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Parameters Influencing Dynamic Soil Properties: A Review Treatise

Shiv Shankar Kumar[1], A. Murali Krishna[2], Arindam Dey[3]

Research Scholar, Dept. of Civil Engg, IIT Guwahati[1]

Assistant Professor, Dept. of Civil Engg, IIT Guwahati[2, 3]

Abstract — Determination of dynamic soil properties is a critical task but an extremely important aspect in geotechnical earthquake engineering problems. Dynamic soil properties include shear modulus, modulus reduction and damping variations with cyclic strains. Field evaluation of dynamic soil properties predominantly aids in the estimation of the shear modulus/shear wave velocity at low strain level. Laboratory based evaluations helps in the estimation of a realistic range of dynamic soil properties (e.g. experiments carried out in a specific strain-controlled environment) at varying strain levels. Factually, the cyclic triaxial method has been the most widely used to measure the strength, deformation and dynamic characteristics of soils. Such experiments can also help to simulate and comprehend the liquefaction characteristics and evaluate the liquefaction potential of the concerned medium. Various parameters like: relative density, confining pressure, soil plasticity, strain amplitude, frequency and magnitude of cyclic loading influence dynamic soil properties. This paper presents a review on the dynamic soil properties and their influencing parameters. Earlier studies on dynamic soil properties are presented systematically to highlight the importance of the each influencing parameter. Subjected to similar testing conditions, a significant difference in the dynamic soil properties for characteristically different soils have been observed by earlier researchers. It has been observed that the dynamic soil properties are affected by many factors like: method of sample preparation in the laboratory (whether intact and reconstituted samples), relative density, confining pressure, methods of loading, overconsolidation ratio, loading frequency, soil plasticity, percentage of fines and soil type.

Keywords— Shear modulus, Damping ratio, Liquefaction potential, Cyclic triaxial

I. INTRODUCTION

Soil is the most valuable natural resource which is formed due to disintegration of parent materials (rock) by physical and/or chemical weathering. The geological conditions, topographic characteristics and climatic conditions play a vital role in the formation of soil in any region. Soil is generally considered as a three-phase system (air, water and solid) causing significant changes in the system characteristics due to interaction of these phases under applied static and/or dynamic load. Static loads remain unchanged over space and time, while dynamic load represents loading conditions which vary both in their direction/position and/or magnitude. Several researchers have been involved in exploring the complex behaviour of soils under various types of loading conditions. Damage due to dynamic loading (e.g. earthquake strong motions) is substantially influenced by the response of soil deposits which is governed by the dynamic soil properties. Comprehending the dynamic properties of soils aid to predict and/or analyse the dynamic behaviour. Dynamic soil properties namely shear wave velocity, variation of stiffness or modulus reduction and material damping with strain levels, and liquefaction susceptible parameters are the primary input parameters for various dynamic studies and investigations. The determination of dynamic soil properties is an utmost critical and important aspect of geotechnical earthquake engineering problems. In general, soil properties depend on different state

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parameters such as the state of stress, void ratio, confining stress and water content, stress history, strain levels, and drainage condition to name a few. Apart from the influence of the above-mentioned parameters, dynamic soil properties are significantly influenced by the dynamic amplitude and frequency of the applied load. Hence, determination/estimation of the dynamic soil properties requires the consideration of all the above-mentioned influencing parameters. Dynamic soil properties can be determined from different field and/or laboratory tests as shown in Table 1 [1]. They can also be evaluated using suitable empirical correlations established from earlier standard field and laboratory investigations carried on a particular type of soil ([1]–[3]). One of the important aspect commonly looked into, is the behavior of cyclically loaded soil subjected to different strain levels. At low strain levels (< 0.001%), the soil portrays higher stiffness and lower damping ratio, with the stress-strain behavior being relatively linear. However, at higher strain levels, more nonlinearity effect is displayed along with the portrayal of higher damping ratio. Under such condition, the influence of the rate of loading and number of loading cycles on shear strength and volume change characteristics of the soil are extremely important. Basically, when a soil is subjected to earthquake or cyclic loading, the shear modulus and damping ratio of the soil are influenced by many factors like soil type, plasticity index, cyclic strain amplitude, relative density, frequency of loading cycle, effective confining pressure, overconsolidation ratio, and number of loading cycles [1]. Thus stiffness and damping properties are generally characterized by shear modulus (represented by modulus reduction curve) and damping ratio (represented by damping curve) of soil which decreases and increases with the strain respectively [1].

TABLE 1
FIELD AND LABORATORY TESTS EMPLOYED FOR DYNAMIC INVESTIGATION OF SOIL

Field tests		Laboratory tests	
Low strain (< 0.001%)	High strain (> 0.01%)	Low strain (< 0.001%)	High strain (> 0.01%)
Seismic reflection	Standard penetration test (SPT)	Resonant column test	Cyclic triaxial test
Seismic refraction	Cone penetration test (CPT)	Ultrasonic pulse test	Cyclic direct shear test
Steady-state vibration	Dilatometer test (DMT)	Piezoelectric bender element test	Cyclic torsional shear test
Spectral and Multi-channel analysis of surface waves (SASW and MASW)	Pressuremeter test (PMT)		
Seismic borehole survey (Cross-hole, Down-hole and Up-hole)			
Seismic cone tests			

Further, liquefaction susceptible parameters are also important dynamic soil properties. Liquefaction phenomenon was initially coined by Hazen (1920) during investigation of failure of the Calaveras Dam in California [4] and initially introduced by Terzaghi in 1925 [5]. Many structures, foundations and slopes did experience failures due to liquefaction during the earthquakes of Dhubri (1930), Bihar (1934), Niigata (1964), San Fernando (1971), Koyna (1995), Bhuj (2001), and the Great East Japan earthquake (2011). Several researchers ([6]–[17]) have carried out significant studies on liquefaction of different soils under different loading and testing conditions.

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This paper presents a review on the dynamic soil properties and their influencing parameters. Earlier studies on dynamic soil properties are reported here systematically to highlight the importance of the each influencing parameter. Subjected to similar testing conditions, a significant difference in the dynamic soil properties for characteristically different soils have been observed by earlier researchers.

II. DYNAMIC SOIL PROPERTIES

Dynamic response of soil subjected to dynamic loads will be governed by the dynamic soil properties. The responses obtained for different dynamic loadings needs to be back analysed to determine the dynamic soil properties. A typical soil subjected to cyclic loading exhibits hysteresis response. This hysteresis behaviour/response is idealised as a simple hysteresis loop as shown in Fig. 1. The loop can be described by the path of the loop itself or by two parameters that describe its general shape (slope and breadth of loop). Slope of the loop is represented as secant shear modulus (G_{sec}) and breadth of the loop is represented in terms of damping. As the strain amplitude of cyclic loading is varied, different size of loops will be developed and the locus of the points corresponding to the tips of these loops is called the backbone curve (or skeleton) as shown in Fig. 2(a). As the cyclic strain increases, the secant shear modulus will decrease. Variation of shear modulus with cyclic strains is being represented as shear modulus degradation with cyclic strain, by means of the modulus reduction curve [Fig. 2(b)]. From the modulus reduction curve, normalization of the shear modulus (G) is carried out with respect to the maximum shear modulus (G_{max}), which is commonly referred to as the modulus ratio. G_{max} is the shear modulus at very low strain levels ($<10^{-3}$ %) which can also be determined from geophysical tests. The shear modulus in that range remains constant and is commonly used as an elastic parameter.

When soil deposits are subjected to dynamic loading, energy is dissipated and that amount of dissipated energy is generally represented by the hysteresis loop of shear stress-shear strain response curve. Energy dissipation phenomenon of soils, generally defined by damping, affects the soil-structure interaction and ground response significantly during cyclic loading/earthquakes. Many researchers have found that the damping ratio increases with increasing strain amplitude and decreasing effective stresses, while it is not much significantly affected by void ratio and number of cycles. Damping is often expressed as the damping ratio, which is defined as the damping coefficient (c) divided by the critical damping coefficient (c_c) of the system. This is obtained from the hysteresis loop by dividing the area of the loop by the triangle defined by the secant modulus and the maximum strain (energy dissipated in one cycle by the peak energy during a cycle). Damping ratio represents the ability of a material to dissipate dynamic load or dampen the system. It should be noted that many factors contribute to the damping ratio of soils during cyclic loading, such as, plasticity index, relative density, mean principal effective stress, over consolidation ratio, number of cycles and void ratio.

In the lab/in-situ tests, the magnitude of excess pore pressure build up to initiate liquefaction depends on the amplitude and duration of the cyclic loading, the number of cycles, the type of tests and soil type. There are two most common approaches to evaluate the liquefaction potential, one is cyclic stress approach and other is cyclic strain approach, in which earthquake induced loading expressed in terms of cyclic shear stress and cyclic shear strain respectively [1]. Several researchers have reported that the cyclic stress ratio and pore pressure generation are liquefaction parameters and experimentally investigated that loose soil liquefy in few cycles if large cyclic shear stress is applied; however, dense soils require large number of cyclic shear stress or cyclic stress ratio as shown in Figs. 3 and 4.

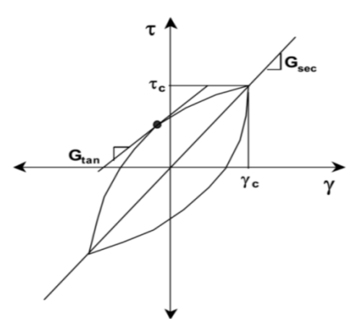

Fig. 1 Hysteresis loop showing secant and tangent shear modulus [18]

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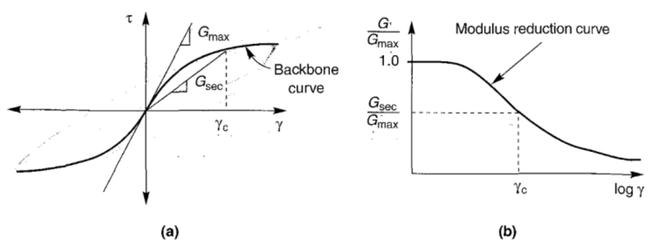

Fig. 2 (a) Stress-strain curve with variation of shear modulus (b) Modulus reduction curve [1]

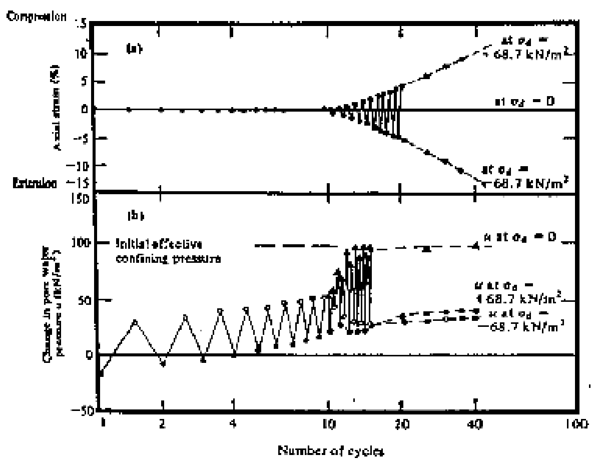

Fig. 3 Undrained cyclic triaxial test on dense (D_r = 78%) Sacramento river sand [6]

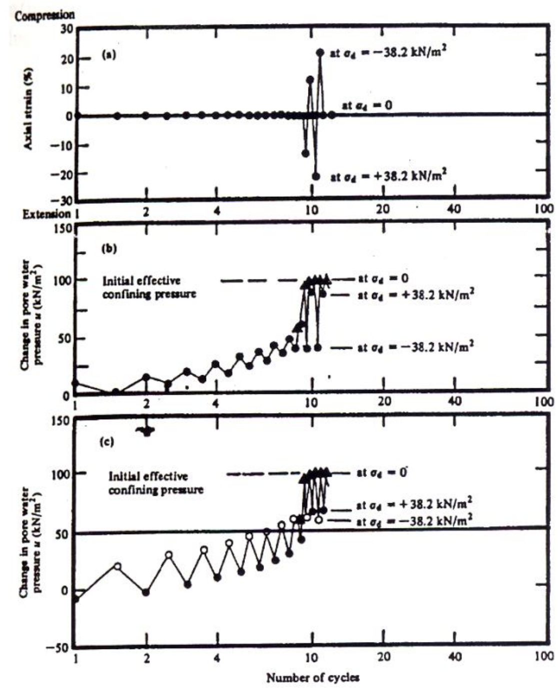

Fig. 4 Undrained cyclic triaxial test on loose (D_r = 38%) Sacramento river sand [6]

III. CRITICAL FACTORS INFLUENCING THE DYNAMIC PROPERTIES OF SOIL

The effects of testing procedures and material characteristics on the cyclic strength and dynamic properties of different soils were reviewed and it has been observed that these properties are affected by many factors such as method of sample preparation in laboratory (whether intact and reconstituted samples), relative density, confining pressure, methods of loading, overconsolidation ratio, loading frequency, soil plasticity, percentage of fines and soil type.

A. Methods of Sample Preparation

Several researchers have proposed different method for sample preparation like air-pluviation, wet-tamping, moist-vibration, trimming, spooning and raining technique. The loosest of the specimens were formed by air-pluviation technique, while the densest were formed moist-vibration technique shown in Fig. 5 [19]. It has

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also been reported that the methods of sample preparation ([20], [21]) and methods of testing [22] also affect the strength of soil. Mulilis et al. [19] have observed that the variation of sample diameters does not significantly affect the cyclic strength. However, Wong et al. [23] compared the effects of size considering 70 mm and 300 mm (2.8 in. and 12 in.) diameter specimens with similar height-to-diameter ratios and showed that the 300 mm (12 in.) diameter specimen was approximately 10% weaker than the 70 mm (2.8 in.) diameter specimen (Fig. 6). Ishihara et al. [20] reported that the cyclic strength of the undisturbed specimens was about 15% greater than that of the reconstituted specimens. Silver and Ishihara [24] have also reported that the strength ratio of undisturbed and reconstituted samples ranged between 1.14 – 1.22. Shear modulus obtained from cyclic triaxial stress-controlled tests were slightly higher than cyclic triaxial strain-controlled tests at a given shear strain level, due to the influence of the method of sample preparation ([5], [25]); however, in some cases methods of sample preparation did not affect significantly [26]. Damping ratios were not significantly affected by methods of sample preparation while the effect on the shear modulus was vivid as shown in Figs. 7 and 8. Undisturbed sample depicted almost double the shear modulus than the disturbed sample as depicted in Fig. 7 [27].

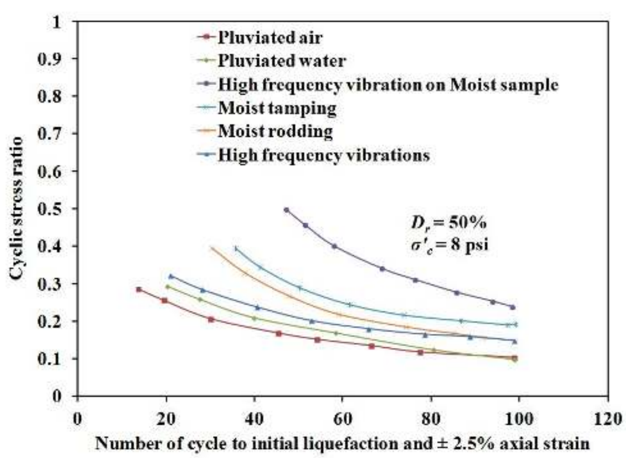

Fig. 5 Cyclic stress ratio versus number of cycles for different compaction procedures [adapted from 19]

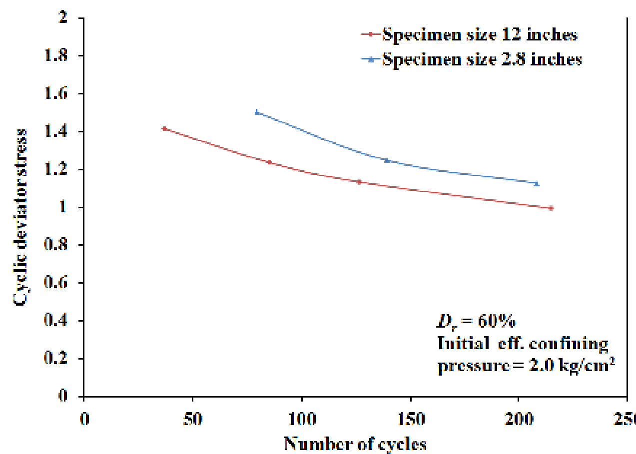

Fig. 6 Effect of specimen size on cyclic stresses causing initial liquefaction of Monterey sand [adapted from 23]

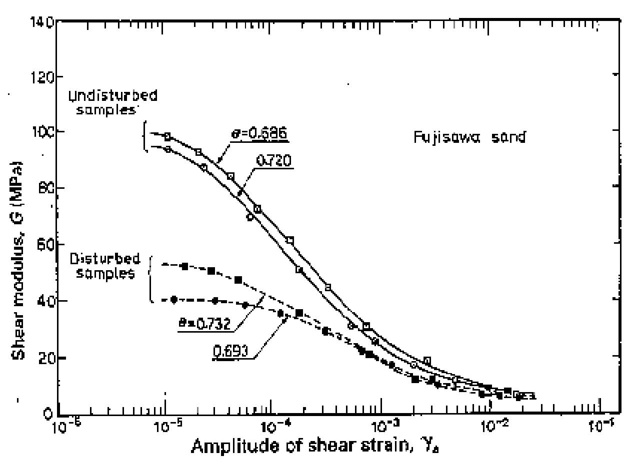

Fig. 7 Comparison of shear modulus of dense sand of undisturbed and disturbed samples [27]

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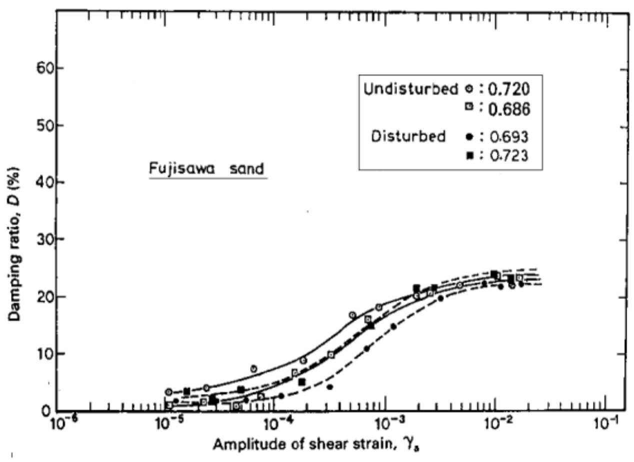

Fig. 8 Comparison of damping ratio of dense sand of undisturbed and disturbed samples [27]

B. Effects of Confining Pressure

Shear modulus, damping ratio and liquefaction are significantly affected by confining pressure. As the confining pressure increases, the shear modulus increases and damping ratios decreases because of the densification/compactness of soil sample (Figs. 9 and 10). Densification causes an increase in the relative density which further results in the increment of shear modulus and number of cycles required to initiate liquefaction. A series of different tests have been performed on soils to observe the effect of confining pressure over its strain-dependent dynamic properties. In the range of shear strains tested, it has been observed and reported that as the confining pressure increases, the shear modulus increases significantly and the damping ratio decreases ([5], [25], [26], [28]–[34]). For a given deviatoric stress, many researchers ([4], [6], [7], [20], [22], [35], [36]) have also reported that the number of cycles, to cause initial liquefaction and failure, increased with increase in confining pressure. Mulilis [37] reported that liquefaction is also influenced by the methods of sample preparation and effective confining pressure as shown in Fig. 11.

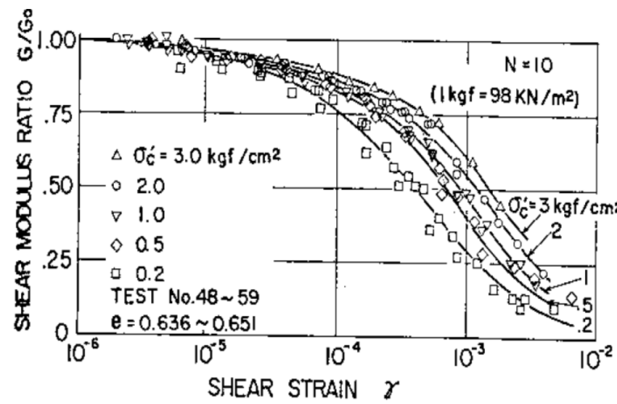

Fig. 9 Variation of shear modulus ratio and shear strain for dense sand with different confining pressures [30]

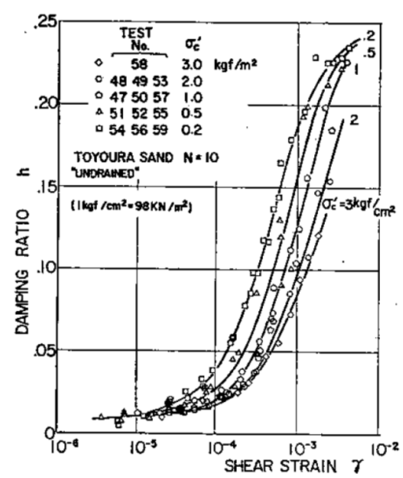

Fig. 10 Variation of damping ratio and shear strain for dense sand with different confining pressures [30]

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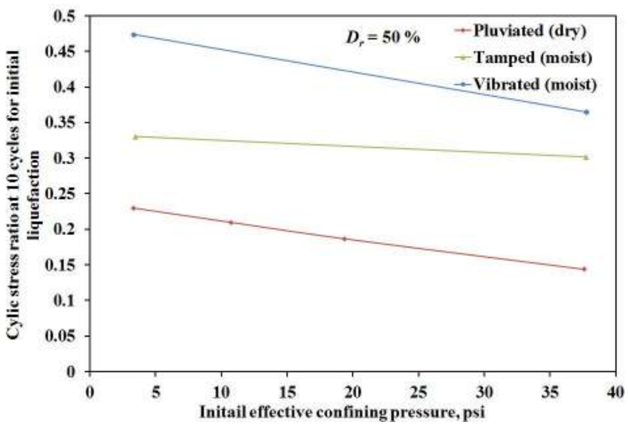

Fig. 11 Cyclic stress ratio at 10 Hz for initial liquefaction versus initial effective confining stress [adapted from 37]

C. Effects of Void Ratio

Void ratio is one of the mechanical properties of soil which is mainly influenced by the static/dynamic actions of loading. As the void ratio becomes lesser under the application of load, soil particles come closer to each other resulting in densification of soil sample. Densification or reduction in void ratio of soils due to confining pressure and method of sample preparation are the main causes increasing the cyclic strength. Kokusho [30] performed a series of cyclic triaxial tests on isotropically consolidated saturated Toyoura sand (void ratios: 0.64 – 0.80) subjected to specified effective confining stress (19.6 kPa - 294 kPa) and frequency (0.02 Hz - 0.1 Hz) and reported about the influence of void ratio on the strain dependent shear modulus and damping ratio (Fig. 12). It was observed that shear modulus decreases with increase of void ratio. Dash and Sitharam ([38], [39]) performed tests at constant gross void ratio approach, constant sand skeleton void ratio approach, and constant interfine void ratio approach to study the effect of non-plastic fines on pore pressure response of sand–silt mixtures. At a constant gross void ratio, the rate of generation of excess pore water pressure increased drastically with the increase in silt content [till a limiting silt content (≈ 15%)], since the relative density of a specimen decreases with increase in silt content till the limiting value and thereafter, it increases.

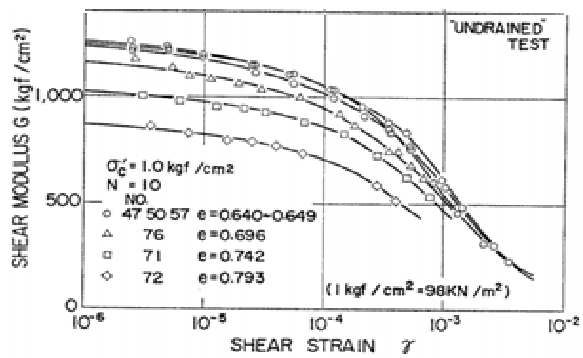

Fig. 12 Shear modulus versus shear strain for σ'_c = 98 kN/m^2 with different void ratios [30]

D. Effects of Method of Loading

Different cyclic loading waveforms like sinusoidal, rectangular and triangular waves are used to evaluate the dynamic properties of soil and the cyclic strength as well. Seed and Chan [40] and Thiers [41] have investigated that the triangular loading waveform gives 5 – 20% higher strength than the rectangular loading. Generally, sine wave is used for cyclic loading which gives approximately 30% higher cyclic strength than the rectangular or triangular wave forms as represented in Fig. 13 [42].

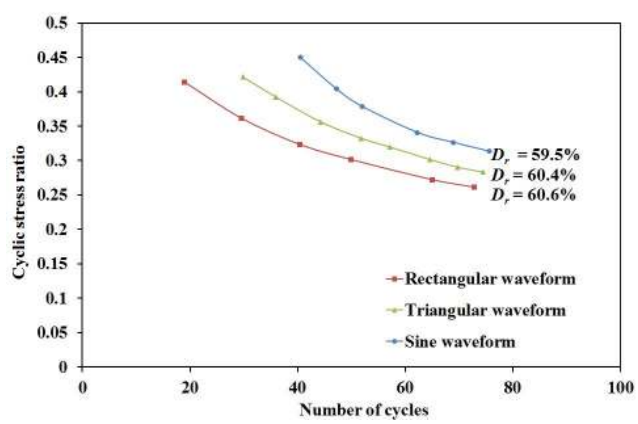

Fig. 13 Effect of loading waveform on cycles to initial liquefaction for moist tamped specimens [adapted from 42]

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E. Effects of Overconsolidation Ratio

The overconsolidation ratio (OCR) is a geotechnical parameter, which represents the historical changes in state of stress in the subsoil. The stress history, as indicated by the profile of OCR, of a soil deposit is one of the most dominant factors that influence the engineering behaviour of the soil [43]. Ishihara et al. [20] performed a series of cyclic triaxial tests on reconstituted and undisturbed sandy soil containing fines in the range of 0-100% as represented in Fig. 14. The reconstituted specimen was overconsolidated to OCR range of 1.0-2.0. The rate of gain in cyclic strength due to overconsolidation increases with an increase in fines content or a decrease in mean grain size of the soil specimens.

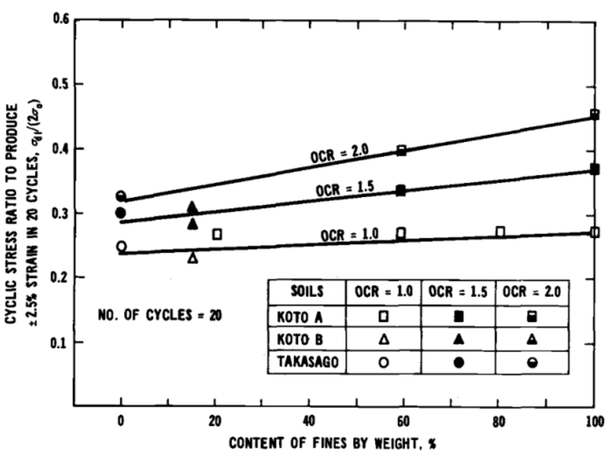

Fig. 14 Relationship between cyclic strength and content of fines in soils [20]

F. Effects of Excitation Frequency

Based on the experimentation for a wide range of excitation frequency, Hardin [44] had reported that the damping behaviour of dry sand is independent of the frequency. This concept has been widely accepted and applied in the ground response analysis in frequency domain. However, if the soil damping becomes frequency dependent, the analysis in frequency domain is not valid, and it will be very complicated to analyse the ground response and soil-structure interaction accounting for frequency effect of soil damping. Lee and Fitton [45] reported that the lower loading frequency produced slightly lower strength. However, Wong et al. [23] and Wang [46] reported that the slower loading frequency gives slightly higher strength, which is in contrast to the above-mentioned finding. Based on the both resonant column and cyclic torsional shear tests performed by Lin et al.[31, 47] (Figs. 15 and 16) and cyclic triaxial tests by GovindaRaju [5] (Figs. 17 and 18), it has been observed that the shear modulus is not significantly affected while damping ratios are significantly affected by the excitation frequency. Dash and Sitharam [40, 41] have identified that the rate of excess pore pressure generation increased with the increase in frequency and magnitude of loading. At shear strain amplitude of 0.4 %, GovindaRaju [5] studied the effect of loading frequency on pore pressure generation with number of loading cycles on Assam sands, which demonstrated that the difference between the amounts of pore water pressures at any given cycle is not much pronounced in the range of frequencies 0.2 - 3.0 Hz.

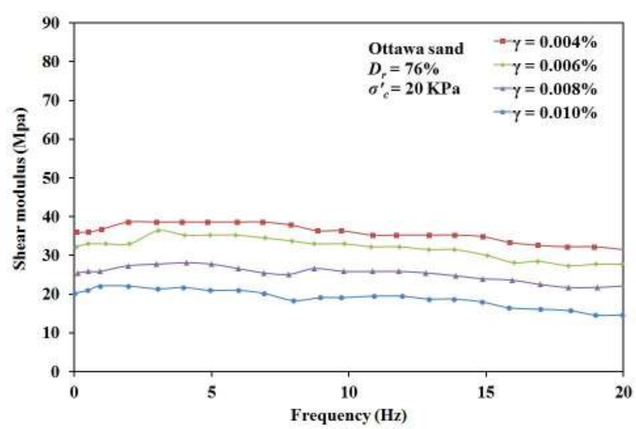

Fig. 15 Variation of shear modulus with frequency of Ottawa sand [adapted from 31]

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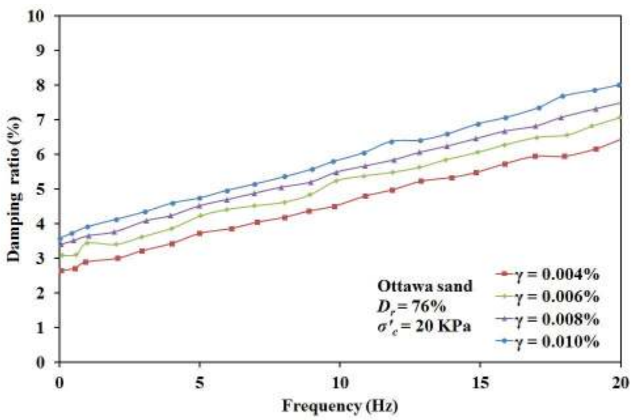

Fig. 16 Variation of damping ratio with frequency of Ottawa sand [adapted from 31]

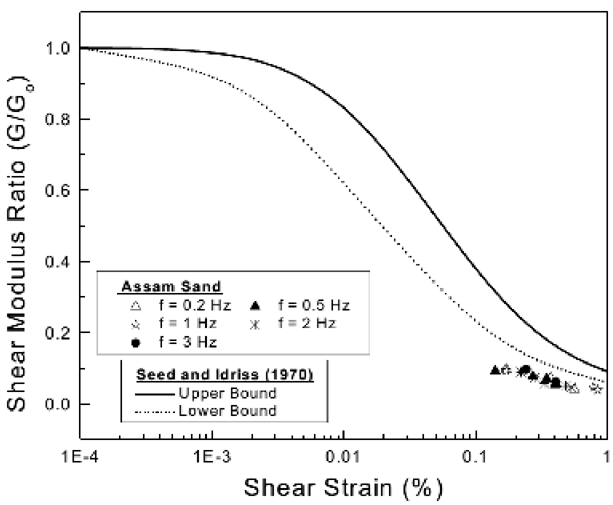

Fig. 17 Variation of normalized modulus ratio with shear strain for different frequencies [5]

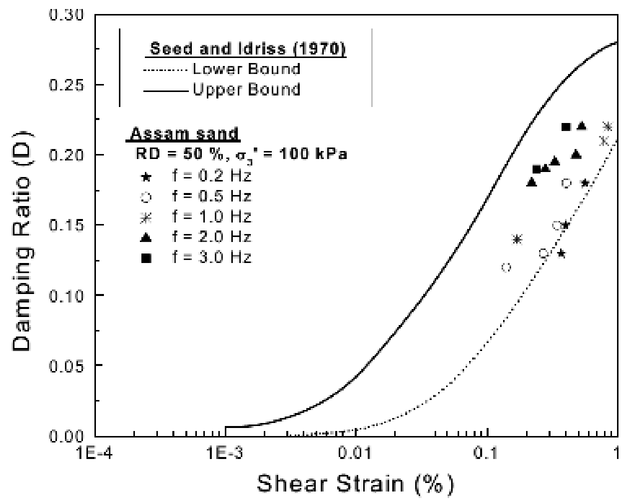

Fig. 18 Variation of damping ratio with shear strain for different frequencies [5]

G. Effects of Soil Plasticity

Vucetic and Dobry [48] studied the influence of the plasticity index (PI) on the cyclic stress-strain parameters over normally consolidated and overconsolidated (OCR = 1–15) clay (Figs. 19 and 20) and reported that, compared to the soils with a lower PI, soils with higher plasticity tend to have a more linear cyclic stress-strain response at smaller strains and degrades less at larger shear strain (γ_c). Puri [49] and Prakash and Puri [50] conducted an experimental investigation on the cyclic strength of undisturbed and reconstituted samples of a loessial soil at different plasticity index values. It has been seen that the cyclic stress ratio causing the 5% double amplitude axial strain condition increases with an increase in the plasticity index (Fig. 21). However, Prakash and Sandoval [51] performed stress controlled cyclic triaxial tests to investigate the effect plasticity index on the liquefaction potential of silty soils of low plasticity and reported that the cyclic stress ratio causing liquefaction at a given number of cycles decreases with the increase in plasticity index (Fig. 22).

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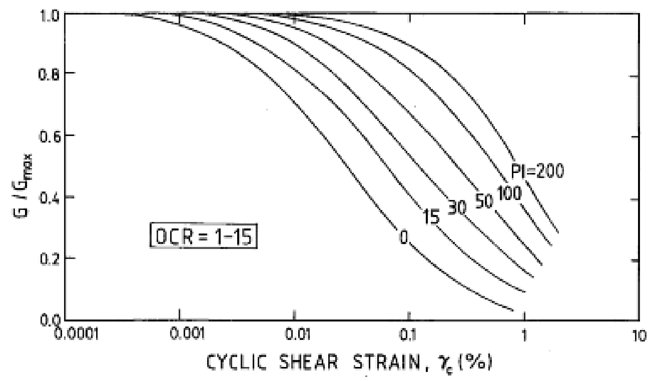

Fig. 19 Correlations between G/G_{max} and Plasticity Index (PI) for normally and overconsolidated soils [49]

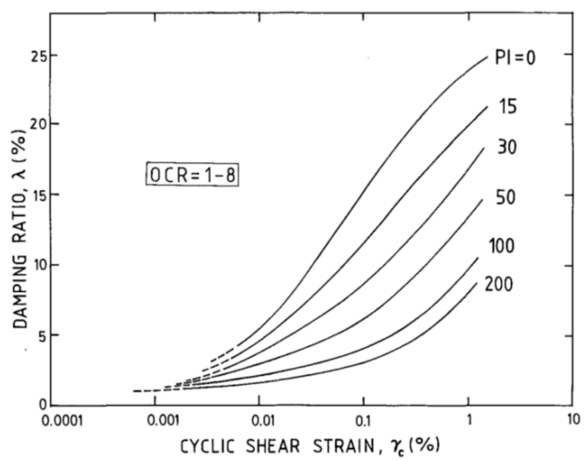

Fig. 20 Correlations between damping ratio and Plasticity Index (PI) for normally and overconsolidated soils [49]

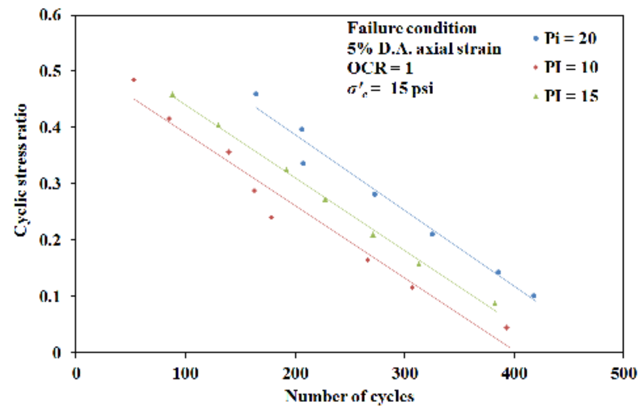

Fig. 21 Cyclic stress ratio versus number of cycles for reconstituted saturated samples for different PI values at 5% D. A. axial strain [50]

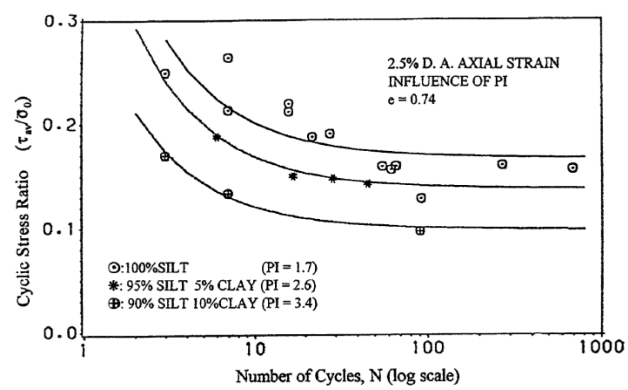

Fig. 22 Cyclic stress ratio versus number of cycles for low plasticity silts at 15 psi effective confining pressure; PI = 1.7, 2.6, and 3.4, for density 97.2 – 99.8 pcf [51]

H. Effects of Percentage Fines

Most of the earlier researches were focused on clean sands with an idea that presence of fines in a sand deposit resists the development of pore water pressure. However, large scale liquefaction related failures in silty sand deposits in earthquakes of recent past changed this idea and most of the present research are more focused on the influence of fines in controlling the pore pressure response and hence the liquefaction behaviour of sandy soils. The pore pressure generation is dependent on the

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deformational characteristics of silty sands which is quite different from that of clean sands. Seed et al. [52] have reported that the liquefaction resistance of sand is not influenced by fines unless the fines comprise more than 5% of the soil. Ishihara and Koseki [53] have also observed that the low plastic fines (PI<4) does not influence the liquefaction potential. Hanumantharao and Ramana [54] performed stress and strain controlled undrained cyclic triaxial tests on remoulded sand and sandy slit (silt content: 0 – 100%) specimens of 70 mm diameter and 140 mm height under a sinusoidal loading at 1 Hz frequency for evaluating the modulus reduction and damping curves (Figs. 23 and 24) and reported that the shear modulus is not significantly affected, although with the increase in silt content, the damping ratio was observed to decrease.

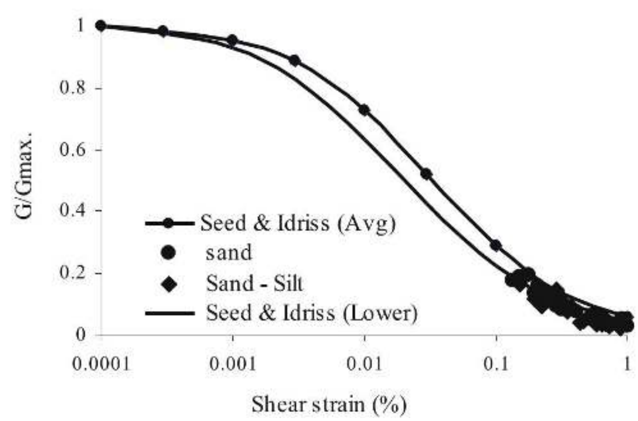

Fig. 23 Normalized shear modulus (G/G_{max}) versus shear strain [54]

Palito and Martin [55] have conducted undrained cyclic triaxial tests on Yatesville and Monterey No. 0/30 sand with non-plastic silt to evaluate the effects of non-plastic fines on the liquefaction susceptibility of sands. It was observed that the liquefaction resistance increases with increasing silt content for a given value of the sand skeleton void ratio for Yatesville sand, however, the similar trend was not observed for Monterey sand (Fig. 25). Zlender and Lenart [56] have reported that the liquefaction resistance of lacustrine carbonate silt is higher than that of clan sand.

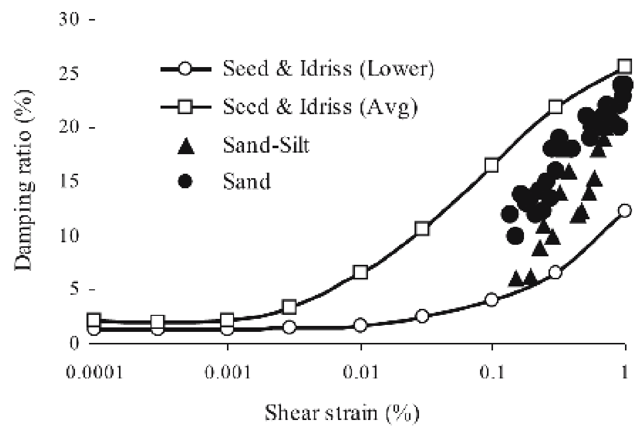

Fig. 24 Damping ratio versus shear strain [54]

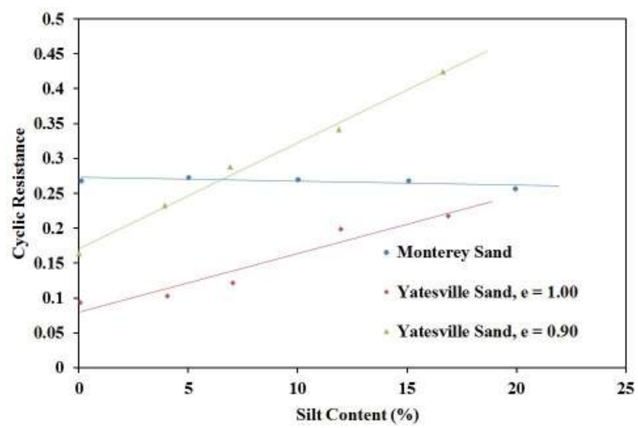

Fig. 25 Variations in cyclic resistance with silt content at constant sand skeleton void ratio for Yatesville sand and Monterey sand [adapted from 55]

IV. CONCLUSIONS

The effects of testing procedures and material characteristics on the cyclic strength and dynamic properties of different soils were reviewed. It has been observed that dynamic properties of soils are affected by many factors like: method of sample preparation in laboratory (intact and reconstituted samples), relative density, confining pressure, methods of loading, overconsolidation ratio, loading frequency, soil plasticity, percentage of fines and soil type. Summary of the observations are as follows.

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- The weakest (loose) specimens were formed by air-pluviation technique, while strongest (dense) formed moist-vibration technique. Unlike shear modulus, damping ratios were not significantly affected by methods of sample preparation. Intact specimens are found to be stronger (higher shear modulus) than the reconstituted specimens, their strength being governed by the reconstitution methods adopted.
- Shear modulus, damping ratio and liquefaction are significantly influenced by confining pressure. As the confining pressure increases, the shear modulus increases and damping ratio decreases. Subjected to higher confining pressure, the number of loading cycles required for liquefaction increases.
- Densification or reduction in void ratio of soils due to confining pressure and method of sample preparation lead to increase cyclic strength.
- Cyclic loading or excitation waveform affects the dynamic response of the specimen. Sinusoidal waveform loading gives approximately 30% higher cyclic strength than the rectangular or triangular waveforms.
- The rate of gain in cyclic strength due to overconsolidation increases with an increase in fines or a decrease in mean grain size of the soil specimens.
- Frequency of cyclic loading does not significantly affect the shear modulus, although there is a significant influence on the damping ratio.
- Shear modulus, damping ratio and liquefaction parameters are also significantly affected by the quantity of plastic and non-plastic fines/silts present in the specimen.

Few contradictory observations related primarily to the effect of sample preparation and excitation/loading frequency on the dynamic properties of soil were also reported in the literature. For a better comprehension of the subject, further investigations on dynamic properties of soil are required to critically identify the influence of different parameters, so that the outcome of the understanding can be used more fruitfully for further research and practical application.

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