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Incremental filling ratio of pipe pile groups in sandy soil

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Abstract. Formation of a soil plug in an open-ended pile is a very important factor in determining the pile behavior both during driving and during static loading. The degree of soil plugging can be represented by the incremental filling ratio (IFR) which is defined as the change in the plug length to the change of the pile embedment length.
The experimental tests carried out in this research contain 138 tests that are divided as follows: 36 tests for single pile, 36 tests for pile group (2×1), 36 tests for pile group (2×2) and 30 pile group (2×3). All tubular piles were tested using the poorly graded sand from the city of Karbala in Iraq. The sand was prepared at three different densities using a raining technique. Different parameters are considered such as method of installation, relative density, removal of soil plug with respect to length of plug and pile length to diameter ratio. The soil plug is removed using a new device which is manufactured to remove the soil column inside open pipe piles group installed using driving and pressing device. The principle of soil plug removal depends on suction of sand inside the pile.
It was concluded that the incremental filling ratio (IFR) is changed with the changing of soil state and method of installation. For driven pipe pile group, the average IFR for piles in loose is 18% and 19.5% for L/D=12 and 15, respectively, while the average of IFR for driven piles in dense sand is 30% and 20% for L/D=12 and L/D=15 respectively. For pressed method of pile installation, the average IFR for group is zero for loose and medium sand and about 5% for dense sand. The group capacity increases with the increase of IFR. For driven pile with length of 450 mm, the average IFR % is about 30.3% in dense sand, 14% in medium and 18.3% for loose sand while when the length of pile is 300 mm, the percentage equals to 20%, 17% and 19.5%, respectively.

Keywords: pipe pile; group; incremental filling ratio; sand; pressed

1. Introduction

Pipe piles can be either open-ended or close-ended. It has been documented that the behavior of open-ended piles is different from that of closed-ended piles (Szechy 1961, Klos and Tejchman 1981, Lu 1985, Smith *et al.* 1986, Paikowsky and Whitman 1990, Lee *et al.* 2003). According to the field test results of Szechy (1959) and Fattah and Al-Soudani (2016a, b), the blow count necessary for driving a pile to a certain depth in sands is lower for an open ended pile than for a closed-ended pile. Thus, it is generally acknowledged that an open-ended pile requires less installation effort than a closed-ended pile under the same soil conditions (McCammon and Golder 1970, Lu 1985, Smith *et al.* 1986, Brucy *et al.* 1991) have shown that the mode of pile driving is an important factor indriving resistance. If a pile is driven in a fully coring (or fully unplugged) mode, soil enters the pile at the same rate as it advances. On the other hand, if a pile is driven under plugged or partially plugged conditions, a soil plug finally attaches itself to the inner surface of the pile, preventing additional soil from entering the pile. A pile driven in the plugged mode behaves similarly as a closed-ended pile, typically, a large-diameter pipe pile.

Unplugged and plugged phenomena

In unplugged phenomena, pile is a steel tube which is open at both ends and is driven into the ground with blows to the top of the pile. After the pile is driven, the ground level is approximately the same both inside and outside the pile. During installation of open-ended pipe piles, the soil enters the pile at a rate that is equal to, or larger than, the rate of pile penetration. This mode of penetration is referred to as coring or cookie cutter. As penetration progresses, the soil core inside the pile may develop sufficient frictional resistance along the inner pile wall to prevent further soil intrusion, causing the pile to become plugged**.** Plugging is important, not only because it directly contributes to the tip bearing capacity, but also because it indirectly contributes to the developed shaft capacity (Gavin and Lehane 2003, Paik and Salgado 2003), since a plugged pile displaces more soil than a coring one, which increases the effective stresses surrounding the pile. Plugging also influences the dynamic behavior of piles, which complicates the dynamic analyses of piles (Paikowsky and Whitman 1990, Raines *et al.* 1992)**.**

Paikowsky and Whitman (1990) investigated the effect of soil plugging on the axial resistance developed by open-ended (pipe) piles installed in sand and clay. They described the process of soil plug formation during the initial stages of

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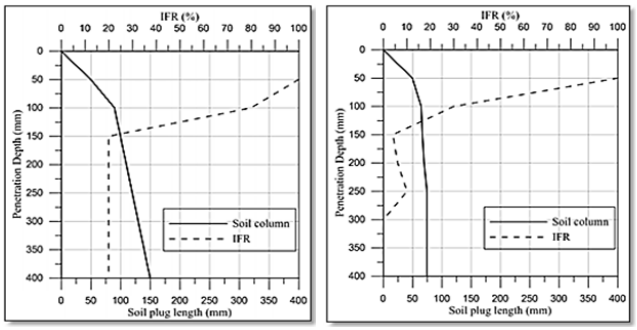


(a) (b)

Fig. 1 IFR and soil plug length versus penetration depth for open-ended pile (a-driven, b- pressed) (after Sheghait, 2016)

pile installation, the length of the soil plug (Lp) inside the pipe equals the pile penetration depth (L), and the pile is said to be coring (IFR=100%). As the pile penetration depth increases, frictional stresses between the inside wall of the pile and the soil plug may cause partial plugging (0%> IFR, 100%), and in some cases the pile may become completely plugged (IFR=0%). They noted that plugging resulted in a large increase in the axial resistance of piles installed in sand and caused a large increase in the zone of excess pore water pressure surrounding piles in clay, causing a delay. Open-end pipe piles are driven in order to reduce driving stresses during driving; a soil plug can develop inside the pipe pile (Paik and Salgado 2003). The development of the soil core during installation is quantified by the plug length ratio (PLR) or the incremental filling ratio (IFR)

$$\mathrm{PLR} = \frac{L\mathrm{p}}{L} \tag{1}$$

$$\mathrm{IFR} = \frac{\Delta L\mathrm{p}}{\Delta L} \tag{2}$$

Paik *et al.* (2003) prepared many samples by the raining method with a constant fall height. The falling soil Paik and L particles passed through a sand diffuser composed of No. 8 and No. 10 sieves in order to control flow uniformity and fall velocity. The soil samples had relative density of 23, 56, and 90%. The samples were consolidated to the desired stress state during approximately 30 hours by compressed air transferred to the rubber membranes. The data were obtained from a full-scale pile with diameter of 356 mm driven into submerged dense sands. The remaining data were obtained from model pile tests using piles with various diameters driven into dry sand ranging from loose to medium dense. The relationship between PLR and IFR for the calibration chamber tests can be expressed as follows

$$\mathrm{IFR}(\%) = 109\ \mathrm{PLR} - 22 \tag{3}$$

This equation slightly underestimates the IFR for PLR values greater than 0.8 and slightly overestimates it for PLR values lower than 0.7. In general, it is known that the IFR is a better indicator of the degree of soil plugging than the PLR (Paikowsky *et al.* 1989, Paik and Lee 1993). In the field, however, it is easier to measure the PLR than the IFR. Eq. (3) can be used to estimate the IFR from the PLR, when only the PLR is measured in the field.

Fig. 1 shows changes of the soil plug length and IFR with penetration depth during pile driving and pressing. It can be seen from the figure that the open-ended pile is partially plugged from the outset of pile driving. It can also be seen that the pile reached a fully plugged state (for which IFR would be equal to zero) for pile pressed in loose and medium sand and partially plugged 10% in dense sand. For driven pile, the IFR is about 30% in loose sand, 20% in medium sand and 30% in dense sand (Sheghait 2013).

Fattah and Al-Soudani (2016a, b) studied the effect of different parameters such as pile diameter to length ratio, type of installation in sand of different densities on the bearing capacity of closed and open-ended piles. Removal of plug was done in three stages (50%, 75% and 100%) with respect to length of plug. The total number of 84 model pile tests were carried out to assess the effect of soil plug on the model pile capacity. The piles were embedded in sand of different densities with different lengths of piles and types of pile ends. Piles with circular cross section were tested under the effect of vertical static compression load.Itwas concluded that the percentage of reduction in pile load capacity for open-ended pile increases with increase of the length of removal of the soil plug and increase of sand density, and The pile reached a fully plugged state (for which IFR would be equal to zero) for pressed pile in loose and medium sand and partially plugged (IFR=10%) in dense sand. For driven pile, the IFR is about 30% in loose sand, 20% in medium sand and 30% in dense sand.

There are two important groups of variables that affect the values of IFR in sands: soil and geometry variables. The relative density is the most important soil variable. The geometry variables include the pile cross-sectional dimensions and driving depths. It is known that, as the relative density increases, the IFR decreases (De Nicola and Randolph 1997). This is because a loose soil plug tends to densify, while a dense soil plug tends to dilate due to the pile driving vibrations (Murff *et al.* 1990, De Nicola and Randolph 1997).

The plug capacity is mainly mobilized from the friction along the inner pile wall, particularly along the lower part of the soil plug where soil arching is significant and a large lateral coefficient of earth pressure is achieved. This arching effect was well observed infield testing of a concrete pipe pile (Liu *et al.* 2012). The degree of soil plugging in an open-ended pile affects pile behavior significantly. The IFR is a good indicator of the degree of soil plugging.

In the study of Wang *et al.* (2016), a series of geotechnical centrifugal tests were conducted to investigate the effectiveness of settlement control of two types of rigid pile structure embankments (PRSE) in collapsible loess under high-speed railway embankments. The research results show that ground reinforcement is required to reduce the postconstruction settlement and settlement rate of the embankments. The rigid pile structure embankments using rigid piles can substantially reduce the embankment settlement in the construction of embankments on collapsible loess, and the efficiency in settlement reduction is affected by the pile spacing. The pile-raft structure embankments (PRSE) have much stronger ability in terms of the effectiveness of settlement control, while the pilegeogrid structure embankments(PGSE) provides rapid construction as well as economic benefits. Rational range of pile spacing of PRSE and PGSE are suggested based on the requirements of various railways design speeds.

Zhang *et al.* (2017) was concerned with the model testing of piles socketed in soft rock which was simulated by cement, plaster, sand, water and concrete hardening accelerator. Model tests on a single pile socketed in simulated soft rock under axial cyclic loading were conducted and the bearing capacity and accumulated deformation characteristics under different static, and cyclic loads were studied by using a device which combined oneself-designed test apparatus with a dynamic triaxial system. The accumulated deformation of the pile head, and the axial force, were measured by LVDT and strain gauges, respectively. Test results show that the static load ratio (SLR), cyclic load ratio (CLR), and the number of cycles affect the accumulated deformation, cyclic secant modulus of pile head, and ultimate bearing capacity. The accumulated deformation increases with increasing numbers of cycles, however, its rate of growth decreases and is asymptotic to zero.

The main objectives of this work are to offer a better realization regarding the performance of soils and pipe pile group under vertical loading with soil plug, and to provide valuable geotechnical data and parameters necessary for foundation design. Experimental laboratory models for single and groups of pipe pile, closed and open with plugged and unplugged case were tested to study the effect of soil plugging with different densities and determine pipe pile group capacity with soil plug and when the soil plug is removed compared with closed ended piles.

2. Experimental Work

The soil used in the research was brought from a site at the center of Karbala city west of Baghdad city in Iraq. The soil is classified as SP type (Poorly graded clean sand). Standard experiments were performed to determine the physical properties of the sand. The properties details are listed in Table 1. Laboratory tests carried out on soil used included the grain size distribution, specific gravity, direct shear test, and maximum and minimum dry unit weights.

Sieve analysis was performed according to ASTM D422-2000. Grain size distribution of the soil used related 96% sand. The soil is classified, according to the Unified Soil Classification, as SP type (Poorly graded sand). The maximum and minimum dry unit weight is determined by using ASTM (D4253-2007) and ASTM (D4254-2007). Specific gravity experiment was performed accordance with ASTM D 854-05.

Direct shear box experiment was performed according to ASTMD 3080-98. The values of (ϕ) for loose, medium and dense sands are listed in Table 2.

Maximum and minimum index density experiments were done in accordance with ASTM D 4253-2000 using a vibratory table and ASTM D4254-2000, respectively. In the experimental program of compression test, the sand relative density, Dr, values shown in Table 3, were chosen. The table also shows the corresponding values of the sand dry

Table 1 Physical properties of sand

D_{60} (mm)	0.95
D_{30} (mm)	0.63
D_{10} (mm)	0.33
Gravel (%)	0
Sand (%)	96
Silt and clay (%)	4
Coefficient of uniformity (Cu)	2.88
Coefficient of curvature (Cc)	1.27
Specific gravity (Gs)	2.65
Maximum dry unit weight (kN/m^3)	18.8
Minimum dry unit weight (kN/m^3)	15.1
Maximum void ratio ($e_{max.}$)	0.73
Minimum void ratio ($e_{min.}$)	0.42

Table 2 Angle of friction values for the sand used

State of soil	Angle of internal friction ( )
Loose	31
Medium	36
Dense	40

Table 3 Relative densities and the corresponding dry unit weights values for soil used

State of sand	Relative density %	Dry unit weight (γ_d) kN/m^3
Loose	20	15.5
Medium	45	16.1
Dense	75	17.8

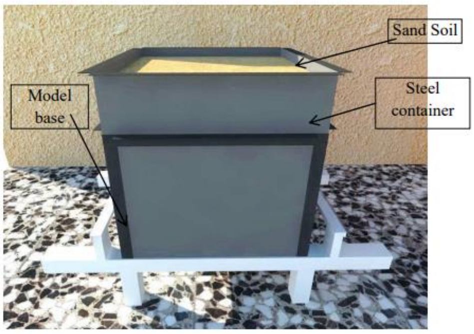


Fig. 2 Steel container

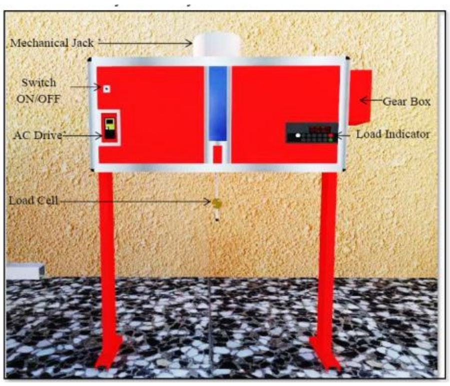


Fig. 3 Steel loading frame and axial loading system.

unit weights used in preparation and placement of sand in the model tank.

2.1 Model setup formulation

To simulate the pile load experiment in the area, a new apparatus was used. It consists of the following parts: Steel container, Steel base, Steel loading frame, Axial loading system, Raining frame, Impact hammer device, Mechanical jack , Load cell, Digital weighing indicator, Gear box, AC Drive (speed regulator), Pile driving system-pressing system installation, Soil plugs removal and measurement system, Strain gauges, Data logger, Linear variable differential transformer (LVDT), Digital dial gauges.

The steel container has the dimensions of 750 mm in length, 750 mm in width, and 750 mm in height, as shown in Fig. 2. It is made of five separated parts, one for the base and the others for the four sides.

A steel base was designed for this study to support the container and the loading frame weight. The box is rested on two channels with the ability of lateral movement. A steel loading frame was manufactured for this study to support the gear box motor, axial loading system and mechanical jack, as shown in Fig. 3. The axial loading system was designed for the purpose of this study, the load is submitted through a mechanical jack joint by a gear box motor and AC drive (speed regulator), which in turn controls the speed of the gear box motor as shown in Fig. 3. The maximum load that can be submitted is 1 ton. The loading rate is kept constant at 1 mm/min as recommended by ASTM D1143-2007. The model is possible to move in horizontal and vertical directions to a pile group, and so one can make sure that the load is in the middle of the pile system and there is no evidence of any eccentricity.

A compression/tension load cell “SEWHA, Korea” model S-beam (SS300) type is used to determine the load. It is made from stainless steel (LS300), with a maximum capacity of 1 ton, locally calibrated, as shown in Fig. 3.
To displaying the load amount “SEWHA, Korea” model (SI4010) the digital weighing indicator is used with an input sensitivity of 50 gm. A gear box used to control the applied load, it is a motor with a high horsepower; a capacity to apply high torques, as shown in Fig. 4. It can control the rotation speed through AC drive (speed regulator). It is joined by a shaft to the mechanical jack. AC drive (speed regulator) is connected directly to (gear box) to control the speed of rotation by inserting the value of the required speed. Linear variable differential transformer (LVDT) is used to measure the displacement.

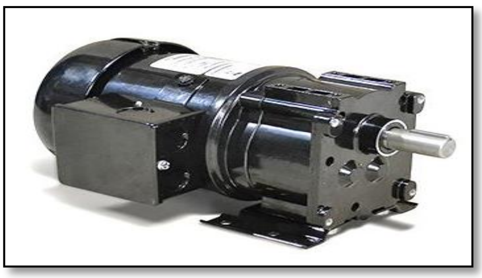


Fig. 4 Gear box

Fig. 5 Raining frame used for controlling sand density

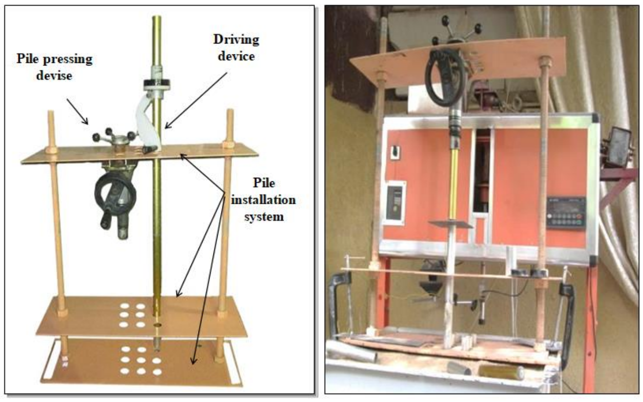


Fig. 6 Pile group system installation

2.2 Sand raining frame

The raining frame consists of two columns with changeable height. It was made to achieve any desired elevation. The frame height change is done by holes with equidistance steps (15 cm). It is joined from top and bottom to the column with two to 4joints beams together and these beams are bolted at their ends. To support the U-section beams, the two beams in the longitudinal direction have (U-section) and the other beams are used. Another beam was designed as a roller, which are rests on the longitudinal beams to move along these beams. This (rolled-beam) is jointed from the bottom with another beam, it is supported with screw and it can be moved horizontally along with the beam; this beam was designed to carry the cone that is used to pour the sand. The raining frame is illustrated in Fig. 5. This raining frame configuration helps get a uniform density by controlling the height of fall. The rolled-beam and the screw which is jointed with the cone to ensure each particle drop at equal height and uniform intensity. A mesh piece (the aperture diameter is 10 mm) is put inside the cone to reduce the effect of the particles. To control the fall height, additional tubular elongations at the cone end were used by using adapted tubes.

An impact hammer was used in this study to maintain the required density of dense sand, consists of square aluminum plate (250 mm×250 mm) and 10 mm in thickness. The plate is tied to a rod of length (500 mm) and diameter (30 mm), the weight of the group is (2.0) kg.

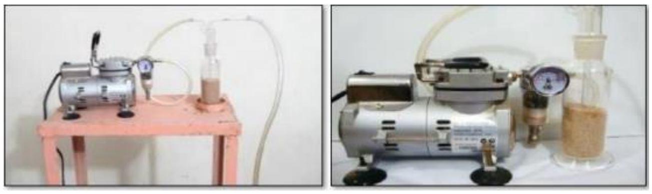


Fig. 7 Soil plug removal system

2.3 Pile driving-pressing system

The piles setup system consists of a base plate with dimensions of (850 mm×200 mm) and 4 mm in thickness. This plate includes nine holes (31 mm) in diameter and the spacing between holes is (91 mm), these holes are considered as focus place for the piles to penetrate the soil in the box. To support the two beams that designed from stainless steel the two tube columns with (28 mm) diameter are fixed vertically. The main part in the driving hammer is the aluminum rod, it contains steel helmet in the rod head and steel cylinder, which is used as a base for dropping the hammer weight. The steel helmet was designed with various holes that are suitable for all model pile sizes used in the experiments. These grooves are designed to ensure the piles are as fixed as possible to reserve the vertical direction for penetration of pile without tilting through the driving process, and these parts are shown in Fig. 5. Mechanical jack is used for pressing pile into the soil at a constant rate. This jack is fixed to the pile during installation system, and these parts are shown in Fig. 6.

The hammer masses used in the experiments are circular in shape and formed from steel material. They have holes in the center to enable lifting and lowering along the hammer rod. The hammer mass which is lifted to a specified height (220 mm) by means of half-plastic plate with handle is fixed to small steel.

2.4 Soil plugs removal and measurement system

This study is based on the system of cleaning pile raise plug. The mechanism is based on pulling out of sand from inside the pile after the completion of the pressure or driven piles. This system consists of motor with specifications following input operating vacuum (675 mm Hg) and output-air flow (26 LPM) and voltage 220-240 v, AC 50Hz connected to the flask to collect sand banter from inside the pile and then measuring the sand column height inside the pile, or a pile group, Fig. 7. The instrument is relying on the withdrawal of sand and measurement system rod which consists of aluminum diameter 1.5 mm with different lengths based on the lengths of the pile that has been relegated in the sand as it was the work of signals every 10 mm to measure the length of the sand column after the clouds to find out the sand size that has been removed from inside the pile.

2.5 Pipe pile properties

Regarding the physical properties of the adopted piles' sections, piles were experimented as per ASTM E8 with the collaboration of the Central Organization for Standardization and Quality Control. Four aluminum pipe pile samples have been taken randomly and experimented then the average value has been reported for each property as shown in Table 4.

Table 4 Aluminum pipe pile properties

Experiment	Results			
	Sample B1	Sample B2	Sample B3	Sample B4
Tensile strength (N/mm^2)	215	243	199	240
Yeild strength (N/mm^2)	184	196	169	186.5
Elongation (mm)	7	10.5	12	11
Modulus of Elasticity (N/mm^2)	50400	52400	59100	54200
Outer Diameter(mm)	32.56	32.58	33.06	33.02
Thickness (mm)	1.45	1.40	1.50	1.40

Table 5 Model pile types and dimensions used in the experiment

Pile No.	Pile type	Soil plug situation	Diameter d (mm)	Length (mm)	
				L/d=12	L/d=15
1-pile	Open - ended	Full Plug	32.8	360	450
1- pile	Open - ended	Unplugged			
2 - pile	Open - ended	Full Plug			
2 - pile	Open - ended	Unplugged			
4 - pile	Open - ended	Full Plug			
4 - pile	Open - ended	Unplugged			
6 - pile	Open - ended	Full Plug			
6 - pile	Open - ended	Unplugged			
1 - pile	Closed - ended	--			
2 - pile	Closed - ended	--			
4 - pile	Closed - ended	--			
6 - pile	Closed - ended	--			

2.6 Details of model piles

Two types of piles have been used in this study, these were: open ended and closed ended tube piles. These two types have been experimented as single pile as well as group piles with two, four and six piles. All the piles in the experimental work were used with 32.8 mm diameter and 1.44 mm thickness. The embedment length of the model piles, which is considered in the experimental programs of the experiments, based on the ratio of embedment length to pile diameter, (L/d) ratio. The pile type, outside diameter, and length of each pile size are shown in Table 5.

2.7 Setting up of model driven piles

The model piles are vertically installed in specific hole that is made in the hammer plate and the rod of hammer is lowered to the model piles until the pile helmet is connected with the model pile. After the model pile head enters inside the helmet, the process of driving begins with dropping a specific weight from a specified height, and the blows number results are recorded each (25 mm) of model pile length until reaching the final desired length of penetration. The ram weight used to drive the model piles equals (1.9 kg). This weight was chosen to determine the best driving energy based on the weight ratio of pile to hammer (P/W) where P is the pile weight and W is the hammer weight.

Table 6 Identification of open-ended pile groups with different lengths of soil plug

No.	Type of Installation	Type of pipe pile	ID of pile	L/d
1	Driven	Single Open - ended - Full plugged	1(12)DOF	12
2	Driven	2- pile - Open - ended- Full plugged	1(12)DOF	12
3	Driven	4- pile - Open - ended - Full plugged	4(12) DOF	12
4	Driven	6- pile - Open - ended- Full plugged	6(12) DOF	12
5	Driven	Single Open - ended - Un plugged	1(12)DOU	12
6	Driven	2- pile - Open - ended- Un plugged	2(12) DOU	12
7	Driven	4- pile - Open - ended- Un plugged	4(12) DOU	12
8	Driven	6- pile - Open - ended- Un plugged	6(12) DOU	12
9	Pressed	Single Open - ended - Full plugged	1(12) POF	12
10	Pressed	2- pile - Open - ended- Full plugged	2(12) POF	12
11	Pressed	4- pile - Open - ended - Full plugged	4(12) POF	12
12	Pressed	6- pile - Open - ended- Full plugged	6(12) POF	12
13	Pressed	Single Open - ended - Un plugged	1(12) POU	12
14	Pressed	2- pile - Open - ended - Un plugged	1(12) POU	12
15	Pressed	4- pile - Open - ended - Un plugged	4(12) POU	12
16	Pressed	6- pile - Open - ended - Un plugged	6(12) POU	12
17	Driven	Single Open - ended - Full plugged	1(15)DOF	15
18	Driven	2- pile - Open - ended- Full plugged	2(15)DOF	15
19	Driven	4- pile - Open - ended - Full plugged	4(15)DOF	15
20	Driven	6- pile - Open - ended- Full plugged	6(15)DOF	15
21	Driven	Single Open - ended - Un plugged	1(15)DOU	15
22	Driven	2- pile - Open - ended - Un plugged	2(15)DOU	15
23	Driven	4- pile - Open - ended - Un plugged	4(15)DOU	15
24	Driven	6- pile - Open - ended - Un plugged	6(15)DOU	15
25	Pressed	Single Open - ended - Full plugged	1(15)POF	15
26	Pressed	2- pile - Open - ended- Full plugged	2(15)POF	15
27	Pressed	4- pile - Open - ended - Full plugged	4(15) POF	15
28	Pressed	6- pile - Open - ended- Full plugged	6(15) POF	15
29	Pressed	Single Open - ended - Un plugged	1(15)POU	15
30	Pressed	2- pile - Open - ended - Un plugged	2(15)POU	15
31	Pressed	4- pile - Open - ended - Un plugged	4(15) POU	15
32	Pressed	6- pile - Open - ended - Un plugged	6(15) POU	15

Table 7 Identification of closed-ended pile groups with different lengths of soil plug

No.	Type of Installation	Type of pipe pile	ID of pile	L/d
1	Driven	Single Closed– ended	1(12)DC	12
2	Driven	2- pile – Closed - ended	2(12)DC	12
3	Driven	4- pile - Closed - ended	4(12)DC	12
4	Driven	6- pile - Closed - ended	6(12)DC	12

Table 7 Continued

No.	Type of Installation	Type of pipe pile	ID of pile	L/d
5	Pressed	Single Closed – ended	1(12)PC	12
6	Pressed	2- pile – Closed - ended	2(12)PC	12
7	Pressed	4- pile - Closed - ended	4(12)PC	12
8	Pressed	6- pile - Closed - ended	6(12)PC	12
9	Driven	Single Closed – ended	1(15)DC	15
10	Driven	2- pile – Closed - ended	2(15)DC	15
11	Driven	4- pile - Closed - ended	4(15)DC	15
12	Driven	6- pile - Closed - ended	6(15)DC	15
13	Pressed	Single Closed – ended	1(15)DC	15
14	Pressed	2- pile – Closed - ended	2(12)PC	15
15	Pressed	4- pile - Closed - ended	4(15)PC	15
16	Pressed	6- pile - Closed - ended	6(15)PC	15

2.8 Identification of Model Pile Used in the Testing Program

In order to simplify the notation used for piles, identification symbol is given for each model as indicated in Tables 6 and 7. Each pile is identified according to the ratio of length of pile to diameter, type of installation and type of pile.

2.9 Setting up of model pressed piles

In the installation frame the mechanical jack is used and fixed on the box to press the model pile to penetrate the desired length.

2.10 Measurement of IFR and PLR

During the push piles in the soil, whether manner pressing or driven, the sand column will develop with increasing piles entry into the soil and thus will calculate the sand column length breached necessary to know the bearing capacity for single or group pile. A soil plug formation in an open-ended pile is a very important factor. The soil plugging degree can be represented by the Incremental Filling Ratio (IFR) and Plug Length Ratio (PLR) defined by (Iskander 2010), IFR expresses the increase in soil plug length inside pile per unit increase of penetration depth of pile in soil. The IFR was measured by measuring the length of soil plug formed inside the pile each 50 mm during installation of the pile.

3. Results and discussion

Table 8 shows the measured height of soil column within each pile installation stage after dividing the pile into fixed heights to measure the amount of increase generated in the height of sand. From table, it can be noted that the ratio of sand column height inside the open ended pile may reach value between (40.5-68.2)% of the pile length in case of driven piles, while in the pressed piles, the ratio

Table 8 Length of soil plug inside open-ended pipe pile groups

Installation method		No. of pile	Length of soil plug inside pile (mm)						Percentage of sand column length to pile length (%)					
			L/D=15			L/D=12			L/D=15			L/D=12		
			Soil state											
			Loose	Medium	Dense	Loose	Medium	Dense	Loose	Medium	Dense	Loose	Medium	Dense
Driven	1(DOF)	1	185	198	240	163	160	185	41	44	53	45	44	51
	1(DOU)	1	0	0	0	0	0	0	0	0	0	0	0	0
	G1 (DOF)	1	185	193	243	163	160	185	41	43	54	45	45	51
		2	216	224	258	177	189	204	48	50	58	49	53	57
		$L_{av.}$	201	208	251	170	175	194	45	46	56	47	49	43
	G1(DOU)	1, 2	0	0	0	0	0	0	0	0	0	0	0	0
	G2 (DOF)	1	182	193	239	161	160	185	41	43	53	45	45	51
		2	218	225	256	175	189	204	49	50	57	49	53	57
		3	256	250	300	189	175	216	57	56	67	53	49	60
		4	195	205	270	165	202	232	43	46	60	46	57	65
		$L_{av.}$	213	218	265	173	225	209	47	49	59	48	63	58
	G2 (DOU)	1, 2, 3, 4	0	0	0	0	0	0	0	0	0	0	0	0
	G3 (DOF)	1	184	198	239	163	168	188	41	44	53	45	47	52
		2	215	223	260	175	192	204	48	50	58	49	53	57
		3	252	250	300	191	195	215	56	56	67	53	54	60
		4	198	212	273	170	180	230	44	47	61	47	50	64
		5	268	275	318	215	218	245	60	61	71	60	61	70
		6	285	285	325	226	229	253	63	63	72	63	64	68
		$L_{av.}$	234	241	286	190	197	223	52	53	53	53	55	62
	G3 (DOU)	1, 2, 3, 4, 5, 6	0	0	0	0	0	0	0	0	0	0	0	0
Pressed	1(POF)	1	147	150	200	124	125	154	33	33	45	35	35	43
	1(POU)	1	0	0	0	0	0	0	0	0	0	0	0	0
	G1(POF)	1	145	147	200	124	124	154	32	32	33	35	35	43
		2	158	175	205	138	136	165	35	35	46	38	38	46
		$L_{av.}$	152	161	203	131	130	160	34	36	45	37	36	44
	G1(POU)	1, 2	0	0	0	0	0	0	0	0	0	0	0	0
	G2(POF)	1	148	150	202	125	124	155	33	33	45	35	35	43
		2	160	165	208	138	135	163	36	37	46	38	38	45
		3	166	169	218	145	143	179	37	38	48	40	40	50
		4	170	173	225	158	153	185	38	39	50	35	34	41
		$L_{av.}$	161	164	213	141	139	170	36	37	47	39	39	47

Table 8 Continued

Installation method		No. of pile	Length of soil plug inside pile (mm)						Percentage of sand column length to pile length (%)					
			L/D=15			L/D=12			L/D=15			L/D=12		
			Soil state											
			Loose	Medium	Dense	Loose	Medium	Dense	Loose	Medium	Dense	Loose	Medium	Dense
		1												
	G2 (POU)	2	0	0	0	0	0	0	0	0	0	0	0	0
		3												
		4												
Pressed	G3(POF)	1	148	150	197	125	127	157	33	33	44	28	28	35
		2	160	165	210	138	140	165	36	37	47	31	31	37
		3	166	169	218	145	143	179	37	38	48	40	40	50
		4	170	173	225	158	153	185	38	39	50	35	34	41
		5	177	180	248	167	165	197	39	40	55	37	37	44
		6	184	186	237	175	177	209	41	41	53	39	39	47
		1												
		2												
	G3(POU)	3	0	0	0	0	0	0	0	0	0	0	0	0
		4												
		5												
		6												

ranged between (27.7-55.1)% of pile length which were implemented depending on the soil density and pile length.

The bearing capacity of the soil beneath the soil plug should, initially, be greater than the sum of the plug weight and the friction between the soil and the inner wall of the pile. The height of the soil plug then tends to increase until a limiting equilibrium is achieved and a fully plugged mode is formed. In view of the previous observation, for practical purposes, it is both necessary and desirable to develop an improved method that allows determination of the individual resistance of the annulus and the plug from considerations of the mechanics involved. The plug capacity is mainly mobilized from the friction along the inner pile wall, particularly along the lower part of the soil plug where soil arching is significant and a large lateral coefficient of earth pressure is achieved. This arching effect was well observed in field testing of a concrete pipe pile (Liu *et al.* 2012). The friction along the inner pile wall is closely related to the development of plug length during pile installation, and the arching effect is also responsible for the rotation of principal stresses in the soil adjacent to the inner wall.

The height of soil plug, indicates that only imperfect plugging of pipe pile occurred during driving. This was caused by the inertia of the soil plug inside the pile, which encouraged the slippage between the soil plug and the pile and prevented perfect plugging of the pile.

Figs. 8 to 15 show the change in the soil column with the amount of penetration of the pile with length of 450 mm and 300 mm using both driving and pressing methods and for different conditions of soil (loose, medium and dense).

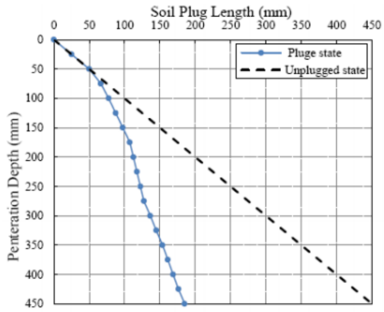
In these figures, it can be noted that the dashed line represents the theoretical value for the case of fully coring (unplugged state) in which the soil plug length is equal to the pile penetration depth.

Table 9 demonstrates the reduction in load carrying capacity after the soil column plug was removed. It can be shown that the load carrying capacity for the group G3 has higher ratio of reduction up to 83% in dense soil and for driven case, while the reduction ratio for single pile reaches to 41.7%. From these results, it can be concluded that the soil plug removing causes more risk to pile group than single pile and it is recommended that group of pipe piles should be tested if the soil plug is removed to decide the load carrying capacity for design.

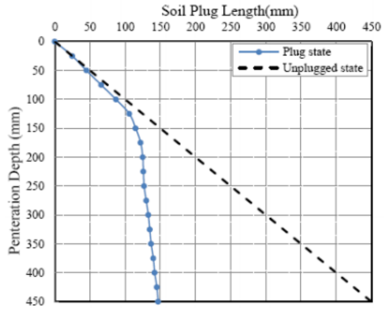
The soil plug length generally increased linearly with the penetration depth, implying that IFR may not vary significantly during pile driving. Therefore, we used PLR to investigate the effect of the soil plugging on the unit end bearing.

Fig. 16 shows the changes of penetration depth with IFR during pile installation for group of pipe piles. Fig. 16(a)-16(c) shows the IFR with different sand densities loose, medium and dense soil respectively for driven method, while Fig. 15(d)-15(f) presents the same tests of soil density with change in the method of pile installation.

This installation effect is best described by the incremental filling ratio (IFR) measured over the final stages of installation and is referred to here as the final filling ratio (FFR). As the FFR approaches zero approaches that of a closed-ended pile with the same outer diameter. The FFR value varies from unity for a pile installed in a



(a)



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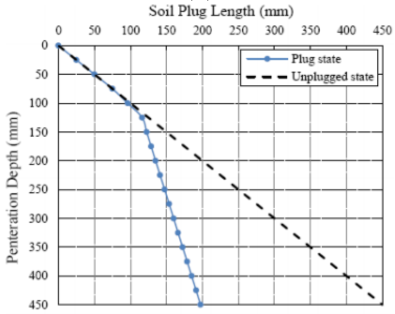
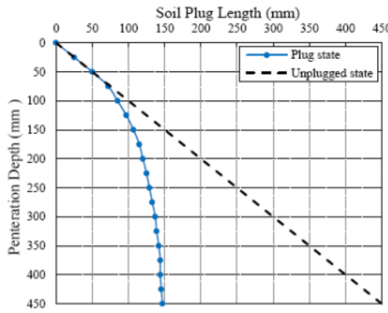
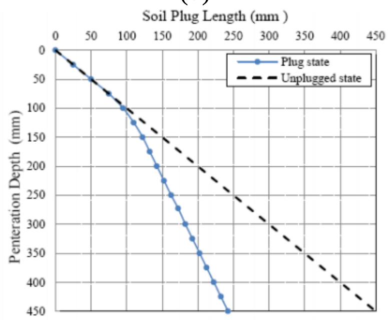


(c)

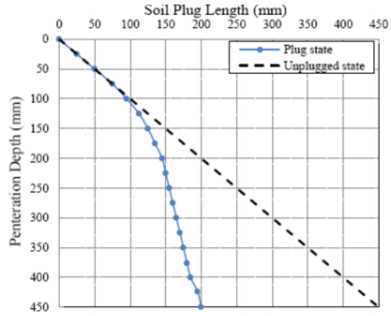


(d)



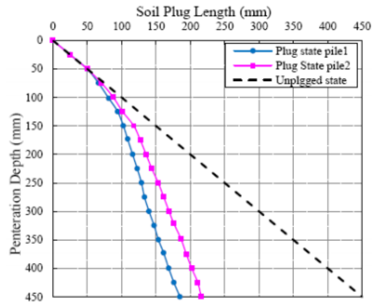
(e)

Fig. 8 Soil plug length in single pipe pile of length 400 mm, (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing

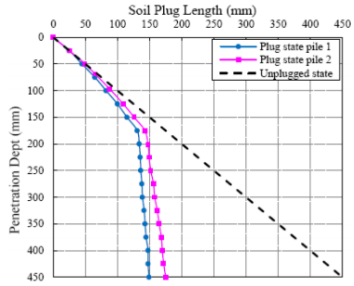


(f)

Fig. 8 Continued



(a)



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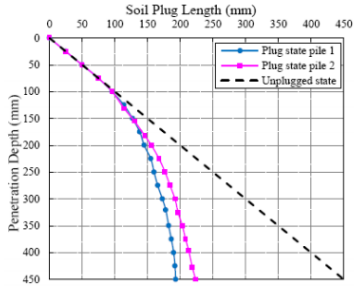
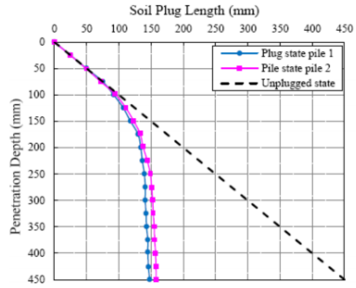
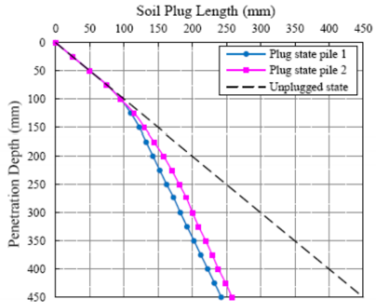


(c)

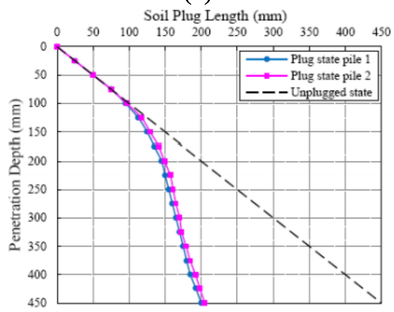


(d)

Fig. 9 Soil plug length in group pipe pile G1(1x2) of length 400 mm, (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing

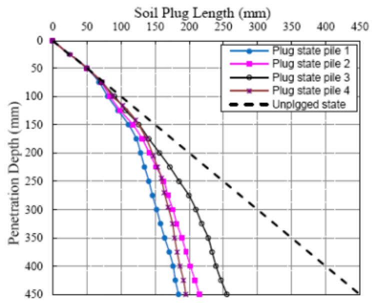


(e)

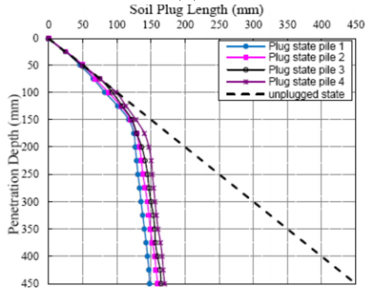


(f)

Fig. 9 Continued



(a)



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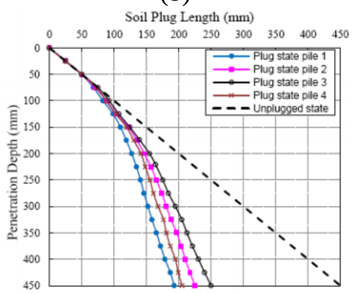
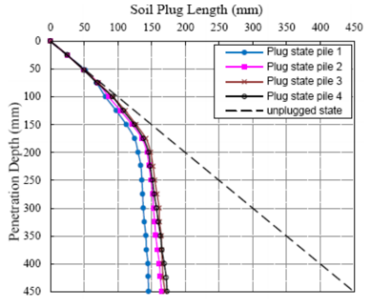


(c)

Fig. 10 Soil plug length in group pipe pile G2(2x2) of 400 mm, (a) loose driven, (b) loose pressing, (c) medium driven,(d) medium pressing, (e) dense driven and (f) dense pressing



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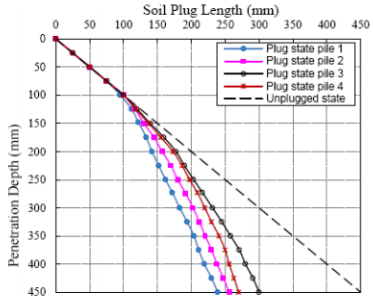
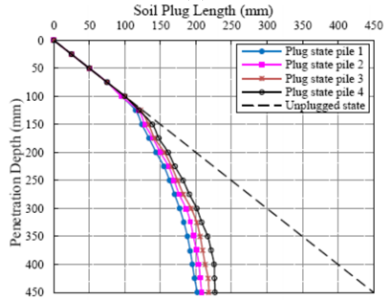


(e)



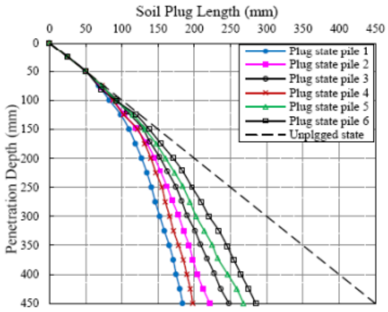
(f)

Fig. 10 Continued

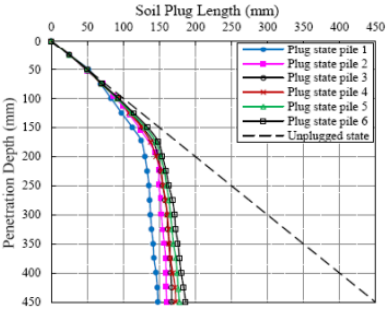
fully plugged mode to about 0.08 for a pile installed in a coring mode with L/D of 50 (Lehane *et al.* 2007).

Table 10 summarizes the values of the IFR% that are measured during 72 tests for single pile and pile group. It can be seen that the pile reaches fully plugged state what it is pressed in loose and medium sand and partially plugged 12%, 10%, 6% respectively for group piles with number 1, 2 and 3 and fully plugged for pile length 400 mm. For pile length equal to 300 mm the partially plug 7%, 5% and 5% for the same number of piles and the other pile fully plugged (IFR% equals to zero) in dense sand. For driven pile with length of 450 mm, the average IFR % is about 30.3% in dense sand, 14% in medium and 18.3% for loose sand while when the length of pile is 300 mm, the percentage equals to 20%, 17% and 19.5%, respectively.

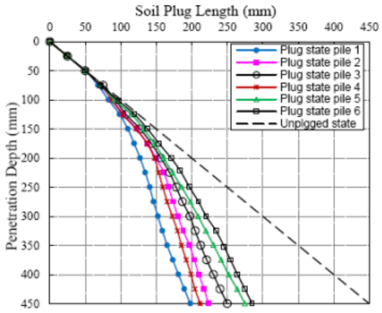
The change in density around the test pile is lower in dense sands than in loose sands. A higher density of the soil tends to a higher IFR. Nevertheless the IFR does not converge to a fixed value. It was increasing and also decreasing during driving, which means that the soil inside was plugging and loosening again. This phenomenon was also identified by Luking and Kempfert (2013) during the static pile test loading. However during both test series the value never reached IFR=0. The minimum was IFR=0.2. This means that only a partially plugged soil could occur



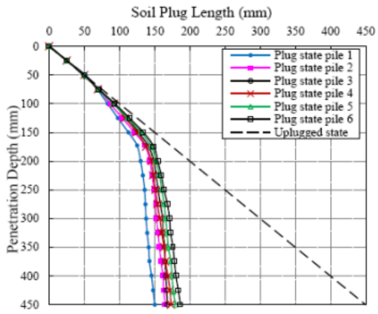
(a)



(b)



(c)



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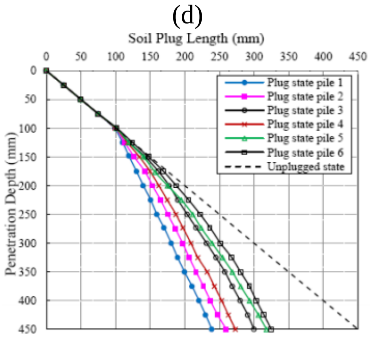
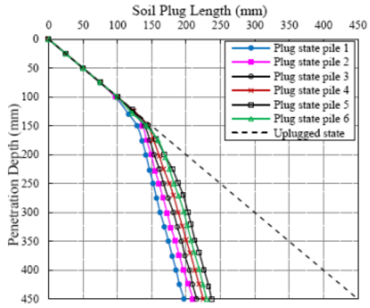


(e)

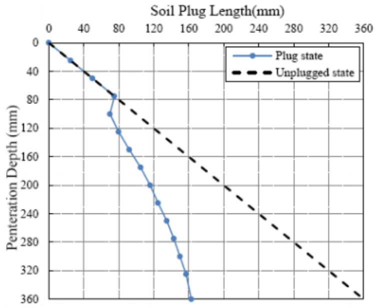
Fig. 11 Soil plug length in group pipe pile G3(2x3) of length 400 mm, (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing



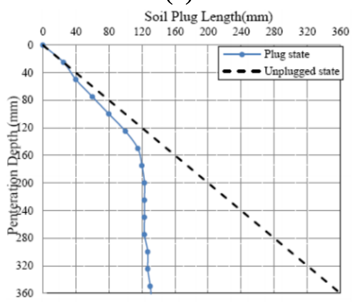
(f)

Fig. 11 Continued

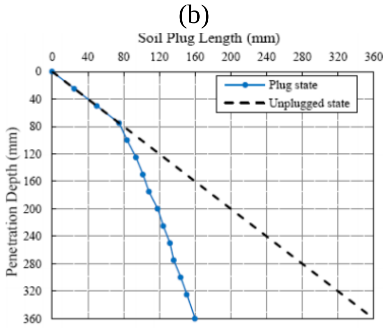
and based on this the concept of a monolithical soil plug should be analyzed critically. Lehane and Randolph (2002) suggested that the base resistance provided by the soil plug for a fully coring pile (with FFR=1) is approximately equivalent to that of a bored pile. Lehane and Randolph (2002), and others, have shown that, if the length of the soil plug is greater than 5 internal pile diameters (5Di), the plug will not fail under static loading, regardless of the pile diameter.



(a)

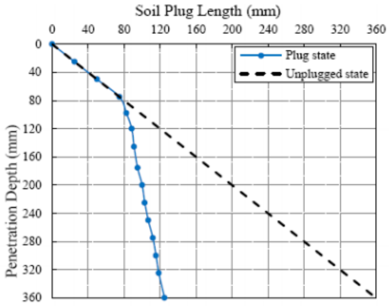


(b)



(c)

Fig. 12 Soil plug length in single pipe pile of 360 mm, (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing



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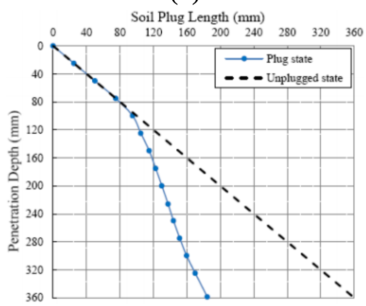
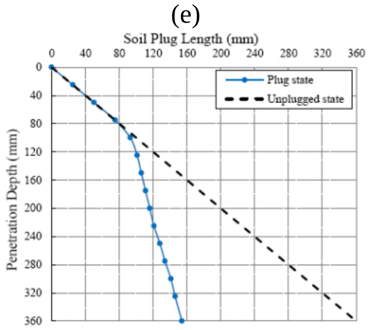
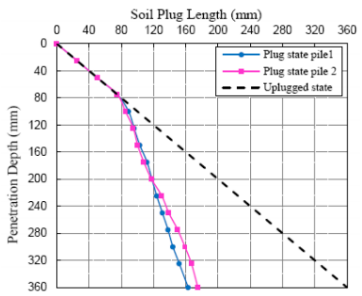


(e)

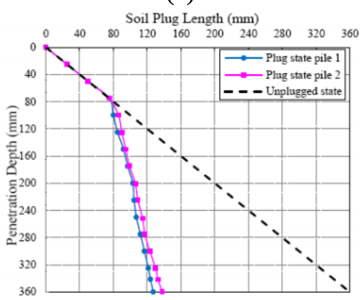


(f)

Fig. 12 Continued

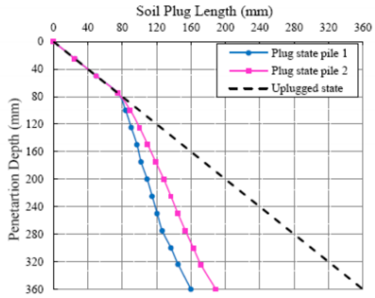


(a)

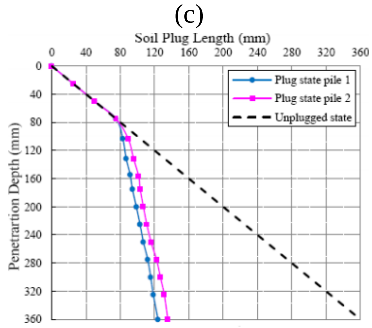


(b)

Fig. 13 Soil plug length in G1(1x2) pipe pile with embedded pile length 360 mm, (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing



(c)



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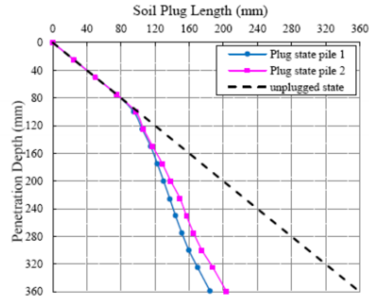

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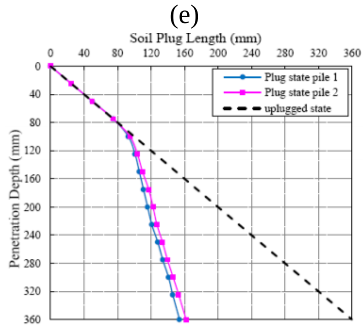
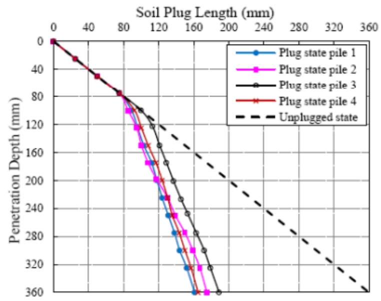


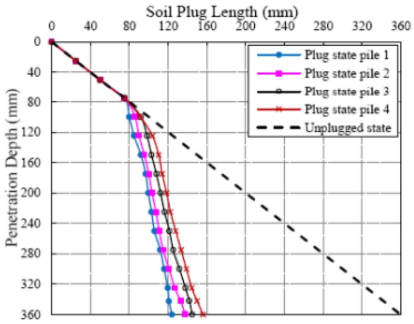
(f)

Fig. 13 Continued



(a)

Fig. 14 Soil plug length in G2(2x2) pipe pile with embedded pile length 360 mm. (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing



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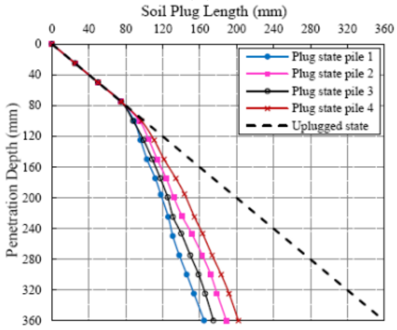

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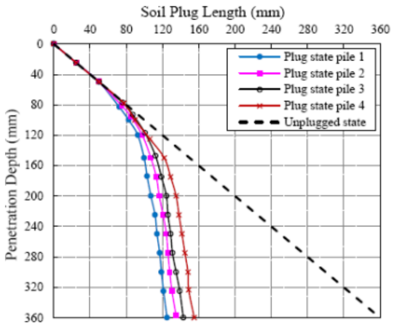

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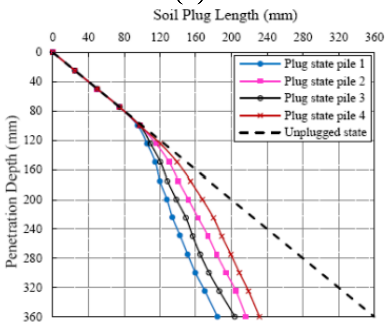

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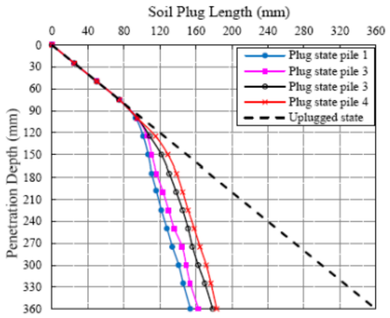
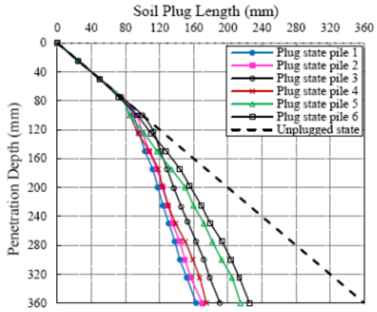
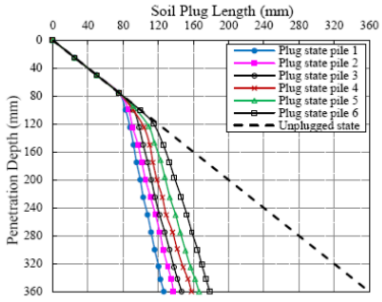


(f)

Fig. 14 Continued



(a)



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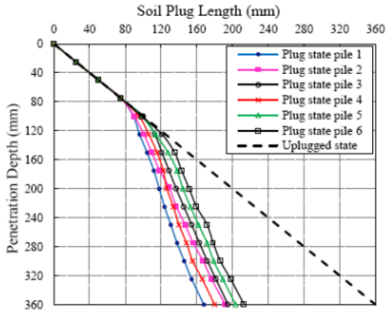

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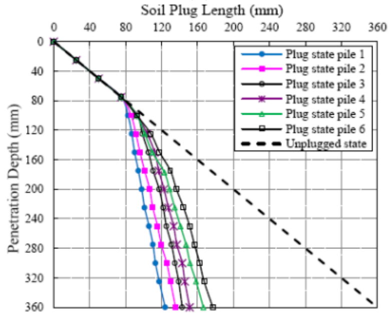
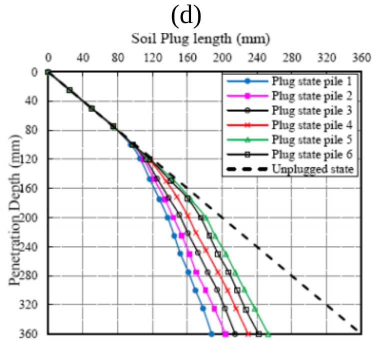
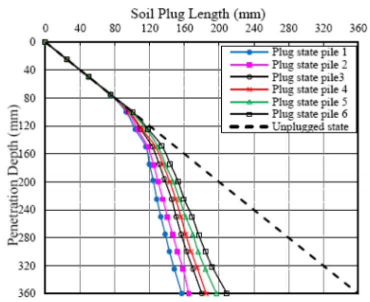


(d)



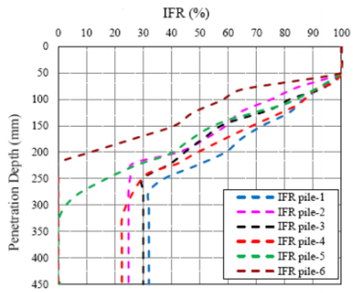
(e)

Fig. 15 Soil plug length in G3(2x3) pipe pile with embedded pile length 360 mm. (a) loose driven, (b) loose pressing, (c) medium driven, (d) medium pressing, (e) dense driven and (f) dense pressing

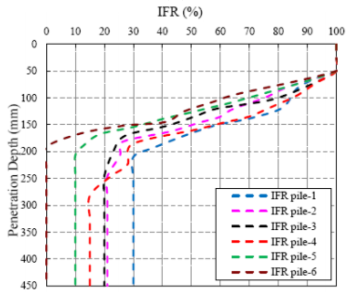


(f)

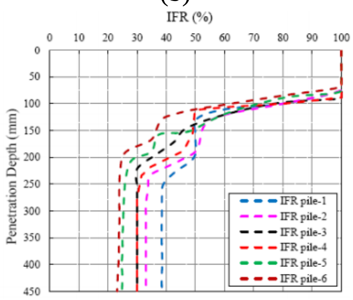
Fig. 15 Continued



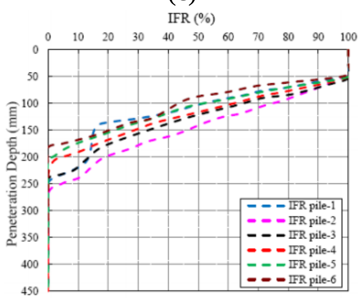
(a)



(b)

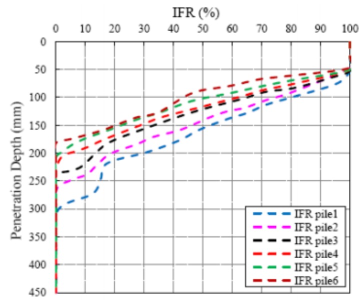


(c)

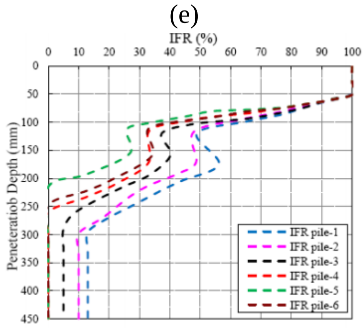


(d)

Fig. 16 IFR% versus penetration depth in open-end pile group with embedded pile length 450 mm. (a) 6(15) DOF loose, (b) 6(15) DOF medium, (c) 6(15) DOF dense (d) 6(15) POF loose, (e) 6(15) POF medium and (f) 6(15) POF dense



(e)



(f)

Fig. 16 Continued

Table 9 Reduction in pile load capacity for single and group open-ended piles due to removal of soil plug inside piles

Method of installation	Type of pipe pile	Pile length (mm)	State of soil	Reduction in pile load capacity (%)			
				Single pile	Group pile		
					G1	G2	G3
Driven	15 (DOF)	450	Loose	41.67	67.98	75.56	77.93
	15 (DOU)						
	15 (DOF)		Medium	48.73	64.00	71.25	77.03
	15 (DOU)						
	15 (DOF)		Dense	59.14	69.65	73.01	82.99
	15 (DOU)						
Pressed	15 (POF)		Loose	51.82	65.40	74.50	78.29
	15 (POU)						
	15 (POF)		Medium	55.79	67.38	66.51	76.05
	15 (POU)						
	15 (POF)		Dense	61.51	67.61	65.00	---
	15 (POU)						
Driven	12 (DOF)	300	Loose	48.99	58.71	65.69	72.37
	12 (DOU)						
	12 (DOF)		Medium	48.09	58.56	68.23	71.46
	12 (DOU)						
	12 (DOF)		Dense	54.49	50.80	71.09	82.96
	12 (DOU)						
Pressed	12 (POF)		Loose	54.85	62.67	66.40	72.19
	12 (POU)						
	12 (POF)		Medium	50.00	52.96	61.75	69.25
	12 (POU)						
	12 (POF)		Dense	52.94	55.51	58.63	---
	12 (POU)						

Table 10 IFR values for pipe pile group with different densities and using two methods of installation

Method of installation	State of soil	Pile length (mm)	IFR (%)						
			1	2	3	4	5	6	Average
Driven	Loose	450	32	25	30	22.5	0	0	18
	Medium		30	21	20	15	0	0	14
	Dense		38.5	33	30	30	25	23	30
Pressed	Loose		0	0	0	0	0	0	0
	Medium		0	0	0	0	0	0	0
	Dense		12	10	6	0	0	0	5
Driven	Loose	300	35	29	28.5	25	0	0	20
	Medium		30	24	27	20	0	0	17
	Dense		35	32	29	25	0	0	20
Pressed	Loose		0	0	0	0	0	0	0
	Medium		0	0	0	0	0	0	0
	Dense		10	5	5	5	0	0	5

4. Conclusions

1. The incremental filling ratio (IFR) is changed with the changing of soil state and method of installation. For driven pipe pile group, The average IFR for loose is 18% and 19.5% for L/D=12 and 15, respectively, while the average of IFR for piles dense sand is 30% and 20% for L/D=12 and L/D=15 respectively. For pressed method of pile installation, the average IFR for group is zero for loose and medium sand and about 5% for dense sand.

2. The group capacity increases with the increase of IFR.

3. PLR which is defined similar to the IFR except that the PLR is not an incremental value and is only measured once at the end of the installation process, the value of PLR decreases with the decreasing of soil relative density and the horizontal stress.

4. The pile reaches fully plugged state when it is pressed in loose and medium sand and partially plugged for group piles with number of piles 1, 2 and 3. For driven pile with length of 450 mm, the average IFR % is about 30.3% in dense sand, 14% in medium and 18.3% for loose sand while when the length of pile is 300 mm, the percentage equals to 20%, 17% and 19.5%, respectively.

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