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Viscous fluid characteristics of liquefied soils and behavior of piles subjected to flow of liquefied soils

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Abstract

Lateral movement of sloping ground due to flow liquefaction has caused many pile foundations to fail, especially those in ports and harbor structures. Several researchers have found and verified that the behavior of liquefied soils can be simulated appropriately by modeling the liquefied soils as viscous fluid. In this study, the influence of the lateral movement of liquefied sloping ground on the behavior of piles was analyzed on the assumption that the flow of liquefied soils can be treated as viscous fluid flow. Sinking ball tests and pulling bar tests were performed to measure the viscosity of liquefied Jumoonjin sand. Then, the behavior of a single pile installed in liquefiable infinite slopes consisting of sand was investigated by numerical analyses. The liquefied sand behaved as non-Newtonian fluid, whose viscosity decreased with increasing shear strain rate. Furthermore, the flow of liquefied soils had a crucial effect on the stability of piles installed in the sloping ground.

Keywords: Flow liquefaction; Viscosity of liquefied soil; Numerical analysis; Infinite slope; Pile

1. Introduction

Permanent lateral movement of ground has extensively damaged pile foundations of buildings, bridges, ports, and harbor structures. Lateral movement of ground may occur on many occasions, e.g. in unstable or marginally stable ground slopes, in liquefied soils, and in soft clay layers subjected to large embankment loading, and so on. In many cases, pile foundations were damaged by liquefaction-induced lateral movement.

During the 1964 Niigata earthquake, lateral movement of liquefied soils resulted in excessive bending and failure of reinforced concrete piles supporting several buildings, including the NHK Building, the Niigata Family Courthouse, and the Niigata Hotel [1,2]. And lateral soil movements caused deformation of steel piles, which led to the collapsing of five bridge spans in the Yachiyo Bridge. Also, lateral movement of ground damaged more than 250 bridge structures during the 1964 Alaska earthquake [3].

Effects of lateral soil movements on piles can be estimated by several methods: (i) empirical methods, (ii) methods based on subgrade reaction model, (iii) linear elastic theory, (iv) limit equilibrium analysis, (v) viscous flow theory, and (vi) numerical analysis based on finite element method.

Recently, several researchers [1,3,7] have been studying liquefaction-induced ground movement. Seismic resistant designs have considered the effects of liquefied soil movement on pile foundations and other underground structures. Towhata et al. [4], Uzuoka et al. [5], and Hadush et al. [6] assumed liquefied soils as viscous fluid, and verified that their model based viscous fluid assumption can simulate the behaviors of liquefied soils appropriately. Hamada and Wakamatsu [7] concluded from the results of various model tests on liquefied ground that liquefied soils behaved as psuedoplastic fluid during ground movement.

In this study, behavior of a single pile installed in submerged sand slopes was analyzed. In the analysis, soil liquefied by earthquake was assumed to be a viscous fluid.

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Sinking ball tests and pulling bar tests were performed to exactly measure and properly estimate the viscosity of liquefied sand, which is an essential input parameter for simulating the behavior of the liquefied soil. Then, the behavior of a single pile subjected to lateral movement of infinite liquefied slopes was investigated by numerical analysis.

2. Flow liquefaction

Liquefaction can be divided into two main categories—flow liquefaction and cyclic mobility. Flow liquefaction can be initiated by cyclic loading only when the shear stress level of soil at static equilibrium is higher than the steady-state strength or residual strength of soil; otherwise, cyclic mobility may occur.

Fig. 1 shows the zone susceptible to flow liquefaction and the effective stress path of flow liquefaction. In the figure, point A indicates the stress state of a soil element at static equilibrium with static shear stress τ_{static}, which is greater than the steady-state strength S_{su} of the soil element. If a cyclic load is applied to the soil element at point A under undrained condition, the effective stress state of the soil element would change, thus point A would move to the left since positive excess pore pressure develops with permanent strain. If the effective stress path reaches the flow liquefaction surface (FLS) at point B, the soil element becomes unstable and its effective stress state rapidly moves to the steady-state at point C, where the soil element undergoes sudden failure with large deformation.

In submerged slopes of lakes or rivers, upstream slopes of dams, and submerged slopes of pile-supported wharves, the level of shear stress of soil is considerably high at static equilibrium. Thus, flow liquefaction can be easily generated by an earthquake. However, if the static shear stress is smaller than the steady-state shear strength of the soil, cyclic mobility generally occurs in the soil undergoing limited deformation during earthquake.

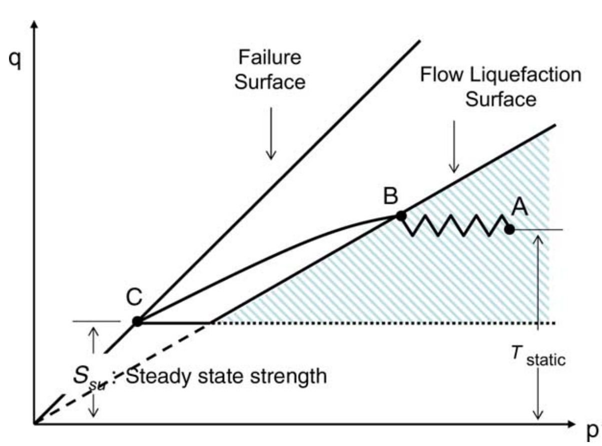

Fig. 1. Zone susceptible to flow liquefaction and effective stress path of flow liquefaction initiated by cyclic loading.

3. Viscosity of liquefied sand

Liquefied soils can be assumed to be a viscous fluid, based on the study of Hamada and Wakamatsu [7]. Therefore, physical and mechanical properties of liquefied soils can be represented by function of viscosity. In this study, sinking ball tests and pulling bar tests were performed to estimate the viscosity of liquefied soil. Jumoonjin sand, which is a clean and uniform sand, was used for the tests. The grain-size distribution of Jumoonjin sand is shown in Fig. 2. Other basic engineering properties of Jumoonjin sand are listed in Table 1.

3.1. Sinking ball tests

Fig. 3 shows the schematic diagram of the sinking ball test, which was designed to estimate the viscosity of a completely liquefied soil. Miyajima et al. [8] studied the relation between the viscosity of a liquefied soil and the magnitude of the input acceleration of the soil by conducting similar tests using a shaking table. They used a 5 Hz sine wave to liquefy the model sand ground. But in our tests, an impact load was generated by hitting the bottom of the soil container with the hammer.

The soil container was a transparent acryl cylinder of 400 mm in diameter and 800 mm in height. Samples of model sand ground of 50 cm in height with various relative densities D_r ranging 34–64% were prepared. The ball was a steel sphere of 5 cm in diameter. Input acceleration was measured by the accelerometer attached on the bottom of the soil container, excess pore water pressure by pore pressure transducer installed 10 cm deep in the model grounds, and ball displacement during sinking by wire-type LVDT connected to the ball.

According to the Stoke's law, viscous resistance F_D acting on a ball sinking in a viscous fluid at a constant speed V can be expressed by Eq. (1). And the viscous resistance required for equilibrium with the sinking ball can be expressed by Eq. (2) as a function of its effective weight. From Eqs. (1) and (2), viscosity μ of the viscous fluid can be

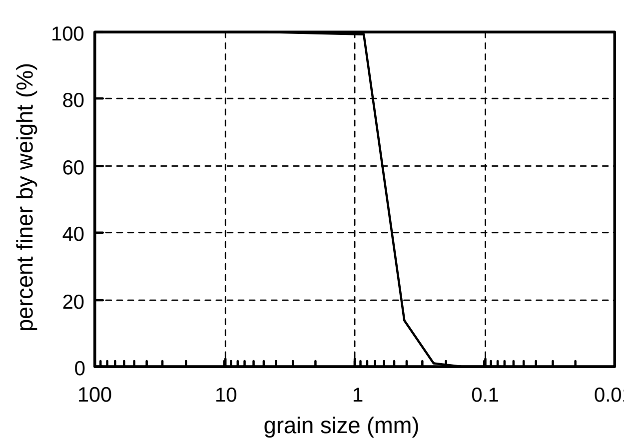

Fig. 2. Grain-size distribution of Jumoonjin sand.