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In situ evaluation and analysis of improvement effects of pervious concrete pile on alluvial silt ground

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ABSTRACT
Since the concept of pervious concrete pile (PCP) was put forward as a technology of ground improvement, some numerical simulations and small-scale tests have been performed to study the properties of PCP composite foundation. However, this technology has not been implemented in field. In this work, PCPs were installed by employing the method of vibrating-sinking tube and a series of tests are performed to evaluate the properties of PCP composite foundation. The tests on pile cores indicate the method of vibrating-sinking tube is suitable for installation of PCP. Compared with gravel column and soil-cement mixed pile, PCPs significantly increase the time rate of consolidation, improve the bearing capacity of composite foundation and increase pile-soil stress ratio. PCPs can also effectively reduce the acceleration and excess pore water pressure induced by vibration, and thus mitigate liquefaction of ground and reduce the damage of upper structure. This work is helpful for the design and installation of PCP.

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KEYWORDS
Pervious concrete pile; composite foundation; vibrating-sinking tube method; bearing capacity; liquefaction

1. Introduction

In recent years, the composite foundation technologies have been widely used to enhance the bearing capacity of foundation, and reduce settlement and liquefaction potential of ground (Haldar and Babu 2010, Ariyarathne *et al.* 2013). Vertical reinforcement of composite foundation may be divided into granular pile, flexible pile and rigid pile. Granular piles such as gravel column (GC) have been widely used in engineering, as they can accelerate the time rate of consolidation, and also reduce the liquefaction potential of sand or silt ground (Hughes and Withers 1974, Poorooshasb and Meyerhof 1997, Lee and Pande 1998, Ferreira Pinto and Delgado Rodrigues 2008). But the stiffness and strength of granular pile are low, and are greatly related with the confining pressure of the surrounding soil (Guetif *et al.* 2007). When granular piles are applied to soft clay, organic soil or peat soil, the shallow part of granular piles are prone to expansion failure, and thus the bearing capacity of the ground has little improvement. While the rigid piles such as low-grade concrete pile and cement fly-ash grave pile have overcome the weak bonding problem of granular piles (Zheng *et al.* 2008, Sariosseiri and Muhunthan 2009, Le Hello and Villard 2009, Jia *et al.* 2011), they have poor permeability, and this induces slow consolidation rate of ground. Flexible piles such as soil-cement mixed pile (SCMP) have low strength and permeability, so the bearing capacity of the composite foundation is low and its consolidation velocity is slow.

Recently, an innovative ground improvement concept using pervious concrete pile (PCP) has been proposed (Suleiman *et al.* 2011b; Ni *et al.* 2013, 2016, Suleiman *et al.* 2014). Pervious concrete, also referred to as porous concrete, is a mixture of Portland cement, gap graded aggregate and water with or without a small amount of fine aggregate. There are a large number of connective pores within the aggregate skeleton. Generally, the porosity of pervious concrete is between 15% and 25%, and the permeability is typically between 2 and 6 mm/s but can be as high as 10 mm/s (Tennis *et al.* 2004, Montes *et al.* 2005, Luck *et al.* 2006). With the high permeability, pervious concrete can also provide a compressive strength between 3.5 and 28 MPa (Schlüter and Jefferies 2002; Suleiman *et al.* 2011a, Kevern *et al.* 2008, 2007, Suleiman *et al.* 2006, Schaefer *et al.* 2006). Therefore, piles made by pervious concrete have fast drainage with high bearing capacity; that is to say, PCP has the advantages of granular pile and rigid pile (Zhang *et al.* 2015). The fast drainage capacity of PCP can accelerate the dissipation of excess pore water pressure and consolidation of subsoil, and reduce the post-construction settlement of the upper construction such as road embankment. However, at present, the performances

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of PCP composite foundation were studied only by numerical simulations (Cui *et al.* 2012, Zhang *et al.* 2013, Ni 2014) and instrumented model laboratory tests (Ni 2014, Suleiman *et al.* 2014), and have not been constructed and assessed in field yet.

In addition, low-liquid limit alluvial silt is widespread throughout the world, especially in large river basins such as the Mississippi in United States (Wang and Ronaldo Luna 2012) and the Yellow River in China (Cui *et al.* 2014). It has unique characteristics of low-liquid limit and plasticity index, small cohesion, low strength, intensive capillary action and poor gradation and water stability, and is of liquefiable soil. The silt is easy to liquefy (Zhang *et al.* 2017) so that the silt soil shows large settlement under dynamic load.

In this study, PCPs were installed in field and by a series of in situ tests, the performances of PCP composite foundation in alluvial silt soil were assessed and compared with composite foundations of GC and SCMP.

2. Installation of piles

2.1. Description of site

The test site is the construction site of highway between Jinan and Dongying, which is located in the Yellow River delta alluvial plain. The deposits mainly consisted of silt, silty clay and silty sand, as shown in Table 1. The underground water level is 2.7 m.

2.2. Materials of piles

The materials used for PCP casting include single-sized aggregates between 5 and 10 mm, 42.5 slag Poland cement and water reducer. Physical properties of aggregate and cement are presented in Tables 2 and 3, respectively. The water reducer is the naphthalene series water reducer, as shown in Table 4. The mixing proportion is shown in Table 5.

The mixing procedure of pervious concrete is shown in Table 6. During the mixing, aggregates, cement and 20% of total water should be added firstly and mixed for 30 s. Then, additives and the rest of water were added to the mixer and mixed for 1 min.

According to the *Standard for test method of mechanical properties of ordinary concrete* (GB50081-2002), 21 cubic pervious concrete samples were prepared. The average 28 days compressive strength of these samples was 20.7 MPa and met the design requirements of strength (Wang 2013).

2.3. Pile installation method

The vibrating-sinking tube method is used to install PCP, as shown in Figure 1. Piles should be installed at interval (double-pile spacing) to reduce negative effects induced by adjacent piles installation.

In the installing process of PCP, when the tube tip attains to the designed depth, the calculated volume of pervious concrete was poured into the tube by feeding inlet. Starting the motor, the tube should be kept vibrating for 10 s. And then the tube is gradually withdrawn with continuous vibration. The withdrawing speed is controlled between 2.2 and 2.5 m/min. If there is sludge discovered in the process of withdrawing, the withdrawing speed need proper decrease.

To compare with PCP, GC, SCMP and gravel-pervious concrete composite pile (GPCCP) were also installed in the construction site. The so-called GPCCP is the connection of PCP and GC. For GPCCP in this work, the length proportion of PCP and GC is 7:3, as shown in Figure 2. Setting the GC as the lower part of GPCCP is to enhance the confining pressure of surrounding soil on GC and preventing its expansion failure in shallow deposit. Compared to the cost of PCP, the cost of GPCCP is lower.

All piles have 50-cm diameter and 10-m length. GC is also installed using the method of vibrating-sinking tube. The cement used for SCMP is 42.5 slag Poland cement.

The PCP cores were cored 28 days after installation, as shown in Figure 3. It can be seen that the pores on the sample surface are evenly distributed. Seven core samples were randomly selected from these cores to test compressive strengths and permeabilities. The test results (Table 7) show that the properties of these pile cores are similar except number 3 pile core. Figure 4 shows compressive

Table 1. Physical properties of soil.

Soil	Depth (m)	Thickness (m)	Water content (%)	Unit weight (kN/m^3)	Void ratio	Liquid limit (%)	Plastic limit (%)	Compression coefficient (MPa^{-1})	Compression modulus (MPa)
Plain fill	0.6	0.6	–	–	–	–	–	–	–
Silt	5.30	4.70	25.9	18.5	0.809	27.7	18.3	0.23	7.86
Silty clay	6.50	1.20	37.3	18.1	1.044	42.9	26.6	0.62	3.51
Silt	10.20	3.70	28.9	19.8	0.678	29.6	18.7	0.26	8.32
Silty clay	11.50	1.30	38.1	18.2	1.029	43.7	26.3	0.52	3.90
Silty sand	13.60	2.10	–	–	–	–	–	–	–
Silt	21.20	7.60	19.7	20.4	0.556	24.5	16.8	0.18	8.90
Silty clay	24.90	3.70	33.0	19.2	0.846	36.3	22.7	0.42	4.47
Silty sand	30.00	5.10	–	–	–	–	–	–	–

Table 2. Physical properties of aggregates in PCP.

Diameter (mm)	Apparent density (g/cm^3)	Stacking density (g/cm^3)	Porosity (%)	Crushed value (%)	Silt content (%)
5–10	2.605	1.616	38.26	8.8	0.4

Table 3. Properties of cement.

		Setting time (min)		Flexural strength (MPa)		Compressive strength (MPa)	
Density (g/cm^3)	0.08-mm sieve (%)	Initial setting	Final setting	3 days	28 days	3 days	28 days
2.98	3.7	150	280	4.3	8.6	23.1	52.2

Table 4. Properties of water reducer.

Appearant feature	Solid content (%)	pH value	Water reducing rate (%)	Density (g/cm^3)
Claybank powder	94	8 ~ 10	>25	1.63 ± 0.02

Table 5. Mixing proportion of pervious concrete.

Cement (kg/m^3)	Water (kg/m^3)	Aggregate (kg/m^3)	Water reducer (kg/m^3)	Coagulants (kg/m^3)	Addictives (kg/m^3)
325	123	1585	3.9	0.2	3.9

Table 6. Mixing procedure of pervious concrete.

	Mixing procedure
Step 1	Add aggregate and 20% of water to mixer.
Step 2	Mix for 30 s.
Step 3	Add addictives and rest of water to mixer.
Step 4	Mix for 1 min.

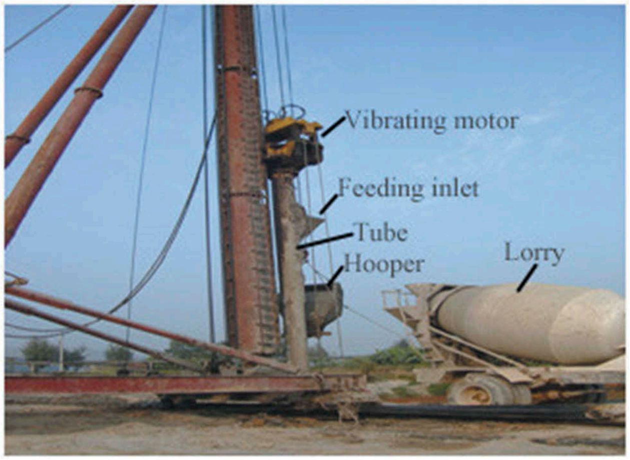

Figure 1. Installation facility of PCP.

strength–porosity curves and compressive strength–permeability curves. With the increase of compressive strength of PCP, the porosity and permeability decrease.

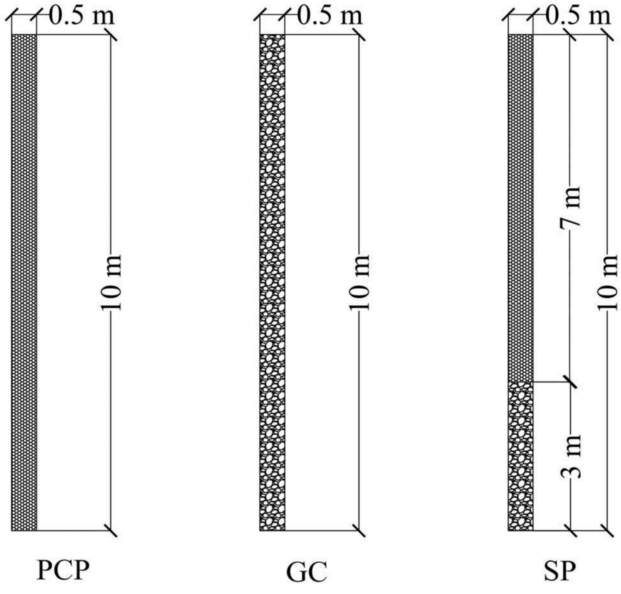

Figure 2. Diagram of pile samples.

Figure 3. Core samples of PCP.

Table 7. Tested properties of PCP cores.

Pile number	Porosity (%)	Permeability (mm/s^2)	28 Days compressive strength (MPa)
1	15.63	3.2	18.5
2	14.65	2.81	19.8
3	21.87	6.85	14.2
4	13.35	2.35	21.9
5	16.62	3.46	17.8
6	12.58	2.11	23.4
7	15.24	3.04	19.1
Average value	15.70	3.40	19.24
Standard deviation	3.04	1.47	2.74

2.4. *Evaluation of soil around piles*

The standard penetration tests (SPTs) were performed for the soil around piles. The test results are shown in Table 8. Compared to the natural

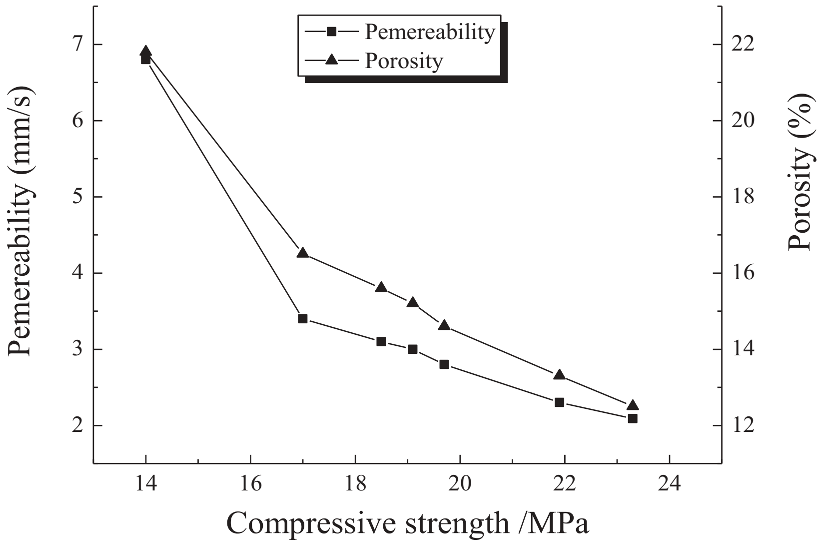

Figure 4. Compressive strength–porosity and strength–permeability curves.

Table 8. Results of SPT.

Depth (m)	SPT Numbers Natural ground	PCP composite foundation	GC composite foundation	SCMP composite foundation
2	7	9	9	8
4	4	8	7	6
6	6	11	13	7
8	8	18	9	8
10	11	20	8	7

ground and SCMP composite foundation, the SPT numbers obviously increase for PCP composite foundation. This indicates the method of vibrating-sinking tube can significantly improve the bearing capacity of soil around piles.

2.5. *Capacities of composite foundations*

For different composite foundations, tests on the bearing capacity were performed according to the *Technical code for ground treatment of buildings* (JGJ79-2012). Figure 5 shows the load–settlement curves. The characteristic value of bearing capability for all foundations is determined by the specified s/d (s is the settlement; d is the diameter of bearing plate, d = 1200 mm for PCP, GC and GPCCP, and d = 1600 mm for SCMP). In *Technical code for ground treatment of buildings* (JGJ79-2012), the specified s/d is 0.01 for PCP, GC and GPCCP, and 0.006 for SCMP.

The tested bearing capacity characteristic values of PCP, GPCCP, GC and SCMP are 310, 260, 100 and 160 kPa, respectively. This indicates that PCP can improve the bearing capability of ground more significantly than other piles.

3. Evaluation of PCP composite foundation under seismic load

3.1. *Test case*

Dynamic compaction was performed in this work to study the responses of composite foundation under dynamic load. The tamper has 2-m diameter and 10 tons weight, and the height of drop is 10 m. Three rows of pile were arranged for each type of foundations, as shown in Figure 6. Two kinds of distances were designed between the tamping points and the second-row piles: the distance of 4 m is used to simulate strong vibration and the distance of 8 m is used to simulate weak vibration, as shown in Figure 6. The two acceleration sensors are used to test the horizontal acceleration of pile head and soil surface. The dynamic pore pressure sensor is used to test the excess pore water pressure in soil at the depth of 6 m. Every tamping point was tamped for four times.

3.2. *Results and analysis*

3.2.1. *Weak vibration*

Figures 7 and 8 show the time histories curves of horizontal acceleration for the distance of 8 m between the tamping point and the second-row piles. Among PCP, SCMP and GC composite foundations, the accelerations of pile head and soil surface are least for PCP composite foundation and largest for SCMP composite foundation. This indicates that PCPs have better anti-seismic abilities. Additionally, with the increasing of tamping numbers, the acceleration firstly increases and then decreases after the second tamping because of the liquefaction of soil.

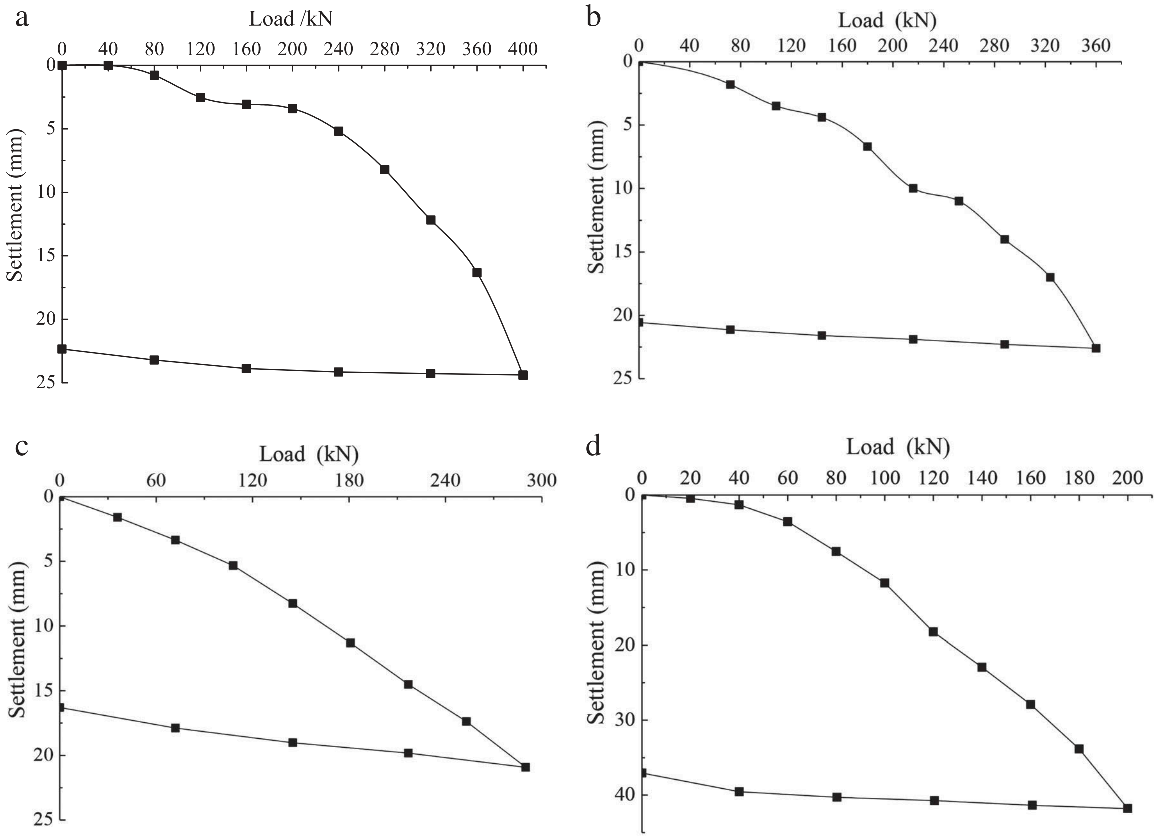

Figure 5. Load–settlement curves in bearing capacity test: (a) PCP composite foundation; (b) GPCCP composite foundation; (c) SCMP composite foundation; (d) GC composite foundation.

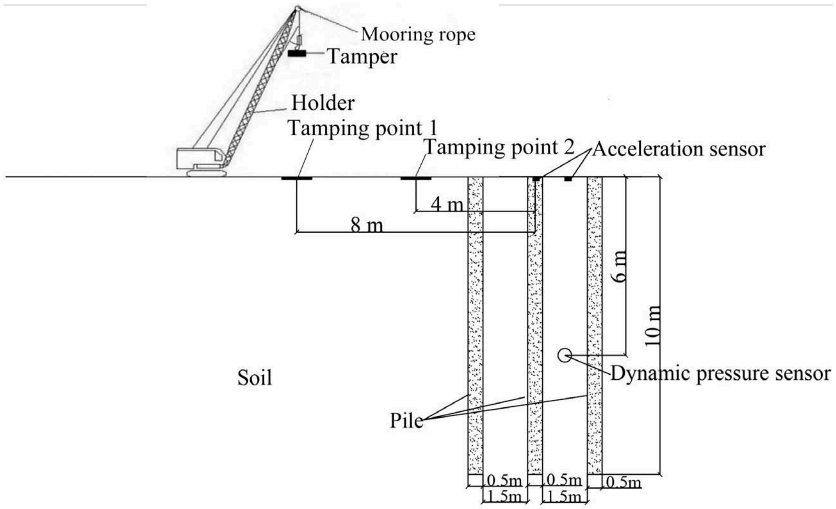

Figure 6. Layout diagram of piles and tamping points.

Figure 9 shows the time histories curves of excess pore water pressure at the depth of 6 m with the weak vibration. The excess pore water pressure in PCP composite foundation is least and that of SCMP composite foundation is largest, which corresponded to the numerical results of Cui *et al.* (2012). This indicates PCPs can efficiently mitigate the liquefaction of soil. This is because the strength and stiffness of PCP are high, and effectively prevent the volumetric deformation of soil and development of pore water pressure. Another reason is that the

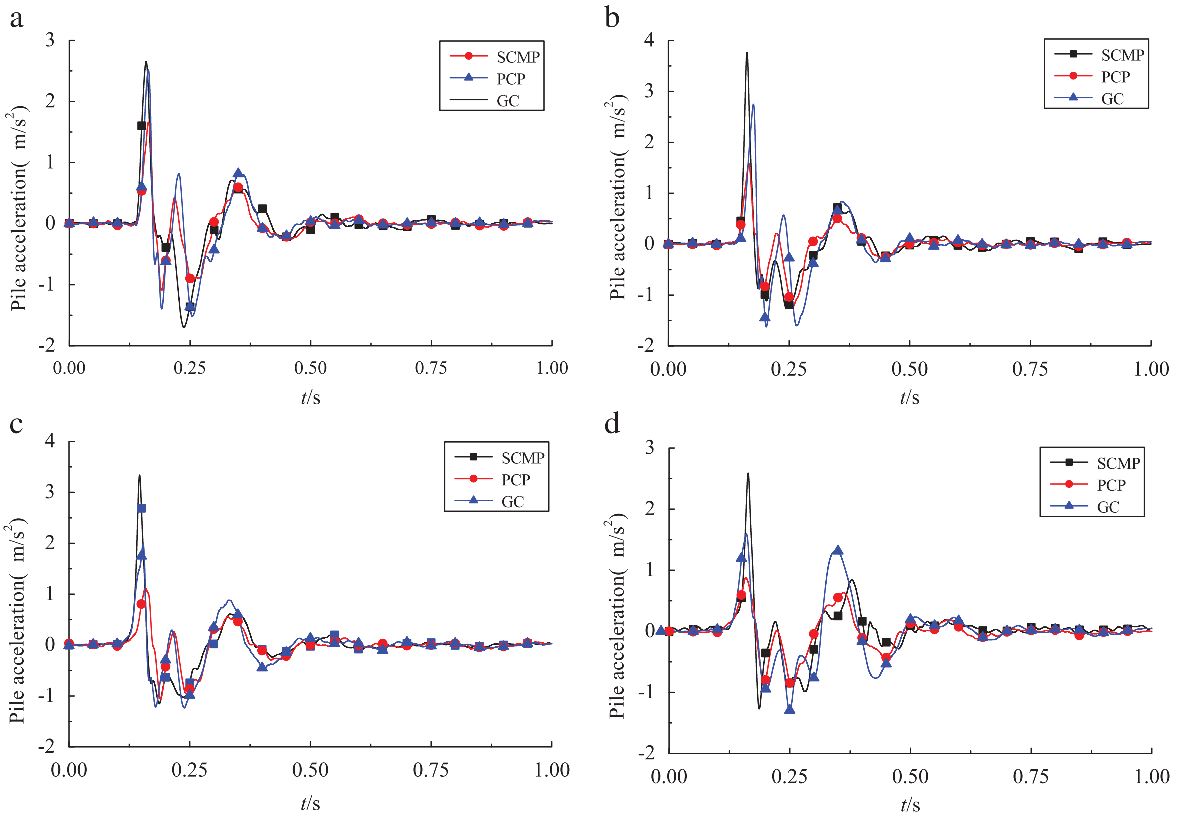

Figure 7. Time histories curves of pile head acceleration at the distance of 8 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

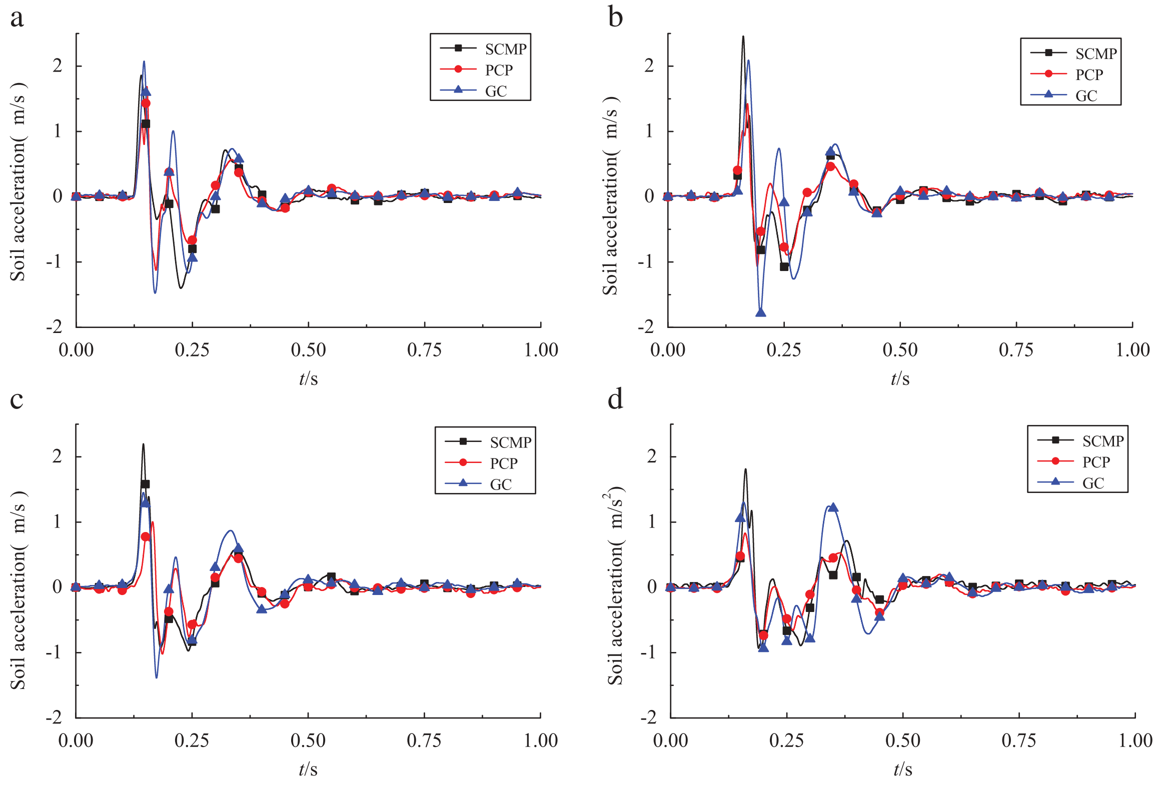

Figure 8. Time histories curves of soil acceleration at the distance of 8 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

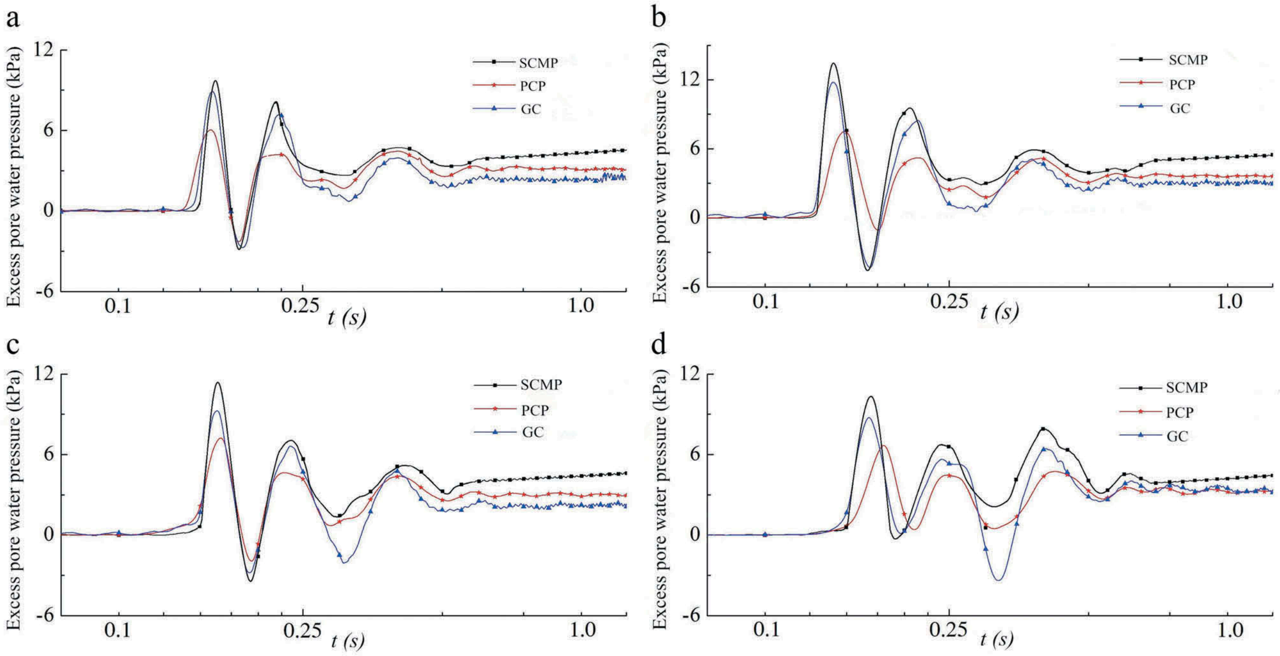

Figure 9. Time histories curves of excess pore water pressure at the distance of 8 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

porosity of PCP is large, which is beneficial to the dissipation of excess pore water pressure.

3.2.2. Strong vibration

According to the *Chinese seismic intensity scale* (GB/T 17742–2008), in strong vibration tests, the seismic intensities were IX-X for PCP and GC composite foundations, and X-XI for SCMP composite foundation. Figures 10 and 11 show time histories curves of horizontal acceleration at the distance of 4 m. Compared to the acceleration at the distance of 8 m in Figures 7 and 8, the accelerations at the distance of 4 m significantly increase. The horizontal accelerations of pile head and soil surface are least for PCP composite foundation and those are largest for SCMP composite foundation. This is similar to the response curves shown in Figures 7 and 8.

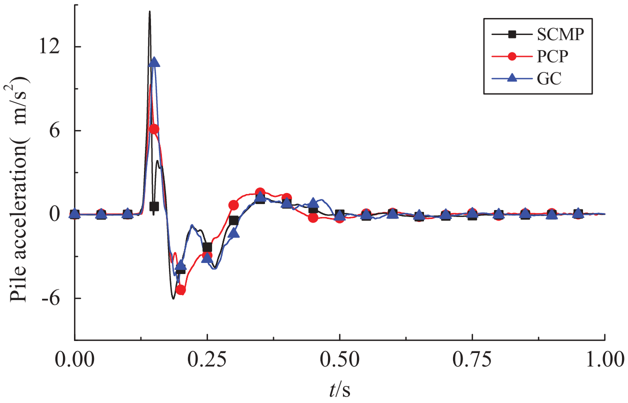

Figure 10. Time histories curves of pile head acceleration at the distance of 4 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

Figure 12 shows the time histories curves of excess pore water pressure at the depth of 6 m with strong vibration. In Figure 12, the excess pore water pressure in PCP composite foundation is similar to that in GC composite foundation. Compared to the results in Figure 9, where weak vibration caused less excess pore water pressure in PCP composite foundation than GCs composite foundation, the gap of the excess pore water pressure between PCP and GCs composite foundation narrows. This is because the excess pore water pressure in PCP composite foundation rapidly increases under the strong vibration, while GCs with large porosity can accelerate the dissipation of excess pore water pressure.

In general, PCPs can significantly reduce the horizontal acceleration and mitigate the excess pore water pressure.

4. Evaluation of PCP composite foundation under embankment load

The road embankments with 8-m height were constructed on different composite foundation (natural ground, PCP, GPCCP, GC and SCMP), and pore water pressure sensors were installed 5- and 13-m underground surface, respectively, as shown in Figure 13. Pile spacing is 1.5 m, the pile length is 10 m and the replacement ratio of the pile is 0.101.

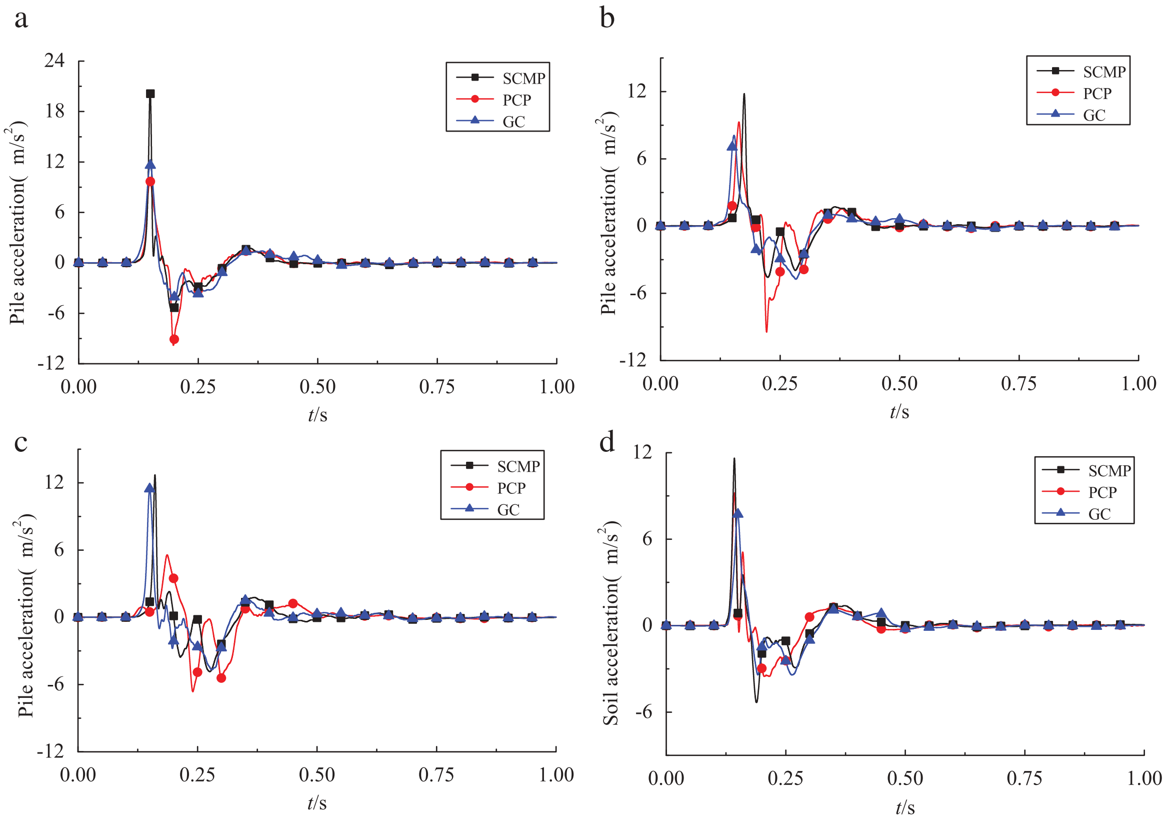

Figure 11. Time histories curves of soil acceleration at the distance of 4 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

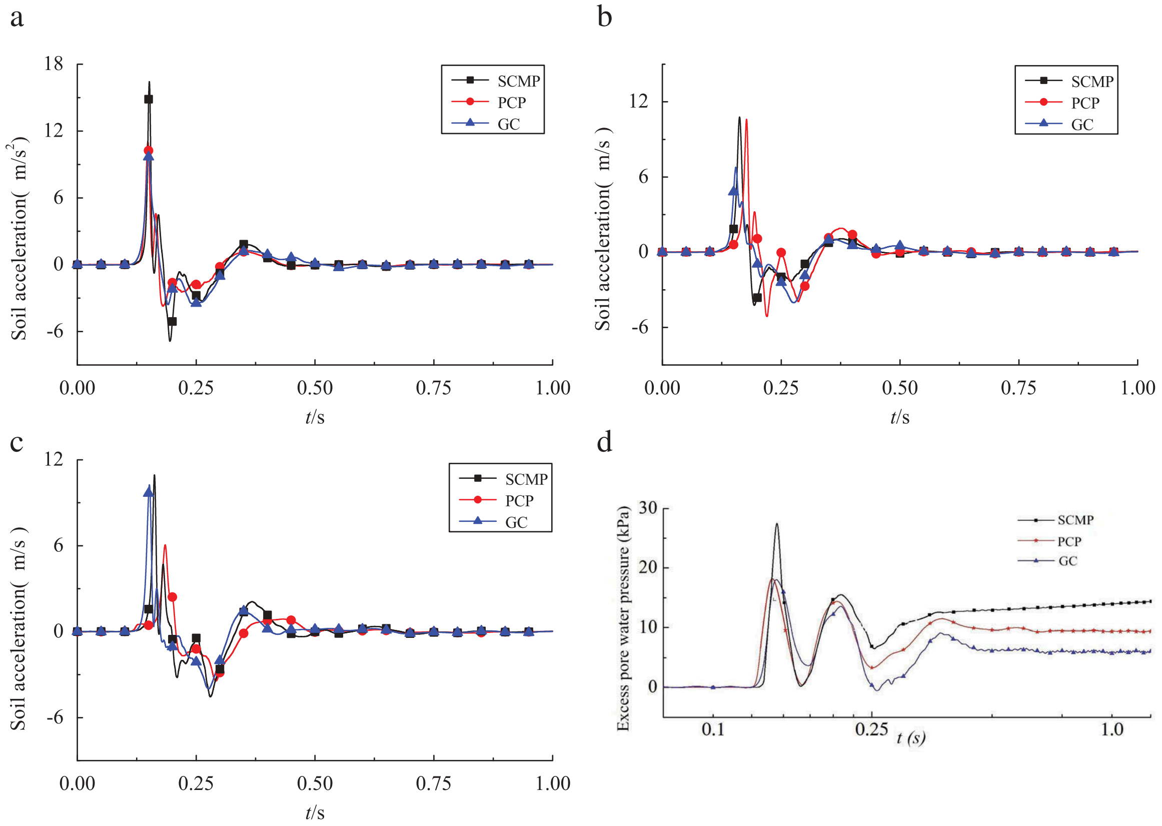

Figure 12. Time histories curves of excess pore water pressure at the distance of 4 m: (a) first tamping; (b) second tamping; (c) third tamping; (d) fourth tamping.

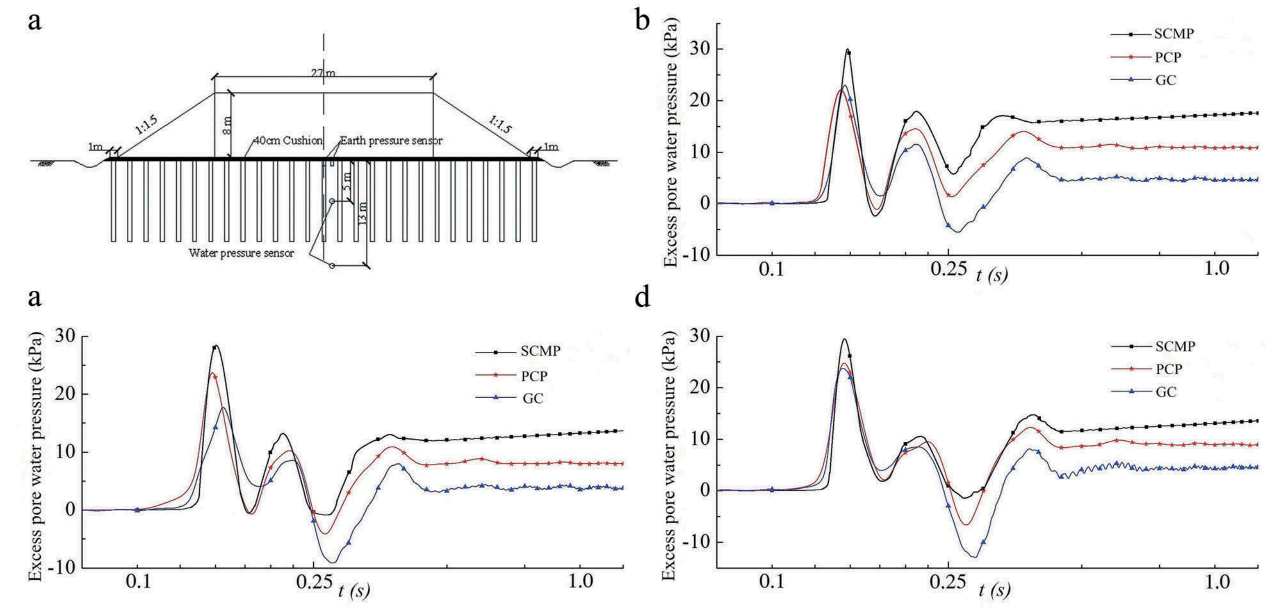

Figure 13. Diagram of subgrade cross-section.

Geogrid reinforced sand cushion is of 0.4-m thickness. The excess pore water pressures were tested during the construction of road embankment.

4.1. Pile-soil stress ratio

Earth pressure sensors were set up on the ground surface to test the pile-soil stress ratio. Figure 14 shows the vibration curves of pile-soil stress ratio with embankment height. With the increasing embankment height, the pile-soil stress ratio gradually increases for the SCMP, PCP and GPCCP composite foundation. Moreover, the pile-soil stress ratio of PCP composite foundation is largest because PCP has the highest stiffness and strength. But for the GC composite foundation, the pile-soil stress ratio gradually increases with the embankment height when the height is less than 4 m and then gradually decreases when the height is more than 4 m. This is because the strength of GC is lower than those of the other piles. When the load is up to a certain value, the bearing capacity of GC cannot support the loads and then more loads will be supported by the soil.

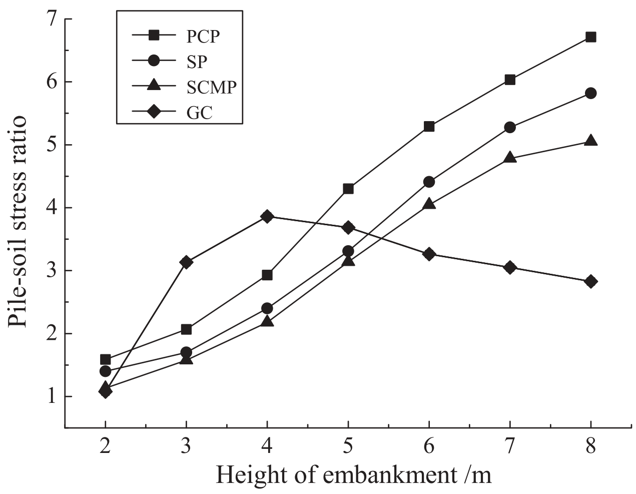

Figure 14. Vibration curves of pile-soil stress ratio with the height of embankment.

4.2. Drainage properties of composite foundations

Figure 15 shows the vibration curves of excess pore water pressure with time. The excess pore water pressure of natural ground is the largest. The excess pore water pressure in PCP composite foundations and GPCCP composite foundations is close to that in GC composite foundations. Compared to the natural ground and SCMP composite foundation, the excess pore water pressure in PCP composite foundation and GPCCP composite foundation significantly decreases, especially in the substratum shown in Figure 7(b). This indicates that PCP can increase the time rate of consolidation in the substratum, which is consistent with the results presented by Zhang *et al.* (2013).

5. Conclusions

In order to evaluate the performances of PCP as a technology of ground treatment, PCPs were installed and a series of in situ tests were carried out. Some conclusions were drawn:

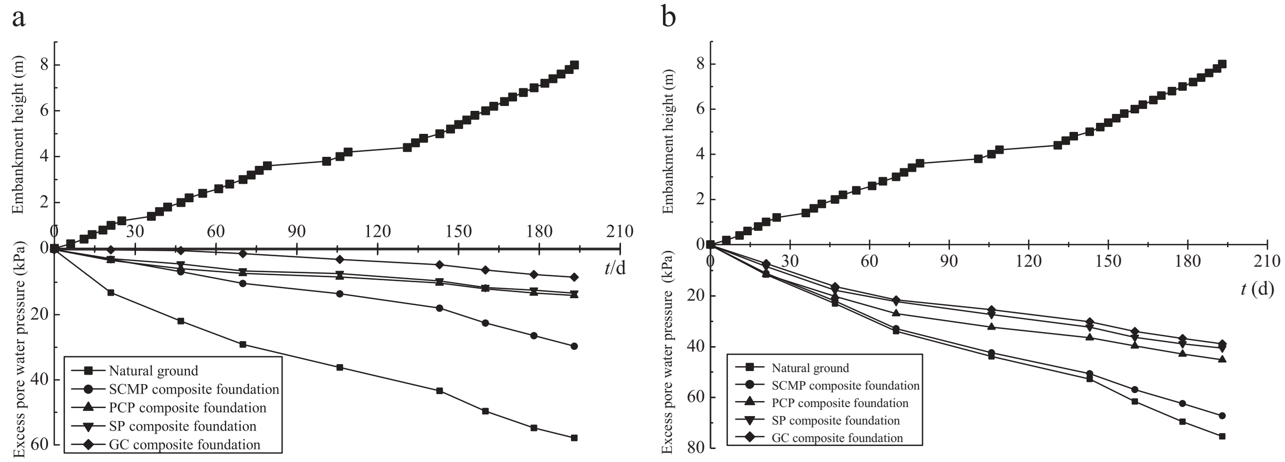

Figure 15. Vibration curves of excess pore water pressure with time: (a) depth of 5 m; (b) depth of 13 m.

(1) Vibrating-sinking tube method is suitable for the installation of PCP. The withdrawing speed of tube should be controlled between 2.2 and 2.5 m/min.

(2) Bearing capacity of PCP composite foundation is significantly larger than those of GC and SCMP composite foundations. This is because pervious concrete can provide higher strength and the vibrating-sinking tube method improves the strength of soil around piles. Additionally, the installation of PCP increases the time rate of consolidation of ground. Compared with GC and SCMP, PCP can significantly increase the pile-soil stress ratio.

(3) PCP can significantly reduce the ground surface acceleration and excess pore water pressure in ground induced by vibration. So the liquefaction of ground and the fracture of superstructure can be effectively mitigated.

Disclosure statement

No potential conflict of interest was reported by the authors.

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