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Liquefaction evaluation of dam foundation soils considering overlying structure

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ABSTRACT

The liquefaction analysis procedure conducted at a dam foundation associated with a layer of liquefiable sand is presented. In this case, the effects of the overlying dam and an embedded diaphragm wall on liquefaction potential of foundation soils are considered. The analysis follows the stress-based approach which compares the earthquake-induced cyclic stresses with the cyclic resistance of the soil, and the cyclic resistance of the sand under complex stress condition is the key issue. Comprehensive laboratory monotonic and cyclic triaxial tests are conducted to evaluate the static characteristics, dynamic characteristics and the cyclic resistance against liquefaction of the foundation soils. The distribution of the factor of safety considering liquefaction is given. It is found that the zones beneath the dam edges and near the upstream of the diaphragm wall are more susceptible to liquefaction than in free field, whereas the zone beneath the center of the dam is less susceptible to liquefaction than in free field. According to the results, the strategies of ground improvement are proposed to mitigate the liquefaction hazards.

1. Introduction

Based on empirical correlations of some observed performance of "liquefaction/non-liquefaction" case histories, several simplified approaches employing in situ test indices have been developed for assessing liquefaction potential of soils (Seed and Idriss, 1971; Seed, 1979). These simplified approaches can only be used to evaluate liquefaction triggering for level or nearly level free field ground without structures. While in practice these simplified approaches were widely used to evaluate the liquefaction potential of soils beneath or near a structure, the soils beneath a structure are treated as if they are in the free field under level ground conditions and the effect of the buildings resting on the ground surface is ignored.

Field case histories, model tests and numerical analysis suggested that conditions influencing liquefaction near a structure may be substantially different from those for the same soil profile in the free field. Although the influence of structures on potential liquefaction damage has not been well understood, the following conclusions can be drawn (Liu and Qiao, 1984; Rollins and Seed, 1990; Cetin et al., 2012). (1) The excess pore water pressure distribution near a building can be much different from that in the free field. (2) The liquefaction potential of soil may be greater or lesser beneath a structure, depending mainly on the structure type and soil density. For instance, sands underneath low-rise and short-period structures appear to have higher liquefaction potential, while sands underneath tall and long-period structures appear to have lower liquefaction potential than in the free-field. (3) The ground under the edges of a structure is more susceptible to triggering liquefaction than that under the center of the structure. Some modifications were suggested for the free-field liquefaction evaluation procedure to account for the structure effects. Men et al. (1998) proposed a simple method to evaluate dynamic stress of the ground exerted by aboveground structures, and developed a simplified method to evaluate liquefaction of building's subsoils. Jing et al. (2001) further considered the subsoil's nonlinearity in the framework of the method proposed by Men et al. (1998). Yang et al. (2010) adopted an equivalent influence depth to consider additional stress exerted by a finite building base, and revised the standard penetration test (SPT)-based method adopted by Chinese code GB 50287–2008 (MOHURD, 2008). Noorzad et al. (2009) evaluated the effect of structures on the wave-induced liquefaction potential of seabed by applying a structure force on the underlying sand deposits. Based on numerical results of generic soils, structure and earthquake combinations, Cetin et al. (2012) developed an alternative simplified procedure for three-dimensional

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(3D) dynamic response assessment of soil and structure systems, which can produce unbiased estimates of the representative and maximum soil–structure–earthquake-induced cyclic stress ratio values. Meanwhile, Oka et al. (2012) considered the effect of heavy structures on the liquefaction potential of the foundation soils by incorporation of mean stresses in the framework of the simplified procedure.

Although some advances have been made on seismic liquefaction assessment of foundation soils beneath structures, to consider the effect of overlying structures on liquefaction evaluation still remains a controversial and difficult issue. The effect of structures on the liquefaction potential of foundation soils depends on both the characteristics of structures and soils, so direct applicability of the simplified methods (e.g. Seed–Idriss procedure or Chinese simplified procedure) to foundation soils beneath structures is impossible, unless the soil–structure–earthquake interaction is reliably addressed in the estimation of cyclic stress ratio (CSR) (Cetin et al., 2012). Numerical method can not only consider almost all the factors influencing the interaction between structures and subsoils but also be an efficient way to solve this problem. The key problem in numerical method is the criterion for judging liquefaction triggering in complex stress conditions. To illustrate these trivial but essential matters in the numerical method, the liquefaction analysis procedure of a practical case, a dam built on the foundation with a liquefiable sand layer, is presented. The procedure includes two aspects: (1) detailed field exploration and comprehensive laboratory tests to determine the criterion for liquefaction triggering of the sand layer, and (2) 3D finite element analysis to calculate the static and dynamic interaction between the dam and underlying soils.

It should be noted that some exciting progress has been achieved in the aspects of constitutive modeling of sand and the codes for fully coupled dynamic response analysis of saturated porous media (Wang and Zhang, 2007; Wang et al., 2011; Zhang and Wang, 2012). The whole liquefaction process, including the onset of liquefaction, the process of generation, diffusion and release of excess pore water pressure, and even the development of liquefaction-induced deformation, can be simulated by the fully coupled dynamic numerical methods. The whole liquefaction process simulation involves comprehensive constitutive models with complicated codes of fully coupled dynamic consolidation and large amount of testing work (e.g. Zhang and Wang, 2012). As a result, it is not very appealing and sometimes impractical for small engineering projects. The procedure adopted in this study intends to overcome these issues, so that it would be efficient and economical for middle or small projects.

2. A sluice dam in China

A typical sluice dam in China is taken as an example to illustrate the procedure for liquefaction assessment. This type of dam is not very high, and natural deposits are usually taken as the foundation. As shown in Fig. 1, the dam is composed of four sluice segments in the middle of the river and two gravity dam segments located at the left and right abutments, respectively. The sluice segments are 27.5 m in height. The alluvial deposits underlying the sluice segments are from 35 m to 47 m in depth. The deposits are composed of 3 layers. The soils from top to bottom are gravel, sand and gravel, respectively. The sand layer is 5–10 m in thickness, and is distributed all over the dam site.

The content of the particle size less than 5 mm of the sand layer is greater than 70% and the fine particle content is less than 13%, therefore the sand is classified as fine sand. The maximum and minimum dry densities of the sand layer are 1.72 g/cm^3 and 1.28 g/cm^3, respectively. The specific gravity G_s of the sand is 2.72. Site exploration reveals that the relative density of the intact sand layer is around 50%. The designed earthquake intensity of the dam is VII degree (corresponding peak ground acceleration is about 100 cm/s^2). According to GB 50287–2008 (MOHURD, 2008), the sand layer is preliminary judged to be susceptible to liquefaction. Further judgment of liquefaction triggering is based on the blow counts of SPT proposed by GB 50287–2008 (MOHURD, 2008). The in situ SPT blow counts $N'_{63.5}$ is about 8–9. Considering that the operation conditions of the sluice dam are different from the test conditions, the in situ SPT blow counts $N'_{63.5}$ should be corrected, which is something like the surcharge pressure correction in Seed's simplified procedure, and the corrected average SPT blow counts $N_{63.5}$ is 6.7. According to GB 50287–2008 (MOHURD, 2008), the critical SPT blow counts N_{cr} for triggering liquefaction is 7.5 for earthquake intensity VII, so the liquefaction would be triggered in the sand layer under the earthquake of intensity VII.

3. Numerical procedure for liquefaction evaluation

The stress-based approach compares the earthquake-induced CSR with the cyclic resistance ratio (CRR) of the soil to judge whether liquefaction would be triggered. The factor of safety (*FS*) against the triggering of liquefaction can then be computed as the ratio of the sand's CRR to the earthquake-induced CSR:

$$FS = CRR/CSR \tag{1}$$

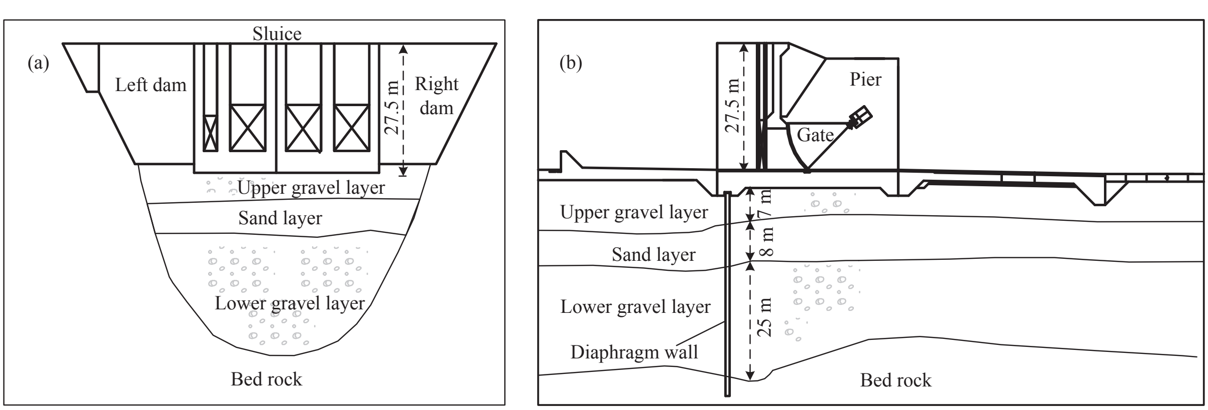

Fig. 1. Geological profile of the dam foundation. (a) Longitudinal section, and (b) Transverse section.