

Laboratory tests for permeability of sand during liquefaction



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ABSTRACT

The permeability is a very important property affecting drainage, pore pressure buildup and dissipation, and ground settlement for saturated sand during and after seismically induced liquefaction. A laboratory experiment was developed to conduct tests for evaluating the water movements and permeability in a sand column before, during and after liquefaction. The excess pore water pressures at various depths within the sand specimen, hydraulic gradients, and water flow rates were recorded continuously throughout the tests. The permeability of the sand specimen during the process of liquefaction was calculated from these measurements. Results showed that the permeability of fine Vietnam sand during liquefaction was about 4–5 times the initial value before liquefaction, while it reduced to 0.9–0.97 times the initial value after complete dissipation of the excess pore pressures depending on the density of sand. The permeability of sand during excess pore pressure dissipation after liquefaction was also evaluated.

1. Introduction

Soil liquefaction during earthquakes can cause great damage of structures due to the loss of the soil strength and ground settlements. The permeability of sand is an important parameter affecting the pore pressure buildup and dissipation during the liquefaction process. Ishihara [1] summarized the results of various predictions for VELACS model 1 and concluded that the post-liquefaction behavior of liquefied sand is significantly affected by the soil permeability at the time of liquefaction. Sharp et al. [2] presented the effect of permeability on the behavior, including liquefaction depth, lateral spreading and settlement, of sand during liquefaction by comparing the results of centrifuge tests using different pore fluids. A modified consolidation theory was proposed by Scott [3] to consider the relation between solidification velocity and permeability of saturated sand. Kim et al. [4] combined Scott's theory with their centrifuge test results and developed a non-linear solidification model. It was found that the solidification velocity increased with increase of particle size and relative density of the specimens. Centrifuge tests were conducted by Arulanandan and Sybico [5] to characterize the soil structure during and after liquefaction using resistivity measurement. They found that the coefficient of permeability of the soil specimen during liquefaction increased 6–7 times its initial value as the pore shape factor and tortuosity of the flow path within the sand specimen decreased. It further indicated that it would underestimate the settlement using the initial permeability of the specimen prior to liquefaction. Ha et al. [6] examined the dissipation pattern of excess pore pressure after liquefaction and found permeability during

liquefaction increased by 1.4–5 times compared with the original permeability. Greater increases of permeability were observed for larger effective grain size and lower coefficient of uniformity. Combining the test results of 1-g shaking table tests with the nonlinear solidification model and consolidation theory, Shahir et al. [7] proposed a relationship between permeability and pore pressure ratio in sand during pore pressure buildup, liquefaction and pore pressure dissipation phases. According to the results of numerical simulations of the centrifuge liquefaction experiment by Gonzales et al. [8] to calibrate the parameters of the propose relationship, they found the permeability increased 20 times during liquefaction. Wang et al. [9] concluded that the post-liquefaction behavior can be predicted well if the change of permeability after liquefaction, which is about 4 times its initial value, was considered. After fluidizing the sand specimen with an upward flow (sand boiling), Haigh et al. [10] then lowered the flow rate and measured the permeability under various low effective stresses for various types of sand. Their results showed that permeability under near-zero effective stresses ranged from 1.1 to 5 times the original permeability before boiling.

Most of these previous studies obtained the permeability of liquefied sand based on the results at the stage of pore pressure dissipation and sedimentation of sand particles after liquefaction rather than that at the time of liquefaction. There were no verifications of the flow condition considered in these evaluations truly represented that within the soil during and after liquefaction. Neither the magnitude of changes of the permeability after liquefaction was confirmed. A new experimental approach is developed in this study by combining seepage and

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liquefaction tests together to directly measure the permeability of a specimen of saturated sand during and after liquefaction. Thus, the soil from a liquefiable site can be tested to obtain this important parameter in site-specific response analysis including liquefaction and ground settlement subjected to earthquake shakings.

2. Methodology of experiment and analysis

The pore water pressure distribution along the depth of a soil column without any water flow is under a hydrostatic condition. In a conventional seepage experiment, an upward water flow with a velocity of v is induced by a hydraulic gradient across the soil specimen, usually by applying a higher excess pore water pressure at the lower part of the soil column. The excess pore water pressure u_e is the amount of pore water pressure in excess of the hydrostatic pressure at that depth of soil. Hydraulic gradient, i , is the difference of hydraulic heads, or the difference of the excess pore water pressures (in terms of height of water) measured at two different depths in the soil column divided by the distance between these two depths. The permeability (hydraulic conductivity) of the soil is then obtained according to Darcy's law, i.e., $k = v/i$. The vertical effective stress in a soil column reduces by the amount of the excess pore pressure due to the drag on the soil particles (seepage force) by the upward flow. Sand boiling occurs when the flow velocity reaches a critical value to uplift the soil particles and the vertical effective stress becomes zero at this moment with excess pore pressure equal to the initial effective stress. The theoretical critical hydraulic gradient $i_{cr} = \gamma'/\gamma_w$, where γ' is the buoyant unit weight of the soil and γ_w is the unit weight of water.

When a saturated sand column subjected to vibrations, excess pore water pressure is generated due to the tendency of volume contraction of the sand skeleton while the viscosity of water transiently hinders the relative movements between sand particles and water and impedes pore pressure dissipation in a very short time during vibrations. As a result, a portion of the effective stress (contact forces between grains) in sand transfers to the pore water pressure. Liquefaction of sand occurs when the excess pore pressure reaches the initial effective stress if the vibration is sufficiently strong, in magnitude and duration. At this stage, the sand loses contacts between grains and behaves like a liquid of a sand-water mixture with a unit weight of $(\gamma' + \gamma_w)$. If no water enters or exits the sand column, then there is no net water flow through the liquefied sand. The pressure distribution along the depth of the liquefied sand is attributed to the weight of this sand-water mixture. At the moment reaching liquefaction, it can be considered as a hydrostatic condition for this material, even though it exhibits an upward hydraulic gradient, γ'/γ_w , relative to the initial hydrostatic condition prior to vibrations. This hydraulic gradient is the potential for the relative movements between sand and water during the sedimentation and reconsolidation of the sand particles after liquefaction. After stop of vibrations, the excess pore pressure u_e starts to diminish and the hydraulic gradient decreases when sand grains regain their contacts. It is worth noting that, although sand is under a zero-effective stress condition in both cases of sand boiling and liquefaction, sand particles move upwards during sand boiling induced by the upward flow while sand particles tend to settle downwards during liquefaction induced by vibrations.

In order to directly measure the permeability of the liquefied sand, a water flow with a velocity of v_L passing through this sand-water mixture under the same state of liquefaction is introduced with an additional hydraulic gradient i_L and the permeability can then be determined as $k_L = v_L/i_L$ assuming Darcy's law is valid. If the flow velocity is substantially below the critical velocity for sand boiling, i.e., the dragging force is less than the buoyant weight of sand particles, the upward flow will not carry away the sand particles; it only hinders sedimentation of the sand particles. This additional hydraulic gradient would result in an apparent excess pore water pressure exceeding the initial effective stress prior to vibrations. A schematic illustration of

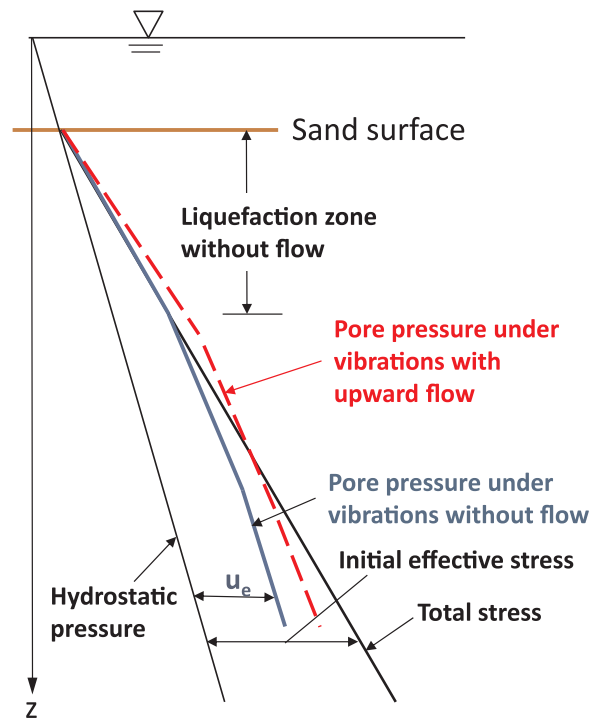


Fig. 1. Schematic diagram of excess pore pressure profiles along a sand column in liquefaction tests.

excess pore pressure heads in the aforementioned situations is given in Fig. 1. In this study, liquefaction tests with an upward flow were performed by first introducing a water flow to the sand column followed by application of vibrations to induce liquefaction of the sand specimen. The excess pore water pressures at different depths in the sand column and the flow velocity were measured continuously during and after liquefaction. These results were then compared with those in liquefaction tests without flow. The extra hydraulic gradient i_L within the liquefied sand in addition to that without flow was obtained for this flow velocity v_L . The permeability of the liquefied sand was then calculated accordingly. Experiment equipment, sand specimen preparation, test procedures, test program, test results and data analyses are presented in details in the following sections.

3. Test equipment and specimen preparation

The experimental system shown schematically in Fig. 2 includes an acrylic permeameter containing a sand specimen of 100 mm in diameter and 500 mm in length, a constant head water supply system, and an instrumentation and data acquisition system for continuous measurements of water pressure, flow rate, and input vibration during the tests. Detailed descriptions of the experiment system and specimen preparation are given in Wang [11].

The permeameter is made of a transparent acrylic tube of an inner diameter of 100 mm, an outer diameter of 120 mm and a length of 1000 mm with an overflow device on top. A 100-mm thick filter layer comprising of glass beads and mesh screens (sieve #100) was installed at the bottom of the permeameter to ensure a uniform flow through the entire cross-sectional area of the sand specimen. A miniature accelerometer was attached at the base of the permeameter measuring the applied vibrations in the horizontal direction.

A continuous flow of water was supplied from a reservoir of a constant water level. The flow rate was regulated using a needle valve and measured continuously during tests with an impeller flowmeter.

Four pressure transducers, P1, P2, P3, and P4 were installed on the wall of the permeameter at heights of 550 mm, 450 mm, 300 mm and 150 mm, respectively, from the base of the acrylic tube followed by

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