Load path and loading velocity as potential condition indicator for liquefaction of silty soils

Chemin et vitesse de chargement comme indicateurs de condition potentiels pour la liquéfaction des sols limoneux

J. Laue & J. Buchheister
Institute for Geotechnical Engineering, Swiss Federal Institute of Technology Zurich, Switzerland

ABSTRACT

Condition indicators for liquefaction are mainly given by the soil properties gained from gradation curves and empirically, using relationships between number of SPT blows or CPT results and liquefaction potential. Recent earthquake events as well as recent studies have shown that silty soils, which had been thought to be less prone to liquefaction than sands, are still likely to liquefy. Therefore, the influence of the loading path, and in particular the loading velocity and loading direction, on the liquefaction susceptibility of silty soils will be discussed. It can be deduced that the earthquake profile as well as the boundary conditions related to loading functions have a significant influence on the liquefaction susceptibility. Also liquefaction observed in the field is not only to be related to the liquefaction of the soil under the free field boundary conditions but the reduction of effective stress during an earthquake has to be regarded in terms of the actual stress interplay in the subsoil. The “starting” conditions as well as the influence of the loading function (frequency and form, stress ratios) will be discussed based on a literature review, which will be enhanced in the future with results obtained with the new cyclic hollow cylinder apparatus. The results will be introduced in a new concept of risk management for earthquakes for buildings and lifelines in an urban environment.

RÉSUMÉ

Des indicateurs de condition pour la liquéfaction sont principalement donnés par les propriétés du sol, par exemple, par les courbes granulométriques, ou par corrélation empirique des résultats de reconnaissance de site. Dans des tremblements de terre récents, ces indicateurs de condition ont été trouvés moins valides car les sols limoneux ont montré une probabilité élevée de liquéfaction. Pour expliquer ceci, l'influence du chemin de chargement (vitesse de chargement et direction de chargement) sur la susceptibilité de liquéfaction des sols limoneux doit être discutée car ils ont une influence significative. En outre, la liquéfaction observée dans un environnement urbain doit être considérée en termes d'interaction de tensions dans le sous-sol au-dessous d'une fondation ou dans une pente. L'influence de la fonction de chargement (fréquence et forme, rapports de tensions) sera discutée a basé sur une recherche dans la littérature, et sera améliorée à l'avenir avec des résultats obtenus avec le nouvel appareillage cyclique de cylindre creux de l'institut de géotechnique. Les résultats seront présentés dans un nouveau concept de gestion des risques pour des tremblements de terre pour des bâtiments et des lignes de sauvetage dans un environnement urbain.

1 INTRODUCTION

Establishing the liquefaction susceptibility of soils is one of the main objectives of any risk assessment or risk management procedure. In typical microzonation projects, the assessment is done using classical analogues as given e.g. by the well known graduation curves, the “modified Chinese criteria” (Finn et al., 1994) or correlations of soils, which have been known to be liquefied under earthquakes and the respective number of SPT blows measured after the event (e.g. Youd et al., 2001). These criteria are still used as the state of the art and have to be enhanced for new situations e.g. Iyisan (1996) for the Kocaeli region in Turkey. The disadvantage of the criteria described above is their limitations given by their derivation. Gradation curves and the modified Chinese criteria are based on the knowledge of the detailed soil conditions and they require more detailed testing of the soils are to be found in the critical range. The correlations of soundings and liquefaction susceptibility are highly dependent on a wider range of other boundary conditions (magnitude of the earthquake among others) and are not directly related to the state, kind and conditions of the subsoil, so that the physical behaviour of the soil in an earthquake might be neglected while applying those indicator automatically in a microzonation project (compare Fig.1 and Fig.2). Certain areas in the city of Adapazari, detected as prone to high liquefaction susceptibility using SPT correlations in an automatic way (Fig.1), show less liquefaction potential when taking detailed knowledge of the subsoil and other available information into account (Fig.2). Thus, neglecting main influencing variables in determination of risk can lead to unsatisfactory results.

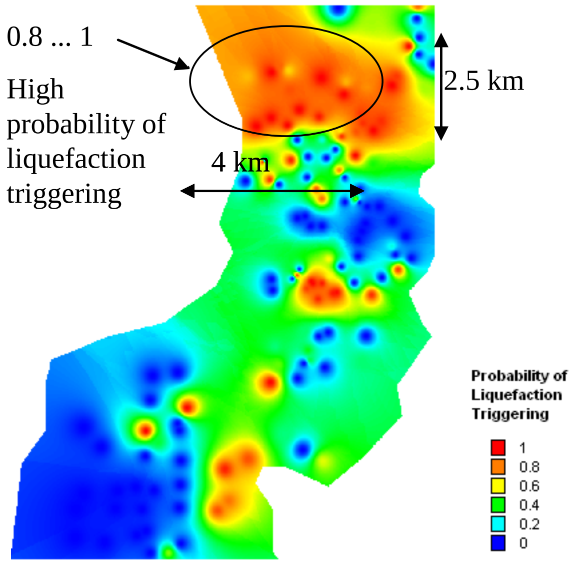

Figure 1. Liquefaction triggering potential of Adapazari after the 1999 Kocaeli earthquake in terms of probability of liquefaction (Cetin, 2003).

In the framework of a recently started project on managing earthquake risk based on decision making by means of a Bayesian net (Bayraktarli et al., 2004) an attempt will be made to formulate condition indicators as a basis for risk assessment and risk management as a function of more detailed influencing parameters such as the type of building or slope as well as their reliability. In addition, the gradation curves and respective state of soils are taken into account. The type of earthquake is crucial as the number of loading cycles as well as the loading velocity determines the increase of pore water pressure causing liquefaction as the worst case. The location of the soil element in question is important to determine the potential hazard to existing buildings or slopes in any environment. In opposite to the usually taken default free field stress states for determining liquefaction potential higher mobilised shear strength (as obvious in slopes) required less increase of pore water pressure to reduce the stability and leading to failures (e.g. Jacka, 2001).

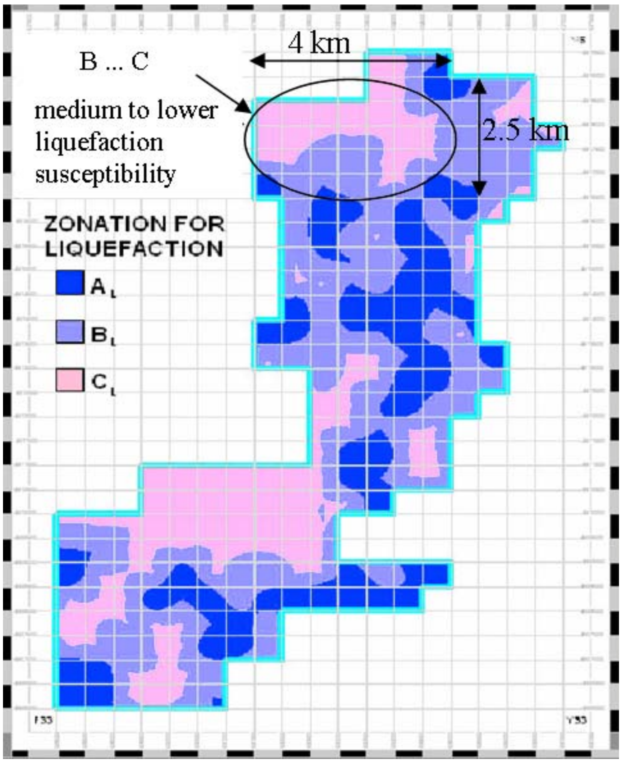

Figure 2. Variation of liquefaction susceptibility in Adapazari. Zone A shows higher, zone B average and zone C shows lower liquefaction susceptibility (Ansal et al., 2003).

2 LIQUEFACTION SUSCEPTIBILITY OF SILTY SOILS

Most studies dealing with conditions leading to liquefaction to date focus on sands (e.g. Dobry et al.,1982; Robertson & Fear, 1997). Fewer studies focus on the cyclic and dynamic behaviour of silts (e.g. Koester, 1994; Erten & Maher, 1995; Xenaki & Athanasopoulos, 2003; Yang et al., 2004).

Clays are only affected minimally in terms of liquefaction due to the inertia of the clay, the plate-shaped structure of the grains and the attracting forces between the particles, large deformations have been observed in silty and clayey soils not only after the 1999 Kocaeli earthquake. This has lead to another deformation based proposed extension of the term liquefaction away from its physical meaning by Ishihara (1993) and relating it, in terms of the potential hazard, to the expected deformation under cyclic loading.

In the case of sands, a lot of influencing factors on liquefaction have been already studied. Even though Mitchell (1993) stated that the attraction forces in silts can be neglected during an earthquake and it is known that the shape of silt grains is similar to that of sand, the research on silts - especially under cyclic and dynamic loading - has not gone into great depth. Nevertheless, in the Kocaeli earthquake 1999 liquefaction or at least large amounts of cyclic mobility of the particles caused deformation in the meter range both in silty sands and sandy silts. This can be seen comparing the well known condition indicator given in Figure 3, which has been adopted in many building requirements (e.g. IAEA, 2002) and is compared with liquefied soils in the area of Adapazari in the Kocaeli 1999 earthquake.

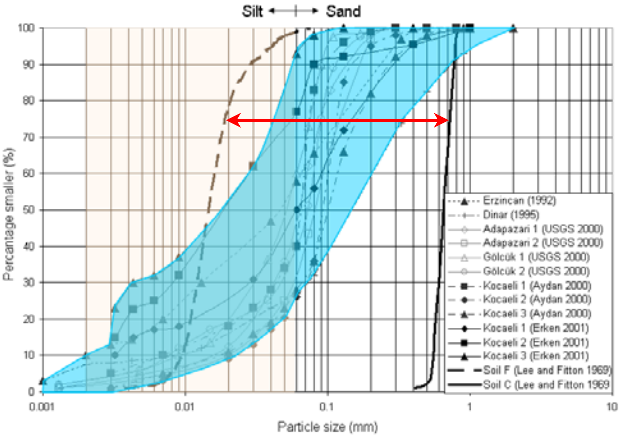

Figure 3. Gradation curves of liquefied silty sands and sandy silts in Turkey in between the boundary curves for liquefaction susceptible soils of Lee and Fitton (1969).

In addition to the less prominent occurrence of liquefaction in silty soils during past earthquakes, another reason for the less available findings are the controversial results, leading to statements by some authors that the process of liquefaction cannot be derived in an analytical way (e.g. Morris, 1983). Thus, until recently, research has not focused in great depth on sand with some amount of silts and from these studies, sands with higher amount of silt have been considered not to have a high liquefaction potential and hence have not been assessed as high risk.

Most laboratory studies on liquefaction focus on the influence of void ratio of the sample on the behaviour under various loading functions, which are in most cases harmonic sinusoidal with frequencies between 0.1 Hz and 1.5 Hz. In most earthquake related studies, the findings under those ideal conditions are related to additional tests exposing the sample to a recorded earthquake reading. For silty soils, variations of the amount of silts are added to the extremes studied for sands. The findings for a higher amount of fines on liquefaction potential are somehow controversial. Reference will be given here to two different studies while a broader summary of available studies from the literature can be found in Laue and Buchheister (2004).

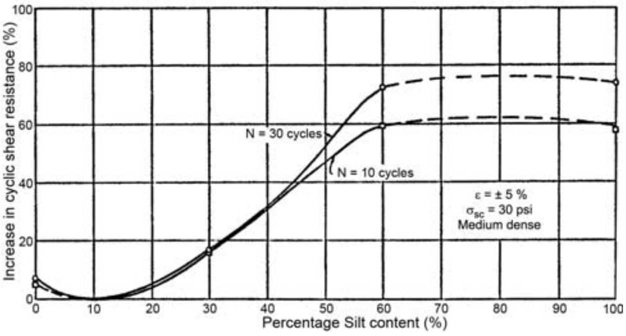

Figure 4. Effect of silt content on cyclic shear resistance (Chang et al., 1982).

Chang et al. (1982) showed an averaged effect of silt content on the cyclic shear resistance based on 68 undrained triaxial tests of sand-silt mixtures (Fig.4). They identified a critical silt content giving the lowest shear resistance for medium dense samples to be 10%. Above a fines content of about 45%, cyclic hardening can be observed upon comparing the available data for 10 and 30 load cycles. They also assume a constant resistance for silt contents higher than 60%, which is supported by findings from Yamamuro et al. (1999), who studied static liquefaction for a wide range of silt contents and found constant probability of liquefaction for fine contents higher than 50%.

On the other hand, results given by Xenaki and Athanasopoulos (2003) identify a fines content between 42% and 44% as most critical for liquefaction (Fig.5). This tendency has been found for void ratios between 0.62 and 0.69.

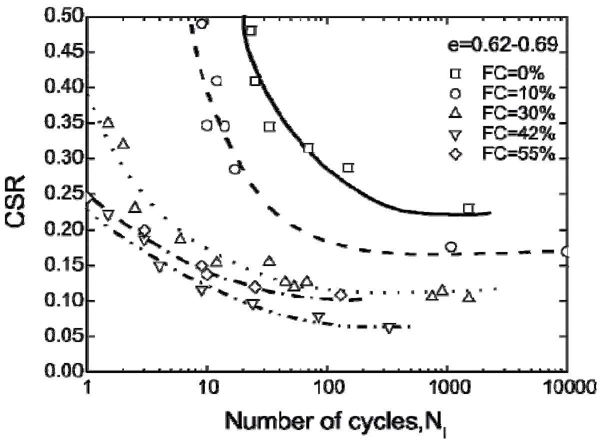

Fig. 5: Effect of fines content on the liquefaction resistance of sand – non-plastic fines mixtures for constant values of global void ratio and varying the cyclic stress ratio (CSR) (Xenaki & Athanasopoulos, 2003).

Findings of other authors seem to support these findings. Erten and Maher (1995) showed that the increase in pore water pressure is significantly reduced above a 60% silt content in a sand sample. This could not be proven by other authors using different soils, void ratios and/or load functions. Koester (1994) stated the lowest resistance against liquefaction in uniformly graded loose sand with fines content between 25% and 30%. Troncoso (1986) indicated that silty sands have only one-half of the liquefaction resistance compared to clean sands.

3 INFLUENCE OF LOADING PATH AND LOADING VELOCITY

Comparing the available studies towards liquefaction susceptibility, it has to be stated that better or additional criteria for liquefaction should be derived. These should not only be based on gradation curve and a cyclic stress ratio (maximum shear stress divided by twice the initial effective confining stress), but should also take into account the loading conditions of a soil element during an earthquake. In previous investigations main variations are given by the load function varying different CSR for a single soil (for void ratios). Loading frequency as representative for different loading conditions is usually only varied among different studies. In most cases the findings of these studies have not been linked to the physics behind pore water pressure built up. Therefore a first attempt will be made here to define a common parameter for a comparison of these studies. For a combined recognition of the soil parameters, the permeability coefficient has to be incorporated. Liquefaction depends on the build up of pore pressures and drainage conditions, while the pore pressure build up depends on the permeability of the material. Therefore BWG (2003) defines the permeability of liquefaction prone soils between $1\cdot10^{-5}$ m/s and $1\cdot10^{-6}$ m/s.

With this assumption it is possible to define a dimensionless parameter k* to relate the boundary conditions of the soil sample with the loading function in terms of CSR, the frequency f and the gravity g.

$$k^* = CSR \cdot k \cdot f / g \qquad (1)$$

In order to compare the available results of the tests, clearly described parameters are most important. Since each study usually focuses on different aspects in the interpretation, information about the soils is given with varying details. Assumptions for the derivation of the dependency of the parameter k* have been made. Most concern has to be related towards the derivation of the permeability, while also the factors of loading frequency and CSR have to be discussed.

Usually the permeability k is never explicitly determined in the available publications. As a starting point the determination of k is based on the formula of Beyer (1966) (eq. 2) has been chosen as most appropriate (Uniformity Index Cu (derived as the quotient of d60/d10) and correction factor c(U)):

$$\text{For } 1 < C_u < 20\text{: } k = c(U)\cdot d_{10}^2 \text{ (m/s)} \qquad (2)$$

Using equation 2 it was possible to derive the permeability index for some of the available studies. However in most cases essential information has not been presented. Koester (1994) e.g. refers to different types of sand by a relative density D_r and void ratio e with a certain amount of fines content, which is only specified further by the Vicksburg buckshot but not in terms of the grain size distribution. Vaid (1994) gives the grain size distribution of the sands but not of the silt. Chang et al. (1982) indicates the soils by the parameter D_{50}. In case of Troncoso (1986), who indicated that silty sands have only one-half of the liquefaction resistance compared to clean sands, detailed description of the material used is missing. The permeability of the herein analysed sands lies around $3.6\cdot10^{-4}$ m/s and $6.2\cdot10^{-5}$ m/s, whereas the silty sands or sandy silts have k-values of up to $1.0\cdot10^{-8}$ m/s.

Further, the influence of the loading function and the cyclic stress ratio have to be taken into account. Here focus is given to studies with regular harmonic loading functions. Those studies can be summarized by loading range and the frequency. For further use of defining indicators based on harmonically loaded laboratory experiments, the findings given by Ishihara and Yasuda (1975) have to be regarded. Earthquake loadings are classified into two types of loadings: vibration and shock type loading. Reaching liquefaction under the vibration type of load function applied on the sand requires smaller stress ratios than for the shock type loading. For some of the studies with defined soils, an average frequency had to be determined as the frequency was not specifically extracted from the reported tests. Xenaki and Athanasopoulos (2003) applied frequencies to the silt-sand samples in the range of 0.1 to 1.5 Hz. Tests taken into account here had cyclic stress ratios between 0.15 and 0.40 and void ratios in the range of e=0.6-0.7. The plasticity index of the fines of the specimen taken into account is low (PI<5%).

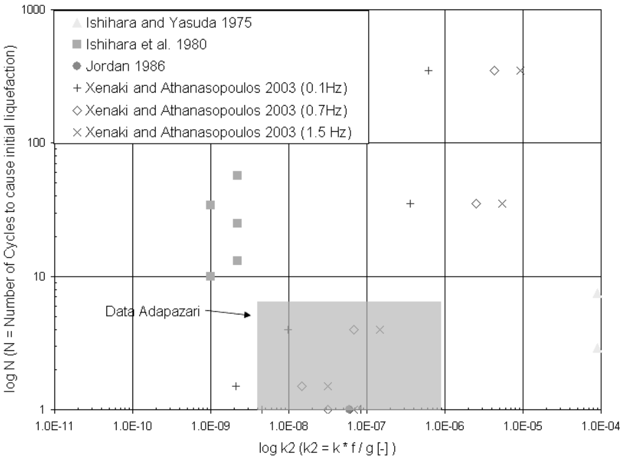

Figure 6. Dimensionless factor k2 = k*/CSR versus the number of loading cycles to reach initial liquefaction.

The summarized data is presented in Figure 6 as number of loading cycles to cause liquefaction versus the log of a dimensionless parameter k_2 defined as k*/CSR in order to be able to compare the findings from laboratory tests with soils from Adapazari, which have shown liquefaction in the Kocaeli 1999 earthquake assuming a maximum number of major loading cycles of 5 and a frequency of these cycles of approximately 1 Hz.

A hyperbolic distribution of the available data points can be seen in well defined boundaries for the investigation described by Ishihara et al. (1980) and Xenaki and Athanasopoulos (2003), showing a minimum at about k2=5·10-8 (k* = 1·10-8). The data derived from Ishihara and Yasuda (1975) though did not fit in the proposed form, which might be due to the rude assumptions being made to derive the permeability based on the available information.

4 CONCLUSION AND OUTLOOK

The introduction of the permeability coefficient into a criteria for determination of liquefaction susceptibility seems to be a promising way of defining a more mechanical based condition indicator. Even though the results presented here are only based on rude assumptions a tendency can be observed. The method will be improved in the frame of a multidisciplinary research project for more defined soils and complex loading functions using the new established Hollow Cylinder Apparatus at the Institute for geotechnical Engineering at ETH. This machine allows the application of cyclic loading in axial and torsional direction up to frequencies of 10 Hz. It allows further to simulate the three-dimensional stress condition as experienced by a soil element at any point in the half-space and to take into account the specialties of foundation loads or stress paths around tunnels. These upcoming tests in the HCA are a promising way to understand the soil behaviour under earthquake conditions and allow to add the local stress conditions into the investigation.

A parameter like the parameter k* is intended to be found by a detailed evaluation of existing data on sand as well as on additional tests with focus on different materials (silty sands, sandy silts) and load paths. To be able to conduct the effects of sampling as well as sample preparation techniques need to be regarded as an important influence on the measured response (e.g. Sayao & Vaid, 1991).

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