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Technical Paper

Effect of saturation on liquefaction resistance of iron ore fines and two sandy soils

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Abstract

Over the past several years, the International Maritime Organization (IMO) has become increasingly concerned about the liquefaction of unsaturated solid bulk cargo (e.g. iron ore fines) during maritime transportation. This concern has arisen due to several accidents including the capsizing of vessels. In addition, although the resistance against liquefaction of ordinary unsaturated soils is higher than for saturated soils, possible key parameters governing the liquefaction resistance of unsaturated soils ($R_{L,unsat}$) have not yet been clearly identified. Therefore, in this study, undrained cyclic loading tests of saturated and unsaturated iron ore fines and two sandy soils were conducted using a triaxial apparatus to reveal the liquefaction behavior of iron ore fines and to find the key parameters governing $R_{L,unsat}$. Through comparisons, it was found that the liquefaction behavior of iron ore fines is similar to that of sandy soils. The degree of saturation and potential volumetric strain, which have been proposed as the governing parameters of $R_{L,unsat}$, were examined based on experimental data obtained in this study and by other researchers. It was shown that neither of the two parameters correlate with the liquefaction resistance ratio (LRR), a ratio of $R_{L,unsat}$ to the liquefaction resistance of the saturated soils ($R_{L,sat}$) with a unique relationship, especially when considering soils with considerable fines content. Following the concept of potential volumetric strain, which considers the compressibility of pore air in the unsaturated soils, volumetric expansion due to the reduction in confining pressure during cyclic loading is further considered, and a new index, the volumetric strain ratio (R_v) is proposed in this study. According to the experimental data obtained in this study, R_v exhibits a much better correlation with LRR than the two former parameters.

Keywords: Iron ore fines; Unsaturated soils; Liquefaction; Volumetric strain ratio; Triaxial test

1. Introduction

Awareness was recently raised among the International Maritime Organization (IMO) due to the substantial losses caused reportedly by liquefaction of solid bulk cargo e.g. iron ore fines, nickel ore, sinter feed bauxite etc. during maritime transportation (Isacson, 2010a, b; LPC, 2011; Gard, 2012 etc.). Though such solid bulk cargo is usually loaded into the vessels under the unsaturated condition, the capsizing of vessels due to the liquefaction of such cargo subjected to ocean wave motion, for example, cannot be prevented in some cases due to a lack of knowledge about the liquefaction of these materials.

In addition, in earthquake-prone countries, such as Japan, the liquefaction resistance of unsaturated soils is a much-researched topic in the field of geotechnical engineering. A great number of liquefaction sites were reported in the Tohoku

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Nomenclature

CSR cyclic stress ratio ($=q_{cyclic}/2\sigma_0'$)
D_c compaction degree before applying cyclic loading
D_r relative density before applying cyclic loading
e void ratio
e_{max} maximum void ratio
e_{min} minimum void ratio
DA=5% 5% double amplitude of axial strain
DA=5% criterion criterion for liquefaction based on the condition of DA=5%
F_c fines content
G_s specific gravity
IMO International Maritime Organization
LRR liquefaction resistance ratio, a ratio of $R_{L,unsat}$ to $R_{L,sat}$
$\text{LRR}_{DA=5\%}$ LRR, in which R_L is determined based on DA=5% criterion
$\text{LRR}_{\Delta u=0.9\sigma 0'}$ LRR, in which R_L is determined based on $\Delta u=0.9\sigma_0'$ criterion
$N_{DA=5\%}$ number of cycles to trigger liquefaction based on DA=5% criterion
$N_{\Delta u=0.9\sigma 0'}$ number of cycles to trigger liquefaction based on $\Delta u=0.9\sigma_0'$ criterion
p total mean principal stress
p-constant condition a condition to maintain p constant during applying vertical cyclic loading
$p-u_a$ net mean principal stress of unsaturated soil
$p-u_w$ effective mean principal stress of unsaturated soil
$p-u$ effective mean principal stress denoting either $p-u_a$ or $p-u_w$
q_{cyclic} single amplitude of vertical cyclic stress
R_L resistance against liquefaction
$R_{L,sat}$ R_L of the saturated soil
$R_{L,unsat}$ R_L of the unsaturated soil
R_v volumetric strain ratio ($=\varepsilon_{\nu,air}/\varepsilon_{\nu,\sigma'}$)
S matric suction ($= u_a-u_w$)
S_r degree of saturation
u_a pore air pressure
u_w pore water pressure
w_{opt} optimum water content
Δu excess pore pressure, denoting either Δu_a or Δu_w
Δu_a excess pore air pressure
Δu_w excess pore water pressure
$\Delta u=0.9\sigma_0'$ a condition when Δu equals 90% σ_0'
$\Delta u=0.9\sigma_0'$ criterion criterion for liquefaction based on the condition of $\Delta u=0.9\sigma_0'$
$\varepsilon_{\nu,air}$ volumetric strain caused by pore air compression
$\varepsilon_{\nu,0.9air}$ volumetric strain caused by pore air compression when $\Delta u_a=0.9\sigma_0'$
$\varepsilon^*_{\nu,air}$ potential volumetric strain, namely, $\varepsilon_{\nu,air}$ when $\Delta u_a=\sigma_0'$
$\varepsilon_{\nu,\sigma'}$ volumetric strain caused by reduction of σ'
$\varepsilon_{\nu,0.9\sigma'}$ $\varepsilon_{\nu,\sigma'}$ due to reduction of σ' by 90%
$\varepsilon_{\nu,\tau}$ volumetric strain caused by contraction (or negative dilatancy)
ρ_{dmax} maximum dry density obtained from compaction test
σ' confining pressure
σ_0' initial confining pressure
σ_h cell pressure

district (Yamaguchi et al., 2012) and the Kanto district, including the Tokyo Bay area (Yasuda et al., 2012; Towhata et al., 2014) after the Great East Japan Earthquake Disaster in 2011. Severe damage to houses (e.g. tilting, cracking etc.), roads and lifeline facilities was incurred in the liquefaction affected areas. As a possible countermeasure against liquefaction, which can be applied to the narrowly constructed residential areas, ground desaturation by either dewatering the ground or the injection of micro air bubbles has been given particular attention in recent years due to its low cost (Okamura et al., 2006; NILIM, 2011, 2013).

To the authors' knowledge, starting from the early work by Sherif et al. (1977), it has been repeatedly shown that soils under the unsaturated condition show higher resistance against liquefaction than those under the saturated condition. However, the governing parameters determining the liquefaction resistance of unsaturated soils remain unclear. Attempts were made to determine the role played by the degree of saturation S_r (Yoshimi et al., 1989; Goto and Shamoto, 2002), pore-pressure coefficient B value (Yoshimi et al., 1989; Unno et al., 2008; Arab et al., 2011), elastic wave velocity (Huang et al., 1999; Ishihara et al., 2001; Tsukamoto et al., 2002; Yang, 2002; Yang et al., 2004) and potential volumetric strain (Okamura and Soga, 2006). It seems that the first three parameters can work well only for a given soil under similar test conditions, and the last parameter needs to be verified on soils with considerable fines content.

In this study, undrained cyclic loading tests were conducted on one type of iron ore fines and two types of sandy soils by employing a stress-controlled triaxial apparatus. The liquefaction behaviors of iron ore fines were compared with those of ordinary sandy soils. Based on the test data obtained in this study and that reported in the literature, two parameters proposed to be the governing factors of liquefaction resistance of the unsaturated soil are discussed. Finally, following relevant findings from past studies, a new governing index is proposed.

2. Apparatus

Both saturated and unsaturated specimens were tested on the same apparatus, while extra components were added to the apparatus for the unsaturated tests as schematically illustrated in Fig. 1. Sinusoidal vertical cyclic loading with frequency of 0.1 Hz is applied by a double action cylinder controlled by a function generator and an E/P regulator. There is another set of