Experimental study on bearing behavior of a single model pile in unsaturated sandy ground with various groundwater levels

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ABSTRACT

Matric suction, the pressure difference between pore air and pore water pressure, generally occurs in unsaturated soils near the ground surface. Considering soil strength changes according to suction, changes in suction due to groundwater level variations could influence the bearing characteristics of piles. There have been some experimental studies on the bearing capacity of single piles and pile groups in unsaturated ground. In these studies, however, only the performance of bored precast piles was investigated, while that of driven piles has not been fully clarified yet. In this study, a soil tank was first proposed applying the hanging water column technique to control suction in the model ground. Then, a series of model tests were conducted to investigate the vertical bearing behaviors of an open-ended model pile in the unsaturated sandy ground with various groundwater levels, i.e., 0, 300, 500 mm from the ground surface and infinite depth (completely dry). According to the experimental results, the changes in groundwater levels could influence both the tip and shaft resistances of model piles, and for the open-ended pile, this influence of shaft resistance on the height of soil plugs could not be ignored.

Key words: *Open-ended pile, Model test, Unsaturated ground, Bearing capacity*

1. Introduction

Matric suction, the pressure difference between pore air and pore water pressure, generally occurs in unsaturated soils near the ground surface. Considering soil strength changes according to suction as a function of the degree of saturation, changes in suction due to groundwater level variations could influence the bearing characteristics of piles.

Though laboratory experimental studies are generally conducted on piles on saturated or dry ground, several researchers have carried out investigations on the bearing capacity of piles on unsaturated soils. Al-Khazaali and Vanapalli (2019) conducted forty different model tests on single piles and pile groups by varying the water-table levels, to investigate the behavior of a single model pile and pile groups in sand under both saturated and unsaturated conditions. Test results suggest that the ultimate load-carrying capacity of a single pile and pile groups increased by twofold to 2.5-fold, and settlements decreased significantly due to the matric suction's contribution in comparison with saturated conditions. Liu and Vanapalli (2021) investigated a single model pile mechanical behavior variations associated with suction changes in an unsaturated expansive soil under a service load. In these studies, however, only the performance of bored precast pile was investigated, while that of driven piles (displacement piles) has not been fully clarified yet. That is, pile penetration effect and the soil plug of open-ended piles on unsaturated ground have not been considered.

Therefore, in this study, a soil tank was first proposed applying the hanging water column technique to control suction in the model ground. Then, an open-ended model pile was penetrated into the unsaturated sandy ground with various groundwater levels and vertical load test on the pile were conducted to investigate its bearing behavior.

2. Experiment description

2.1. Model ground

A cylindrical chamber with a height of 400 mm and a diameter of 400 mm was used to prepare the model ground, as shown in **Fig. 1**. To control suction distribution in model grounds, the hanging water column technique was adopted. A water tank was connected to the bottom of the soil container to adjust the groundwater level of the model ground. And a microporous membrane filter (MMF) with an air entry value of 480 kPa was set between the model ground and the water tank to prevent air from entering the water path.

The following procedure was used to prepare the model ground. First, a 20 mm-thick drainage layer of silica sand #3 was set at the bottom. Subsequently, seven 50 mm thick layers and a 30 mm thick layer of air-dried silica sand #6 were placed and uniformly compacted to achieve the target relative density D_r = 80%. The physical properties of silica sand #6 are shown in **Table 1**. After that, except for dry model ground, the water tank was moved upward to fully saturate the model ground. To make unsaturated ground, the water tank was then moved below the ground surface to generate a negative pore water pressure (suction).

In this study, 4 conditions of groundwater levels were considered. In Case WL0, the depth of groundwater level (WL) was set the same as ground surface elevation, i.e. WL=0 mm. In Case WL300 and WL500, WL was set as 300 and 500 mm from the ground surface, respectively. In Case Dry, the water tank was not connected with the soil tank and the water content of silica sand #6 was around 0% to represent an infinite WL.

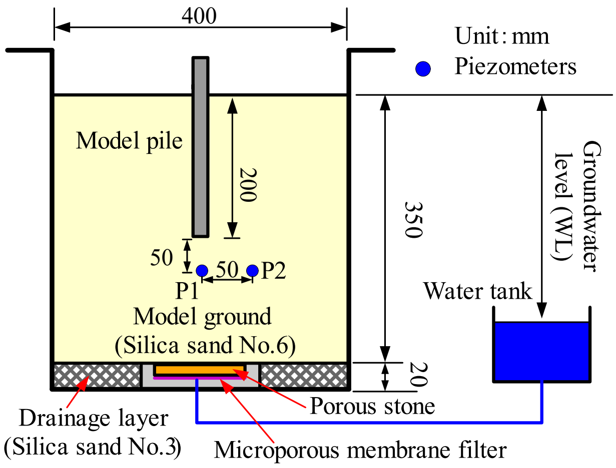


Fig. 1 Schematic diagram of the soil tank

Table 1. Physical properties of Silica sand #6

Property	Value
Soil particle density, ρ_s (ton/m^3)	2.68
Minimum dry density, ρ_{dmin} (ton/m^3)	1.28
Maximum dry density, ρ_{dmax} (ton/m^3)	1.62
Maximum void ratio, e_{max}	1.09
Minimum void ratio, e_{min}	0.65
Model ground relative density, D_r (%)	80.0
Model ground dry density ρ_d (ton/m^3)	1.54
Model ground void ratio, e	0.74

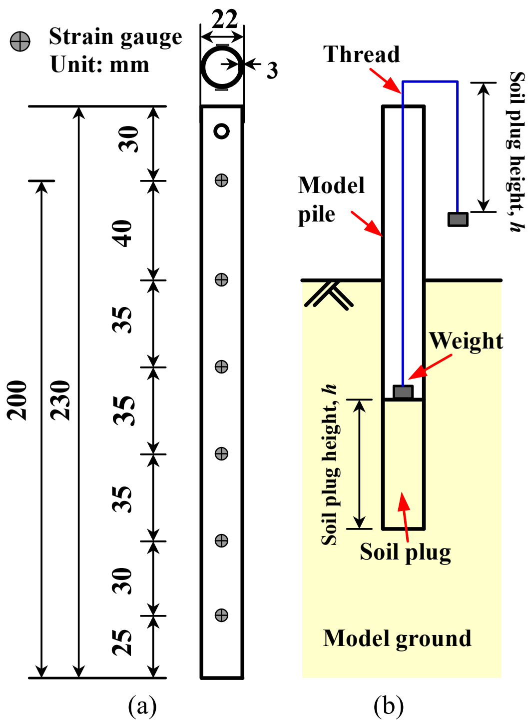


Fig. 2 Model pile: (a) Dimensions and strain gauges; (b) Method for measuring the height of soil plugs

2.2. Model pile

Model piles used in this study were open-ended polyvinyl chloride pipes, with dimensions of 22 mm outer diameter D, 16 mm inner diameter d, 3 mm wall thickness t, and 230 mm length l, as shown in **Fig. 2(a)**. Young's modulus and Poisson's ratio of the model pile were 3.07 GPa and 0.34, respectively. To measure axial forces along each pile, strain gages (SGs) were attached on the pile shaft at 6 levels.

A simple method was used to measure soil plug height of the model pile, as shown in **Fig. 2(b)**. A thread with a weight tied to both ends was put into the pile before pile penetration. When the soil enters the pile, the external weight will drop, and the height of the soil plug can be determined by the distance the external weight moves.

2.3. Test instrumentation and procedure

Fig. 3 shows the experimental devices and instrumentation used in the model tests. A screw jack was employed to apply the vertical load during the tests. The load was measured using a load cell, and vertical displacements were measured using an encoder and a dial gauge. Two piezometers with a ceramic filter were set 250 mm below the ground surface to measure changes in pore water pressure, and their locations are shown in **Fig. 1**.

Procedure for the load tests of the model pile was as follows: the model pile was first installed into the center of model ground using the screw jack until the pile tip reached 200 mm depth (Pile Penetration Test, PPT). The penetration rate was 0.2 mm/s. After the dissipation of excess pore water pressure (EPWP) in saturated and unsaturated cases, vertical load test (VLT) of the model pile was conducted with a loading rate of 0.2 mm/s. Thereafter, to investigate the ground conditions, cone penetration tests (CPTs) were conducted at 3 different locations, 100 mm away from the sidewall of the soil tank and 89 mm away from the model pile. At these locations, the influence of the pile penetration on the ground could be minor.

Note that piezometers were initialized before PPT and VLT, thus they could measure EPWP during PPT and VLT directly. In this study, it is assumed that air pressure was constant in an atmospheric pressure environment, and the changes in suction could be calculated from changes in EPWP measured by piezometers.

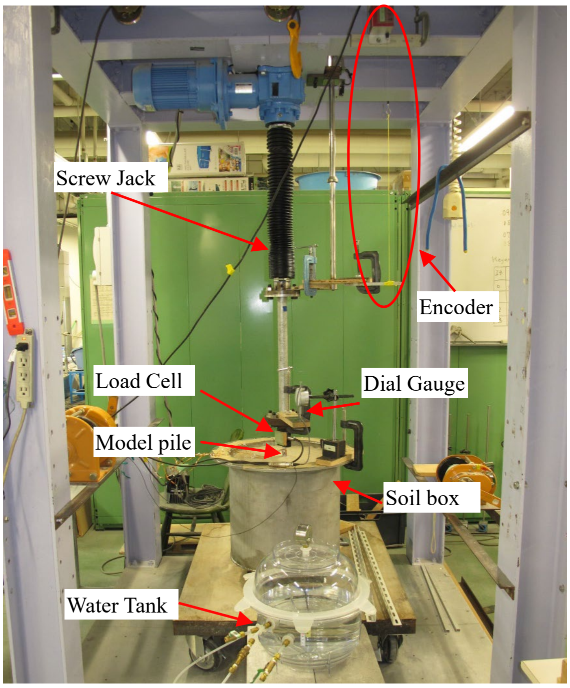


Fig. 3 Experimental set-up

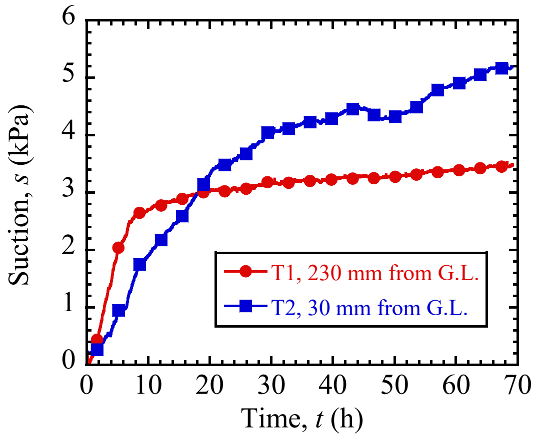


Fig. 4 Changes in suction after moving the water tank (WL=500 mm)

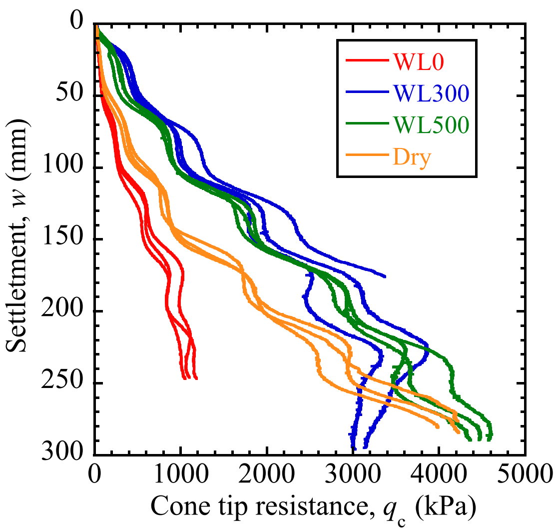


Fig. 5 Results of CPTs in model ground

3. Experimental results

3.1. Results of model ground preparation

In a pilot study, to verify the proposed ground preparation method, two piezometers with a ceramic filter were installed at the center of the ground, which were 30 and 230 mm below the ground surface, respectively. The ground was saturated by the water tank first. Then the water tank was moved 520 mm below the ground surface to apply negative pore water pressure (suction) to the ground, and the changes in suction were measured, as shown in **Fig. 4**. It is found that suction increased sharply at first, after which the increasing trend leveled off. At the end of ground preparation, suction at T1 and T2 reached around 5.2 and 3.4 kPa, respectively. Under atmospheric pressure, the suction in the unsaturated ground can be calculated theoretically by multiplying the absolute distance from the groundwater level by the gravitational acceleration. Hence, the measured suction was close to the calculated value, which means the ground preparation method used in this paper is reasonable. This suction equalization process lasted 70 hours.

The results of CPTs are shown in **Fig. 5**. Generally, there is no significant difference between 3 locations. The cone tip resistance of Case WL0 was the smallest among all cases, due to the highest groundwater level and the smallest effective stress. For unsaturated grounds, Bishop-type effective stress could be used:

$$\sigma' = (\sigma - u_a) + S_r \cdot (u_a - u_w) = (\sigma - u_a) + S_r \cdot s \qquad (1)$$

where u_a is pore air pressure, u_w is pore water pressure, S_r is degree of saturation and s is suction. Due to the effect of suction, the cone tip resistance of unsaturated grounds were generally greater than that of dry ground. It is interesting to note that at depths of less than 200 mm, the cone tip resistance in Case WL300 was greater than that in Case WL500. At depths greater than 200 mm, the cone tip resistance in Case WL300 began to decrease because of the decrease in suction. At depths greater than 250 mm, the cone tip resistance in Case WL300 was even smaller than that in Case Dry.

3.2. Results of PPTs

Fig. 6 shows the relations of the vertical load P_h and the pile head settlement w during the PPT in the four cases. The results show that when settlement w was less than 160 mm, the penetration resistance of model pile in Case Dry was smaller than those in unsaturated cases, which is similar to the results of CPTs. However, when settlement w was greater than 170 mm, the penetration resistance in Case Dry increased significantly, quickly exceeding the penetration resistance in Case WL500 and slightly exceeding that in Case WL300 at w = 200 mm.

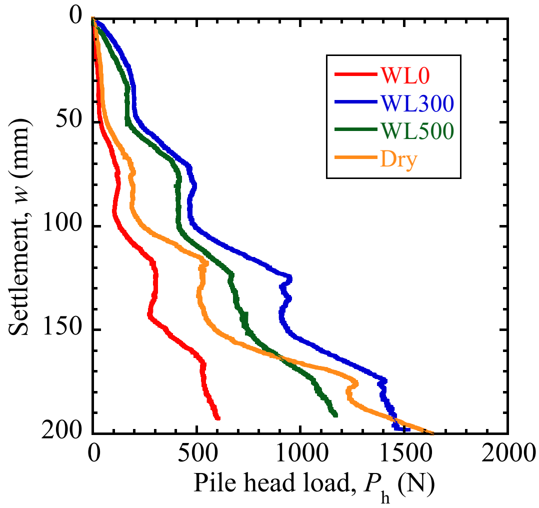


Fig. 6 Load-settlement curves during PPTs

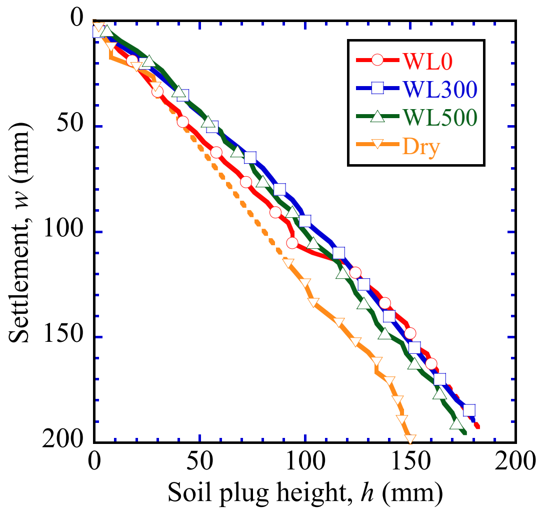


Fig. 7 Soil plug height-settlement curves during PPTs

To discuss these behaviors, the relations of the soil plug height h and the pile head settlement w shown in **Fig. 7** should be taken into consideration. Notably, the dotted part is the part that was not successfully measured, due to technical problems. It can be found from **Fig. 7** that the soil plug height generally increased with the increase in the settlement in all cases. However, at the end of PPTs, the soil plug height was around 180 mm in Cases WL0, WL300 and WL500, while it was around 150 mm in Case

Dry. This means that the pile pushed more soil outwards and increased the soil density around the pile in Case Dry. In addition, when the settlement increased from 170 mm to 200 mm, the soil plug height hardly increased in Case Dry, indicating the occurrence of a perfect plugging.

Therefore, different from the CPTs' results, when settlement w was supposed to be greater than 170 mm, the penetration resistance in Case Dry increased and eventually exceeded that in Cases WL300 and WL500, due to pile penetration effect and plugging effect.

Fig. 8 shows the relations of EPWP Δu_w and the pile head settlement w during the PPT in the Cases WL0, WL300 and WL500. Negative EPWP occurred around the pile tip in Case WL300, which means dilatancy behaviour of soil occurred due to the effect of suction and may lead to the greater penetration resistance of model pile in Case WL300.

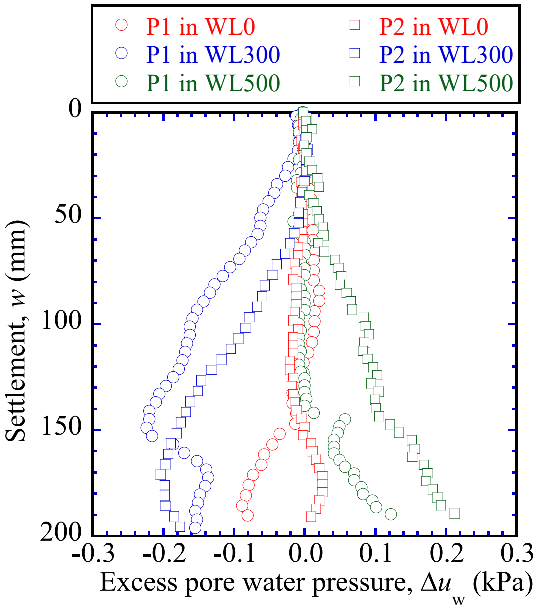
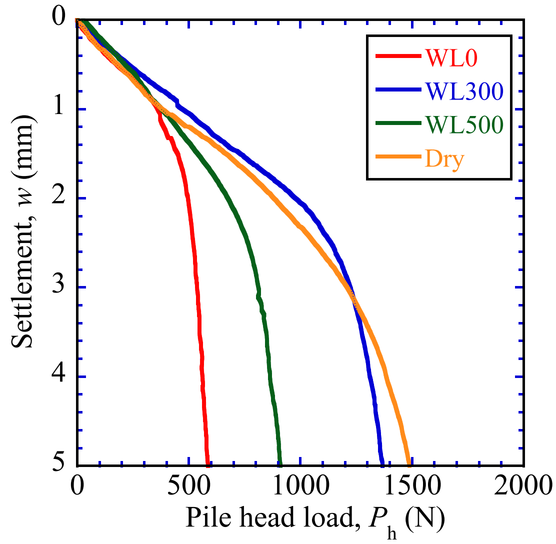


Fig. 8 EPWP-settlement curves during PPTs

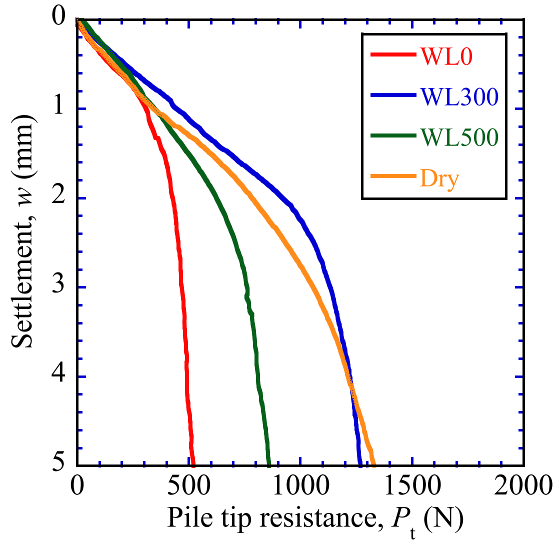
3.3. Results of VLTs

Fig. 9 shows the results of VLT in the four cases. Pile tip resistance was obtained from strain gauges near the pile tip, and shaft resistance was obtained by subtracting the pile tip resistance from the pile head load.

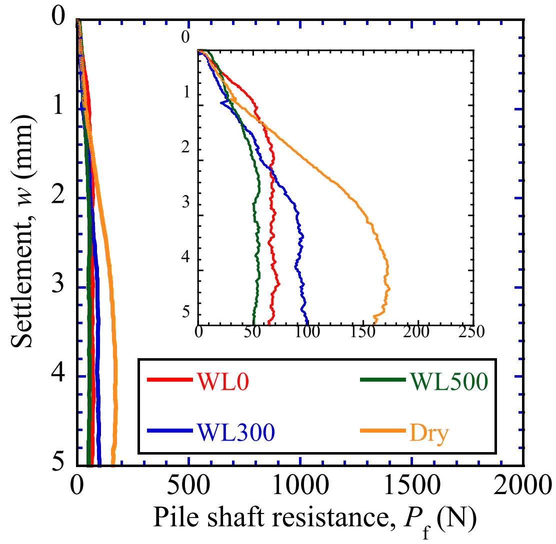
It can be found in **Fig. 9(a)** that the initial stiffness of load-settlement curve in Case WL300 was slightly greater than that in other cases. Moreover, when settlement w = 2.2 mm (0.1D), the pile head load was around 1060 N in Case WL300 and was the largest among all cases. Due to



(a) Pile head load vs. settlement



(b) Pile tip resistance vs. settlement



(c) Shaft resistance vs. settlement

Fig. 9 Load-settlement curves during VLTs the pile penetration effect and plugging effect explained in Section 3.2, the pile head load in Case Dry was greater than that in Case WL500 and exceeded that in Case WL300 when the *w* was greater than 3 mm. However, the bearing capacity of model pile in Case WL0 was still much smaller than that in unsaturated cases.

The relations of pile tip resistance P_t and the pile head settlement *w* shown in **Fig. 9(b)** were similar to those in **Fig. 9(b)**. For shaft resistance, as shown in **Fig. 9(c)**, the shaft resistance in Case Dry was the largest among all cases. Interestingly, even the effective stress was greater in Case WL500 than that in Case WL0 according to **Eq. (1)**, its shaft resistance was the smallest. This behavior will be discussed in detail in Section 3.4.

Fig. 10 shows the relations of EPWP Δu_w and the pile head settlement *w* during the VLTs. Compared with **Fig, 8**, EPWP occurred during VLTs, especially at P2, was minor. Considering the lower permeability of unsaturated soil and the distance between the pile tip and the piezometers, greater EPWP could still occur around the pile tip.

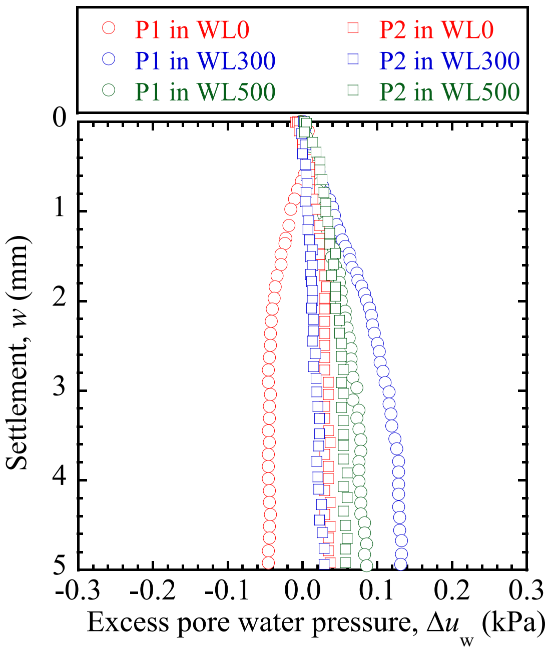


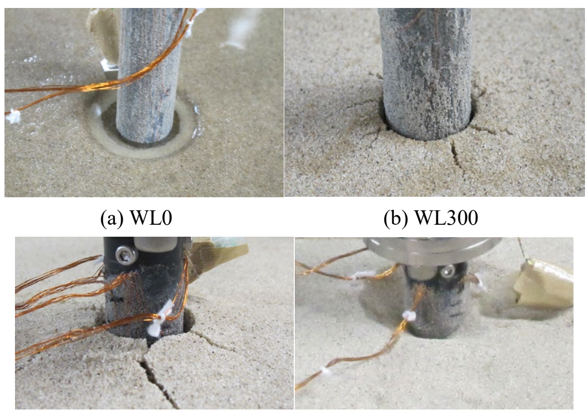
Fig. 10 EPWP-settlement curves during VLTs

3.4. Discussion

Comparison of Case WL0 with Cases WL300 and WL500 is performed first. Since the soil plug height was almost the same in these three cases, the differences caused by penetration effect and plugging effect could be ignored. It can be found from **Figs. 5** and **9(a)** that the relationship between the bearing capacity of the model piles in these three cases is generally consistent with the results of the CPTs. This means that even in unsaturated ground, the bearing capacity of piles could still be estimated based on the results of in-situ tests, such as CPT.

There are two reasons considered for differences between the test results under unsaturated and saturated conditions. When only saturated soil mechanics are considered, the higher groundwater level under saturated condition leads to smaller effective stress in soil surrounding the pile, and results in a decrease in soil strength and stiffness. For unsaturated soil, according to **Eq. (1)**, due to the presence of suction, effective stress of the soil increased, causing an increase in soil strength and stiffness under unsaturated condition. As a result, the pile bearing capacity and initial stiffness of P_h-*w* curve were greater under unsaturated condition.

Nevertheless, as shown in **Fig. 9(c)**, even the effective stress was greater in Case WL500 than that in Case WL0, its shaft resistance was smaller. **Fig. 11** shows photos of ground surface near the pile head in four cases. It is interesting to found some cracks occurred near the pile head and the contact between soil and piles near the ground surface was not perfect in Cases WL300 and WL500. The reason is considered to be that due to the presence of suction, the behavior of unsaturated sand may behave similarly to that of cohesive soils. This imperfect contact between the pile and the soil could result in lower shaft friction. However, in practice, considering the level of earth pressure, this phenomenon may not occur.



(a) WL0 (b) WL300

(c) WL500 (b) Dry

Fig. 11 Ground surface near the pile head

For Case Dry, even there is no effect of suction, greater penetration effect and plugging effect could still result in greater bearing capacity, which could not be simply estimated from the results of CPT in dry ground. Therefore, for driven piles, especially open-ended piles, in unsaturated ground, their bearing characteristics are complicated, and both groundwater level and penetration effect may be the main factors affecting their bearing capacity. Although in the tests of this paper, the soil plug height was almost the same in saturated and unsaturated cases, further research is still necessary.

4. Concluding remarks

In this research, a series of model tests were conducted to investigate the bearing behavior of a single model pile in unsaturated sandy ground with various groundwater levels. Interesting findings from this experimental study are as follows:

(1) The ground preparation method proposed in this paper can successfully control the suction in the model ground, which allows for the repetitive preparation of a model ground with the same suction distribution.

(2) For open-ended model pile driven into sandy ground with various groundwater levels, both groundwater level and penetration effect may be the main factors affecting their bearing behavior.

(3) In case of penetration effect and plugging effect are almost the same, when the groundwater level is 300 mm from the ground surface, the initial ground stiffness of P_h-w curve and the bearing capacity of the model pile were the the largest presumably due to the increase of the effective stress in the ground.

(4) The bearing capacity of piles in unsaturated ground could still be estimated based on the results of in-situ tests, such as CPT. However, special attention needs to be paid to the influence of penetration and plugging effects.

5. Acknowledgements

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