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General Report —Session III: Liquefaction and Ground Failure

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General Report - Session III
Liquefaction and Ground Failure

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INTRODUCTION

Since the earthquakes of 1964 in Niigata, Japan and Alaska, USA, considerable studies have been conducted on the subject of earthquake induced liquefaction. These studies have led to progress in understanding the liquefaction phenomenon, in the assessment of liquefaction potential, and in the engineering solutions to mitigate the liquefaction hazard. Many aspects of the liquefaction, however, remain controversial as seen in the many stimulating papers presented in this session.

The 26 papers in this session may be conveniently divided into the following categories:

1. Evaluation of liquefaction susceptibility (12 papers)
2. Settlements and horizontal displacements (7 papers)
3. Remedial measures (4 papers)
4. Simplified assessment of liquefaction potential (3 papers)

The authors represent 11 countries: Canada, China, England, France, Italy, Japan, Kuwait, Russia, Singapore, Sweden and USA. The growth of interests in a world-wide scale is noteworthy in the subject of liquefaction and ground failure.

In what follows, a certain perspective will be offered to organize the discussion on the subject of liquefaction and ground failure. To do justice to the individual papers by offering concise introduction with specific praise or criticism is out of the scope of this report.

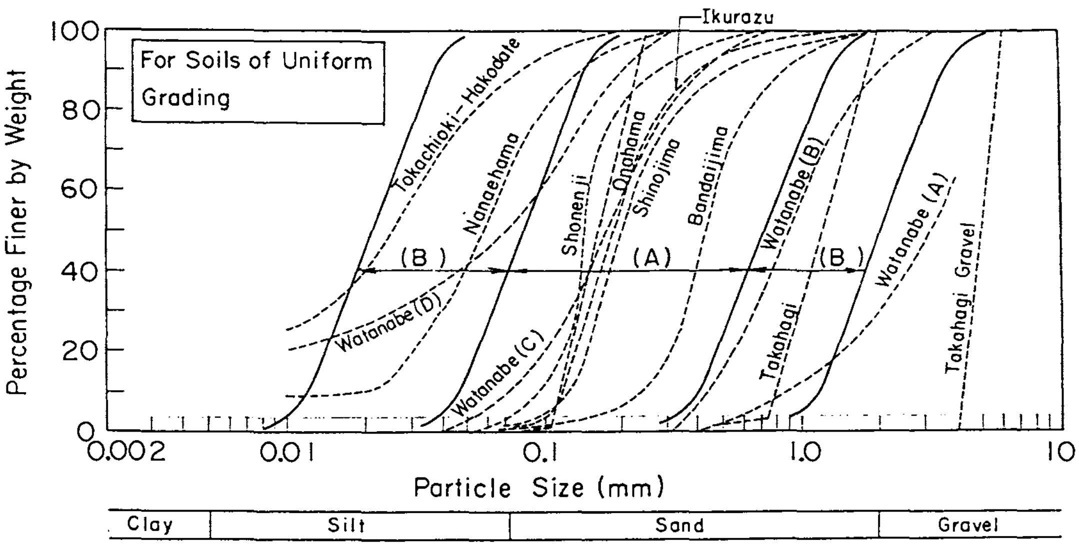
EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

As early as in 1970, types of liquefiable soils were known to the geotechnical engineers in terms of gradation curves of soils as shown in Fig. 1 (Tsuchida, 1970); the zone (A) represents high possibility of liquefaction, the zone (B) moderate possibility, and the rest low possibility. A background to this chart was an understanding that clayey soils do not liquefy because of its plasticity nor do coarse grained soils because of its high permeability but only those soils which are neither plastic nor highly permeable, i.e. sandy soils, do liquefy.

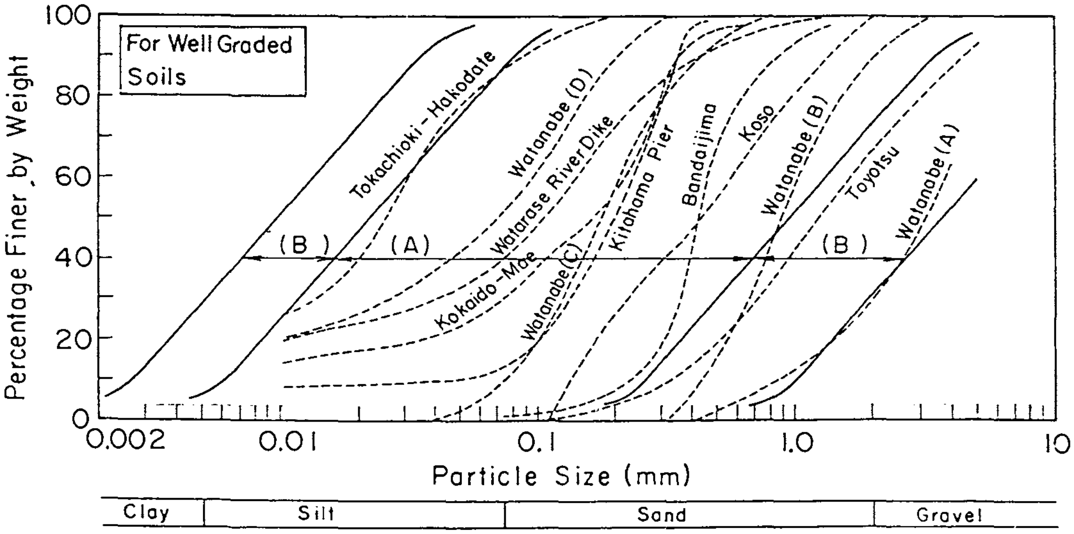
Our knowledge and understanding of the liquefiable soils have been increased by well-documented field observations, carefully conducted in-situ and laboratory testing, and development of realistic soil models, as presented in 12 papers in this session.

Disturbance during tube sampling of sands is known to dramatically change the results of cyclic loading test of loose and dense sands. The effect of the sampling disturbance, however, may be corrected by cyclic prestraining (i.e. cyclic loading of 10,000 cycles or more under drained condition with a double amplitude axial strain of about 0.1 %) as discussed by **Pelli, Tokimatsu, Yoshimi and D'Appolonia** (3.13). A shear modulus is used as a controlling index to link the state of a prestrained sample to the soil in-situ. A careful look should be given, however, to the method for measuring the shear modulus in the laboratory. For example, **Tatsuoka and Shibuya** (1992) found through careful laboratory testing that the shear modulus at very small strains (less than 0.001%) was not altered by the cyclic prestraining as shown in Fig. 2 whereas the undrained cyclic resistance increased considerably by the application of the cyclic prestraining as shown in Fig. 3. This is contradictory the approach adopted by **Pelli, Tokimatsu, Yoshimi and D'Appolonia** (3.13). To resolve this controversy will lead us to better fundamental understanding of elastic and plastic properties of soils as well as much better practice and standardization of laboratory testing.

The use of in-situ freezing method to obtain undisturbed samples of clean sands have been developed since mid 1970s and is known to give minimum disturbance during sampling of sands and coarse grained soils (**Yoshimi et al., 1994**). Increasing number of samples are obtained by this technique. This technique is used to obtain a reliable CPT correlation by **Suzuki, Tokimatsu, Taya and Kubota** (3.22). This technique is also used to assess the stability of an existing dam as reported by **Pillai, Plewes and Stewart** (6.25). The technique is also used by **Kokusho, Tanaka, Kudo and Kawai** (3.20) to evaluate liquefaction resistance of volcanic debris flow gravel with a mean diameter of 30 mm. The use of in-situ freezing method should continue to be encouraged for clean sands and coarse grained soils. This will lead us to more reliable field correlation for assessing liquefaction susceptibility. In this regard, a fundamental study to look into the nature of the in-situ test such as shown by **Saitta, Canou and Dormieux** (3.33) should be encouraged for linking the constitutive parameters of soils to the in-situ test results. The efforts along this line of work will solve to a certain extent a controversy over correlation



(a) For Soils of Uniform Grading



(b) For Well Graded Soils

Fig. 1 Ranges of Gradation Curves of Liquefiable Soils (after Tsuchida, 1970)

of elastic and plastic properties of soils mentioned earlier. Development of new in-situ testing techniques is also encouraged such as the use of resistivity and dielectric constants as discussed by **Kaya and Fang** (3.54).

As better and better quality of sampling of soils is conducted to preserve its in-situ state, our understanding of the state of soil in-situ will be expanded. The state of soils may be represented by such factors as current in-situ stress state and its history, intrinsic anisotropy and fabric of soils and the effects of aging. Studies on these aspects of soils are encouraged. The examples are the study on the effects of static shear stress and the effects of confining pressures varied over a wide pressure range such as reported by **Pillai, Plewes and Stewart** (6.25), the study on effects of fabric anisotropy by **Miura, Yagi and Kawamura** (3.06), and the study on the effects of thixotropy of fines by **Voznesensky** (3.51).

Up to recent years, considerable studies have been conducted on clean sands, which is recognized as most susceptible to liquefaction as shown in Fig.1. Since mid 1980's, studies on soils other than clean sands has been conducted and continue to be encouraged. The efforts should include not only those in laboratory studies such as seen in **Erken, Ansal and Alhas** (3.51) but also in-situ studies such as seen in **Kokusho, Tanaka, Kudo and Kawai** (3.20) and **Miura, Yagi and Kawamura** (3.06) based on actual case history during earthquakes.

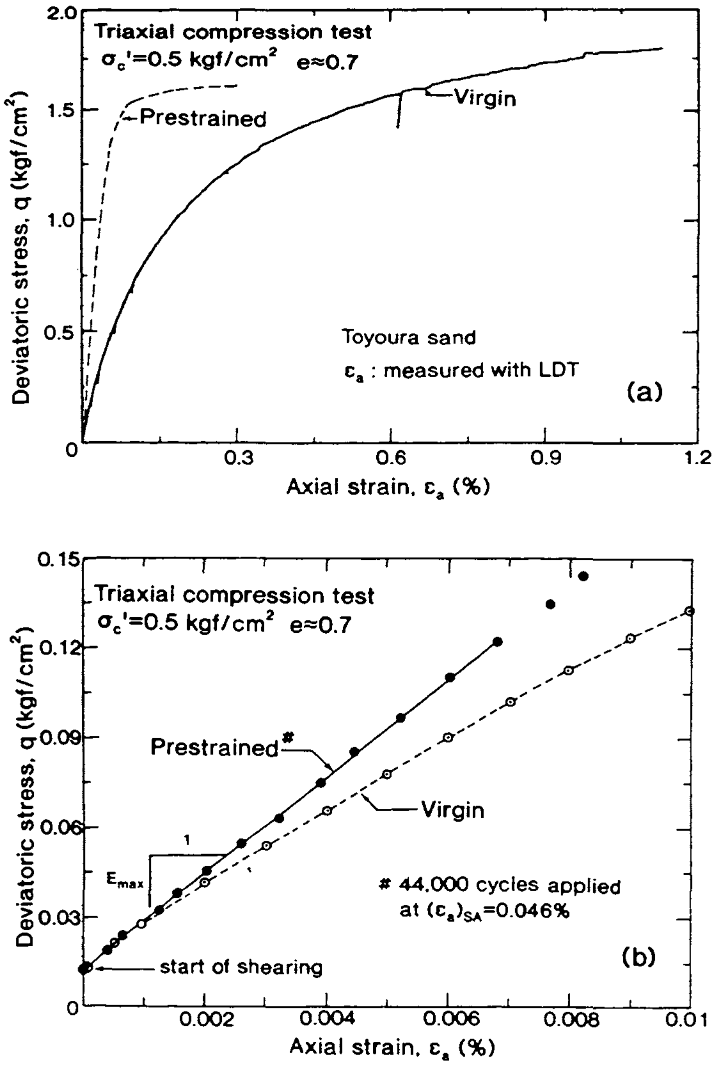


Fig. 2 Stress-strain relations of Toyoura sand at virgin and cyclic-prestrained conditions plotted in (a) large and (b) small strain scales (after Teachavorasinskun, 1991, as reported by Tatsuoka and Shibuya, 1992)

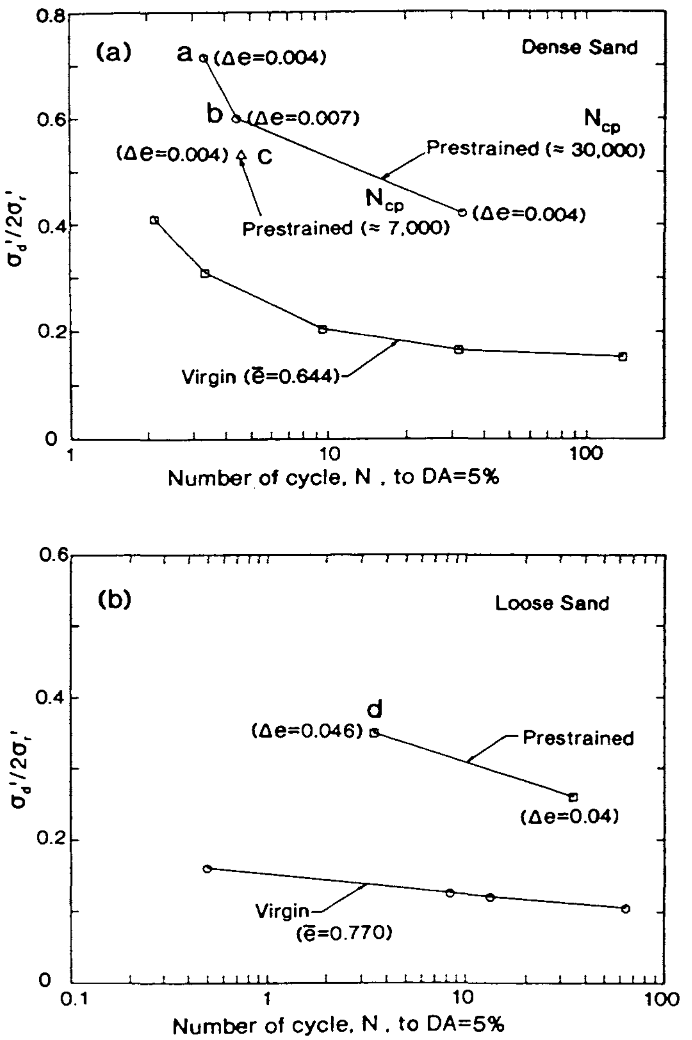


Fig. 3 Cyclic undrained resistance of Toyoura sand at virgin and cyclic-prestrained conditions; (a) dense and (b) loose Toyoura sand (after Kenkyo et al, 1991, as reported by Tatsuoka and Shibuya, 1992)

Less studied area of liquefaction of in-situ ground is the effects of spacial variability of ground conditions. **Popescu, Prevost and Vanmarcke (3.35)** presents one of the pioneering attempts to evaluate those effects through a stochastic analysis. This study may pose us a challenging question as to what types of in-situ testing techniques we have to develop for efficiently investigating the horizontal variability of ground other than doing a lot of boring or penetration testing.

Constitutive modeling of soils will be discussed in other sessions but obviously this should play an important role in our understanding of liquefaction of soils. Its modeling include simulation of generation of excess pore water pressures during cyclic loading such as discussed by **Hwang and Chen** (3.11) and **Figueroa, Saada and Liang (3.07)** but more and more attention will be paid for simulation of deformation of soils at post-liquefaction phase such as discussed by **Byrne and McIntyre (3.49)**. Overall current status of the predictive ability (in CLASS A prediction) of constitutive models may be seen in NSF funded research project **VELACS (Arulanandan and Scott, 1993)**.

SETTLEMENTS AND HORIZONTAL DISPLACEMENTS

Liquefaction as observed in the field takes various forms such as sand boils, settlements, lateral spreads, loss of shear resistance and flow slides. Among these forms of liquefaction, settlements and horizontal displacements may be conveniently chosen as two of the representative quantities to evaluate the effects of liquefaction at post-liquefaction stage as seen in 7 papers in this session. The Rankine lecture by **Ishihara** (1993) offers many stimulating results and views and adds more momentum to accelerate the progress in the study currently on-going in this field. For example, clear definitions are given to the different states of soils such as the Steady State and the Quasi Steady State by **Ishihara (1993)** as shown in Fig.

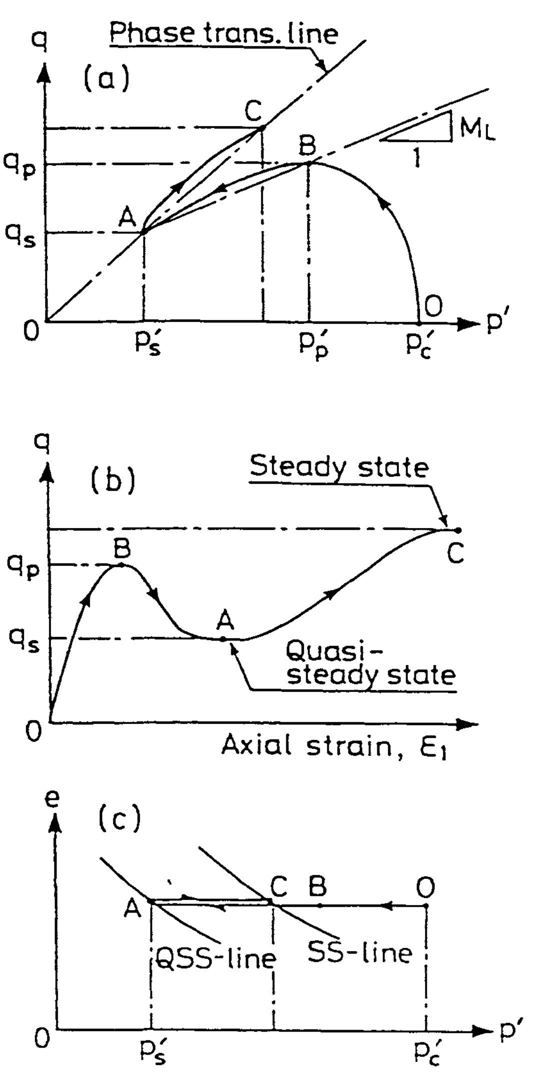


Fig. 4 Characteristics of undrained behavior of loose sand (after Ishihara, 1993)

4, leading to dissolve the existing confusion of terminology occasionally seen in the literatures.

Settlements of level ground can be a fundamental quantity because of their direct relevance to plastic volumetric strain of soils such as seen in **Shamoto, Sato and Zhang (3.15)** for clean sands and **Jian and Yasuhara (3.44)** for clays. Settlements of a structure resting on liquefiable ground, however, is another matter because they are governed by the loss of shear resistance of foundation soils (i.e. loss of bearing capacity) as well as plastic volumetric strain of soils such as discussed by **Liu (3.39)**. It is seen in these studies that a fundamental issue still remains controversial as to what constants of foundation soils we should choose (and what constants we can forget) to better quantify the liquefaction induced settlements.

Horizontal displacements of ground has a significant effects on long buried structures such as lifeline facilities. Extensive set of case history data on the horizontal displacements has been compiled by **Hamada and O'Rourke (1992)**. These case history data, as discussed by **Satoh, Hamada, Isoyama and Hatakeyama (3.17)**, suggest that the horizontal displacements D (m) may be estimated from the thickness of liquefiable layer H (m) through the following empirical relations.

$$D = 0.34H \quad \text{in urbanized area} \qquad (1)$$

$$D = 1.20H \quad \text{in non-urbanized area} \qquad (2)$$

These relations indicate that we need to evaluate the post-liquefaction behavior of sands in the strain levels ranging from D/H = 34% to 120% or greater. **Yasuda, Yoshida, Masuda, Nagase and Kiku (3.40)** and **Towhata (3.21)** are now successful in dealing with the post-liquefaction behavior of sand in these strain levels. The studies dealing with these large strain levels are encouraged.

Understanding as to the mechanism of horizontal displacements, however, remains controversial. One approach is to adopt residual strength (i.e. steady state strength) of soils as a fundamental quantity to govern the horizontal displacements. In this approach, a sliding block type analysis is conducted to estimate the horizontal displacements. The other approach is to regard horizontal displacements as a consequence of "limited liquefaction" in which a limiting shear strain mobilized by cyclic loading governs the horizontal displacements. The laboratory study by **Yasuda, Yoshida, Masuda, Nagase and Kiku (3.40)** is conducted along the latter approach. To resolve the controversy, shaking table tests using unusually loosely deposited sand such as presented by **Towhata (3.21)** should be encouraged.

Effects of liquefiable sand lenses may also affect the horizontal ground displacements as discussed by **Holchin and Vallejo (3.30)**. Much remains to be done on the effects of the variability of ground as mentioned earlier.

REMEDIAL MEASURES

After we have learned so much about liquefaction potential and liquefaction hazards, growing attentions are now directed towards developing efficient remedial measures against liquefaction and improving our design practice in liquefaction remediation.

Number of case histories on implementation of liquefaction remediation has been increased in recent years, forming a basis for a useful guideline in the implementation of remediation measures such as presented by **Armijo, Sola and Oteo (3.01)**. Case history data on the effects of liquefaction remediation measures during strong earthquakes have been recovered from recent large earthquakes in Japan in 1993 and 1994 and will be soon reported in detail. Obviously these case history data are the seeds of research and the source of wisdom and are encouraged to be compiled and reported to the geotechnical engineering community. Field instrumentation to monitor the performance of liquefaction remediation measures during strong earthquake shaking is continued to be encouraged.

Liquefaction remediation often requires innovative ideas. An innovative combination of several remediation measures can often offer a good solution to mitigate liquefaction induced damage such as presented by **Raison, Slocombe, Bell, and Baez** (3.02).

Design of liquefaction remediation includes designing of area of ground improvement such as discussed by **Tanaka, Komine, Tohma, Ohtomo, Tochigi, Abe and Fukuda** (3.34). It is most often that deformation of foundation becomes the key parameter in optimum design of area of ground improvement such as presented by **Atukorala, Wijewickreme, Fitzell and McCammon** (3.19). To improve our current design procedure in terms of both cost and reliability, development of deformation-based design is encouraged.

SIMPLIFIED ASSESSMENT OF LIQUEFACTION POTENTIAL

The decade of 1990s is the International Decade for Natural Disaster Reduction (IDNDR). More and more attention is paid towards natural hazard reduction in developing countries. In the assessment of liquefaction potential in these countries, a simplified procedure plays a major role. The Standard Penetration Test (SPT) is often conducted for assessment of liquefaction potential as seen in the case of Bangladesh as reported by **Mollah** (**3.38**) and in the case of Costa Rica as reported by **Hafstrom, Skogsberg and Bodare** (**3.14**). The neural network may have a potential to be a useful tool for simplified assessment as discussed by **Goh** (**3.31**). In developing countries, however, it is often necessary to adopt a methodology which does not require in-situ geotechnical testing. To solve this problem, the **Technical Committee for "Earthquake Geotechnical Engineering", TC4, of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE)** compiled a manual for zonation on seismic geotechnical hazards (TC4, ISSMFE; 1993). Further efforts for IDNDR is called for from our geotechnical earthquake engineering society.

ISSUES FOR DISCUSSION

The reporter presents the following comments and questions for discussion. Some of the fundamental and important issues for discussion originally raised by **Campannela and Sy** (**1991**) are also included here to see the progress in our understanding since 1991. Early submission of written discussions is encouraged. Please come prepared to discuss some of the following issues or others raised in this general report.

1. The in-situ shear modulus can be obtained from shear wave velocity measured with surface wave testing technique or with conventional crosshole or downhole methods. The use of shear modulus or shear wave velocity for liquefaction susceptibility evaluation purports to show considerable promise, or does it ? How well can we answer the following fundamental question on the soil behavior: does the elastic behavior of soils in the small strain levels closely correlate with the plastic behavior of soils in larger strain levels ?

2. Increasing number of quality undisturbed samples, such as those retrieved by in-situ freezing technique, have become available for laboratory testing of soils, preserving its in-situ state or close approximation of it. The state of soils may be governed by such factors as current in-situ stress state and its history and intrinsic anisotropy and other fabric of soils. Majority of current practice of cyclic loading tests, however, remains to do the cyclic triaxial tests under the isotropic confining stress. Are we fully utilizing the advantage of quality undisturbed sampling in the laboratory testing ?

3. Less studied area of liquefaction of in-situ ground is the effects of spacial variability of ground conditions. Differential settlements and differential horizontal displacements may have a significant effects on lifeline facilities. How are we going to approach for this issue ? Do we have to develop a new types of in-situ testing technique for efficiently measuring the horizontal variability of ground ?

4. Predicting settlements of liquefiable level ground and a structure resting on it may be one of fundamental issues in liquefaction induced deformation. How well can we predict the settlements ? What are the most important constants we need to measure (and what are the constants we can forget) for reliable but simple estimation of settlements ?

5. Predicting horizontal displacements of ground is another important issue in liquefaction induced deformation of ground. The observed horizontal ground displacements at post liquefaction stage are associated with the soil behavior in the shear strain levels ranging from 34% to 120% or greater. How well do we understand the properties of sands ? Are we confident, for example, that the shear resistant angle and the permeability of sands remain constants ? Isn't it about time that we concentrate efforts on testing soils in the post-liquefaction stage ?

6. Understanding as to the mechanism of horizontal displacements remains controversial. One approach is to adopt residual strength (i.e. steady state strength) of soils as a fundamental quantity to govern the horizontal displacements. In this approach, a sliding block type analysis is conducted to estimate the horizontal displacements. The other approach is to regard horizontal displacements as a consequence of "limited liquefaction" in which a limiting shear strain mobilized by cyclic loading governs the horizontal displacements. How are we going to resolve this controversy ?

7. In designing remedial measures against liquefaction, deformation of soils often poses a problem. For example, densified sand is rather stable unlike loose sand against cyclic loading but exhibit cyclic mobility phenomenon, in which shear strain gradually increases as cyclic loading goes on. How are we going to incorporate the deformation of soils in our simplified design practice ? Do we need to develop a new methodology which is more realistic than the Newmark-type analysis yet much

simpler than the fully-coupled elasto-plastic analysis ?

8. The decade of 1990s is the International Decade for Natural Disaster Reduction (IDNDR). Attention is paid towards natural hazard reduction in developing countries. In the assessment of liquefaction potential in these countries, simplified procedure plays a key role. It is often necessary to adopt a methodology which does not require in-situ geotechnical testing. How are we going to solve this problem ?

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