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Estimating severity of liquefaction-induced damage near foundation

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Abstract

An empirical procedure for estimating the severity of liquefaction-induced ground damage at or near foundations of existing buildings is established. The procedure is based on an examination of 30 case histories from recent earthquakes. The data for these case histories consist of observations of the damage that resulted from liquefaction, and the subsurface soil conditions as revealed by cone penetration tests. These field observations are used to classify these cases into one of three damaging effect categories, 'no damage', 'minor to moderate damage', and 'major damage'. The potential for liquefaction-induced ground failure at each site is calculated and expressed as the probability of ground failure. The relationship between the probability of ground failure and the damage class is established, which allows for the evaluation of the severity of liquefaction-induced ground damage at or near foundations. The procedure presented herein represents a significant attempt to address the issue of liquefaction effect. Caution must be exercised, however, when using the proposed model and procedure for estimating liquefaction damage severity, because they are developed based on limited number of case histories.

Keywords: Liquefaction; Earthquake; Ground failure; Ground damage severity; Cone penetration test

1. Introduction

Earthquake-induced liquefaction is a phenomenon of temporary loss of shear strength of a soil during an earthquake. During the past three decades, a large volume of literature on geotechnical earthquake engineering, and in particular, on soil liquefaction, has been published [1,2]. Among the various methods for evaluating liquefaction potential of soils, the simplified procedure of Seed and Idriss [3], which has been modified several times [4–6], is the most widely adopted in practice. With this simplified procedure, liquefaction resistance of a soil is expressed as Cyclic Resistance Ratio (CRR), whereas liquefaction 'loading' applied to this soil is expressed as Cyclic Stress Ratio (CSR). Empirical or semi-empirical equations are available for calculating CRR and CSR [6]. The potential for soil liquefaction is generally 'measured' by the ratio of CRR over CSR, which is referred to as the factor of safety (F_S) against the triggering of soil liquefaction. Thus, liquefaction of a soil element at depth is predicted to occur if $F_S \leq 1$, and no liquefaction is predicted if $F_S > 1$.

Although liquefaction is a major cause of earthquake damage, little harm occurs unless the liquefied condition leads to some form of ground surface disturbance or ground damage [7]. Determining liquefaction potential of a soil is only the first step in assessing liquefaction hazard. What is more important to the practicing engineer is the effect of liquefaction [8,9], in particular, ground damage at or near buildings. Whereas the engineer's ability to assess the liquefaction potential of a soil has been greatly enhanced over the years, relatively little progress has been made on assessing ground damage at or near buildings. Although recent advances in physical model experiments [10,11] and computational modeling of liquefaction-induced ground deformation [12,13] are quite promising, challenges remain on this critical yet unresolved problem. It is believed that empirical, simplified methods will remain the method of

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choice for many years to come in the field of geotechnical earthquake engineering.

In this paper, an empirical method for assessing ground damage at or near buildings is developed and presented. This method is based on field observations from recent earthquakes, and while empirical and approximate in nature, it is shown that it can explain observations of ground damage at or near buildings in limited case histories.

2. Liquefaction-induced ground failure—an overview

Youd and his co-workers have studied the issue of ground failure triggered by earthquakes extensively [14–17]. Youd and Perkins [18] defined liquefaction severity index (LSI) to describe the severity of the damaging ground effects that might accompany an episode of liquefaction. The introduction of this index was very significant, because liquefaction potential maps developed by many investigators [19–21] showed the likelihood of liquefaction, but provided no indication of the severity of ground failure. Maps of LSI provide a better indication of potential damaging effects triggered by earthquakes. To determine the actual liquefaction hazard at a particular locality, however, site-specific geotechnical investigations and analyses are required [18].

Hamada et al. [22] developed an empirical model for estimating liquefaction-induced ground displacement based on limited data from Japan. Bartlett and Youd [16,17] derived empirical equations for estimating liquefaction-induced lateral spreads based on a series of multiple linear regression analyses of a much larger database, and their work was an important milestone for estimating ground failure triggered by liquefaction. A recent update of their work was documented by Youd et al. [23]. Chiru-Danzer [24] developed neural network models for predicting liquefaction-triggered ground displacements. Rauch and Martin [25] presented an empirical model for predicting liquefaction-induced lateral spreading in three levels of sophistication.

Based on a database compiled from Romanian, Chinese, and Japanese earthquakes, Ishihara [26] studied the influence of the overburden non-liquefied soil layers on the emergence of ground failure (mainly sand boiling) on the ground surface. According to Ishihara, the occurrence of sand boiling depends on the relation of the thickness of the overburden non-liquefied soil layer to the thickness of the liquefied soil layer and a_{max}. Youd and Garris [7] examined the Ishihara procedure and confirmed the validity of the thickness bounds proposed by Ishihara [26] for the prediction of ground surface disruption at sites that are *not* susceptible to ground oscillation or lateral spread, but for sites that are susceptible to ground oscillation or lateral spread, the Ishihara procedure is not applicable. Yuan et al. [27] reached similar conclusions based on an examination of the Ishihara procedure with field cases from the 1999 Chi–Chi earthquake.

Another interesting concept that is more closely related to the consequence of liquefaction at the ground surface is the so-called Liquefaction Potential Index, I_L, defined by Iwasaki et al. [28,29]:

$$I_L = \int_0^{20} F_1 W(z)\,dz \quad (1)$$

where F_1 is an index defined as: $F_1 = 1 - F_s$, if $F_s \leq 1.0$; and $F_1 = 0$ if $F_s > 1.0$, where F_s is the factor of safety against liquefaction triggering. The integration in Eq. (1) is carried out from the ground surface ($z=0$) to the depth of 20 m, the depth below which the effect of liquefaction on the failure potential of the ground is considered negligible [28]. $W(z)$ is a weighting function of depth, which is used to account for the effect of soil liquefaction at different depths to the failure potential of the ground. The weighting function is assumed by Iwasaki et al. [29] to be a linear function of depth z (in meters):

$$W(z) = 10 - 0.5z \quad (2)$$

Note that the index I_L defined by Iwasaki et al. [29] was meant to reflect the effect of liquefaction. Thus, it is referred to herein as the Liquefaction Effect Index to avoid possible confusion with the term 'Liquefaction Potential' that is commonly used and understood in the literature [3,6]. Iwasaki et al. [29] proposed the following criteria for assessing liquefaction-induced ground failure potential: (a) no failure potential if $I_L = 0$, (b) low potential if $0 < I_L \leq 5$, (c) high potential if $5 < I_L \leq 15$, and (d) extremely high potential if $I_L > 15$. The Iwasaki method is *in principle* quite attractive as it deals directly with the liquefaction effect that is the subject of field observations. The same view has been expressed by other researchers [30].

Note that with the Iwasaki method, the factor of safety (F_s) in Eq. (1) was determined from an older version of an SPT-based simplified method [31]. Because Cone Penetration Test (CPT) is a more consistent and repeatable in situ test than the SPT [32], and it can provide a nearly continuous profile of liquefaction resistance [6], it is advantageous to adopt CPT-based simplified methods for determining F_s, which can then be integrated into Eq. (1).

An important question arises as to whether the criteria concerning liquefaction effect index (I_L) recommended by Iwasaki et al. [29] are applicable if the factor of safety is calculated with a method different from that used in Eq. (1). A recent study by Lee et al. [33] concluded that I_L should be re-calibrated if a different method was adopted for determining liquefaction resistance and factor of safety. Based on calibration of I_L with 154 case histories each with a CPT sounding and field observation, the following mapping function is developed using the procedure