Liquefaction-Induced Settlement of Structures on Shallow Foundation

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ABSTRACT: Unlike the liquefaction potential assessment, the liquefaction-induced ground settlement has not been studied extensively. The uncertainty of the ground profile and associated soil engineering properties is the major challenging to advance the current knowledge on this subject. Within Ishihara and his colleagues' framework, the liquefaction-induced settlement is computed by the associated post-liquefaction volumetric strain, once the factor of safety for liquefaction is evaluated. For estimating settlement of a building with shallow foundation in liquefiable soils, on the other hand, dynamic behavior of the soils, its relative density, and the thickness of liquefiable soil, building's weight and dimensions, seismic intensity, and structure-soil interaction should be considered accordingly. This paper aims to develop a practical and simple procedure to estimate the liquefaction-induced settlement on structures on shallow foundation, based on the framework proposed by Sawicki and Mierczynski in 2009. A series of comprehensive numerical analyses were carried out to incorporate the above-mentioned factors in the developed procedure. Data of liquefaction-induced settlement of structures on shallow foundation reported in the literature were used to compared with the estimated ones.

KEYWORDS: Liquefaction-induced settlement, Shallow foundation, Finite element analysis

1. INTRODUCTION

Earthquake induced soil liquefaction has drawn many attentions in both structural and geotechnical engineering. The importance of understanding for the shallow foundation sitting on liquefiable soils have been indicated in many past experiences such as 1964 Nigatta earthquake, 1990 Luzon earthquake, 1999 Kocaeli earthquake, Chi-Chi earthquake, and 2011 Tohuku earthquake. Due to heterogeneous nature of granular soil, interactive soil-foundation system, and variably seismic activities, accurate estimations for liquefaction induced settlement of shallow foundation have been very challenging. For calculating settlement of a sinking building with shallow foundation in liquefied soils accurately, dynamic behavior of soils, relative density, and thickness of liquefiable soil, building's weight and dimension, seismic intensity, and soil-structure interaction have been pointed out to be important factors in estimating the liquefaction induced building settlement in previous studies (e.g. Yoshimi and Tokimatsu (1977), Adachi et al. (1992), Acacia et al. (2001), Sancio et al. (2004), Bertalot et al. (2013)).

Dashti et al. (2010a, 2010b) and Dashti and Bray (2013) have devoted great efforts on investigating responses of the structure and soils. Shahir and Pak (2010) proposed a practical relationship for estimation of liquefaction induced settlement of shallow foundation based on a series of numerical approach. However, the conditions of the soil and the seismic activity were not implemented in the formula. Sawicki and Mierczynski (2009) developed a simple equation for calculating a sinking block in the liquefiable soils where they proposed a conceptually assumed viscosity. The viscosity of liquefied soils in their work was considered as a result of dynamic behaviors of soil, seismic activity, and soil-structure interaction.

In this study, we adopt this approach to evaluate liquefaction-induced settlement of soils under a structure, sitting on liquefiable soils. It is postulated that the major settlement of an object occurs due to its sinking into the liquefied subsoils. In this sinking equation, the sinking rate of the structure is a function of block weight, unit weight of water, and the sunk volume of the block under the ground water table. The viscosity of the liquefying soils of the ground is critical in the analysis as it cannot be measured physically. After solving the governing differential equations, where those forces are balanced at each time step, the settlement against time can then obtained. In this paper, we calculated liquefaction induced settlement on shallow foundation through a series of three-dimensional finite element analyses. We then back calculated the viscosity of the soil by comparing settlements simulated by both the numerical analysis and the sinking equation. Details of the method will be introduced in the following sections.

2. METHODOLOGY

Figure 1 describes the process of an object sinking in the liquefied subsoil, where the viscous fluid model can be adopted for the stage when the subsoil has been liquefied. The analysis of stages preceding the sinking of breakwater due to subsoil liquefaction is presented in Sawicki (2003). W is the weight of the structure, while B and L are the length and width of the rectangular foundation. $\gamma_m = ((1-n)\gamma_s + n\gamma_w)$ is unit weight of liquefied soil, in which n is the soil porosity. γ_s is the soil solid unit weight, and γ_w is the unit weight of water.

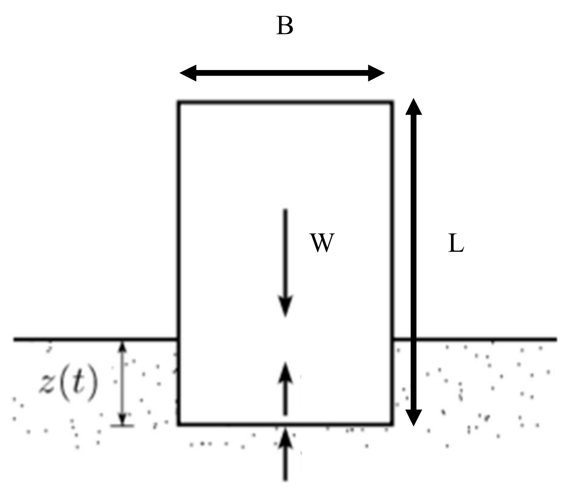

Figure 1 Initial equilibrium of a block before subsoil's liquefaction and forces acting on a block during sinking in liquefied subsoil (after Sawicki and Mierczynski (2009))

$$z = \frac{b}{a}\left[1 - \exp(-at)\right] \tag{1}$$

$$a = \frac{\gamma_m BL}{\xi} \quad b = \frac{W}{\xi}, \ \xi = 8\overline{D}\eta, \text{ and } \overline{D} = 2\sqrt{BL/\pi}$$

Equation (1) can be obtained after integration process of a differential equation. In this equation, sinking of a structure with time can be estimated after the values of *a* and *b* are filled in with, of which only a parameter η is unknown at current step.

In the finite element analysis, a coupled soil-water problem based on a u-p formulation is employed herein. The equilibrium equation for the mixture was derived as follows.

$$\rho \ddot{u}_i^s = \sigma_{ij,j} + \rho b_i \tag{2}$$

in which ρ is the total density, $\ddot{u}_i^s$ is the acceleration of the solid phase, σ_{ij} is the total stress tensor and b_i is the body force vector.
The continuity equation is written as,

$$\rho^f \ddot{u}_{i,i}^s - p_{,ii} - \frac{\gamma_w}{k}\dot{\varepsilon}_{ii}^s + \frac{n\gamma_w}{kK^f}\dot{p} = 0 \tag{3}$$

where ρ^f is the density of fluid, *p* is the pore water pressure, γ_w is the unit weight of the fluid, *k* is the coefficient of permeability, ε_{ii}^s is the volumetric strain of the solid phase, *n* is porosity and K^f is he bulk modulus of the fluid phase.

The cyclic elasto-plastic constitutive model for sand was used in the analysis. Its model parameters and constants were calibrated through hollow cylindrical torsional shear tests. The calibrated model was successfully reproducing the experimental results under various stress conditions such as isotropic and anisotropic consolidated conditions, with and without the initial shear stress conditions and the principal stress axis rotation, as discussed in Oka et al. (1999 and 2004). In this paper, Toyoura sand, Japanese standard sand, is considered as the composition of the ground in the finite element analysis. For the sake of convenience, the parameters of the soil model for Toyoura sand in relative density of 50%, 60%, 70% and 80% is all confirmed by Oka et al. (1999) and widely used in Oka et al. (2004).

2.1 Finite Element Model

The configuration of the finite element model is shown in Figure 2. To obtain the viscosity in various conditions, the dimension of shallow foundation, the weight of the structure loading on the shallow foundation, relative density of soil and the seismic loading were set with various values in each calculation case. The soils were modeled with 8-node isoparametric solid elements. It contained 1386 nodes and 1000 elements in the numerical mesh. All soil layers were set up with the cyclic elasto-plastic model. The parameters for each of soil layers are shown in Table 1. The elements below the water table were treated as fully saturated elements with DOF (Degree of Freedom) of pore water pressure.

For the boundary conditions, the bottom of the mesh was set to be rigid and all lateral boundaries were set to be equal-displacement to avoid unnecessary echo-vibration and to simulate the side boundary conditions of the laminar box. The input acceleration was set at the rigid bottom boundary. The seismic wave used was sinusoidal wave with 1Hz frequency, and 100, 200, 300 and 400 gals of magnitude. The lateral and bottom boundaries were assumed to be impermeable while the water table was permeable.

A time integration step of 0.01 second was adopted to ensure the numerical stability. The hysteresis damping of the constitutive model was used while the Rayleigh damping was assumed to be in proportional to the initial stiffness in order to describe the damping especially in the high frequency domain. β and γ in the Newmark method were set to be 0.3025 and 0.6 to ensure the numerical stability.

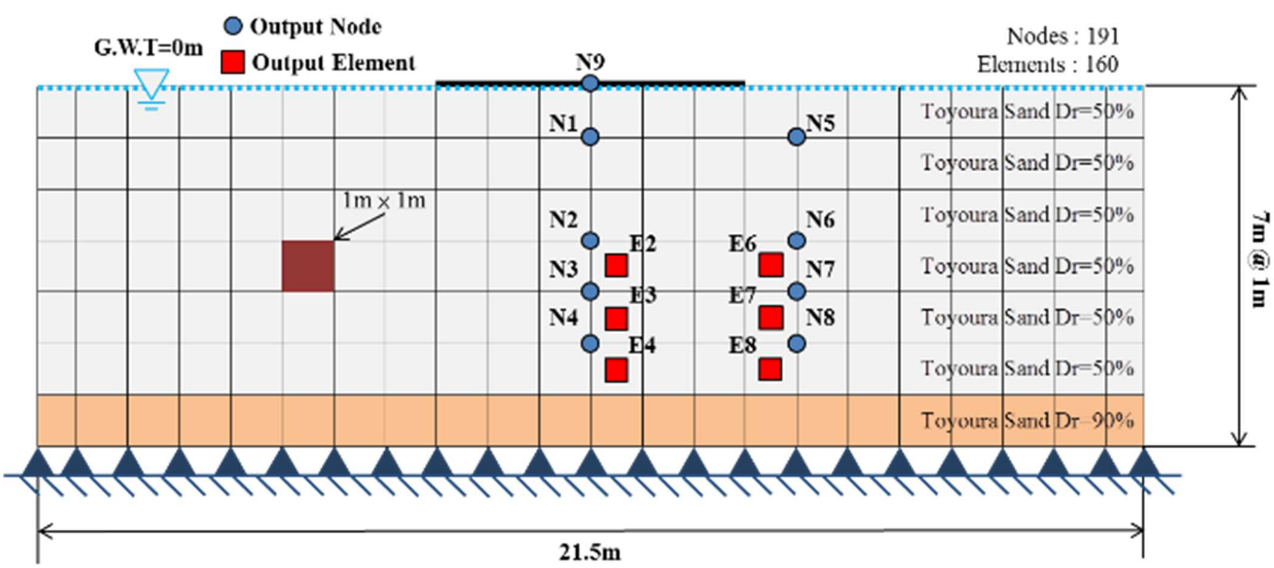

Figure 2 The finite element model

Table 1 Parameters of soil model used in the analysis

Name of soil profile	Unit	Dr = 50%	Dr = 60%	Dr = 70%	Dr = 80%
Density	ρ (t/m^3)	1.879	1.898	1.917	1.938
Coefficient of permeability	k (m/s)	2.2×10^{-5}	2.4×10^{-5}	2.1×10^{-5}	1.9×10^{-5}
Void Ratio	e_o	0.800	0.754	0.716	0.683
Compression Index	λ	0.0250	0.0091	0.0091	0.0091
Swelling index	κ	0.00030	0.00052	0.00052	0.00052
Normalized Shear Modulus	G_o/G'_{mo}	1150	1200	1980	1980
Stress Ratio at Maximum Compression	M^*_m	0.909	0.707	0.707	0.707
Stress Ratio of Failure State	M^*_f	1.229	0.990	1.180	0.990
Harding Parameter	B^*_o, B^*_1, C_f	2000,400,0	4089,54.5,0	4001,100,950	4500,65.4,0
Control parameter of anisotropy	C_d	2000	2000	2000	2000
Parameter of Dilatancy	D^*_o, n	1, 4	0.6, 5.1	0.8, 7	0.52,8.5
Reference Value of Plastic Strain	γ^{P*}_r	0.005	0.002	0.0032	0.005
Reference Value of Elastic Strain	γ^{E*}_r	0.0030	0.0120	0.0030	0.025

3. VERIFICATIONS

A laboratory test which was performed in centrifuge experiment is used to verify the accurate performance of the numerical code adopted herein. The ground was composed of Toyoura sand in relative density of 50% and the 20-sec shake was 300 gal with 1 Hz. The simulated and observed results show a good agreement. Viscosity of liquefied soils have been researched in many previous studies. Many of them conducted laboratory tests to obtain the value of viscosity; however, the obtained values lie in a great range. It is because the viscosity is strongly dependent on the rate of shear strain of the liquefied soils which are controlled by the apparatus. The viscosity for different settling structure into different soils during different earthquake is known not the same; therefore, we conducted a series of numerical analyses to obtain settlement of structure in above-mentioned various conditions. And then use the settlement as a known parameter in the Equation (1) for back analyzing the parameter viscosity. After 336 sets of back analysis, the back analyzed viscosity value in this paper is rearranged with all collected data in Figure 3.

4. DISCUSSIONS

It is important to note again that viscosity obtained herein is a back analyzed result from the numerical analysis. And in this numerical analysis, the time of seismic activity, uniform sine wave and thickness and permeability of liquefiable layer were set due to assumption or the laboratory test. But these factors would give influence on settlement prediction in reality because the seismic activity could never be a sinusoidal wave with a uniform magnitude, water table is not always at ground surface, and permeability of different soils is changeable. Therefore, some modification of the viscosity was made in this study based on regression of numerically simulated results or according to the previous research.

4.1 Amax

The peak value of the transient earthquake loading is named as Amax on this paper. For relating earthquake loading to harmonic laboratory loading, the refereed acceleration on the diagram A is used herein as A = 0.65Amax. The factor 0.65 is a relic of early liquefaction potential evaluation procedures that has been adopted in the current procedures. For the case that loading is harmonic loading, the adjustment is ignorant. The improved performance of the modification can be seen in Figure 4, in which the most of the data fell closer to the 1:1 line.

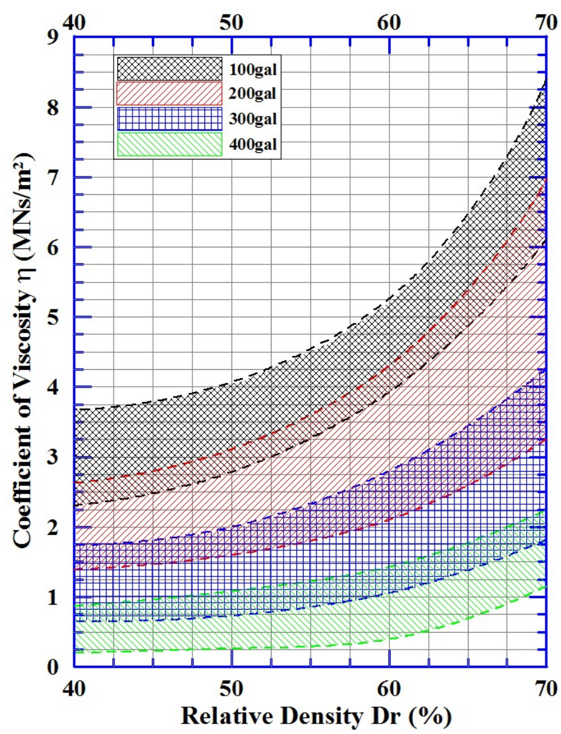

Figure 3 Graph of viscosity as function of seismic loading and relative density of soil

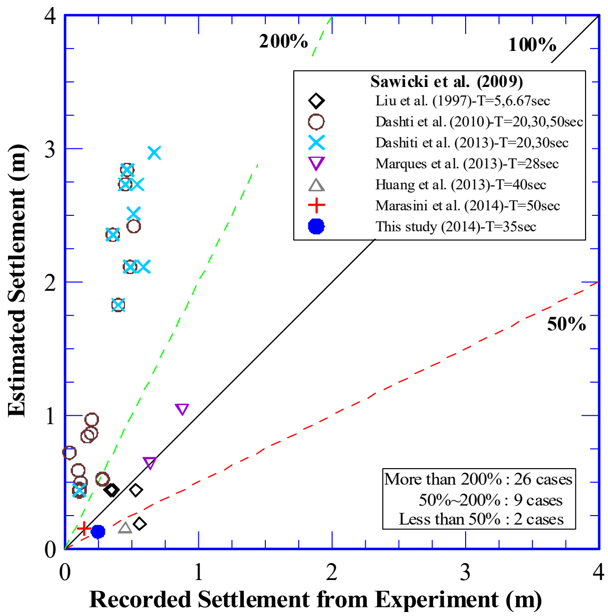

Figure 4 Use of 0.65 Amax and original earthquake time in settlement calculation

4.2 Time Duration Effect

Time duration is of the key factors in the proposed method. With the increase of Time duration, larger calculated settlement becomes. The effective seismic wave, which is 0.65 peak ground acceleration, is used for judging the length of duration. The effectiveness of the correction can be seen in Figure 5. The maximum duration is assumed to be no longer than 30 seconds in this paper after an investigation in previous study.

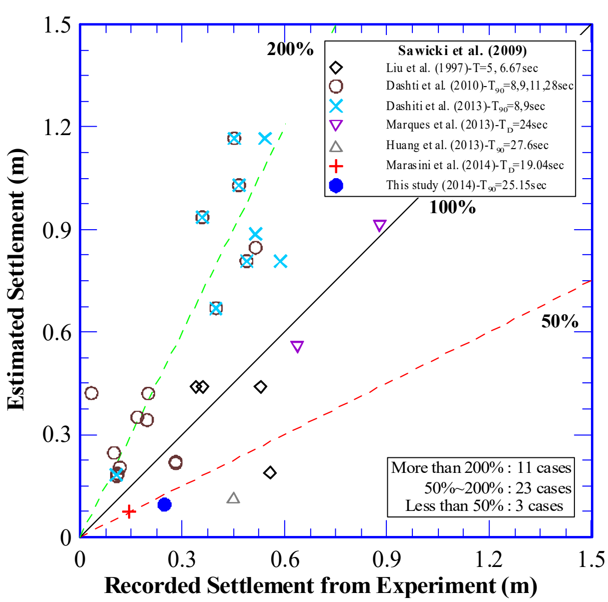

Figure 5 Use of 0.65Amax and modified earthquake time in settlement calculation

5. CONCLUSION

A simplified equation for calculating liquefaction induced settlement of shallow founded structure is proposed by Sawicki and Mierczynski (2009), in which the only unknown is viscosity of liquefied soils. This paper applied on results of a series of numerical analyses to back-analyze the viscosity with a consideration of different relative density of soil, seismic event, and the weight and size of the shallow foundation. The viscosity diagram, hence, was proposed in this paper and demonstrated for its applicability on the case studies in the literatures including data of experiment work, numerical simulation, and field observation, after correction parameters were adopted to help transient the simplified analysis in this paper to meet the conditions of the case studies in the literatures.

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