Condition indicators for liquefaction susceptibility with focus on silty soils

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ABSTRACT: Deformation of the sub-soil is one of the major risk scenarios being confronted in the event of earthquakes. One of the mechanisms involved in causing large deformations under cyclic loading is liquefaction observed for granular soil conditions. This phenomenon has been studied in a lot of research projects mainly in sandy soils. Recent earthquakes have shown that the range of soils prone to liquefaction is wider than assumed and that the nature of the earthquake has to be regarded as one condition indicator for a soil to reach liquefaction as well. Condition indicators used are based on field investigation or on grain size distribution and Atterberg-limits. Studies on other influencing factors are conducted in the laboratory with cyclic investigations. Among those tests, variations in soil graduation curves are rarely studied. Focus is given mainly to the amount of fines for mostly equivalent void ratios for silty soils. As a reasonable basis for defining condition indicators studies on liquefaction susceptibility of silts and sands with fine contents are reviewed. This review sets the base for an upcoming study in the frame of an interdisciplinary research project on developing a generic method on Management of Risk using condition indicators. The first result of the review leads to the proposal of a dimensionless correlation between the physical state of the soil using the permeability coefficient with a load function. The studies being introduced here will aim to develop an analytical description of liquefaction potential of silty soils to be able to define the condition indicators to subdivide the mechanism leading to strain hardening, strain softening and, in the worst case, liquefaction.

1 INTRODUCTION

For recent microzonation procedures as well as for other methods of evaluating local risk and hazards, an understanding of the mechanism involved before during and after a hazard, is crucial. In the case of earthquakes, these hazards include complex interaction between seismological, geological, geotechnical and structural components starting with the incoming earthquake over the propagation of the acceleration through the geological described bedrock as well as through the loose subsoil near to the surface before effecting structures build on or into the soil. A major influencing element of this chain is the near-surface subsoil. The surface layers highly affect the site amplification, influenced by the strain dependency of the material behaviour strain hardening and softening due to the incoming earthquake (e.g. introduced in Schnabel et al. 1972).

In almost saturated conditions, pore water pressure increases in granular soils as the voids are filled and the permeability conditions of the subsoil do not allow the water to be drained out while the granular particles tend to rearrange their location. The increase in pore water pressure goes along with a reduction of the effective stress, which can, in the worst case, reduce to zero (liquefaction). This has been observed in many earthquakes and most researches have addressed the study of the influence of cyclic loadings to pure sands.

Nevertheless, an increase of pore water pressure can be found in other granular soils depending on the soil state, the layering condition and the loading function of an incoming earthquake. For certain geometric boundary conditions like slopes, a combination of pore pressure increase and site amplification can lead to failures and slips, which can cause even more secondary destruction to structures or infrastructure, since this will set the boundary conditions for potential post earthquake failures as described by Jacka (2001) or effect the long-term behaviour of buildings founded on these soils. After an earthquake the soil properties will be changed, e.g. through initial liquefaction and subsequent reorganisation of the particles (Boulanger 1999) or in case of a slip movement, the critical strength of the soil decreases to residual values. These post-earthquake changes should be taken into account in evaluating further risk.

Following the description above liquefaction or cyclic mobility plays a major part in describing the different condition indicators for the soil in the frame of management of risk. In the time scale of a risk management project the condition indicator liquefaction has to be considered for risk evaluation in the planning state, which describes the situation before an earthquake occurs but it also needs to take into account the behaviour of the soil during an earthquake and the changes of the site conditions after an earthquake. All of this needs to be defined on the base of suitable site characterisation and determination of soil properties of a respective area.

2 RATIONALE FOR THE RESEARCH ON LIQUEFACTION OF SILTY SOILS

In this contribution, focus is given on the upcoming research onto the investigation of silty soils in particular on the loss of strength due to the increase of pore water pressure, leading to liquefaction and large deformations. Most studies dealing with this softening conditions to date focus on sands (e.g. Dobry et al. 1982; Robertson and Fear 1997 among many others). Fewer studies focus on the cyclic and dynamic behaviour of silts (e.g. Koester 1994; Singh 1994; Erten and Maher 1995; Xenaki and Athanasopoulos 2003).

Clays are regarded in terms of large deformation, as earthquakes will affect clays only 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.

However, large deformations have been observed in clayey soils not only after the 1999 Kocaeli earthquake (Ansal 2001 ed.), which lead to a proposed extension of the term liquefaction away from its physical meaning by Ishihara (1993) introducing the amount of deformation under cyclic loading as a second possible indicator for liquefaction.

In the case of sands, a lot of influencing factors on liquefaction are already studied. In addition, a lot of experience exists on empirical correlations of soil properties and site investigation with liquefaction potential. 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, silty soils are exposed to the same load scenarios as sandy soils and especially the Kocaeli earthquake in 1999 has shown the relevance of silty soil conditions in terms of damage distribution, while liquefaction or at least large amounts of cyclic mobility of the particles causing deformations in the meter range had occurred in both silty sands and sandy silts. The less prominent occurrence and the empirically based indicators for deriving liquefaction of liquefaction in silty soils during past earthquakes is the main reason for the fewer studies on silty soils even if the available studies show the risk of liquefaction under cyclic loading conditions. In addition, there is the belief expressed by some authors, that the process of liquefaction cannot be derived in an analytical way (e.g. Morris 1983) so that further studies might be less successful.

To determine the potential hazard beforehand, an earthquake appropriate site characterisation and determination of the soil properties will be conducted in order to appropriately design a structure. The results of this site investigation will then be used to apply specified characterisation methods based on empirical relations to investigate liquefaction potential. The most used ones are based on the graduation curve of the soil and the Atterberg limits, which can be found in related textbooks.

These methods require the knowledge of the soil conditions. Site characterisation is mostly done on base of site investigations with SPT and CPT before an earthquake. Boring and samples established even for other measures like buildings and foundation design are seldom taken into account in this kind of studies.

The measures mentioned before suffer under quality and differences in site characterisation techniques and utilisation will influence the quality of the achieved data.

Site characterisation is used in indicating liquefaction susceptibility by use of empirically developed curves linking the liquefaction susceptibility with e.g. number of blows of a Standard Penetration Test and the expected cyclic stress ratio and also including borderlines in dependency of the amount of fines (Youd et al. 2001).

Automatic use of this SPT correlation for identifying risks without considering in detail other condition indicators might easily lead to misinterpretation of liquefaction susceptibility. A good example to show the limitations of the existing methods is given in Laue and Studer (2003) based on the liquefaction probability in the city of Adapazari, which has been heavily effected by the Kocaeli earthquake in 1999.

For a better and more reliable classification and determination of liquefaction susceptibility of soils, further analogies need to be studied, which include under the systematical variation of soils the loading function and thus the type of an earthquake on the liquefaction susceptibility of certain soil strata (Gazetas et al. 2003).

3 REVIEW OF AVAILABLE STUDIES ON SILTY SOILS

Until recently, research has not focused in 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. Some mixtures of higher amounts of silt in sands are investigated and found to be critical, but the results are somehow controversial or even contradictory to the ones cited earlier.

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 are related to additional tests exposing the sample to a recorded earthquake reading or to more complex load functions. For silty soils, variations of the amount of silts are added to the variations studied for sands. The results of these studies will be shown briefly indicating the difference in the interpretation of the results.

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. 1). He identified a most critical amount of silt content giving the lowest shear resistance for medium dense samples. Above a fine 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 will be 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%.

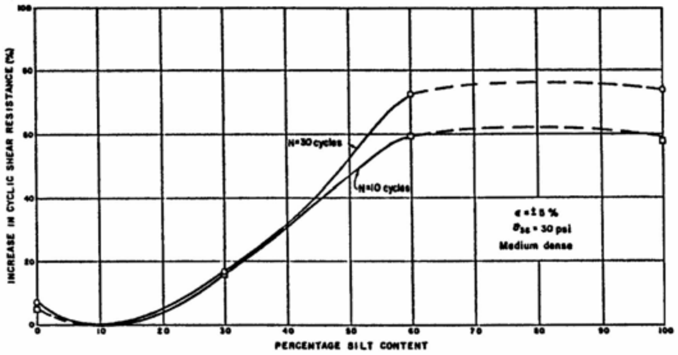

Fig. 1: Average effect of silt content (x-axes 0-100%) on cyclic shear resistance (y-axes 0-100) (Chang et al. 1982)

Results on sands with a systematic variation of fines are given by Xenaki and Athanasopoulos (2003). They used silty sand, which was separated into the different portions of silty grains and sand grains and then mixed together accordingly to achieve defined fines contents in sand. These mixtures are exposed to variations in the Cyclic Stress Ratio (CSR). Loading was continued under defined harmonical load functions until liquefaction could be observed. Figure 2 shows the summary of these tests and fines content between 42% and 44% were derived as most critical for liquefaction. This tendency has been found in all tests with void ratios between 0.62 and 0.69.

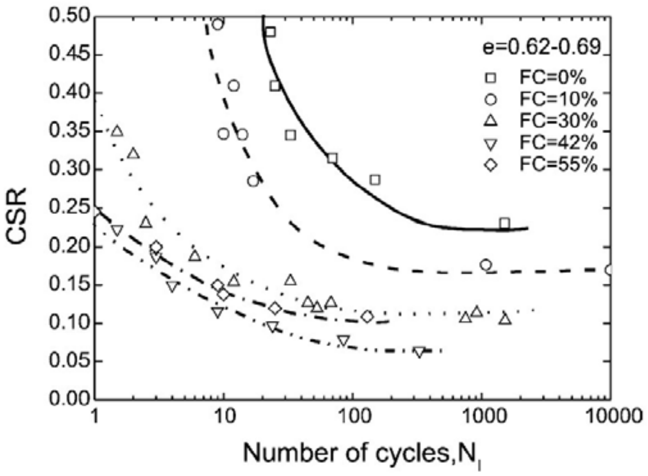

Fig. 2: Effect of fines content on the liquefaction resistance of sand – non-plastic fines mixtures for constant values of global void ratio and varying the cyclic stress ratio (Xenaki and Athanasopoulos 2003)

Findings of other authors seem to support these findings. Erten und 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.

Comparing the available studies and also taking into account the results on sands it has to be assumed, that better or additional criteria for liquefaction should be derived, which is not only based on graduation curve and a cyclic stress ratio, but which should also take into account the relation between void ratio and grain size distribution as well as the interaction between frequency and stress ratio. Only few of these interactive parameters have been studied by means of simple shear and triaxial shear tests.

4 INTRODUCING THE PERMEABILITY COEFFICIENT INTO THE DESCRIPTION OF LIQUEFACTION SUCEPTIBILITY

Reviewing previous investigations on silty soils, main variations are given by the load function (described usually for harmonic loadings by a CSR and a loading frequency) and the properties of the soil usually given by some information on grain size distribution (amount of fines) and the void ratio of the studied samples. In order to define a common parameter for a comparison of these studies, an attempt will be made to combine these parameters in a single non-dimensional set of parameters. For a combined recognition of the soil parameters, the permeability index has been chosen, as this value combines the studied variations. 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, as e.g. gravel is not prone to liquefaction under earthquake frequency conditions. BWG (2003) therefore defines the permeability of liquefaction prone soils between $1 \cdot 10^{-5}$ m/s and $1 \cdot 10^{-6}$ m/s.

With this assumption it is then possible to define a dimensionless parameter k* to relate the boundary conditions of the soil sample with the loading function. This is based on some assumptions, which are identified below and are based on the available results.

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

In order to compare the available results of the tests, clearly described parameters are most important. Since each study usually focuses on a certain detail such as the rate of pore water pressure development or the influence of the loading function on the stress ratio certain assumptions in the interpretation and the derivation of the dependency of the parameter k* have been made. The information on the studies is given with varying details. Most concern has to be related towards the derivation of the permeability, while also the factors of loading frequency and Critical Stress Ratio have to be discussed.

4.1 *Determination of the permeability k (m/s)*

Usually the permeability k is never explicitly determined in the available publications. As a starting point for this study the determination of k is based on empirical correlations on the grain size distribution as e.g. summarized in Smoltcyzk ed. (1996).The formula of Beyer (1966) (eq. 2) has been chosen as most appropriate (Uniformity Index C_u (derived as the quotient of d_{60}/d_{10}) and c(U) is a correction factor introduced by the author):

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

Xenaki and Athanasopoulos (2003) used natural materials for the cyclic triaxial tests and indicated the grain size distribution. In the case of the tests reported by Ishihara et al. (1980), the coefficient of uniformity was known and d_{60} could be taken from the drawn grain size distribution. Often the essential parameters of the investigated material is missing, e.g. Koester (1994) 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 $3.6 \cdot 10^{-4}$ and $6.2 \cdot 10^{-5}$ (m/s), whereas the silty sands or sandy silts have k-values of up to $1.0 \cdot 10^{-8}$ m/s.

4.2 *Influence of the loading function*

This study focuses on the results of tests with regular harmonic loading functions, which can be described by the 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 load 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.

4.2.1 *Frequency f (1/s)*

In order to take the frequency into account into the parameter k* in some cases 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. The very low frequency of f=0.05 Hz examinated by Chang et al. (1982) could not be taken into account because of the lack in material information.

4.2.2 *Cyclic Stress Ratio CSR*

The cyclic stress ratio is herein referred to as the maximum shear stress divided by twice the initial effective confining stress leading to initial liquefaction. Initial liquefaction occurs when the excess pore water pressure becomes equal to the initial consolidation stress of the specimen. In some studies, different definitions of liquefaction have been used. Vaid (1994) defined the development of 2.5% single amplitude axial strain in 10 stress cycles as liquefaction. In other cases it is not clearly indicated which definitions of liquefaction had been used or occurred first (Ishihara et al. 1980). Some results had to be omitted in the current study as the test results do not allow a clear definition of a specified number of load cycles at which liquefaction occurs.

4.3 *Effect of the dimensionless parameter*

The results of the literature survey on the parameter k* (Fig. 4) and k2 = k*/CSR without (Fig. 5) recognition of the CSR are shown. Tests taken into account 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%).

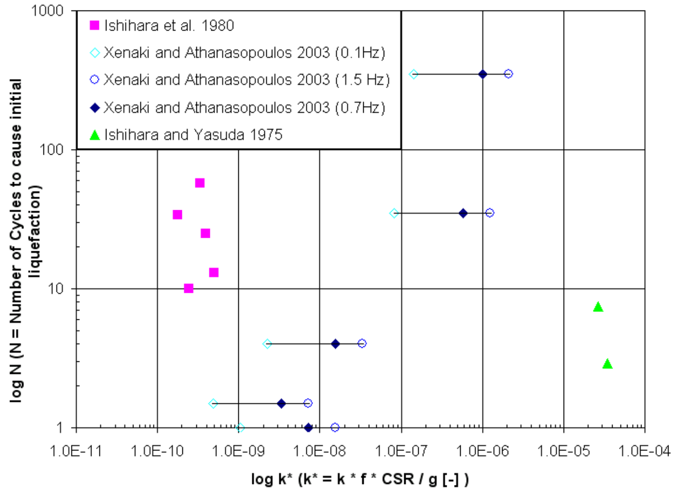

Figure 4: Dimensionless factor k* versus the number of loading cycles to reach initial liquefaction

Comparing the two figures, it can be seen that the attempt of using a factor k* to correlate the different variations on both the soil side and the load function work well between the defined boundaries for the investigation described by Ishihara et al. (1980) and Xenaki and Athanasopoulos (2003), showing a minimum at about k* = $1 \cdot 10^{-8}$ and k2=$5 \cdot 10^{-8}$. 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.

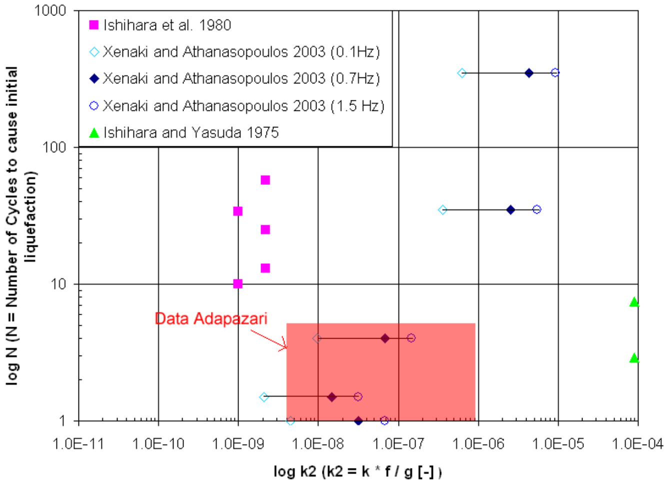

Figure 5: Dimensionless factor k2 = k*/CSR versus the number of loading cycles to reach initial liquefaction

The influence of the frequency can be followed checking the frequency range based on the data from Xenaki and Athanasopoulos (2003) on different frequencies for the same material, where a low frequency shift the factor k* to the right, whereas higher frequencies shift the factor to the left. An approximate range of values of k2 is included in Figure 5 for the soils in Adapazari, which showed liquefaction. Reported data in Ansal (2001) have been evaluated to determine the permeability coefficient. Taking into account, that the Kocaeli earthquake consisted of approximately 5 major cycles with a frequency of approximately 1 Hz, the factor k2 as a condition indicator fits well with the observed behaviour in the field.

In summary it has to be stated, that the proposed factor of k* in this contribution has to be seen as a first attempt. In a next step, more data on sand should be included and proven.

5 OUTLOOK

The newly started research on defining more complex and reliable condition indicators for the liquefaction potential of sandy and silty soils is outlined in Fig. 6. Here the condition indicators are divided into a two-step approach. Condition indicators 1 include the basic soil condition (granular or clayey particles, water content, layering conditions including drainage boundaries and grain size distribution). Based on this first set of indicators the principal behaviour can be defined. For critical soils a second set of indicators should be defined, which should take the material properties and the expected load functions into account.

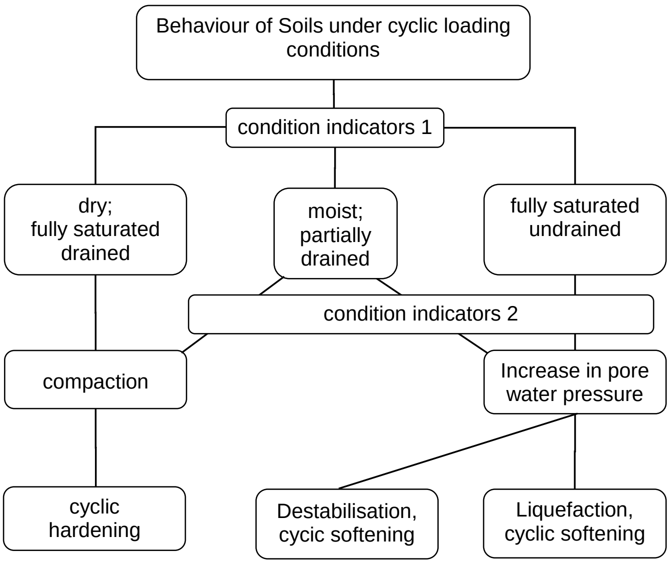

Fig. 6: Decision process for defining soil behaviour in earthquakes

A parameter like the defined 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 and load paths. To be able to conduct this, study effects of sampling as well as sample preparation techniques need to be regarded as an important influence on the measured response (e.g. Sayao and Vaid 1991). Laboratory investigation will be conducted in the new Hollow

Cylinder Apparatus available at IGT (Springman et al. 2004). 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 specialities 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.

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