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Liquefaction of the Alluvial Soils of Bangladesh

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SYNOPSIS: In this paper, the potential of the often-saturated sandy soils that occur within the uppermost sub-surface stratigraphy across the Bangladesh plains to experience initial liquefaction due to seismically induced pore water pressure is evaluated. Bore hole logs from development projects were collected. Standard Penetration Test (SPT) values from the drill holes were utilized as the primary data and a widely practiced computational method was employed to estimate the liquefaction potential.

The analysis of data indicated that the uppermost portion of the sandy soil layer within 20 m of the surface is loose and sensitive to liquefaction under the influence of ground shaking induced by earthquake having a peak acceleration of 0.15 g. Recommendations to control the liquefaction phenomenon in the light of the country's environment are included.

INTRODUCTION

Bangladesh is a developing nation well-known for recurring natural calamities. Located at the Southeastern foot-hills of the Himalayan Range (Fig. 1), the country enjoys extremely heavy downpour during the Monsoon months (June-October) when majority areas get flooded. The soil condition comprises an upper zone of loose unconsolidated materials dominated by sandy texture (Mollah, 1993). Such soil and groundwater table conditions are considered favorable for the occurrence of soil liquefaction, a phenomenon arising from ground shaking often poses disastrous threat to safety and integrity of structure or life-line utility. In Bangladesh, the impact of the phenomenon on the stability of structures has been recognized in recent times more than ever before because of the increasing number of failures. A huge soil liquefaction, preceded by two tremors, occurred in the early hours of November 30, 1988 in the Bhairab Bazaar area, about 90 km Northeast of Dhaka (Development Design, 1990). About 4-5 ha of railway land on the bank of the Meghna, one of the major rivers of the country, was washed away in a span of few hours. The phenomenon threatened the stability of a century old vital railway bridge linking the Eastern and Southern part of the country with the capital. With major developments and construction activities (bridges, earth dams, flood control embankments etc.) going on in Bangladesh, interest grows to have a complete understanding of the liquefaction susceptibility of the soil.

This paper presents a comprehensive evaluation of the geological and geotectonic condition with particular reference to the geomorphological characteristics of the region. The paper also presents a survey of the liquefaction potential of the soils prevailing in Bangladesh.

GEOMORPHOLOGY, RELIEF AND SEISMICITY

Bangladesh consists primarily of deltaic alluvial sediments of the Recent to Sub-Recent Geological Period (Harza et al., 1987). These sediments have been deposited by overflow from the major rivers: Ganges or Padma, Jamuna (in upper reaches called Brahmaputra) and Meghna (all originating from India), and their numerous tributaries (Fig. 1). According to Morgan and McIntre (1959), the entire Bangladesh is a part of the Bengal Basin filled in the Tertiary-Quaternary Geological Period. The thickness of sedimentary cover over the basement rocks starting from about 183 m in the Northwest part increases Southeastward to over 18 km in the eastern part of the country. The flood plains of Bangladesh were affected by earth movements due to geotectonic movements as well as consolidation under the selfweight. Their combined action has resulted in the uplift of some areas and subsidence of others (Fig. 2).

Topographically, Bangladesh is more or less a flat plain with elevation of 3-15 m MSL. The land surface slopes gently from the North towards the Bay of Bengal in the South at a rate of 1 m in 20 km (Alam et al., 1990). But the Eastern and extreme Northeastern belt and, the central and Northwestern region are exceptions to this. The former relief feature is comprised of low elongated hillock of soft shale and sandstones of Tertiary age while in the later region, large areas are covered with the other alluvium of Pleistocene age.

Tectonically speaking, Bangladesh is located in the region characterized by the well-known collision of the Indian Plate moving Northward and under-thrusting the main Asian Plate (Harza Engineering et al., 1987). The major effects of the collision are the orogenesis of the Himalayan thrust and the Eastward extrusion of Tibet. The country is located in the Northeastern wedge of the Indian Plate bounded by the Himalayan thrust & the Assam syntaxis along its North side and the Indo-Burmese ranges & the Sagaing fault along its East side. Fig. 2 shows a generalized tectonic condition of the country and adjoining areas. The main component of the regional tectonic framework are the Shelf area of the Indian Platform in the West and the adjacent Bengal Geosyncline which occupies most of Bangladesh. This Geocyncline is further bounded by the Pre-Cambrian Shilong Massif in the North and the folded belt of Tripura in the East. The Bengal Geosyncline or the Bengal Basin is separated from the Shilong Massif by the Dauki Fault. The Tripura belt is also highly faulted. Therefore, regions of high seismic activity exist to the North and East of Bangladesh in neighboring India and Burma. Earthquakes in these areas affect the adjacent regions in Bangladesh although there exists no seismically active fault in the country excepting some causative faults (say, Bogra fault). The country suffered over 200 earthquakes between August 1833 and July 1971 with magnitudes of 5.0-8.5 on the Richter scale (Committee of Experts, 1979). Amongst them, the country suffered wide spread damage from the following: Great Assam earthquake of 1897 (8.5), Arakan Yoma earthquake of 1762 (8.4), Srimangal earthquake of 1918 (7.6), Bengal earthquake of 1885 (7.1) and Assam earthquake of 1950 (7.1). The values given in the parenthesis represent the magnitude of the earthquake. Liquefaction and landslides were triggered over large areas by these earthquakes. Sand vents and fissures were observed in thousands of places in the country.

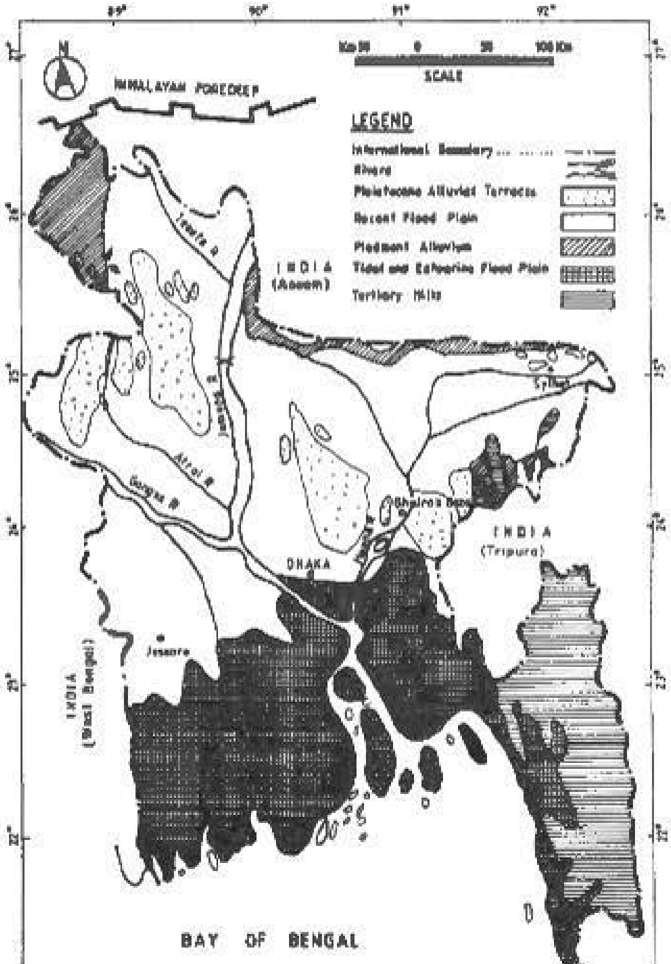

Fig. 1. Map of Bangladesh showing geomorphological zoning (adopted and modified from Development Design, 1990).

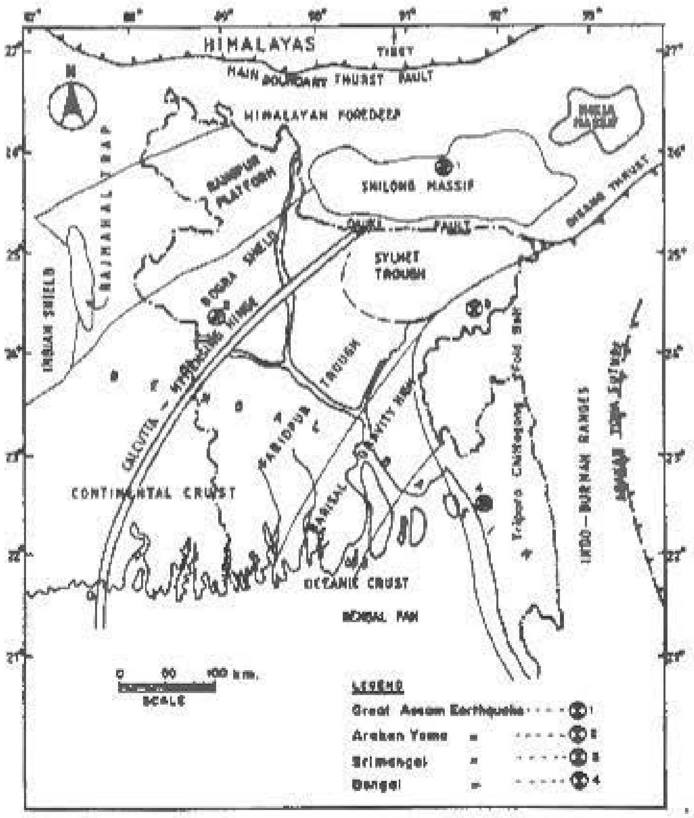

Fig. 2. Generalized tectonic map of Bangladesh and adjoining areas showing the historical seismic events affecting the country (adopted and modified from Alam et al., 1990)

The seismic event affecting Bangladesh was first studied by a Committee of Experts on Earthquake Hazard Minimisation (ibid) who published a report entitled "Seismic Zoning Map of Bangladesh and Outline of a Code for Earthquake Resistant Design of Structures". The Committee sub-divided Bangladesh into three zones I, II and III (Fig. 3). Zone I covers NE Bangladesh and is designated as the most active seismic zone. Zone II runs from NW to SE covering the central part of Bangladesh. Zone III covers the SE part of Bangladesh and is designated as the least active seismic zone. According to the Committee report, earthquake shocks of maximum intensity of IX & VIII in Modified Mercalli Scale are possible in Zone I & II respectively, and the maximum intensity is not likely to exceed VII in Zone III. The report suggests the basic horizontal seismic co-efficient as 0.08, 0.05 and 0.04 for Zone I, II and III respectively.

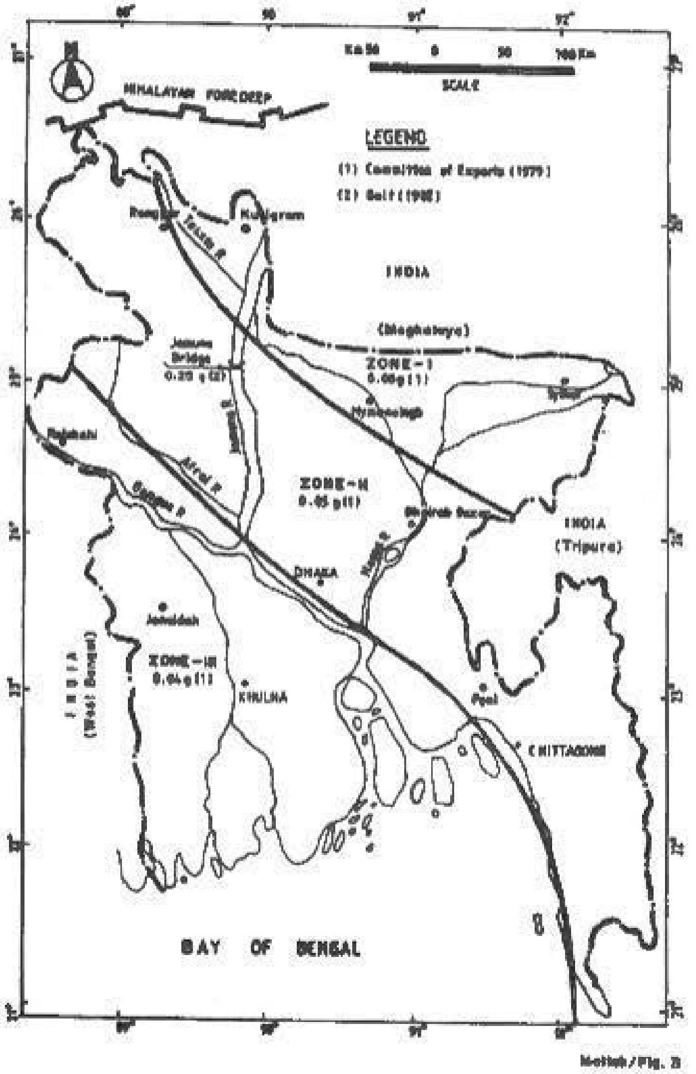

Fig. 3. Seismic zoning map of Bangladesh showing the sites considered for this study (after, Committee of experts, 1979)

More recently, the seismic effect on the design and construction of the on-going Jamuna bridge (Fig. 3) was studied through extensive literature survey of the geological and tectonic structure of the region by Prof Bolt (1987). He considered the four well-known fault zones: Assam Fault, Tripura Fault, Sub-Dauki Fault (all in India) and Bogra Fault for the estimation of peak horizontal ground acceleration. According to Bolt, the area of the Jamuna bridge may be exposed once in the 100 years to a severe earthquake with a magnitude of M=7 and maximum ground acceleration of 0.25 g with a strong ground shaking of upto 20 sec.

LIQUEFACTION ANALYSIS USING SIMPLIFIED PROCEDURE

In an article entitled "The Simplified Procedure for Evaluating Soil Liquefaction Potential", Seed and Idriss (1971) used a compilation of case histories in which sandy soils, under essentially level ground conditions were shaken by earthquakes, and the resulting liquefaction or non-liquefaction was related to the estimated ground surface acceleration, mean grain size of the soil, the relative density and the Standard Penetration Test (SPT) N-value. In order to predict whether or not liquefaction might occur at a given site, a simplified procedure was proposed. The authors have shown that the (uniform equivalent) shear stress (τ_{eq}) on the soil induced by the earthquake at the depth of interest (z) is where

$$\tau_{eq} = 0.65 r_d (\sigma_v) \left(\frac{a_{max}}{g}\right) \tag{1}$$

σ_v = total stress at that depth;
a_{max}/g = peak ground surface acceleration as a function of gravity; and
r_d = the correction factor that converts rigid to deformable (i.e., soil) body response at that depth.

The "Simplified Procedure" was refined & modified, and the method of analysis was improved (Seed et al., 1981; ibid, 1983; ibid., 1985). A study of testing procedures on the N-values resulted in normalization of the number of blows (designated as N_{60}) by reference to that obtained with 60% efficiency in energy transfer to the drill rods by the hammer. A correction factor (C_N) was also introduced to adjust the N_{60} to the equivalent value under an effective overburden pressure of 1 Tsf, in order to account for the differing effect of overburden pressure on N-values and liquefaction resistance (Liao & Whitman, 1985). A further correction to the blow count value to account for the effect of fines was also introduced.

Based on knowledge of the magnitude (M) of the earthquake and the corrected N-values $(N_1)_{60}$ (= C_N x N_{60}) of a material, one uses established correlations (Seed et al., 1983) to assess the shear stress (τ_{liq}) necessary to cause liquefaction of the same material over the course of the earthquake. From a comparison of τ_{eq} vs. τ_{liq} over depth (z), one assesses the possibility of liquefaction of the cohesionless material in the soil profile for that earthquake or magnitude event. Prakash (1981) has recommended the use of certain computational steps leading to evaluation of liquefaction potentials.

ASSESSMENT OF LIQUEFACTION SUSCEPTIBILITY

Geotechnical data

The data used for the liquefaction analysis in this paper came from sub-soil investigations conducted for development projects with which the author was associated in 1990-92. These projects which include Third Flood Rehabilitation (Emergency) and Rural Roads & Markets Improvement Projects cover almost all the plains of Bangladesh. Preliminary review of the reports indicated that most sub-soil investigations are incomprehensive. Six sites (Kurigram, Mymensingh, Bogra, Feni, Rajshahi & Jenaidah) representing all the three seismic zones, were finally selected for the evaluation of liquefaction potential. Fig. 3 shows the distribution of the sites. A review of the borehole logs revealed that the sub-soil stratigraphy consists typically of 1.0-1.5 m of loamy top soil underlain by a variegated sand-silt-clay mixture (ML). Below this, the sub-surface materials comprises predominantly of fine sand. According to the Unified Classification System, this sand can be classified as poorly graded sand (SP-SM) and Silty sand (SM), both of which are potentially liquefiable. The content of fines (<0.074 mm size particles) and mean grain size (D_{50}) of the sand range between 2 & 20 %, and 0.1 & 0.25 mm respectively. The soil lithology together with soil data including the SPT N-values with depth are given in Fig. 4. The BH logs indicate that the sub-soil of upper 10-12 m depth is very loose to medium dense with blows ranging 2 and 10. The N-blows generally increase with depth except at or below 18-20 m depth when these often shoot up to above 40. The depth of groundwater table is 0.5-1.2 m. The bulk density values for ML and SP-SM layers are 1.84-1.90 and 1.91-1.98 Mg/m^3 respectively.

Seismic data

The liquefaction evaluation procedures used in this study do not involve design magnitude of earthquakes. A realistic design earthquake magnitude cannot be reliably extracted from whatever is known so far of the seismicity of Bangladesh. Therefore, the maximum surface acceleration (a_{max}) value is indented to be used in this compilation for which the recommendation by experts vary from 0.04 to 0.25 g. Study of engineering appraisal reports reveal that liquefaction assessment for major barrages across the major rivers involved using acceleration of 0.20 g. For this study, a seismic event of M=7.5 and a_{max} value of 0.15 g (average of both extreme values) have been used. It may be stated here that Prof. Bolt's recommendations of a_{max}=0.25 g, is based on the assumption of stiff soil conditions. Because of the rather low densities of the soil encountered during the sub-soil investigation of the said bridge to depth of 60 m, this assumption is considered to be on the pessimistic side.

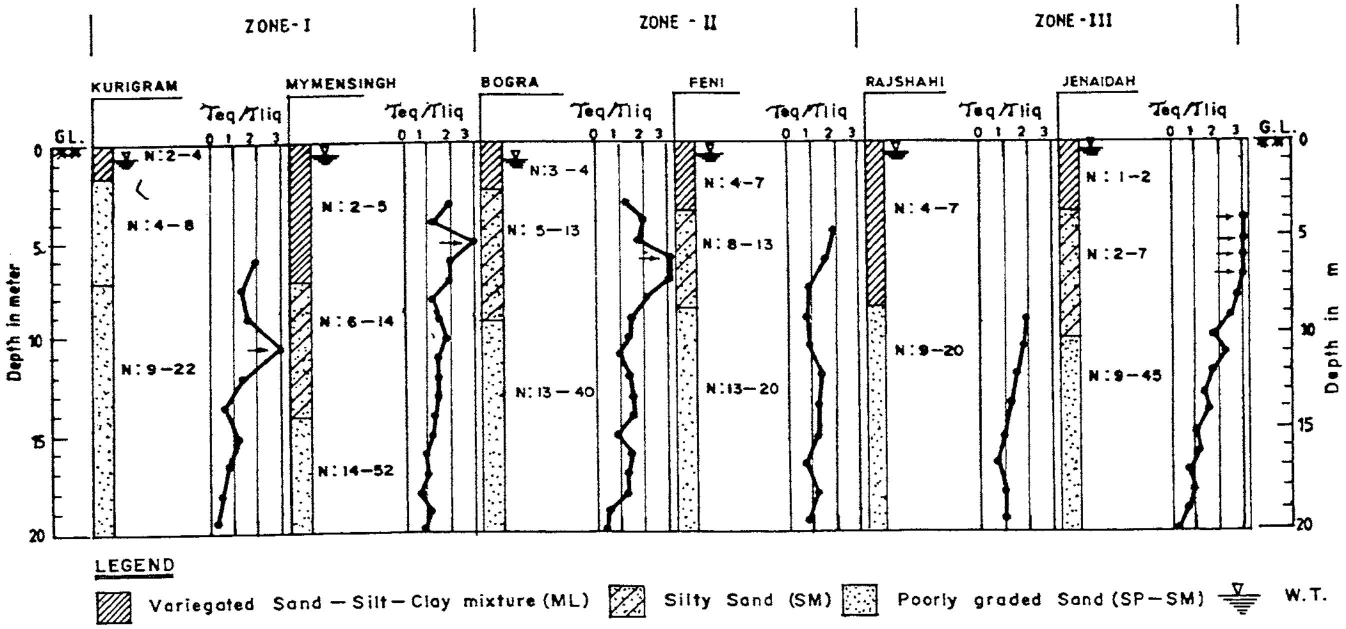

Fig. 4. Liquefaction potential of soils at different sites.

DISCUSSIONS OF RESULTS

Plots of ratio of shear stress that could be developed during earthquakes (τ_{eq}) to shear stress causing liquefaction (τ_{liq}) vs. depth at the six selected sites are shown in Fig. 4. The figure also displays the soil condition which has been assessed by averaging atleast three BH logs at each site. Typical calculations are given in Tables 1 & 2. The calculation for assessment of soil liquefaction has been restricted to sandy strata only, because silt-clay stratigraphic zone is not likely to liquefy by seismic activity. The field N-values were obtained from standard test ASTM D 1587-67 employing rope/drum driving equipment (ASTM, 1988) and, therefore, these were taken as $(N)_{60}$ without any correction (Seed et al., 1984). The SPT N-values $(N)_{60}$ were, however, corrected for overburden effect in accordance with recommendation given by Peck et al. (1974). As the water table in Bangladesh is largely seasonal, the most adverse situation with the water table just above ground level was used in the calculation. The shear average stress (τ_{eq}) for the maximum acceleration (a_{max}) of the design earthquake was computed from the relationship given in eq. 1. The τ_{liq} was calculated for M=7.5 employing $(N_1)_{60}$ vs. Cyclic Stress Ratio (τ/σ_{vo}') relationship by Seed (1979). The probability of liquefaction for a site was assessed from a comparison of τ_{eq} and τ_{liq}. If $\tau_{eq}/\tau_{liq} > 1$, liquefaction occurs; otherwise, it does not occur.

Fig. 4 reveals that the potential zones of liquefaction occur within the variegated sand and silty sand zones down to about 20 m. Liquefaction, in this study, could occur if the magnitude of ground acceleration is equal to or greater than 0.15 g.

Table 1. Calculation of shear stress causing liquefac. (τ_{liq})

District: Bogra Area: Sonakaniya
Earthquake, M: 7.5 Water table: 0 (assumed)

Depth (m)	Aver. N-val N_{60} (Blows)	σ_{v0}' (kPa)	Aver. fines cont. (%)	C_N[1]	$(N_1)_{60}$[2] (Blows)	τ_{liq}[3] kPa
1.0	3.0	9.2	89.4	ND	ND	ND
2.0	4.1	18.4		ND	ND	ND
3.0	5.9	27.9	15.0	1.43	8.6	2.8
4.0	7.2	37.4		1.33	9.3	3.7
5.0	9.3	46.9		1.25	11.3	5.2
6.0	5.1	56.4		1.19	6.0	3.3
7.0	4.9	65.9		1.14	5.7	4.0
8.0	8.2	75.4		1.10	8.8	6.8
9.0	11.0	84.9		1.06	11.7	10.2
10.0	13.3	94.4		1.02	13.3	12.3
11.0	18.0	104.2	9.2	0.99	17.8	18.7
12.0	12.8	114.0		0.96	12.5	14.8
13.0	12.2	123.8		0.93	11.2	13.6
14.0	12.0	133.6		0.90	10.8	14.7
15.0	18.2	143.4		0.88	15.8	22.9
16.0	13.4	153.2		0.86	11.2	16.9
17.0	15.0	163.0		0.84	12.6	21.2
18.0	14.0	172.8		0.82	11.3	20.7
19.0	27.3	182.6		0.80	21.8	38.3
20.0	40.4	192.4		0.78	31.2	67.3

1. See Peck et al. (1974). N-val. averaged from 4 tests
2. Corrected N-value=$C_N x N_{60}$ ND: Not determined
3. See Seed et al. (1985).

Table 2. Calculation of shear stress (τ_{eq})

District: Bogra Area: Sonakaniya
Max. ground acceleration (a_{max}): 0.15g

Depth (z) (m)	Unif. soil classif	γ_b (Mg/m^3)	σ_v[1] (kPa)	r_d[2]	τ_{eq}[3] kPa
1.0	ML	1.92	19.2	1.00	ND
2.0			38.4	0.99	ND
3.0	SM	1.95	57.9	0.98	5.5
4.0			77.4	0.98	7.4
5.0			96.9	0.97	9.2
6.0			116.4	0.96	10.9
7.0			135.9	0.95	12.6
8.0			155.4	0.94	14.2
9.0			174.9	0.93	15.6
10.0			194.4	0.91	17.2
11.0	SP-SM	1.98	214.2	0.89	18.6
12.0			234.0	0.86	19.6
13.0			253.8	0.83	20.5
14.0			273.6	0.80	21.3
15.0			293.4	0.77	22.0
16.0			313.2	0.75	22.9
17.0			333.0	0.72	23.4
18.0			352.0	0.69	23.7
19.0			372.6	0.66	24.0
20.0			392.4	0.63	24.1

1. $\sigma_v = \gamma_b x$ z. ND: Not determined for ML layer.
2. See Fig. 4 of Seed & Idriss (1971).
3. See eq. 1

From the above discussions, it is implied that the deltaic formation prevailing all over Bangladesh are prone to liquefaction even under moderate acceleration. Liquefaction can induce the immediate sinking and /or tilting of shallow foundations. In river regimes, ground failures can completely upset the channel morphology and flow condition. An embankment or natural slope, if subjected to dynamic loading, can be damaged by sliding of its slope or it may collapse because of liquefaction of the underlying layers. Liquefaction of slope often develops in micro-scale at the beginning but once the phenomenon erupts, it flares up in a short span of time in a retrogressive manner to macro-scale depending on the soil condition. Several environmental factors (e.g., heavy downpour, flash flood, steep slope and presence of animal burrow across the slope, wave action, rapid receding of flood water) act favorably in setting stage for the liquefaction failure. Typical failure of road embankment including adjacent areas due to sand liquefaction is shown in Fig. 5

This study is not intended to have a zonal demarcations of Bangladesh plains. Soil lithology, however, reveals that the southern areas are less susceptible to liquefaction. This is because the sediments get finer and finer as the river moves downstream towards the South and, therefore, they are not of sandy texture to the top.

Fig. 5. Illustration of sand liquefaction. A bailey bridge stands along a road segment at Jaimantap, 30 km West of Dhaka where a major sand liquefaction occurred in 1988.

PREVENTION OF LIQUEFACTION

While recognizing liquefaction as a potential risk, it is of utmost importance that causes leading to this condition are suppressed as far as practicable. In general, liquefaction can be controlled by following two general principles: i) improving the foundation soil condition and ii) controlling the pore water pressure.

The soil conditions can be improved by removal and replacement of unsatisfactory material with densified soil, increase of lateral in-situ stress, grouting or chemical stabilization, etc. The exact measure is specific case dependent. Densification of soil may be achieved by the use of deep compaction such as vibro-floatation and sand compaction piles although noise and vibration could be a problem in urban areas. For machine foundations, it is advisable to use raft footing of suitable thickness, to bear the static and dynamic stresses of the structure.

Lowering of the ground water table in a liquefaction-susceptible soil increases its resistance against the hazard. The shallower part of the saturated soil is converted to unsaturated soil which will not liquefy. The measure also increases the effective stress within the saturated zone. A drainage system such as vertical gravel drains is particularly effective in increasing the liquefaction resistance of moderately dense sand deposits.

In case of earth structures, soil properties may also need improvement. This can be achieved through densification by compaction piles, vibratory probes, vibrofloatation, compaction grouting or dynamic compaction, etc. Stability of the earth structure can be increased by the use of geofabrics, piles, sheetpiles, increasing levee freeboard, installing stable embankments behind the levees to retain the liquefiable soils, etc. Other improvement measures against slope failure include construction of retaining wall wherever possible, addition of toe weight, removal of head weight, easing of slope angle, river training, drainage improvement, etc.

CONCLUSIONS

In Bangladesh both natural soil and environmental factors are conducive for the occurrence of liquefaction. A global assessment of liquefaction potential for alluvial soils of the Bangladesh plains have been made from subsurface data by an empirical method. Given a dynamic event with a peak acceleration of 0.15 g, soils including those adjacent to the river and along the water front would be susceptible to liquefaction.

The liquefaction potential data are not intended to suggest that presently existing structures in areas which are identified as being underlain by highly liquefiable soils are at risk since such an evaluation is beyond the scope of the present study. The present evaluations are expected to provide useful information for preliminary selection of foundations, planning of emergency procedures, assessment of land-use, investment decisions, contractual purposes, engineering design, etc..

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