Dynamic Properties and Liquefaction Potential of a Sandy Soil Containing Silt

Propriétés dynamiques et potentiel de liquéfaction d'un sol sablonneux contenant de la vase

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ABSTRACT: The most common cause of ground failure during earthquakes is the liquefaction phenomen which has produced severe damage all over the world. Shear modulus and damping of soil are important parameters. Appropriate evaluation of liquefaction potential, shear modulus and damping characteristics of soil subjected to dynamic loading is the key to accurate dynamic response analysis and soil modeling programs. This paper summarizes the behavior of dynamic properties as well as potential for liquefaction of a sandy soil deposit in Bangladesh. A fine sand sample was collected from a site close to Piyain river of Jaflong, Sylhet, Bangladesh. Another fine sand sample and nonplastic-silt sample was collected from Padma Bridge site. A series of cyclic triaxial tests was performed using fine sands and mixing silt content. Shear modulus decreased with increasing shear strain and damping ratio increased with increasing shear strain. Most interesting finding is that upto 30% silt, liquefaction resistance of sand decreased with increasing silt content. Above 30% silt, liquefaction resistance of soil had insignificant variation with silt content.

RÉSUMÉ : La cause la plus commune d'échec de terre pendant des tremblements de terre est le phénomène de liquéfaction qui a produit des dégâts sévères dans le monde entier. Module de cisaillement et l'amortissement de sol sont des paramètres importants. L'évaluation appropriée de potentiel de liquéfaction, module de cisaillement et les caractéristiques d'amortissement de sol soumis au chargement dynamique sont la clé de l'analyse de réponse dynamique précise et les programmes de modélisation de sol. Ce papier récapitule le comportement de propriétés dynamiques aussi bien que le potentiel pour la liquéfaction d'un dépôt de sol sablonneux au Bangladesh. Un échantillon de sable fin a été rassemblé d'un site près de la rivière Piyain de Jaflong, Sylhet, le Bangladesh. Un autre échantillon de sable fin et l'échantillon de non-plastique-vase ont été rassemblés du site de Pont de Padma. Une série des tests triaxiaux cycliques a été exécutée utilisant des sables fins et mélangeant le contenu de vase. Module de cisaillement a diminué avec l'augmentation de la tension cisaillement et le ratio d'amortissement a augmenté avec l'augmentation de la tension cisaillement. La découverte la plus intéressante est que jusqu'à 30% de vase, la résistance de liquéfaction de sable a diminué avec l'augmentation du contenu de vase. Au-dessus de 30% de vase, la résistance de liquéfaction de sol n'avait aucune variation avec le contenu de vase.

KEYWORDS: Shear Modulus, Damping, Liquefaction, Nonplastic Silt, Cyclic Triaxial Test.

1 INTRODUCTION

Because of geographical, topographical and meteorological conditions of Bangladesh, the country is subject to frequent natural disasters. The country is situated in the moderate seismic zone in world seismic map. Information on earthquakes in and around Bangladesh is available for the last 250 years. The earthquake record suggests that since 1900 more than 100 moderate to large earthquakes occurred in Bangladesh, out of which more than 65 events occurred after 1960. During the last ten years, the occurrence and damage caused by some earthquakes (magnitude between 4 and 6) inside the country and near the country's border, has raised the concern about the effect of earthquake. Most of the land area in Bangladesh has been built up of alluvial deposits brought down by some major rivers. The soil condition is loose silty sand deposit and most of it remains in saturated condition round the year, thereby vulnerable to liquefaction in case of strong ground motions.

The catastrophic landslide caused by the Chili earthquake in 1960 (Duke and Leeds, 1963), Alaska earthquake in 1964 as well as the subsidence and foundation failures due to liquefaction during Niigata Earthquake in 1964 (Seed and Idris, 1967) has strongly established the need for a better understanding of the behavior of soil under dynamic loading conditions. Due to these events, liquefaction and the shear behavior has been extensively studied in the field and laboratory. In recent years evaluation of dynamic properties of soil is a great concern to design geotechnical related problems that are involved with dynamic loading.

The measurement of dynamic soil properties is a critical task in the solution of geotechnical earthquake engineering problem. A wide variety of field and laboratory techniques are available each with different advantages and limitations with respect to different problems. Many are oriented toward measurement of low-strain properties and many other towards properties mobilized at large strains. The cyclic triaxial test has been the most commonly used test for measurement of dynamic soil properties at large strain levels. No research has so far been undertaken to assess the liquefaction susceptibility and dynamic properties of local sands using cyclic triaxial test. This paper presents the liquefaction potential and dynamic properties of a sandy soil using cyclic triaxial test at large strain levels. Effect of nonplastic silt content on liquefaction was also investigated.

2 REVIEWS OF PREVIOUS STUDIES

Previously many researchers extensively studied dynamic properties and liquefaction resistance of soils in the field and laboratory. Cyclic triaxial test results indicate that, higher the void ratio, lower the confining pressure and greater the cyclic stress and the number of cycles, easier the development of liquefaction (Seed and Lee, 1966). Liquefaction resistance of soil increases with increase in density, frequency and confining pressure (Choudhary et al, 2010). Cyclic triaxial test results show that when the degree of saturation reduced, the number of cycles required for liquefaction increased by 1.5 to 2.5 times to that observed in fully saturated sand (Raghunandan and Ashish, 2011). Liquefaction resistance of sands increases with a decreasing degree of saturation (Sherif et al, 1977; Ishihara et al, 2001; Okamura and Soga, 2006). Reduction in the degree of saturation from 100 to 97.8% led to greater than 30% increase in liquefaction strength (Xia and Hu, 1991).

Lowest resistance against liquefaction in uniformly graded loose sand with fines content between 25% and 30% (Koester, 1994). Fines content increasing from 0 to 44 % the liquefaction resistance of mixture with constant global void ratio decrease compared to that of the clean sand, whereas this trend reversed for values of fines content greater than 44 % (Xenaki and Athanasopoulos, 2003). Cyclic strength of silty sands with 15% fines has only one-half of the resistance to liquefaction of clean sands at the same effective confining pressure (Troncoso, 1986). Addition of nonplastic silt with clean sand results in increasing pore pressure up to a limiting value that corresponds to 30% in silt content. Further, addition of low plasticity silt to sand has no significant effect on the generated pore pressures, up to 60% in silt content (Erten and Maher, 1995). Liquefaction of soils occurred with upto 70% fines and 10% clay fraction during Mino-Owar, Tohankai and Fukui earthquakes (Kishida, 1969). Cyclic tests on Ottawa sands showed that, for a constant dry density, the liquefaction resistance decreased as fines were added to sand (Shen et al, 1977). At a constant relative density, additional fines (10% to 50%) acted to increase the liquefaction resistance of sand (Amini and Qi, 2000). Liquefaction of silty soils found that increased plasticity results in an increased cyclic strength and silty soils, having a plasticity index of 15 or more the state of initial liquefaction never developed. It has been demonstrated that the fine grained tailings that were identified as being nonplastic exhibited much smaller cyclic strength than the tailings having a plasticity index of 15-20 (Ishihara et al, 1980). Specimens tested using a fast rise time square wave form, shows strength value about 15% less than those tested using a sine wave loading.

Cyclic strength of the specimens prepared using the dry method is on the order of half the strength of the specimens prepared using the wet method (Marshall et al, 1976). The effect of relative density on shear modulus of dry and saturated sands is significant in the small strain levels (0.1% to 0.5%) and thereafter the effect of relative density on shear modulus with increase in shear strain is not significant. The damping ratios of dry and saturated sands increase with increase in shear strain and the effect of relative density on damping is not very significant in both cases. There is a reduction in shear modulus and an increase in damping at large shear strain levels (Kokusho, 1980; Dinesh, 2004). Relative density has no significant influence on the dynamic properties of soils in the large strain (greater than 1%) levels, but it has considerable influence at small strain levels (Sitharam et al, 2004ab).

This paper summarized the liquefaction potential and dynamic properties of a local sandy soil at constant relative density and constant effective confining pressure. Effect of nonplastic silt on cyclic shear strength of fine sand is also present in this paper.

3 EXPERIMENTAL INVESTIGATIONS

3.1 *Soil sampling and characterization*

A fine sand (hereinafter called Sand-01) sample was collected from the site close to Piyain river of Jaflong, Sylhet, Bangladesh. Table 1 gives the summary of index properties of the sand sample collected and used for testing. It is clear from the index properties that the soils contain a large percentage of fine sand with appreciable amount of fines that are more prone to liquefaction. A fine sand (Hereinafter called Sand-02) and a nonplastic silt was collected from Mawa Padma Bridge site. Figure 1 shows the grain size distribution of the Sand-01 as well as limits in the gradation curves separating liquefiable and non-liquefiable soils (Tsuchida, 1970). Fineness modulus and D_{50} of Sand-02 is 0.92 and 0.20 mm respectively. Sand-02 is finer than Sand-01 (FM=1.01).

3.2 *Sample preparation*

Soil specimens of size 71 mm diameter and 143 mm in height were prepared using wet tamping technique. The sand was initially mixed in a container with 8% to 10% moisture. Then the wet sand was poured into the mold in 5 layers and compacted in 5 layers using 35.5 mm diameter circular aluminum tamper, weighing about 800 g at a relative density of 55%.

Table 1. Index properties of sand sample used for cyclic triaxial test.

Index Properties	*Value*
Specific Gravity	2.65
Fineness Modulus	1.01
Coarse, Medium, Fine sand and Silt %	0.2, 9.8, 78.3 and 11.7
Maximum and Minimum Density	16.7 and 12.15 kN/m^3

The soil specimen was sealed in a water tight rubber membrane with O-ring and confined in a triaxial chamber where it was subjected to a confining pressure of 20 kPa. In order to improve the initial saturation of the specimen, carbon dioxide (CO_2) was allowed to flow through the specimen at a low pressure (less than 20 kPa) in order to replace the air in the specimen pores. After 30 minutes, the flow of carbon dioxide (CO_2) was stopped and a tank of de-aired water was attached to the drainage line on the bottom platen. The de-aired water was then allowed to flow upward through the specimen in order to saturate the specimen. Once the desired volume of de-aired water had flowed through the specimen, the drainage valves on the cell were again closed and the de-aired water line removed. The specimens were then saturated with de-aired water using backpressure saturation. The back pressure was increased gradually while maintaining the effective confining pressure at 10 kPa. This process was continued until the Pore Pressure Parameter B ($B = \Delta u/\Delta\sigma_c$, where, Δu = Change in specimen pore pressure and $\Delta\sigma_c$ = Change in confining pressure) exceeded 0.95. Following saturation, the sand specimen was isotropically consolidated to an effective stress of 50 kPa.

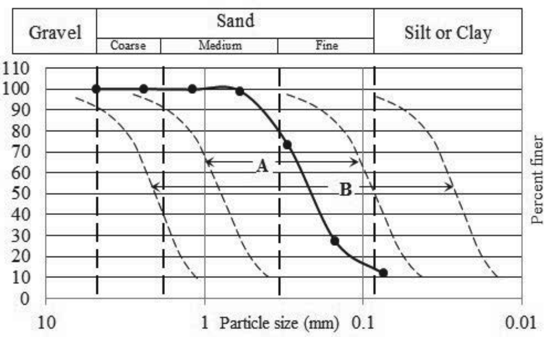

Figure 1. Grain size distribution curve and limits in the gradation curves (A- Boundaries for most liquefiable soil, B-Boundaries for Potentially liquefiable soil) separating liquefiable and non-liquefiable soils.

3.3 *Cyclic loading and data acquisition*

Before the application of cyclic load an air pocket at the top of the triaxial chamber was formed by draining water from the cell without allowing the cell pressure to drop. Then cyclic loading was applied on the soil specimens using the stress-controlled method. The cyclic triaxial strength tests were conducted under undrained conditions to simulate essentially undrained field conditions during an earthquake or dynamic loading. The tests were conducted at a constant Cyclic Stress Ratio (CSR = ($\sigma_{dc}/2\sigma_c'$, where (σ_{dc}= cyclic deviator stress and σ_c'= effective confining pressure). CSR was varied from 0.15 to 0.45 at the interval of 0.05. In the entire test program, a harmonic loading was applied using sine wave with a frequency of 1 Hz, the maximum peak-peak axial strain 10%, the number of cycles limited to 100 cycles and a recording speed of 50 numbers of readings per cycle was specified. Axial deformation, cell pressure, cyclic load, and sample pore water pressure were recorded using automatic data acquisition system.

3.3.1 *Data calculation*

The data recorded during the test program is used to calculate the dynamic properties of the tested soil such as Initial Liquefaction, Cyclic Strength Ratio, Damping and Shear Modulus. The initial liquefaction is defined as the number of cycles required where the excess pore water pressure reached the value just equal to the effective confining pressure and 5% double amplitude axial strain whichever is earlier.

When the soil sample is subjected to symmetric cyclic loading in cyclic triaxial apparatus, a hysteresis similar or its equivalent to one loop shown in Figure 2 will be formed in the plot of shear stress (τ) versus shear strain (γ). In general term, two important characteristics of the hysteresis loop are its inclination and breadth. The inclination of the slope can be describe at any point during the loading process by the tangent shear modulus, G_{tan}. Tangent shear modulus, G_{tan} varies throughout a cyclic loading, but its average value over the entire loop can be approximated by the secant shear modulus, G_{sec}.

The material damping ratio (D) is calculated for a given hysteresis loop using equation

$$D = A_L/(4\pi A_T) \times 100 \quad (1)$$

Where,
A_L = area of hysteresis loop,
A_T = area of shaded right triangle shown in Figure 2, and
D = material damping ratio, %.

Calculations are performed to compute the value of secant shear modulus (G_{sec}) and damping ratio (D) on each of the hysteresis loop at cycle number 1, 5, 10, 20, and 40 (ASTM D 3999-91, 2003).

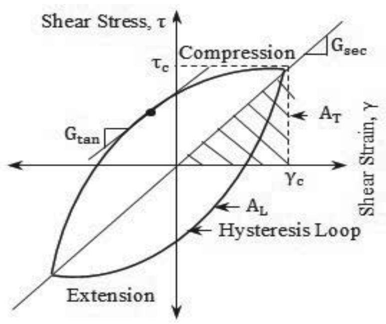

Figure 2. Schematic of typical hysteresis loop generated by cyclic triaxial apparatus.

4 RESULTS AND DISCUSSION

A typical time history of axial load, axial deformation and induced excess pore water pressure obtained at cyclic stress ratio 0.30 for Sand-01 is shown in Figure 3. From this figure it is clear that under a constant cyclic vertical load application the pore pressure increases gradually until cycle 21 where the excess pore water pressure just equal to the effective confining pressure, which is defined as initial liquefaction. In addition, it is clear that small cyclic deformations were induced in the specimen until approximately cycle 19, after which the cyclic deformations built up rapidly.

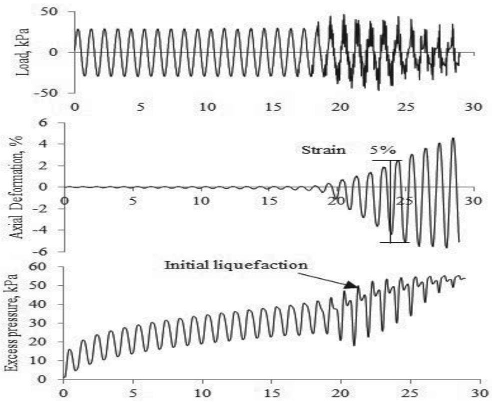

Figure 3. Recorded load, deformation and pore water pressure time history for cyclic stress ratio 0.30.

The relationship between the cyclic stress ratio and the number of cycles needed for liquefaction of Sand-01 are shown in Figure 4. From this figure it is clear that for any definition of failure, the number of cycle required to failure decreases with increasing cyclic stress ratio. Initial liquefaction occurred before the 5% DA axial strain in all tests. The cyclic strength of the soil is specified in terms of magnitude of cyclic stress ratio (CSR) required reaching 5% double amplitude axial strain in 20 cycles of uniform load application, and the cyclic strength ratio of the sand is 0.315.

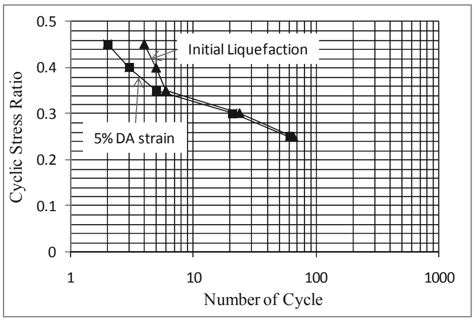

Figure 4. Variation of cyclic stress ratio with the number of cycles for Sand-01.

The variation of shear modulus and damping as a function of shear strain are shown in Figure 5 and Figure 6. Reduction in shear modulus and increase in damping with increasing shear strain was observed. The soil, which is initially stiff, loses its stiffness due to increase in pore water pressure as number of the loading cycle increases. The progression of loading cycles induces higher magnitudes of pore water pressures resulting reduction of shear modulus. It is necessary to perform more tests at different relative densities and confining pressure to see their effect on shear modulus and damping of local sandy soil. These test results would help to evaluate site response analysis.

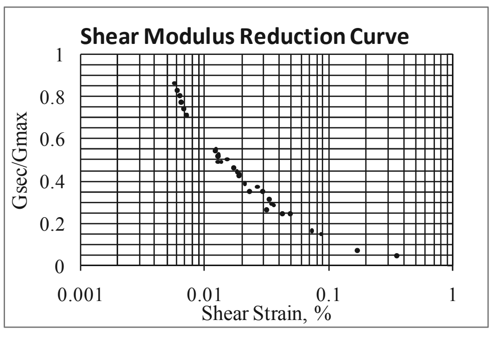

Figure 5. Variation of shear modulus with shear strain for Sand-01.

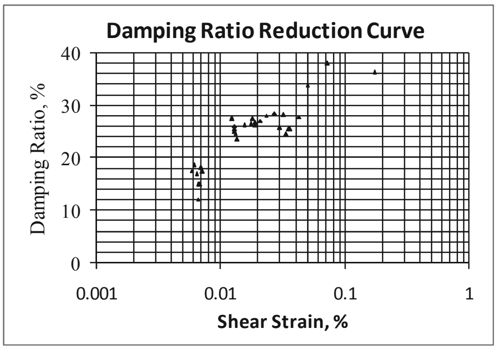

Figure 6. Variation of damping ratio with shear strain for Sand-01.

Effect of nonplastic-silt content in Sand-02 is shown in Figure 7. It is found that upto 30% silt, liquefaction resistance of sand decrease with increasing silt content. Above 30% silt, liquefaction resistance of soil is nearly constant. This result is somewhat similar to Dash and Sitharam (2009). However this result is different with Polito and Martin II (2001).

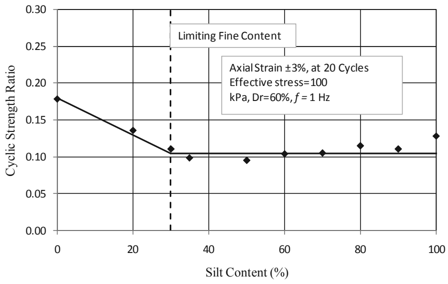

Figure 7. Cyclic Strength Ratio variation of Sand-02 with silt content.

5 CONCLUSIONS

Cyclic strength ratio, shear modulus reduction curve and damping reduction curve were determined for a local fine sand containing 11% silt. Wet tamping method was used to prepare specimen of relative density 55%. Cyclic strenght ratio at 50 kPa confining pressure was found to be 0.315. Shear modulus decreased with increasing shear strain and damping ratio increased with increasing shear strain. Most interesting finding is that upto 30% silt, liquefaction resistance of sand decrease with increasing silt content. Above 30% silt, liquefaction resistance of soil had insignificant variation with silt content.

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