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On the impact of soil permeability in the numerical simulation of seismically induced liquefaction

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ABSTRACT: Soil permeability plays a significant role in the evolution of liquefaction phenomena induced by seismic loading. Experimental and field evidence suggests that soil permeability varies significantly during and after seismic excitation. This variation is mainly attributed to changes in the water flow path, which in turn affects the pore water pressure build-up and dissipation and the associated settlement during and post-liquefaction. Therefore, accurate modelling of the soil response during liquefaction requires an understanding of the permeability variations in addition to an appropriate constitutive model for the mechanical part. In this study, permeability changes are examined in the context of the liquefaction response of a saturated sand deposit. Fully coupled (u-p) dynamic consolidation finite element analyses are performed with the constitutive model PM4Sand in PLAXIS. The permeability variation is examined parametrically and validated against a well-documented centrifuge test (centrifuge model test No.1 of the VELACS project). The response is also compared with analyses adopting the common assumption of a constant permeability corresponding to static conditions.

Keywords: Liquefaction; Constant increased permeability; Variable permeability; PM4Sand; Fully coupled simulation

1 INTRODUCTION

Under cyclic loading, liquefaction phenomena occur when the magnitude of excess pore water pressure reaches the vertical effective stress in the liquefiable soil, resulting in the loss of soil shear strength, lateral spreading, and ground settlement. In addition, rapid monotonic loading also can generate considerable excess pore water pressure in loose contractive soil under saturated conditions. Due to this excess pore water pressure, the effective stress tends to reduce abruptly, causing sudden strength loss and rapid flow failure (Yamamuro and Lade, 1997) which is referred to as flow liquefaction or static liquefaction. Accurate simulation of the ground settlement induced by seismically induced liquefaction is still a major challenge, mostly due to the complexities associated with soil consolidation under seismic loading. Soil permeability, one of the key soil parameters that influence the build-up phase and dissipation of excess pore water pressure, and in turn the ground settlements, varies significantly during and after the earthquake according to field and experimental evidence (Arulanandan and Scott, 1993; Haigh et al., 2012; Ishihara, 1994; Jafarzadeh and Yanagisawa, 1995; Schofield, 1981; Suits et al., 2009; Ueng et al., 2017) contributing to the complexity. During liquefaction, the permeability can reach 5~10 times the initial static permeability before the dynamic excitation. As a first step before exploring a variable permeability model to simulate liquefaction, it is insightful to study the effect of soil permeability on the response of a saturated liquefiable soil deposit.

In this study, effective stress analyses using fully coupled (u-p) dynamic consolidation are performed with the constitutive model PM4Sand (Boulanger & Ziotopoulou, 2015) in PLAXIS v22.02 (Bentley Systems, 2022) to capture the liquefaction behaviour of a soil deposit of Nevada sand employing a series of different values of permeability. The constitutive model calibration and the simulated deposit are based on a well-documented laboratory and centrifuge test data series conducted for the VELACS program (Verification of Liquefaction Analyses by Centrifuge Studies) (Arulmoli et al., 1992), which allowed comparison of the response in terms of acceleration, excess pore water pressure and settlement time histories.

2 NUMERICAL ANALYSIS

2.1 Numerical model

The centrifuge model No.1 of the VELACS programme was conducted in a laminar box which is composed of various rings of negligible mass and interface friction (Arulmoli et al., 1992). Therefore, this centrifuge test can be simulated using a simplified geometry of a plane strain Finite Element (FE) soil column model. All numerical simulations in this study were conducted in model scale (i.e. centrifuge scale), adopting a gravity acceleration of 50g=500m/s^2, simulating the actual stress state during the test. The results of the dynamic analysis are then scaled back into prototype scale by adopting scaling laws with N=50.

All simulations in this study were carried out with the FE software PLAXIS using the u-p dynamic consolidation formulation; the bulk modulus of water was taken as K_f=2.2GPa, while Biot's coefficient was set as $\alpha = 1$, assuming that the soil skeleton is incompressible. FE simulations of liquefaction are significantly nonlinear, causing spurious, irregular, high-frequency oscillations. To deal with these oscillations, the dissipative version of Newmark's time-integration algorithm (Newmark 1959) ($\alpha = 0.3025, \beta = 0.6$) was used (Kontoe et al., 2008). In addition, a 0.5% target damping ratio (in the form of Rayleigh damping) was used following the recommendations of Boulanger and Ziotopoulou (2015), since the hysteretic damping produced by PM4Sand in the low strain range is not sufficient to suppress these spurious oscillations.

The FE soil column model employed for the simulation of the centrifuge test and the respective boundary conditions are illustrated in Figure 1. The lateral and bottom boundaries are impermeable (closed), while drainage is only allowed at the top of the soil column (seepage). Tied degrees of freedom boundaries are used along the side boundaries of the soil column model to ensure the responses of displacement, and pore water pressure for nodes at the same elevation are identical. The acceleration time history, depicted in Figure 2, is applied at the base of the soil column model while the vertical displacement was fixed.

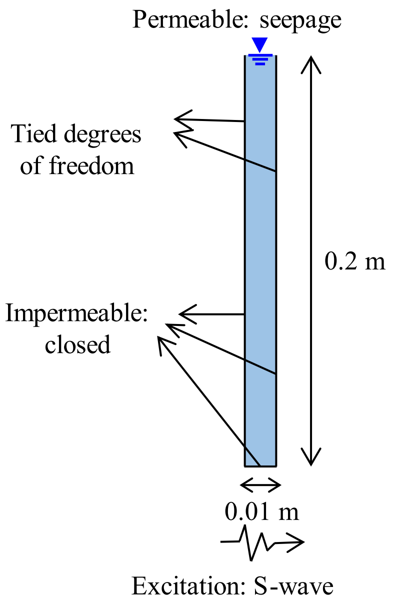

Figure 1. Model arrangement

The simulation of soil liquefaction problems is particularly sensitive to the adopted temporal and spatial discretisation. Detailed parametric studies for the simulation of the VELACS model No.1 were conducted by Taborda (2011) adopting quadrilateral elements with dimensions a time step of 0.1ms yielding a sufficiently accurate dynamic response. In this study, 15-node triangular elements of similar dimensions are employed, but a smaller time step of 0.01ms is used to facilitate convergence of the analysis.

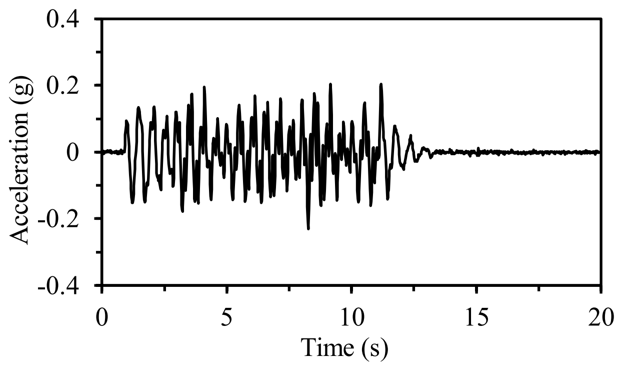

Figure 2. Time history of input seismic loading (Prototype)

2.2 Material properties

Although the u-p formulation is a simplified form of the full hydro-mechanical coupled formulation (u-p-w), where u is the solid displacement, p represents the pore water pressure and w denotes the relative velocity of the fluid to the solid, all cases in this study were checked to be within the range of applicability of the u-p formulation, as defined by Zienkiewicz et al. (1980).

The PM4Sand constitutive model implemented in PLAXIS by Vilhar et al. (2018) is used to simulate the dynamic behaviour of the liquefiable soil during and after liquefaction. Thirteen input parameters are necessary for the PM4Sand in PLAXIS, which are grouped into two categories (primary and secondary parameters). The primary parameters (relative density D_R, shear modulus coefficient G_0, contraction rate parameter h_{po}, atmospheric pressure p_A) are the most significant ones for the model calibration, while a secondary group of 9 parameters listed in Table 1 can be adjusted according to the suggested default values (Boulanger and Ziotopoulou, 2015). Additionally, the rest of basic soil parameters in Table 1 are obtained from the laboratory test results (Arulmoli te al., 1992). In particular, k_{1g} denotes the measured permeability under 1g of gravitational acceleration. In this study to conduct the centrifuge test, the k_{1g} value was specified and was then adjusted to the model scale by applying $\Sigma M_{Weight} = 50$ in PLAXIS.

Settlements induced by liquefaction are directly attributed to the amount of fluid expelled from the top of the soil column, which is governed by the soil permeability. Therefore, it is important to examine parametrically the effect of permeability on the co-seismic and final settlements. A series of scenarios employing different increased permeability values are listed in Table 2. The adopted designations for the scenarios denote the ratio between the increased permeability and the initial static permeability. The dynamic response of the analysis conducted for the static value of permeability will be presented first in Section 3 before moving on to the parametric study on the variation of permeability in section 4.

Table 1. PM4Sand input parameters for Nevada sand

Parameters		Magnitude	Source
Shear modulus	G_0	740.5	Calibrated results
Contraction rate	h_{po}	0.03	
Critical state line	Q	9.22	
	R	0.78	
Relative density	D_R	0.4	Laboratory results
Initial stress ratio	K_0	0.5	
Poison's ratio	μ	0.2	
Initial void ratio	$e_{initial}$	0.424	
Maximum void ratio	e_{max}	0.887	
Minimum void ratio	e_{min}	0.511	
Critical state strength	φ_{cv}	32°	
Saturated unit weight	$\gamma_{sat,1g}$	19.31 kN/m^3	
Permeability	k_{1g}	6.583e-5 m/s	
Bounding surface	n^b	0.5	Default values
Dilatancy surface	n^d	0.1	
Atmospheric pressure	p_A	101.3 kPa	

Table 2. Permeability used for different cases

Scenarios	Permeability: k_{1g} (m/s)	Permeability ratio: k/k_1
k1	6.583e-05	1
k2	1.317e-04	2
k4	2.633e-04	4
k8	5.266e-04	8
k10	6.583e-04	10

3 RESULTS OF THE ANALYSES

3.1 Excess pore water pressure

Figure 3 compares the computed excess pore water pressure time histories at different elevations against the corresponding VELACS No.1 measurements.

Clearly, the simulated rate of excess pore water pressure generation is considerably larger than that suggested by the results of the centrifuge test. This means that the simulated model reaches liquefaction after fewer cycles of seismic loading. Additionally, the maintenance phase of the excess pore water pressure is shorter than the results registered in the centrifuge experiment, which means the simulation shifts into the dissipation phase earlier. The initial time instant at which excess pore water pressure dissipates for points above the depth of liquefaction is designated as the "solidification front" (Florin and Ivanov, 1961). It is clear that, compared with the excess pore water pressure measured in the centrifuge test, the corresponding dynamic response reproduced by PM4Sand with the initial static permeability, dissipates much faster to zero, indicating a significantly faster propagation of the numerical solidification front. Figure 4 illustrates the generation of excess pore water pressure in terms of piezometric isochrones using the effective stress ratio $r_u = \Delta u / \sigma'_{v,0}$,

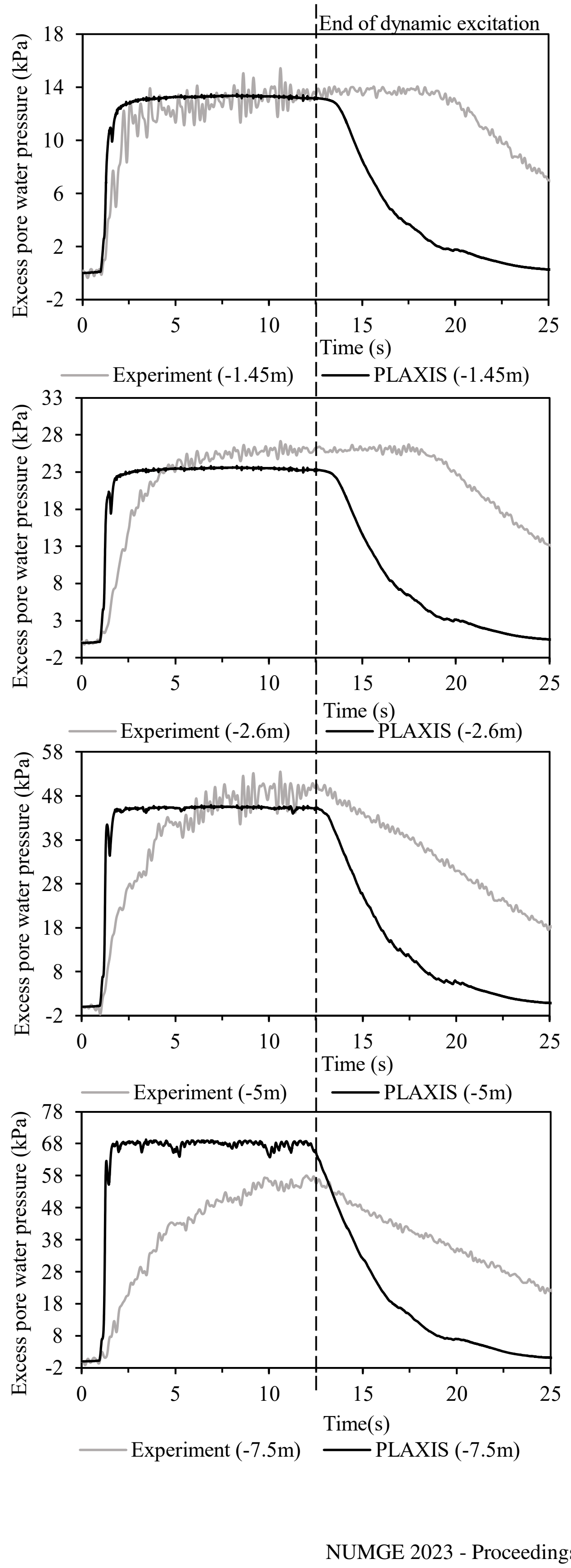

Figure 3. The simulated and measured time history of the excess pore water pressure at different depths (prototype scale)

where Δu is the excess pore water pressure and $\sigma'_{v,0}$ denotes the initial vertical effective stress. During the seismic excitation (within 12.5s), the depth of liquefaction varies significantly with time. According to the piezometric isochrones at t=12.5s, which marks the start of the dissipation phase, the numerically simulated depth of liquefaction is approximately 6.8m, which is larger than the 5.24m estimated in the VELACS centrifuge experiment.

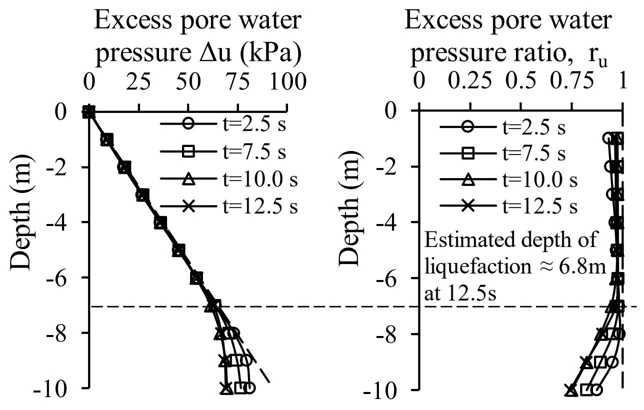

Figure 4. Numerical variation of piezometric isochrones during dynamic loading

3.2 Surface settlement

The long-term surface settlement including the dynamic excitation and the subsequent consolidation phase are depicted in Figure 5, together with the measured results in the centrifuge test. The simulated surface settlement is approximately 26.8mm during the dynamic phase (about 68% of the total settlement), while the long-term settlement is about 38.39mm after the consolidation phase. Both values are considerably smaller than the corresponding experimental measurements. Besides, there is a considerable discrepancy between the numerical and experimental results, in terms of consolidation rate. The above evidence indicates that the numerical model with the initial static permeability is not able to capture accurately the deformation behaviour of liquefied soil, both in terms of the magnitude and rate of the surface settlement. However, these predictions can be improved by adopting increased permeability values which approximate better the changes in permeability that take place during the seismic event.

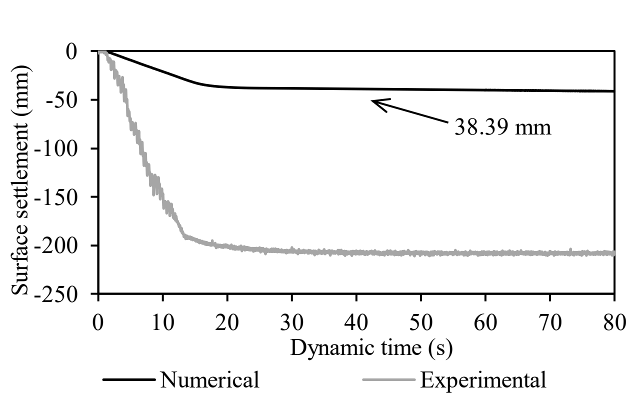

Figure 5. Numerical and measured time history of surface settlement

4 INFLUENCE OF PERMEABILITY

4.1 Excess pore water pressure

As shown in Figure 6, where the simulated evolutions of excess pore water pressure for each considered permeability are illustrated, the rate of generation of excess pore water pressure decreases with the increased coefficient of permeability, while the excess pore water pressure dissipates at a higher rate. This is consistent with the fact that for more permeable soils, the accumulation of excess pore water pressure needs more cycles of seismic loading to reach the onset of liquefaction in the build-up phase. In addition, it is apparent that the simulated period of excess pore water pressure maintenance phase is shorter with increased permeability. This indicates that the solidification front propagates upwards faster in a more permeable material, which is also presented by Florin and Ivanov (1961). Therefore, it is possible to predict that the increase in permeability causes the occurrence of liquefaction at a shallower elevation under seismic shaking.

The predicted depths of liquefaction for each analysed situation are estimated using piezometric isochrones, depicted in Figure 7. As it can be seen, the depth of liquefaction decreases with the increased permeability. The simulated model does not fully liquefy when 8 times and 10 times permeability multipliers are used since the excess pore water pressure ratios r_u of these two situations are always less than unity.

4.2 Surface settlement

Figure 8 illustrates the effect of soil permeability on the modelled surface settlement. It is clear that with a higher magnitude of permeability, the numerical model has a faster rate of consolidation, reaching larger surface settlement. However, all simulated settlements are smaller than that registered in the centrifuge test, although it should be noted that, when the permeability is 10 times the static permeability, the rate of deformation is closest to the experimental one. This means that the constant increased permeability can only partially improve the calculated dynamic results of liquefaction, in terms of the rate and final magnitude of the surface settlement, which is consistent with published literature (Arulanandan and Sybico, 1992; Taiebat et al., 2007). Although a larger permeability can potentially cause a larger quantity of water to be expelled during the shaking, the hydraulic gradient is not sufficient to drive enough water through the top boundary of the soil column, and this results in smaller accumulated settlements. This can also be verified in the predicted evolutions of excess pore water pressure (Figure 6). Additionally, the accurate simulation of ground settlement does not only rely highly on the rigorous modelling of permeability but also on the modelling of soil stiffness by the advanced numerical constitutive model.

Therefore, while the constant increased value of permeability improves the prediction of surface settlement in the simulation of earthquake-induced liquefaction, it is clear that a variable permeability model is needed to capture actual characteristics of pore water pressure generation and dissipation and further improve the simulation of ground settlement.

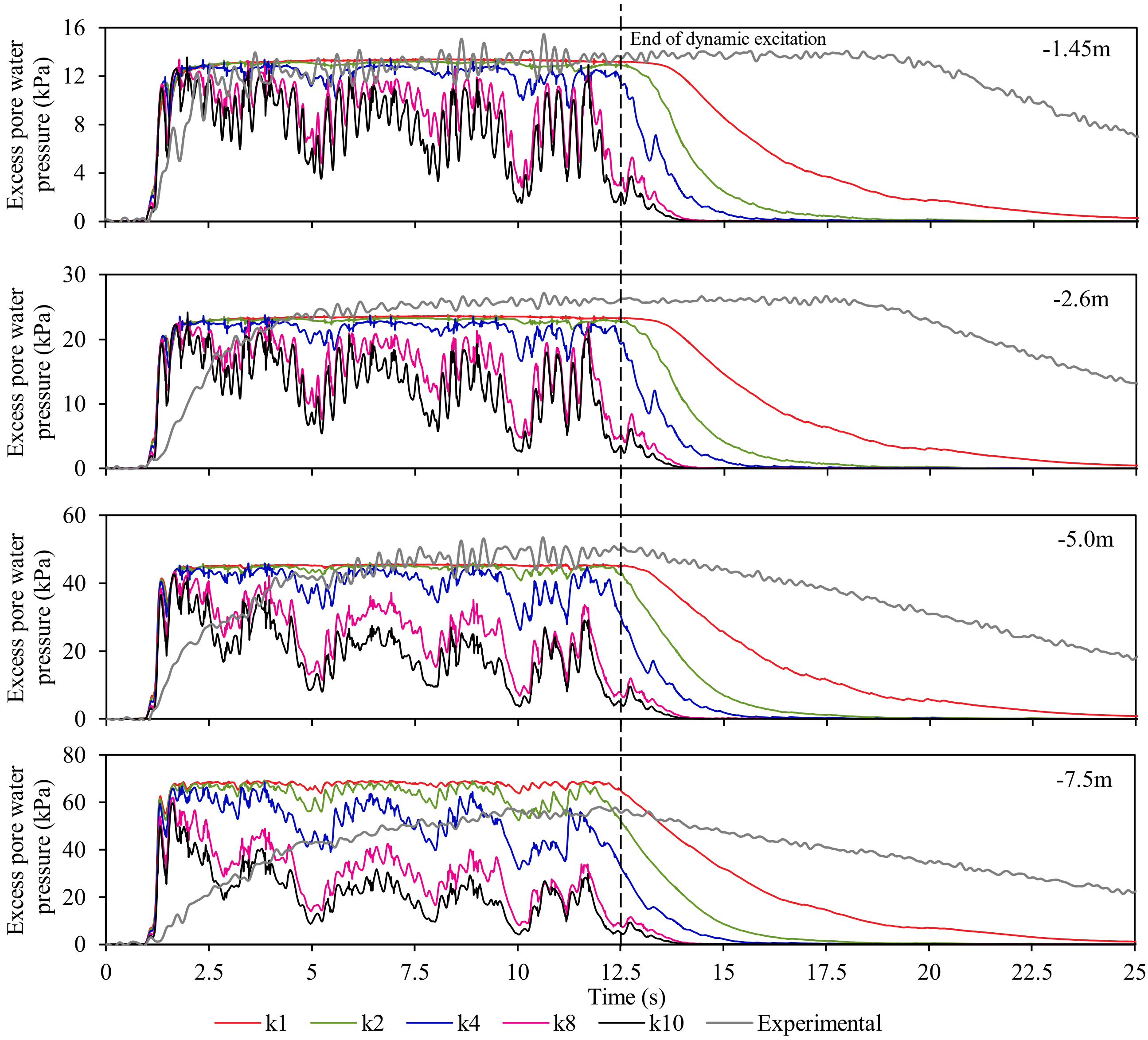

Figure 6. Simulated evolutions of excess pore water pressure using different soil permeability coefficients

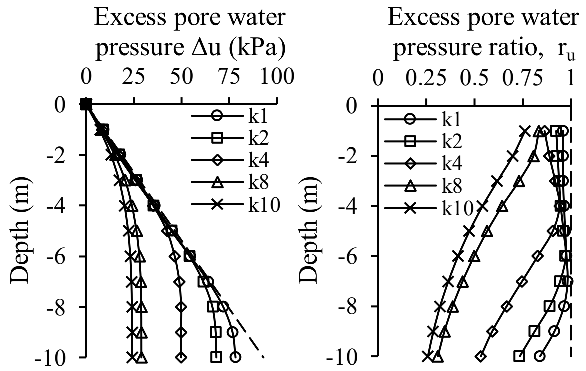

Figure 7. Estimation of liquefaction depth for different permeability at 11.75s

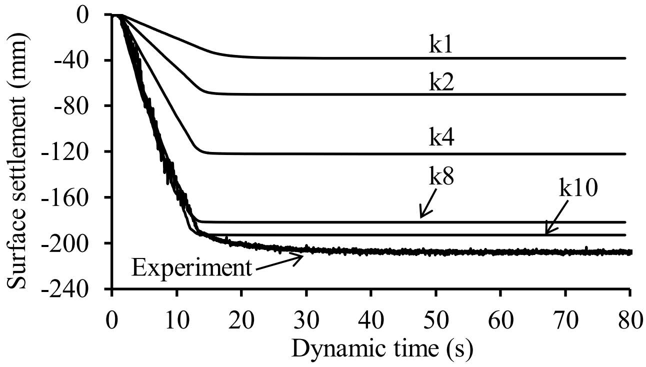

Figure 8. Simulated evolutions of surface settlements using different soil permeability coefficients

5 CONCLUSIONS

In this study, the centrifuge test model No.1 of VELACS was simulated with the aid of fully coupled dynamic consolidation FE analyses with PLAXIS. The impact of soil permeability in the numerical simulation of seismically induced liquefaction was investigated through a parametric study which considered several multipliers applied to the static value of permeability. The conclusions are as follows:

(1) the numerical model with the initial static permeability is unable to capture accurately the deformation behaviour of the liquefied soil, in terms of the generation and dissipation of excess pore water pressure and the predicted surface settlement.

(2) larger permeability results in a smaller depth of liquefaction but a larger simulated surface settlement.

(3) using a constant increased permeability can partially improve the accuracy of both the predicted rate and magnitude of settlement in the liquefaction simulation, but considerable discrepancy between the calculated pore water pressure generation and dissipation and those measured in the centrifuge test still occurs.

(4) the soil permeability is not constant during and after liquefaction. Accurate reproduction of earthquake-induced liquefaction in terms of excess pore water pressure and the ground settlement requires a variable permeability model, which needs further investigation.

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