23° 55´ 28.0272´´	90° 28´ 17.281´´	2.00	19.5	5.04
BH-P12	23° 55´ 26.526´´	90° 28´ 17.645´´	2.00	19.5	0.00
BH-P13	23° 55´ 24.3048´´	90° 28´ 17.944´´	3.50	19.5	2.44
BH-P14	23° 55´ 24.7872´´	90° 28´ 15.964´´	1.50	19.5	0.51
BH-P15	23° 55´ 27.786´´	90° 28´ 14.102´´	2.00	19.5	0.24

As discussed earlier, the 1885 Bengal Earthquake of M_w = 7 is potential for seismic hazard assessment and site characterization, and PGA value at Probashi Palli area is 0.20 g. So, a scenario earthquake of M_w = 7 and PGA = 0.20 g are the basis for LPI computation in this study.

To show the surface effects of liquefaction, we followed the recommendation of Toprak and Holzer [18], i.e., we assumed that surface manifestation of liquefaction would be exhibited if LPI ≥ 5. From cumulative frequency distribution of LPI values of 7 boreholes of Pleistocene terrace deposits and that of 8 boreholes of Holocene flood plain deposits the probability of surface manifestation of seismic soil liquefaction for respective surface geology units were determined. The result shows that 14% and 24% area, respectively, of Pleistocene terrace deposits and Holocene flood plain deposits would show surface disruption due to liquefaction induced by the designed earthquake (M_w = 7, PGA = 0.20 g), as seen in Fig. 4.

For indexing the liquefaction hazard in the study area, we followed the classification scheme of Iwasaki *et al.* [4], where liquefaction severity is categorized as very low (LPI = 0), low (0 < LPI ≤ 5), high (5 < LPI ≤15), and very high (LPI > 15). The liquefaction hazard map of the study area represents this hazard classification scheme (Fig. 5).

In order to illustrate location specific hazard potential on the seismic soil liquefaction hazard map (Fig. 5), following the classification of Iwasaki et al. [4], areas were clustered into three categories, i) very low (LPI = 0), ii) low (0 < LPI ≤ 5) and iii) high (5 < LPI ≤ 9) hazard potential area, as the LPI values were ranging from 0 to 8.754. The zonation has been depicted by assigning specific color for each category that was done in GIS environment by kriging method. So, the hazard map compositely exhibits the likelihood of percentage area of each surface geology unit that would show surface manifestation of the surface geology units of Probashi Palli Dwelling Project area alongside site specific susceptibility to this hazard. In addition, LPI values of each borehole have also been placed on the map.

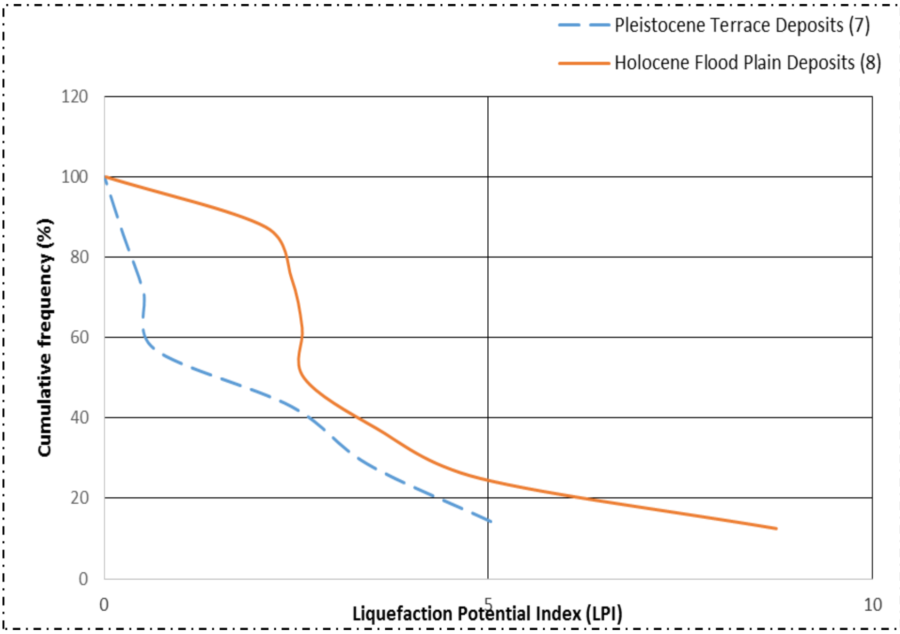

Fig. 4. Cumulative frequency distributions of LPI for two zones of Moulvibazar town. LPI values are along the horizontal axis, and the sum of SPT boreholes of each surface geology unit are in the vertical axis.

4. Discussion

The seismically induced liquefaction hazard map (Fig. 5) of Probashi Palli Abasan area could be used as a preliminary hazard map as it depicts the area coverage of the phenomenon and site specific hazard potential.

LPI values in the area underlain by Pleistocene terrace deposits range from 0 to 5.04, implying this zone has very low to high hazard potential. According to Toprak and Holzer (2003) [18], values like 5 ≥ LPI ≤ 12 may cause sand boil. Moreover, there is a 0.15 probability that 14% of this zone would be liquefied and arbitrarily show surface effects in response to 7 magnitude earthquake. In addition, it is notable that in most of the locations LPI values are very negligible except at one where LPI value exceeds 5, and in three other boreholes the values vary from approximately 2 to below 5. Borehole data reveals that this is because of the presence of either liquefiable sand layer, or low plastic silty clay layer. May be, cohesionless soils from the underlain DupiTila Sandstone Formation has moved up beneath the tracts compared to the adjacent flat area, which is possibly responsible for such uneven distribution of liquefaction susceptibility in this zone. Soils of this zone are composed mainly of geotechnical unit 3, which overlies geotechnical unit 4, as described in Table 1.

On the other hand, areas underlain by Holocene flood plain deposits have LPI values from 0.02 to 8.75, which insinuate low to high hazard potential. So, this surface geology unit is potential too for sand boil generation due to liquefaction [18]. Besides, 24% area of this zone may exhibit surface manifestation of liquefaction. LPI values of individual boreholes are comparatively higher for the subsurface geological materials of this surface geology unit, and this is because of the predominant presence of loose, low resistance (low SPT values) sandy and non-plastic silty clays. Soils of this zone are composed predominantly of geotechnical units 1, 2, and 3.

To depict site specific hazard susceptibility on the hazard map, LPI value of each borehole was placed on the hazard map. On top of that, area with specific hazard index was indicated by assigning a color for each hazard category, which was performed in GIS environment following Kriging method.

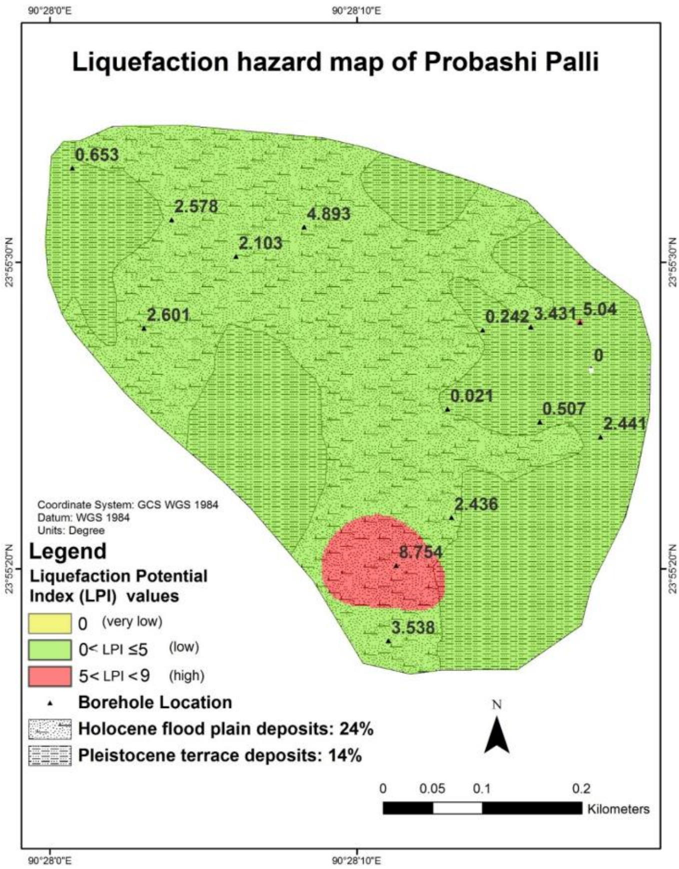

Fig. 5. Seismic soil liquefaction hazard map of Probashi Palli Project area, Pubail, Tongi, Gazipur. Susuceptibility to the liquefaction hazard has been indexed as very low for LPI = 0; low for 0<LPI≤5; high for 5<LPI≤9. The 14%, and 24% areas of Pleistocene terrace deposits and Holocene flood plain deposits, respectively, will exhibit surface manifestation due to liquefaction for a scenario earthquake of Mw = 7, where PGA = 0.20 g.

5. Conclusion

Earthquake induced soil liquefaction potential at Probashi Palli Abasan area, Tongi, Gazipur was evaluated in this research based on LPI, and subsequently a hazard map was produced. The authors divided surface geology of this area into two units—i) Pleistocene terrace deposits and ii) Holocene flood plain deposits based on geological and geotechnical survey. The hazard map illustrates site specific hazard susceptibility by means of color index. Areas underlain by Pleistocene terrace deposits have very low to high hazard potential while areas underlain by Holocene flood plain deposits have low to high potential. Further, cumulative frequency distribution of LPI values in both units reveals that 14% of the Pleistocene terrace deposits would show surface effect of liquefaction phenomenon, while 24% area of the Holocene flood plain deposits would show that if earthquake of magnitude 7 takes place. Safety factor for LPI calculation was done following deterministic procedure, and using SPT borehole data. The authors expect that the hazard map would be helpful to planners and civil engineers for site selection for infrastructure development at the locality.

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