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Laboratory testing procedure to assess post-liquefaction deformation potential

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Abstract

Buildings and infrastructure suffer extensive damage due to liquefaction during strong earthquakes. The FL method has long been considered adequate for evaluating the likelihood of liquefaction, and is widely used. Due to the high frequency of large earthquakes, generally referred to as level 2 earthquakes, the necessity of multi-level assessments has been acutely felt in Japan. This requires the ductility nature of liquefied ground to be assessed. Because these earthquakes do not always occur with the motion level and waveform used in design, new assessment methods are required which take some deviation into account. Another point of consideration in developing a new method is that high quality site investigations are often either not possible or practical in the initial stage of design. Because the site investigation methods should differ depending on the site selection and the precise design of important structures, there is a clear demand for assessment methods with the flexibility to meet the particular objectives of each case. The new laboratory testing procedure proposed in this paper aims to classify soils according to their likelihood to undergo liquefaction in the event of an earthquake. With the proposed procedure, it is possible to classify soils as either 'clearly safe' or 'likely to result in significant damage if liquefied' by testing a small number of specimens. It should be noted that this test is not designed to provide for a highly accurate prediction of liquefaction or the extent of post-liquefaction deformation.

Keywords: Liquefaction; Laboratory test; Undrained cyclic loading; Post-liquefaction deformation

1. Introduction

After the Niigata and Alaska earthquakes of 1964, reports of liquefaction damage were reported after earthquakes. The Christchurch and Tohoku (off the Pacific Coast) earthquakes of 2011 resulted in widespread liquefaction damage that has been extensively reported. Besides the damage sustained by buildings and infrastructure due to tilting and settlement (Kazama et al., 2012; Yamaguchi et al., 2012; Cubrinovski et al., 2012), the widespread occurrence of sand boiling obstructed restoration work after these earthquakes.

To mitigate such post-liquefaction damage, a number of tests and assessment methods have been proposed based on the results of studies conducted in the aftermath of these large earthquakes. Methods employing the stress ratio as an index (Seed and Idriss, 1971; Arulmoki et al., 1985; Iwasaki et al., 1984) for inferring resistance against liquefaction have been widely employed to determine whether liquefaction will occur under predetermined design earthquake motion. In these tests, the stress ratio is determined from an undrained constant stress amplitude cyclic shear test when liquefaction takes place at a fixed number of cycles, generally 15 or 20. In Japan, it is considered necessary to consider either level 1 or level 2 design earthquake motions in earthquake resistant design, depending on the location. The stress ratio corresponding to each design earthquake motion as suggested by design standards

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(Japan Road Association, 2012; Architectural Institute of Japan, 2001) has been utilized. The likelihood of liquefaction is determined by comparing the stress ratios corresponding to liquefaction resistance and design earthquake motion in a test generally referred to as the FL method. In another method prescribed in the standards of The Overseas Coastal Area Development Institute of Japan (2009), equivalent acceleration and N-values are employed instead of the stress ratios, but the concept of comparing external loading and the resistance of ground is identical to the FL method. Both of these methods can be considered adequate in terms of their ability to assess the occurrence of liquefaction against the supposed earthquake motions. However, because of the increasing frequency of large earthquakes, regarded as level 2 earthquakes, and the uncertainty in setting design earthquake motion, demands for a more robust design have been made for an assessment method which considers not only the likelihood of liquefaction but also the extent of post-liquefaction deformation. Besides these two considerations, the 2011 off the Pacific Coast of Tohoku Earthquake suggests it is also necessary to take the earthquake duration into consideration.

In research on post-liquefaction deformation, volumetric strain has been the main focus of study. Lee and Albaisa (1974), Yoshimi et al. (1975), Tatsuoka et al. (1987), Nagase and Ishihara (1988) reviewed the residual volumetric strain generated after liquefaction by applying drainage after cyclic loading. On the basis of these studies, simple evaluation methods have been suggested for determining the extent of post-liquefaction settlement. Ishihara and Yoshimine (1992) established a family of curves showing volumetric strain correlated with density as well as a safety factor against liquefaction, and outlined a methodology for predicting post-liquefaction settlement. Tsukamoto et al. (2004) inferred the relationship between the factor of safety and residual volumetric strain for silty sand, using a large triaxial test apparatus and some of the acceleration time histories captured in the 1995 Kobe earthquake. In prior studies, good correlation was found between maximum shear strain during cyclic loading and liquefaction-induced settlement. In another study, Sento et al. (2004) reported that accumulated shear strain is a better indicator of liquefaction-induced settlement than maximum shear strain, and proposed an idealized relationship between post-liquefaction volume change and effective stress. Unno et al. (2006) and Unno and Tani (2008) also demonstrated that under the same loading history (i.e., of accumulated shear strain), the residual volumetric strain is the same regardless of the drainage condition.

The occurrence of flow failure (including lateral flow) after liquefaction is an important criterion for classifying damage configuration. When drastic shear strain develops, especially on inclined ground, catastrophic flow failures can occur. Extensive research has been conducted on this flow after liquefaction. Yasuda et al. (1999) applied a monotonic shear loading to a liquefied specimen and confirmed that there are two regions: a region where no shear stress is recovered with shearing because of the low rigidity of the soil, and a rigidity recovery region, where the rigidity of the soil is restored with shear loading. Shamoto et al. (1997) showed that shear strain is composed of two different components, i.e. a shear strain component depending on the change in effective stress, and a shear strain component independent of effective stress. The constitutive model they proposed for the evaluation large post-liquefaction shear deformation was validated by comparing their results with actual case studies.

While many studies on post-liquefaction deformation have been conducted, the focus of most of the research has been either on shear strain or volumetric strain. The various methods developed for use to determine the likelihood of liquefaction, the post-liquefaction shear strain, and the post-liquefaction volumetric strain are adequate for their stated purposes. After the Kobe earthquake in 1995, and because of the higher frequency of large “level 2” earthquakes and consequent necessity for multi-level assessment, demands for a new technique to evaluate the ductility nature of liquefied ground have been made. The uncertainty in the design earthquake motion also has indicated the importance of taking deviation into account in earthquake resistant design. Since high quality site investigations in the initial stage of design are not possible and are frequently cost-prohibitive, a simple method capable of determining whether or not large amounts of damage are likely to occur in the event of an earthquake are required. In addition, since the loading history, the irregularity of earthquake waveforms, and the boundary conditions also need to be considered when making precise estimations of post-liquefaction deformation, a numerical analysis is required and a constitutive model needs to be developed.

In this paper, a simple laboratory testing procedure for the assessment of the likelihood of post-liquefaction deformation is proposed. The procedure involves four consecutive tests which are carried out in the laboratory; a constant stress amplitude cyclic test, a constant strain amplitude cyclic test, a monotonic shear test, and a drainage test. The main focus of the procedure is to classify soils specimens as either likely to remain safe or likely to result in large damage if liquefied. The procedure also has potential to provide the data for parameter setting in a numerical analysis and in the development of constitutive model.

2. Cyclic shear testing procedure

2.1. The concept of the test

The concept and procedure of the test method proposed in this study are shown in Fig. 1. The procedure comprises the following steps (STEP 1 to 4): constant stress amplitude cyclic shear, constant strain amplitude cyclic shear, monotonic shear, and drainage. STEP 1 is almost similar to conventional liquefaction strength test. In this step, whether liquefaction occurs against a certain stress ratio