EVALUATION OF LIQUEFACTION POTENTIAL OF SOILS – A REVIEW

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Abstract:Liquefaction of soil during earthquakes results in catastrophic damages to life and property. The deformations of soil during earthquakes pose a serious risk to the stability of structures. Niigata earthquake in Japan and the Bhuj earthquake in India incurred large scale damage to the buildings and dams. It is essential to evaluate the resistance of soils to liquefaction. This paper deals with understanding the process of liquefaction and estimating the liquefaction potential of soils by various laboratory tests and empirical approaches. The undrained behaviour of soils in cyclic shearing is explained with the help of cyclic triaxial testing and cyclic direct simple shear test. The results of the cyclic direct simple shear test conducted on loose Fraser river sand in Vancouver, Canada are discussed in this paper. The empirical approach developed in 1996 NCEER and 1998 NCEER/NSF workshops to determine the liquefaction potential of soils is presented. This empirical approach is a simplified procedure based on field tests which can be used in practice to evaluate the liquefaction potential of soils.

I. INTRODUCTION

The phenomena of liquefaction received attention mainly after the disastrous earthquake in Niigata, Japan on 16 June 1964. In India, the Bhuj earthquake on 26 January 2001 instigated the research on liquefaction. Fig 1 and Fig 2 show damage to the structures due to liquefaction in Niigata and Bhuj earthquakes respectively[1]. In simple terms, liquefaction can be comprehended as a phenomenon in which soil loses its shear strength due to the generation of excess pore water pressure in undrained loading conditions. Liquefaction is defined as the process of conversion of coarse material from a solid to a liquefied state as a result of rise inthe pore water pressure and decrease in the effective stress[2]. It usually takes place in granular soils, since they are frictionless and do not possess significant cementation.

The liquefaction potential of soils is estimated by carrying out various laboratory and field tests. In this paper,the Cyclic Triaxial Test and Cyclic Direct Simple Shear Test will be discussed followed by a simplified procedure to determine the liquefaction resistance of soils developed in 1996 NCEER and 1998 NCEER/NSF workshops[3]. The simplified procedure is an empirical approach based on field tests mentioned above.

fig 1: tilting of apartment buildings at niigata, (courtesy of usgs)[1]

fig 2: failure of upstream crest of fategadh dam, (courtesy of iit kanpur)[1]

II. LABORATORY TESTS

Laboratory tests are carried out to understand the response of the soils towards dynamic loading as close to reality as possible. It is important to replicate field conditions in the laboratory. However, it is difficult to exactly replicate the field conditions in a laboratory. The specimens considered for laboratory testing do not represent the entire soil mass. Despite these limitations, laboratory testing is very important to understand the phenomena of liquefaction. The variation of shear modulus is useful in deciding the point of initiation of liquefaction in the stress-strain curve. The significant decrease in shear modulus indicates a decrease in stiffness of the soil sample.

Sampling Technique

It is very important to carry out laboratory tests on soil samples which are undisturbed in nature. The in-situ stresses are disturbed by conventional sampling techniques. There are some sophisticated methodslike ground freezing to obtain undisturbed soil samples. However, such a method is not economic which limits its usage in research. One possible way to avoid large costs is to retrieve some samples by freezing technique and then comparing its response with the reconstituted specimens prepared by common sample preparation techniques such as air pluviation and water sedimentation. The success of sampling techniques such as air pluviation or water sedimentation to replicate the fabric of soil depends on the investigated deposit. Ghionna carried out an experimental study on marine soils and found out that water sedimentation replicated the in-situ fabric of the soil deposit and served as a substitute to expensive freezing techniques[4]. Sitharam suggested dry pluviation method is capable of creating a grain structure similar to that of naturally deposited river sands[5]. Water sedimentation in river sands would produce inhomogeneous specimens since heavy coarser particles would settle at the bottom and fine fraction would remain at the top.

Cyclic Triaxial Test

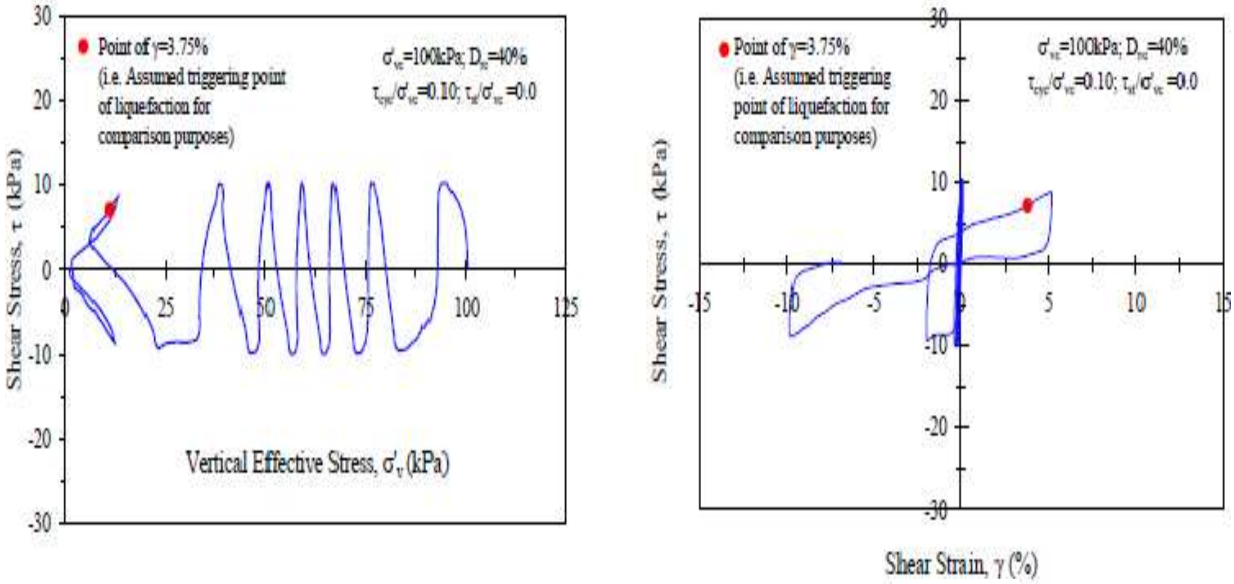
Dynamic properties of soil are usually determined by Cyclic Triaxial Test. In cyclic triaxial test cylindrical specimen of known density is prepared and enclosed in a rubber membrane. The cylindrical specimen is placed between the two platens subjected to an all-round cell pressure by virtue of which consolidation of the specimen takes place. The specimen can be consolidated isotropically or anisotropically producing different stress paths. It is pertinent to note here that the decision to carry out isotropic or anisotropic consolidation is taken based on actual site conditions. Isotropic consolidation is used when the ground is fairly flat such that there are no shear stresses initially. Anisotropic consolidation is used to replicate predominantly sloping sites that are subjected to initial static shear stresses. The time required to complete the consolidation of the soil specimen depends on the type of soil. Soils predominantly sandy in character take less time for consolidation compared to clays. After the consolidation is over, additional stress in the axial direction is applied to the specimen. In mechanics, the difference between the axial stress and cell pressure in a triaxial test is usually referred to as deviator stress. The deviator stress is applied cyclically at a frequency of about 1Hz as suggested by Kramer in his book on Geotechnical Earthquake Engineering[6]. The boundary conditions in the cyclic triaxial test ensure that the principal stresses are always vertical and horizontal like the same way as in conventional triaxial testing[7].

Cyclic Simple Direct Shear Test

The cyclic simple direct shear test is considered more suitable for simulating the process of liquefaction. The stress conditions in this test are closer to the stress conditions generated in earthquake loading as compared to the cyclic triaxial test. In the cyclic shear test, principal planes are not forced in a vertical and horizontal direction. This test also simulates the rotation of principal planes that takes place during earthquake loading. In this test cylindrical specimen of the soil of known density is prepared by conventional sampling techniques. The cylindrical specimen is restrained by rigid platens against any lateral movement in the outward direction. The cyclic horizontal stresses are applied at the top and bottom of the specimen. The deformation profile of the specimen in this test resembles the deformation of the soil element exposed to s-wave[8].

Wijewickreme conducted constant volume cyclic direct simple shear tests on loose Fraser river sand in Vancouver, Canada. The response of Fraser river sand to undrained cyclic direct simple shear tests obtained by Wijewickreme is described below in this section. The specimens for carrying out the tests were consolidated without any difference in static shear. The effective stress path and shear stress – shear strain response obtained by Wijewickreme are shown in Fig 3 (i) and Fig 3 (ii) respectively. The effective vertical stress is initially 100 kPa and decreases with each cycle of loading. The vertical effective stress reaches zero value in 7 cycles of loading. The liquefaction of soil is triggered in the seventh cycle of loading. The shear strains are very small up to the first six cycles and become as large as 10 % in the seventh cycle of loading. The shear strength of the soil after liquefaction. is known as residual shear strength, and the ratio of residual shear strength and initial vertical effective stress is known as shear strength ratio. The shear strength ratio of Fraser river sand comes out to be 0.1 which is evident in Fig 3.

The use of the cyclic direct simple shear test is inhibited by imposing only $K_O$initial stress condition. The shear stresses are applied only at the top and bottom of the specimen. These shear stresses develop a moment which is balanced by the non-uniform shear and normal stresses. These non-uniform shear stresses are produced by the rigid boundary[9].



(i) (ii)

fig 3: (i) effective stress path and (ii) shear stress- shear strain response of fraser[9].

III. SIMPLIFIED PROCEDURE DEVELOPED IN 1996 NCEER AND 1998 NCEER/NSF WORKSHOPS TO EVALUATE THE LIQUEFACTION POTENTIAL OF SOILS

The simplified procedure developed in 1996 NCEER and 1998 NCEER/NSF workshops is an empirical approach to evaluate the liquefaction potential of soils based on field tests such as SPT, CPT, and Shear wave velocity measurements. It is a stress-based approach in which we estimate two variables, Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR)[3]. In a broader sense, CSR is a parameter that gives us an idea of seismic demand on a soil layer and CRR is a parameter that indicates the liquefaction resistance of soil.

Estimation of CSR

Seed and Idriss (1971) developed an empirical equation to estimate the cyclic stress ratio, given below

$$CSR= (\tau_{av} / \sigma'_{vo}) = 0.65 (a_{max}/g) (\sigma_{vo} /\sigma'_{vo}) r_d \quad (1)$$

where a_{max} is horizontal peak ground acceleration generated by the earthquake, g is the acceleration due to gravity, σ_{vo} is total overburden stress, σ'_{vo} is effective overburden stress, r_d is the stress reduction coefficient[10]. The stress reduction coefficients are estimated from equations proposed by Liao and Whitman [11]:

$r_d = 1.0 – 0.00765z$ for $z \leq 9.15$ m (2a)

$r_d = 1.174 – 0.0267z$ for $9.15m \leq z \leq 23m$ (2b)

Estimation of CRR

CRR is evaluated with the aid of field tests such as SPT, CPT, and Shear wave velocity measurements. In the case of soils with considerable gravel content, Becker Penetration Test is used. SPT is the most commonly performed test in the field and this paper, we will discuss the calculation of CRR using SPT only.

Standard Penetration test has been used extensively in geotechnical engineering. CRR values are estimated from SPT with the help of a plot between CRR and $(N_1)_{60}$, shown in Fig 4. $(N_1)_{60}$ represents the SPT blow count corresponding to the overburden pressure of 100 kPa and hammer efficiency of 60%. It is important to note here that CRR vs. $(N_1)_{60}$ has been plotted for earthquake magnitudes of 7.5. The curve in Fig 4 has been plotted for granular soils with fine content of 5%, 15%, and 35 %. The liquefaction resistance of soils increases with the increase in the fine content of the soil. The influence of the fine content is taken care of by an equation put forth by Idriss for correction of $(N_1)_{60}$ values:

$$(N_1)_{60c} = \alpha + \beta (N_1)_{60} \quad (3)$$

$(N_1)_{60c}$ is the corrected SPT blow count, α and β are coefficients depending on the percentage of fine content in the soil. Further corrections such as corrections due to overburden, borehole diameter, and rod length are to be applied. The curve in Fig 4 is only applicable to 7.5 magnitude earthquakes. To account for it, Seed and Idriss (1982) introduced Magnitude Scaling Factors for the earthquakes of different magnitudes[12]. The correction factors due to the sloping ground are also applied since static shear stresses influence the liquefaction response of the soil.

Therefore, CRR and CSR values obtained help in identifying whether the soil will liquefy or not. CRR quantifies the capacity of a soil to resist liquefaction and CSR gives an idea of driving stresses induced due to earthquake loading. The factor of safety can be calculated from the ratio of CRR (obtained after applying all corrections) and CSR.

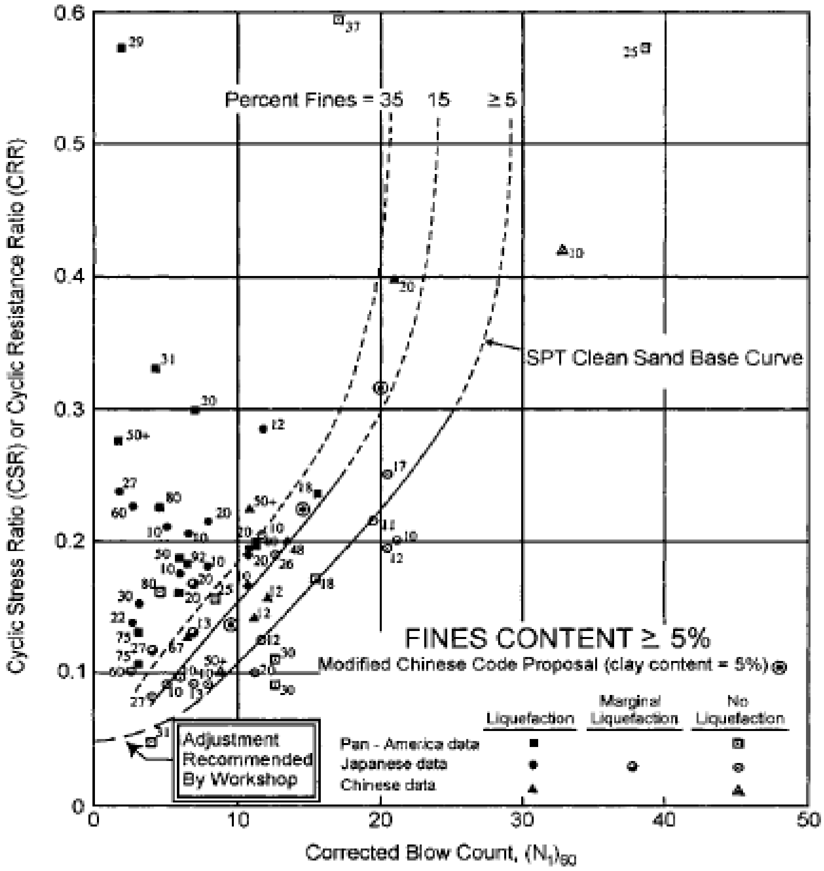


fig 4: CRR vs. SPT curve for magnitude 7.5 earthquakes [12]

IV. SUMMARY AND CONCLUSIONS

The phenomenon of liquefaction poses a significant risk to life and property. The liquefaction potential of soils can be evaluated from laboratory tests, field tests, and empirical procedures developed with the help of past experience in conjunction with laboratory and field tests. In the case of loose sands, obtaining an undisturbed sample is challenging. Specialized techniques like ground freezing are successful in obtaining undisturbed soil samples; however, their use is limited due to the high cost. Therefore, reconstituted samples should be prepared carefully using the appropriate sample preparation method. In this paper, the undrained behaviour of the soils in cyclic shearing is explained with the help of cyclic triaxial testing and cyclic direct shear test. Cyclic triaxial testing is simple and easy to operate since it is an extension of conventional triaxial testing. The cyclic simple direct shear test simulates the earthquake loading condition more accurately. The results obtained by Wijewickreme (2005) ina cyclic simple direct shear test conducted on loose Fraser river sand in Vancouver, Canada have been studied in this paper. It was observed that Fraser river sand liquefied in 7 cycles of loading and shear strain became as large as 10%. The empirical approach developed in 1996 NCEER and 1998 NCEER/NSF workshops to evaluate the liquefaction potential of soils is also presented.

V. ACKNOWLEDGMENT

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