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Settlement behavior and controlling effectiveness of two types of rigid pile structure embankments in high-speed railways

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Abstract. In this study, 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 post-construction 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 pile-geogrid 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. Furthermore, the time effectiveness of negative skin friction of piles and the action of pile-cap setting are also investigated. The relevant measures for improving the bearing capacity and two parts of transition zone forms as positive control mean have been suggested.

Keywords: high-speed railways; embankment engineering; rigid pile structure embankment (RPSE); centrifuge model test; settlement controlling; collapsible loess

1. Introduction

The excessive settlement of embankments causes the irregularity of railway track, which can endanger severely the passenger safety in high-speed trains. The control of foundation settlement under strict criterion is an essential problem. Therefore, in the actual projects we have no way to replace the embankments with bridges in most instances due to the stricter settlement control standards. These methods are forced-choice, and are also more costly (Wang *et al*. 2013, Liu *et al*. 2007, Jiang *et al*. 2014, Tafreshi and Norouzi 2015). Rigid pile foundations as a new ground reinforcing structures are increasingly used to construct highways and construction engineering on collapsible loess that have previously been deemed unsuitable. The main advantages are rapid construction, low costs, small total and differential settlement compared to the traditional foundation improvement methods such as preloading, soil modification or grouting injection.

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The embankments of high-speed railways are required to have high strength, stiffness, excellent stability and durability. The post-construction settlements of embankments, which are mainly caused by the foundations, play a major role in the embankments design and safe-operation of high-speed railways (Wang *et al*. 2013, 2015). Because the requirement of post-construction settlements of embankments in high-speed railways are generally much stricter than that in construction engineering and highway engineering (Marchi *et al*. 2006, British Standard 8006 2010, Nordic Geotechnical Society 2002, Railway Technology Research Institute 2001 and Ministry of Railways of People's Republic of China 2009, Preteseille *et al*. 2014), various measures of foundation improvement such as rigid pile foundations are adopted to control the settlements of weak foundations (Abushara *et al*. 2009, Chen *et al*. 2010, Wang *et al*. 2013 and Jiang *et al*. 2014), including the applications in collapsible loess area. Even though rigid pile foundations as a rapid construction technique, have been increasingly adopted to improve the bearing capacity and reduce the total and differential settlements in construction engineering with some available design methods and guidelines (Liu *et al*. 2007, Wachman *et al*. 2010 and Wang *et al*. 2013), their applications in high-speed railways are limited owing to the following reasons. Firstly, the dead load dominates the performance of building foundations in construction engineering, hence the pile-soil stress ratio is almost a constant in post-construction stage. For railway embankments, especially for low embankments (height < 3 m) which are subjected to dynamic load, significant change in pile-soil stress ratio may occur in the post-construction stage. Secondly, the building foundations in construction engineering usually have rigid cushions and the pile-soil stress ratio in the foundations can be easily determined. In contrast, for the flexible foundations of high-speed railways, the pile-soil stress ratio is affected by many factors and cannot be easily determined. Finally, high-speed railways have much higher standards for the post-construction settlement control, settlement rate and differential settlement than those for building foundations. Currently, the design of rigid pile structure embankments (RPSE) in high-speed railways mainly follows foundation design code in construction engineering. Studies concerning the action mechanism and settlement control of embankments supported by rigid piles in high-speed railways are rare in the literature, particularly for those in collapsible loess. Therefore, it is necessary to carry out the research on embankments supported by rigid piles in collapsible loess, combined with the characteristics of high-speed railways.

The collapsible loess foundation which is an unsaturated and under-consolidated soil with large porosity and low dry density is a typical weak foundation. The most prominent feature of the collapsible loess is that the additional settlement can be intensified by water, self-weight of soil and additional stress. The settlements in collapsible loess have always been focused by geotechnical engineering for a long time (Reznik 2007, Kruse *et al*. 2007 and Yuan and Wang 2009). The centrifuge model test is one of the most reliable physical test methods with rational similarity in the research of geotechnical engineering. Owing to the proper simulation of the prototype stress levels, significant reduction in soil consolidation duration and repeatability of test results, centrifuge modelling technique has gained wide acceptance as a versatile tool to investigate geotechnical problems (Hudacsek *et al*. 2009, McCullough *et al*. 2007, Aslam 2008, Peiris *et al*. 2008, Hossain and Randolph 2010). At present, few researches on the centrifuge model tests of rigid pile structure embankments (RPSE) in high-speed railways have been reported in the literature. The mechanism of interaction between pile and surrounding soils, and the embankment load transfer is inadequately investigated on structure embankments and they needs much further study.

The objective of this paper is to qualitatively investigate the settlements of two types of rigid pile structure embankments (RPSE) in collapsible loess using centrifuge tests. A series of geotechnical centrifugal model tests have been performed in the present study in order to examine the effectiveness control of settlement, settlement rate and differential settlement, and understand the time effect of negative skin friction of piles and embankment load transfer in different rigid pile structure embankments which include regular concrete piles, piles caps, piles with cushion or raft, etc. The effectiveness of these methods and the influence of pile spacing on the embankment settlement were analyzed. This research provides a new method for theoretical research and engineering practice.

2. Centrifuge testing

2.1 Experimental apparatus

The centrifugal apparatus (L-30, Tongji University, China) used in these model tests has the maximum capacity of 20 g-ton, with maximum 200 g centrifugal acceleration. The effective rotating radius is 1.55 m, and inner size of model box is 415 mm × 370 mm × 230 mm.

2.2 Physical model design

The geometric ratio (scale-down ratio) of the physical models to the prototype is 1:100, with 100 g centrifugal acceleration. The soils, classified as Level IV collapsible loess according to the Chinese Code for building construction in collapsible loess regions (2004), were obtained from the third level terrace of the Yellow River in Lanzhou, China. Table 1 shows the main properties of the soils used in centrifuge tests. The block of undisturbed loess samples were manually excavated from borrow pit, and then it was sealed after packing and sent to the laboratory. Both undisturbed and remolded collapsible loess were used to investigate the collapsibility and settlement under overburden pressure induced by wetting in our previous research (Wang *et al*. 2013, 2015). The results showed that remolded loess can reasonably reproduce the process of wetting-induced collapse of undisturbed loess, given that the physical index properties (such as the moisture content and density) are appropriately controlled. The plastic limited moisture of remolded collapsible loess used in tests is 17%. The test method for determining cohesion and friction angle is triaxial test. In these centrifugal model tests, the index properties of the remolded loess were controlled strictly to reproduce those of the undisturbed loess.

Table 1 Main controlling indexes of physical model

Soil	Density ρ (kg/m^3)	Void ratio e	Water content ω (%)	Degree of saturation S_r (%)	Cohesion c (kPa)	Internal friction angle ϕ (°)
Undisturbed collapsible loess	1530	0.91	7.7	23.0	26.5	36.3
Remolded collapsible loess	1600	1.02	19.0	50.7	16.6	24.3
Embankment filling	2080	0.55	19.0	93.5	35.1	30.3

When modeling the performance of rigid pile structure embankments (RPSE) shown in Fig. 1, the centrifuge models use aluminium tubes (elastic modulus is 7.1×10^4 MPa) as the same material of the prototype rigid concrete pile (elastic modulus is 3.5×10^4 MPa). The length of the prototype pile is 16 m (Prototype value, similarly hereinafter), the external diameter is 40 cm, and the wall thickness of pile is 10 cm. The piles were driven 1 m into the bearing stratum (2 m thick pebble bed). The materials of gravel cushion and reinforced concrete slab are sands (the diameter of particles (gravel size) is between 2.5 cm and 4 cm) and aluminum alloy plates respectively. Fig. 1 shows the prototype embankment, loads of trains and track structure with respect to the design code of high-speed railway (Ministry of Railways of People's Republic of China 2009).

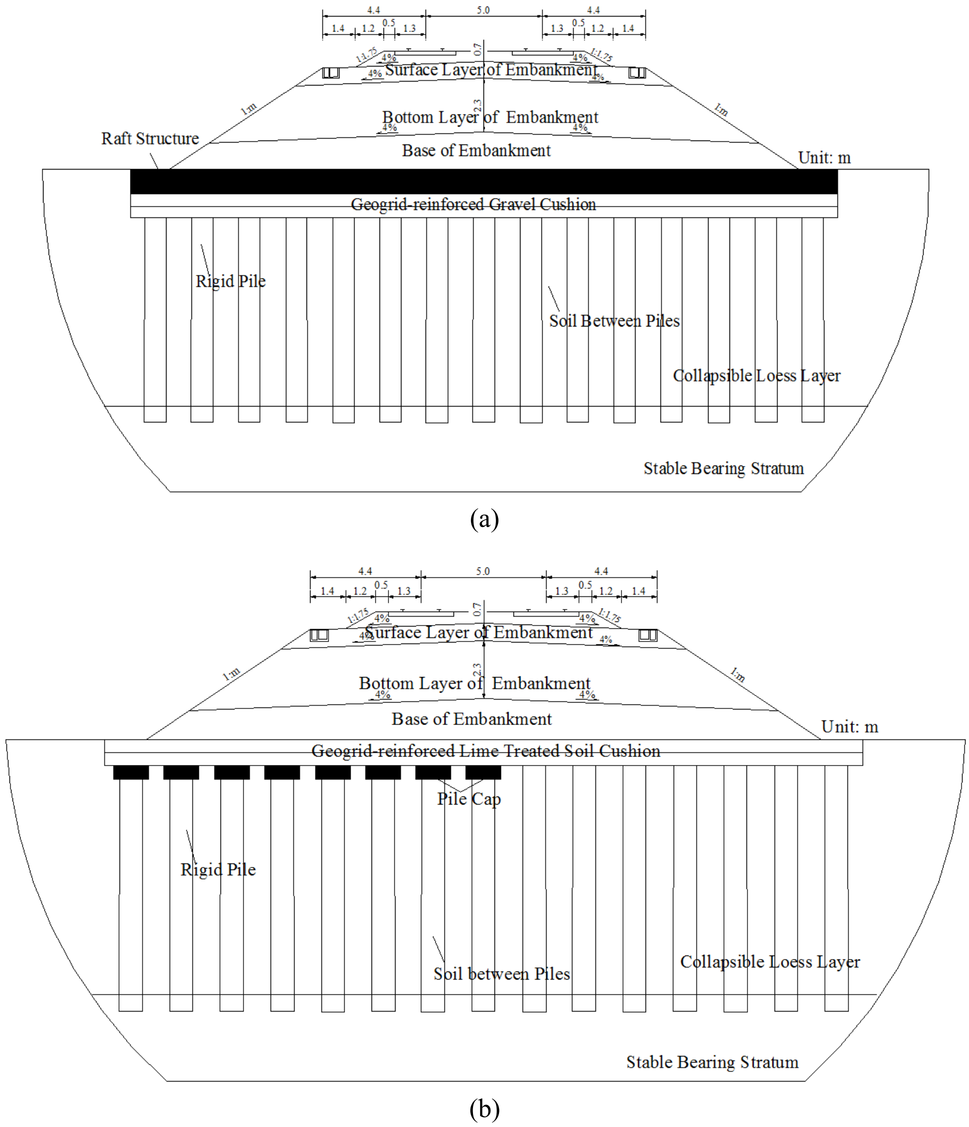


Fig. 1 Typical cross section of rigid pile structure embankments (RPSE): (a) Pile-raft structure embankments (PRSE); (b) Pile-geogrid structure embankments (PGSE)

2.3 Testing program

The following two types of tests were performed: (a) central longitudinal section settlement test on pile-raft structure embankments (PRSE); (b) central longitudinal section settlement test on pile-geogrid structure embankments (PGSE), using the test model in Fig. 2. In Tests (a) and (b), the height of both railway embankments was 6.0 m. The thickness of remolded soils layer was 15 m

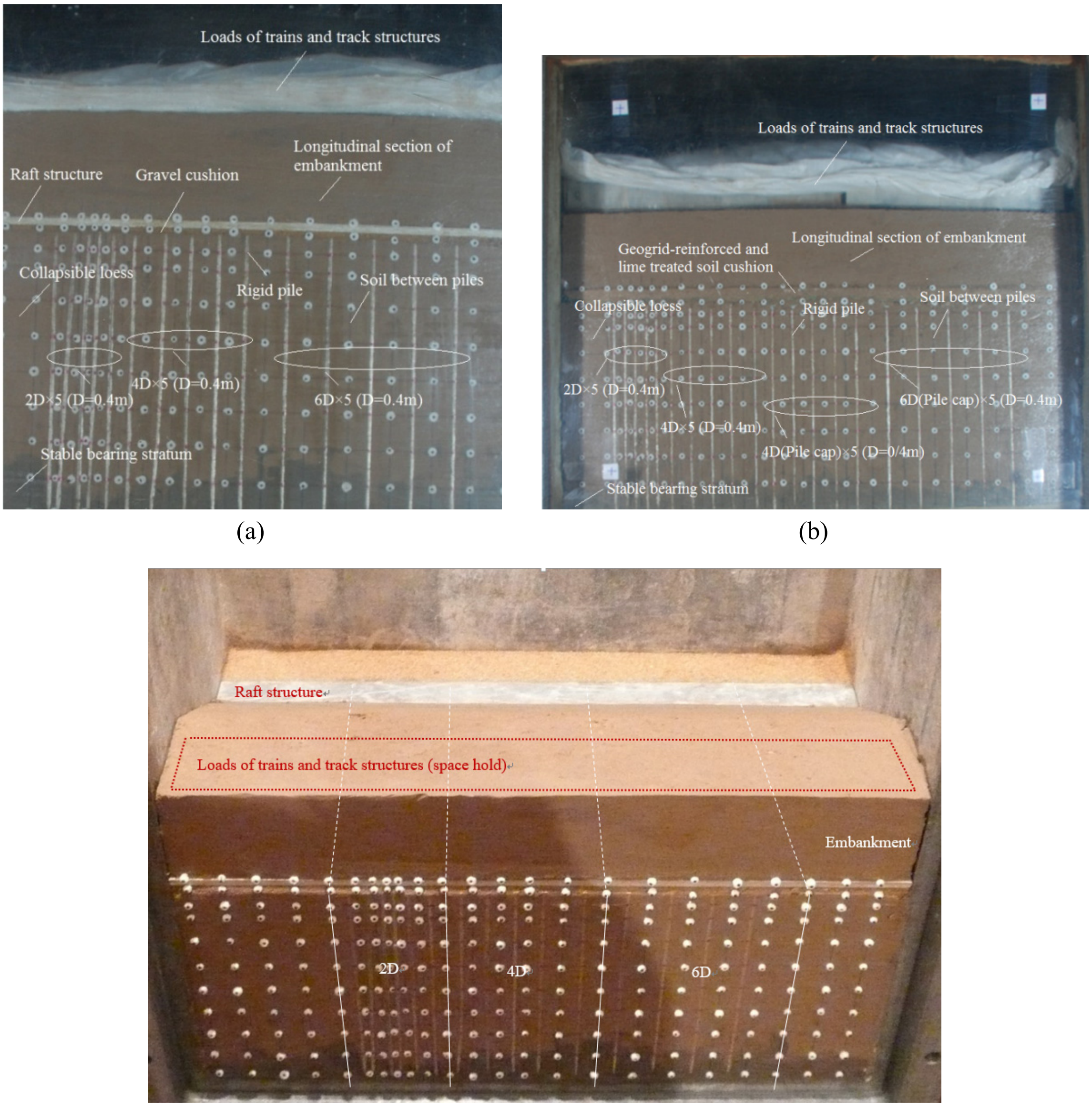


Fig. 2 Test models of rigid pile structure embankments (RPSE: (a) Pile-raft structure embankments (PRSE); (b) Pile-geogrid structure embankments (PGSE); (c) Physical model of PRSE; (d) Physical model of PGSE

(d)

Fig. 2 Continued

Table 2 Summary of parameters and conditions of testing models

Tests (a) & (b)	Thickness of embankment (m)	Thickness of soil layer (m)	Size of equivalent soil column c (m^2)	Pile spacing (D = 0.4 m)	Diameter of pile (m)	Length of pile (m)	Thickness of bearing stratum (m)
	6.0	15.0	3.4×3.0	2D, 4D, 6D	0.4	16	2.0
Test (a)	Thickness of reinforced concrete raft (m)		Diameter of particles (cm)			Thickness of gravel cushion (cm)	
	0.45		2.5-4.0			30	
Test (b)	Thickness of lime-soil cushion (m)		Size of sile cap (m^3)			Geogrid aperture size (mm)	
	1.0		1.0×1.0×0.3			21.8	

on the top of a bearing stratum. The loads of trains and track structures were simulated by an equivalent soil column (3.0 m high and 3.4 m wide with the unit weight of 18.0 kN/m^3) according to the design code of high-speed railways (Ministry of Railways of People's Republic of China 2009). The pile spacing (l) were selected as s = 2D, 4D and 6D (D is the pile diameter). In PRSE (see test (a)), a 30 cm thick gravel cushion with a layer of geogrid was constructed on top of the piles, and polyester geogrid with the fiber spacing of 21.8 mm was placed in the middle height of the gravel cushion. For the raft structure, a 45 cm thick reinforced concrete slab was constructed on the top of gravel cushion. In PGSE (see test (b)), a 1 m thick lime-soil cushion with a layer of geogrid (same as test (a)) was constructed on top of the foundations. Pile groups of various pile spacing were installed in different regions of the physical models in order to reduce the number of centrifuge tests shown in Fig. 2 for tests (a) and (b). The post-construction settlement during 200 and 1980 days was monitored. Table 2 summarizes the details of each physical model.

2.4 Test procedures and deformation determination

In Tests (a) and (b), the process of embankment construction was simulated by adjusting the centrifugal acceleration. The embankment was constructed by multiple stages. In each stage, the height of embankment was increased by 1.2 m and the next stage was started 1 month later to stabilize the settlement of the foundation soils (Yu *et al*. 2005, Ministry of Railways of People's Republic of China 2009, Aslam 2008, Chen *et al*. 2010 and Yapage *et al*. 2012). The deformation of foundation soils was observed at every stage. After the completion of the embankment (when the acceleration reached 100 g in centrifugal model tests), the deformation of the system was monitored for 5 years (1980 days). The advantage of this method is convenient for making model and experiment operating, meanwhile, it may cause some value error in prototype changing process. But for experiments that main pay more attention to post-construction stage (centrifugal acceleration reach the design value), the value error is within permission. A thin layer of vaseline was applied on the inner side of the model box walls in order to reduce friction at the boundaries in the centrifuge model tests. Plastic particles were pinned along the model as the observation monuments (as shown in Figs. 1 and 2). A fixed-point high-speed camera was used to take high-resolution photos of the physical model during the flight. These photos were used to determine the observation monument displacements and the displacement field of the physical model by Digital Image Analysis (DIA). For DIA system, professional digital SLR camera (Canon EOS 5D Mark III) used in these tests with 23.3 million pixels and up to 5760 × 3840 resolution can captures a high quality photo with the function of bulb exposure of camera and hall sensor unit in centrifugal machine. Then, PIV (Particle Image Velocimetry) was used to analysis the two-dimension displacement field of model form high quality photo.

3. Test results and analysis

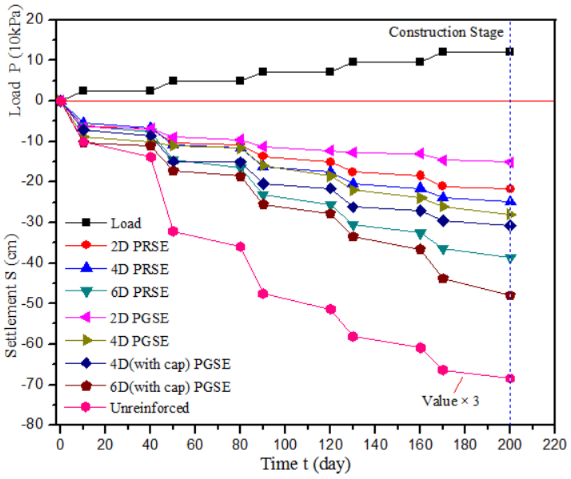
Rigid pile structure embankments (RPSE) which is a coordinated system of piles, geogrid materials, cushion (or raft plate) and soil between piles, can bear load effectively. Moreover, effective work between each unit has significant influence on controlling foundation settlements in different design parameters. In addition to the properties of the foundation soils, many factors affect the settlements of RPSE, including the length of piles, the pile spacing, the thickness and compaction of gravel cushion (or lime-soil cushion), the geogrid materials and raft plates (or pile caps) above the piles and the pile-soil interaction. This section mainly discusses the effectiveness of using two types of RPSE to reduce the settlements of embankments built on collapsible loess by comparing the results obtained from Tests (a) and (b). As indicated previously, remolded loess was used in this series of tests. The embankments settlement control criteria of ballasted track in high-speed railways during post-construction stage in China are shown in Table 3.

3.1 Settlement of rigid pile structure embankments

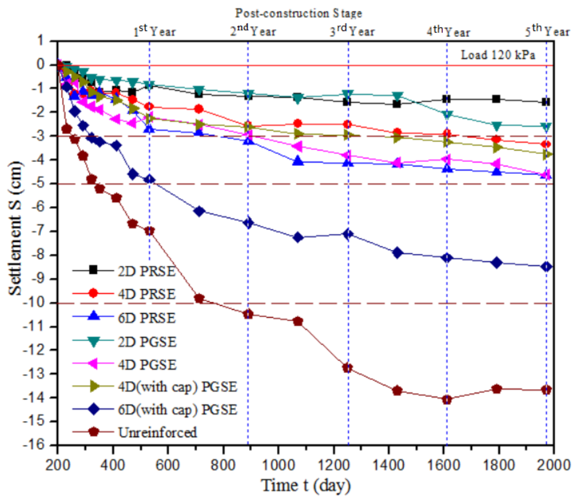
From our previous research results (Wang *et al*. 2013, 2015), for embankments built on untreated loess (which is the foundation of the embankment), the maximum total settlements and the post-construction settlements and settlement rate are both located at the top of the foundation soil and on the centerline of the embankment. Therefore, central longitudinal section tests on RPSE were used to examine the influence of pile spacing on the embankment settlements,

Table 3 Embankment settlement control criteria of ballasted track in high-speed railways during post-construction stage in China

Design speed (km/h)	Settlement in embankment zone (cm)	Settlement in bridge-embankment transition zone (cm)	Settlement rate (cm/year)	Slope ratio
250	10	5	3	1/1000
300, 350	5	3	2	1/1000



(a)



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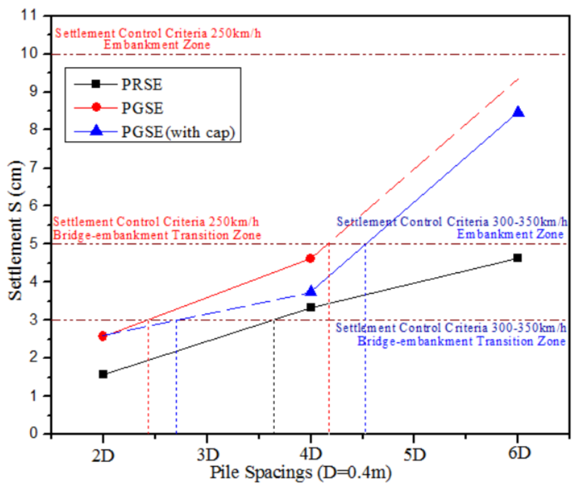


(c)

Fig. 3 Settlement of untreated foundation and rigid pile structure embankments at different pile spacing: (a) time dependent development of settlement in the construction stage; (b) time dependent development of settlement in the post-construction stage; (c) effect of settlement controlling at different pile spacing settlements rate, negative skin friction on the piles and differential settlements.

Figs. 3(a) and (b) present the time-history of foundation settlement (i.e., the settlement measured at the top of raft plate for PRSE and at the top of gravel cushion layer for PGSE) at the centerline of embankment for different pile spacing. The settlement of the centerline of embankment on untreated foundation was 205.5 cm at the end construction stage (ECS) and was 13.6 cm in post-construction stage (PCS). For PRSE, the settlements of raft plate with pile spacing of s = 2D, 4D and 6D were 21.7 cm, 24.9 cm and 38.6 cm at ECS. The settlements were 1.6 cm, 3.3 cm and 4.6 cm in PCS respectively. For PGSE, at ECS, the settlements of gravel cushion with pile spacing of s = 2D, 4D, 4D (with cap) and 6D (with cap) were 15.0 cm, 28.1 cm, 30.8 cm and 48.1cm. In PCS, the settlements were 2.6 cm, 4.6 cm, 3.8 cm and 8.5 cm respectively. One observes that piles under the embankment are installed through collapsible loess layers to transfer the embankment and traffic loads to deep and firm bearing stratum.

The test results of settlement controlling effectiveness at different pile spacing are illustrated in Fig. 3(c). According to the code requirement of post-construction settlements shown in Table 3 above, for high-speed railways of 250 km/h design speed it is appropriate to take s = 2D to 6D as pile spacing in the general case of embankment zone both of PRSE and PGSE. In the bridge-embankment transition zone, pile spacing of s = 2D to 6D can meet the requirements for controlling settlement of PRSE. Similarly, pile spacing of s = 2D to 4D of PGSE and pile spacing of s = 2D to 4.5D of PGSE (with cap) can be able to meet the requirements of settlement control. For railways design speed of 300 to 350 km/h, in the embankment zone pile spacing of s = 2D to 6D of PRSE can meet the control settlement requirements. Similarly, pile spacing of s = 2D to 4.5D of PGSE (with cap) and pile spacing of s = 2D to 4D of PGSE can be able to meet the requirements of settlement control. In the bridge-embankment transitional zone, pile spacing of s = 2D to 3.5D of PRSE can meet the settlement control requirements. Similarly, pile spacing of s = 2D to 2.5D of PGSE (with cap) and s = 2D pile spacing of PGSE can meet the settlement control requirements. The PRSE is shown to have better ability for effectiveness of settlement controlling, while the PGSE provides rapid construction as well as economic benefits. Rigid pile structure embankments (RPSE) have the ability to transfer larger amount of embankment load and surcharge to more competent material at deeper depth due to the arching effect. Consequently, the collapsible loess has little direct impact on the performance of the embankment.

3.2 Settlement rate of rigid pile structure embankments

The time-history of foundation settlement rates at the centerline of embankment for different pile spacing are presented in Figs. 4(a) and (b). The maximum settlement rate of the centerline of embankment on untreated foundation was 7.0 cm/year in PCS. For PRSE, the maximum settlement rates of raft plate with pile spacing of s = 2D, 4D and 6D were 0.8 cm/year, 1.8 cm/year and 2.7 cm/year in PCS respectively. For PGSE in PCS, the maximum settlement rates of gravel cushion with pile spacing of s = 2D, 4D, 4D (with cap) and 6D (with cap) were 0.8 cm/year, 2.7 cm/ year, 2.2 cm/ year, 4.8 cm/ year respectively. Fig. 4(c) presents the test results of effectiveness of settlement rate controlling at different pile spacing. According to the code requirement of post-construction settlement rate, as shown in Table 3 above, for 250 km/h design speed railway it is appropriate to take s = 2D to 6D of PRSE as pile spacing. Similarly, pile spacing of s = 2D to 4D of PGSE and pile spacing of l = 2D to 4.5D of PGSE (with cap) can meet the requirements of settlement rate controlling. For railway design speed of 300 to 350 km/h, pile spacing of s = 2D to 4.5D of PRSE can meet the requirements for controlling settlement rate. Similarly, pile spacing of *s* = 2D to 3.5D of PGSE (with cap) and pile spacing of *s* = 2D to 3D of PGSE can meet the requirements of settlement rate control.

Based on comprehensive analysis of settlements and settlement rates are shown in Figs. 3 and 4 mentioned above. Both the post-construction settlement and the settlement rate of untreated foundation exceed the requirements for ballasted track of high-speed railways, which imply that ground reinforcement is required to reduce the post-construction settlement and settlement rate of the embankments. Using rigid piles can substantially reduce the embankment settlement in the construction stage of embankment on collapsible loess, and the efficiency in settlement reduction is affected by pile spacing. With the increase of pile spacing, the settlement of rigid pile structure

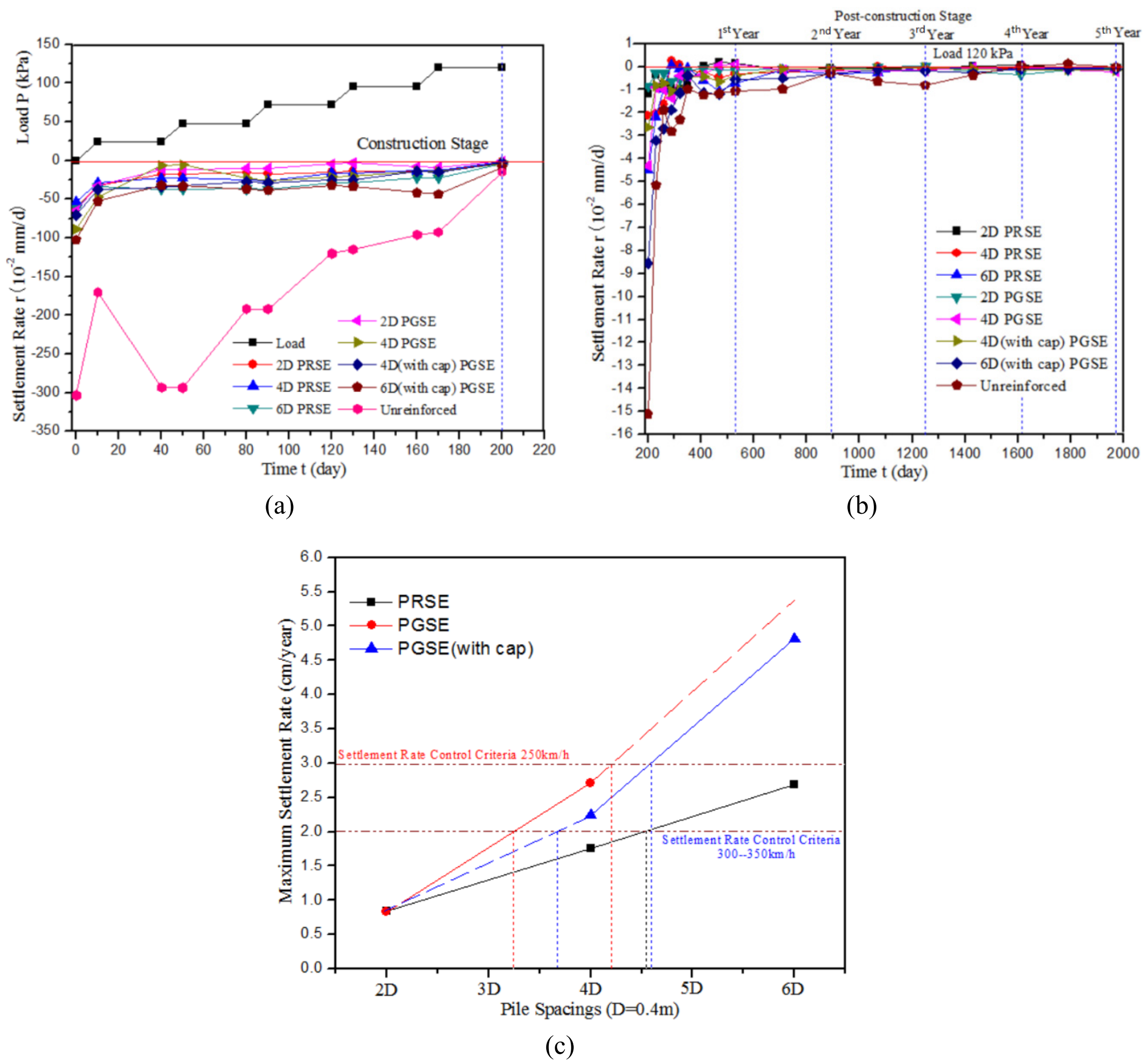


Fig. 4 Settlement rate of untreated foundation and rigid pile structure embankments at different pile spacing: (a) time dependent development of settlement rate in the construction stage; (b) time dependent development of settlement rate in the post-construction stage; (c) effect of settlement rate controlling at different pile spacing

embankments (RPSE) increases and the increment is larger. The settlement of soil between piles is faster than that of the pile and raft plate, which induces negative skin friction on the piles and tends to reduce the bearing capacity (this issue will be discussed in details in later sections). Through these tests, it can be verified that rigid pile structure embankments (RPSE) can effectively control the foundation settlement in collapsible loess, and a soil layer with high bearing capacity is suggested to be the bearing stratum at pile tip. For PGSE, pile-caps can effectively reduce the settlement and settlement rate of embankment with more loads that are transferred to the pile during PCS. Rigid pile structure embankments (RPSE) offer the reduction of the loading at collapsible loess ground by using geogrids, because the embankment load can be transferred with arching effect in the reinforced soil above the plie heads and membrane effect of geogrids.

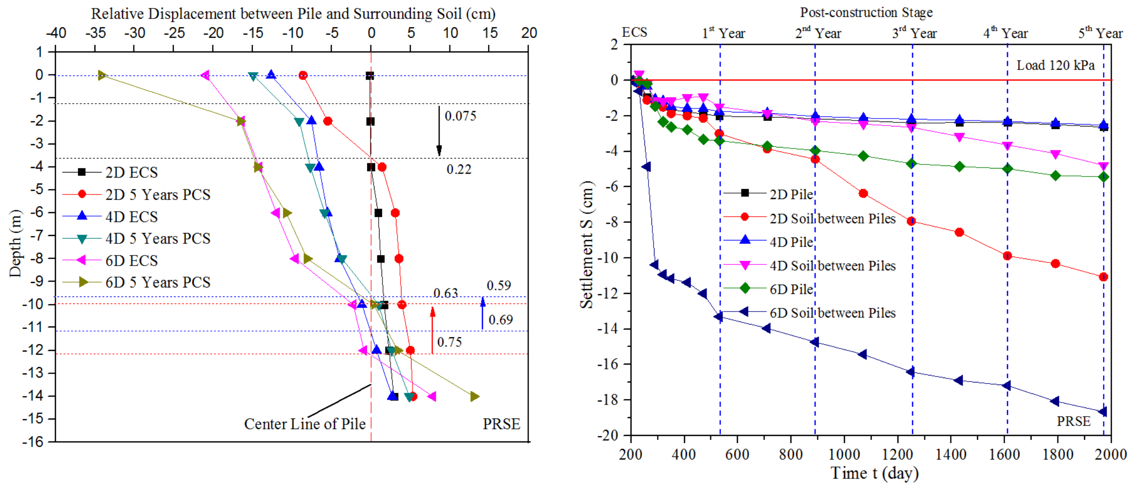
Considering the requirements of settlement and settlement rate shown in Table 3. For 250 km/h design speed railways, it is appropriate to take s = 2D to 6D as pile spacing of PRSE , s = 2D to 4D as pile spacing of PGSE and s = 2D to 4.5D as pile spacing of PGSE (with cap) both in the general case of embankment zone and in the bridge-embankment transition zone. Moreover, for railway design speed of 300 to 350 km/h, in the embankment zone pile spacing of s = 2D to 4.5D can be used to control settlement of PRSE. Similarly, pile spacing of s = 2D to 3.5D of PGSE (with cap) and pile spacing of s = 2D to 3D of PGSE can be used for settlement controlling. In the bridge-embankment transition zone, pile spacing of s = 2D to 3.5D of PRSE can be used to control settlement. The pile spacing of s = 2D to 2.5D of PGSE (with cap) and s = 2D pile spacing of PGSE can also be used for settlement controlling.

3.3 Negative skin friction of piles in rigid pile structure embankments

When analyzing negative skin friction of pile, the piles are assumed to be rigid. The relative displacement between piles and the surrounding soils was used to determine the negative skin friction. The neutral point is the zero point, where relative displacement is vanished. Above the position of neutral point, the displacement of pile body was less than that of the surrounding soils, resulting in negative skin friction (downward) on the pile surface. With the decrease of the relative displacement with depth, the negative skin friction tended to decrease and it became zero at the neutral point. Below the neutral point, the friction was upward and contributed to the bearing capacity of the piles.

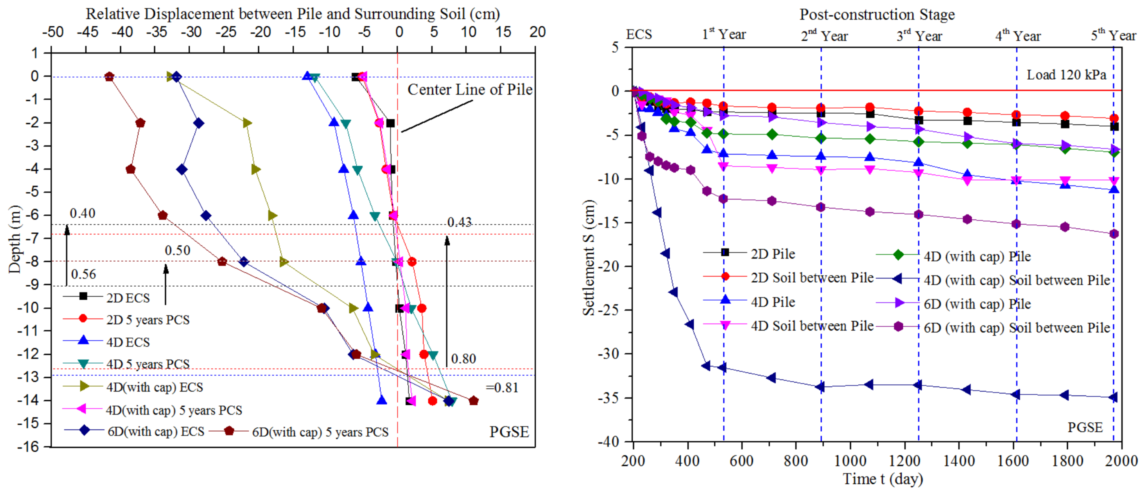
The relative displacements of PRSE in the post-construction stage are showed in Fig. 5. For piles with the pile spacing of s = 2D, the neutral point was at -1.2 m at ECS. During PCS, the position of neutral point dropped from -1.2 m (which corresponded to the ratio between the negative skin friction zone and the length of pile, or the pile length ratio, of 0.075) to the range of -3.5 m (the pile length ratio of 0.22) gradually, which implies that the bearing capacity of the pile slightly decreased with time. When pile spacing s = 4D, at ECS, the position of neutral point was at the depth of -11.0 m (the pile length ratio of 0.69). The neutral point gradually moved upward to -9.5 m (the pile length ratio of 0.59) and became stable in PCS, and the range of variation was 1.5 m. When the pile spacing was increased to s=6D, the neutral point position was at -12.0 m (the pile length ratio of 0.75) at ECS. In PCS, the neutral point position rose to the depth of -10.0 m (the pile length ratio of 0.63). In the construction stage, for PRCF, the relative displacements between pile and the surrounding soils with pile spacing of s = 2D, 4D, and 6D was 0.16 cm, 12.65 cm and 20.95 cm, separately. The maximum relative displacement was 8.59 cm, 14.91 cm and 34.17 cm respectively during PCS.

Fig. 6 presents the relative displacement of PGSE during PCS. For piles with the pile spacing



(a) (b)

Fig. 5 Relative displacement of PRSE in the post-construction stage: (a) Time effect of relative displacement and neutral point; (b) Time dependent development of maximum displacements of pile and surrounding soil

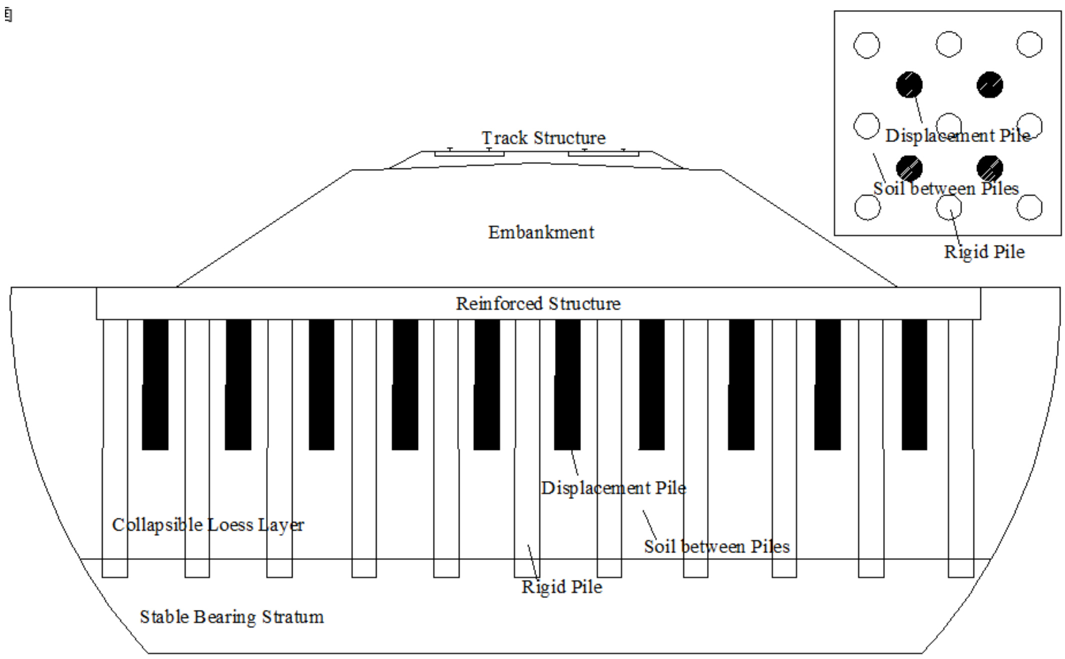


(a) (b)

Fig. 6 Relative displacement of PGSE in the post-construction stage: (a) Time effect of relative displacement and neutral point; (b) time dependent development of maximum displacements of pile and surrounding soil

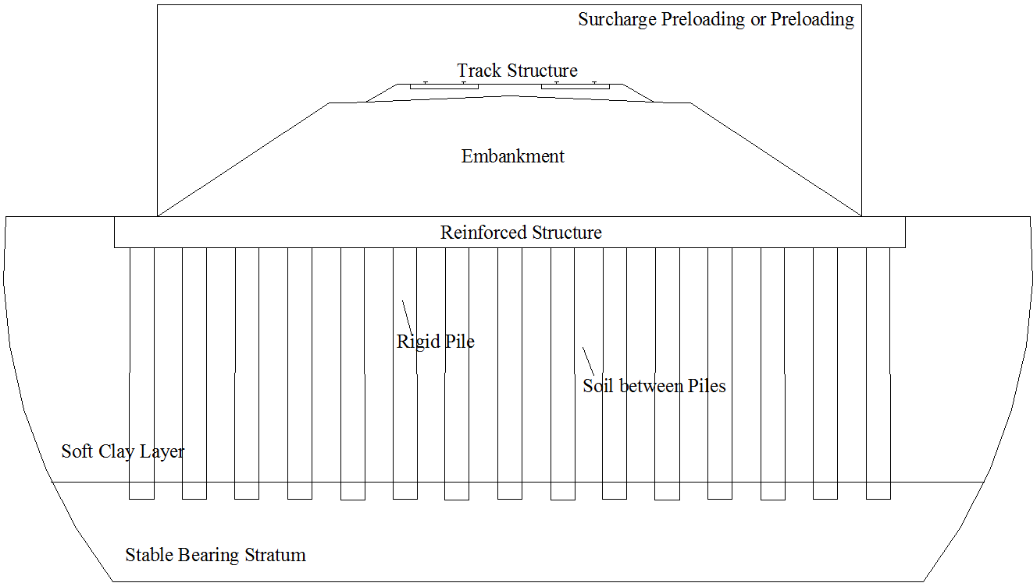
of s = 2D, at ECS, the neutral point was at -9.0 m. In PCS, the position of neutral point moved upward from -9.0 m (the pile length ratio of 0.56) to a range of -6.0 m to -7.0 m (the pile length ratio of 0.37 to 0.43) gradually, which implies that the bearing capacity of the pile significantly increase with time. The maximum negative skin friction was expected to take place at the top of the pile. When pile spacing was increased to s = 4D, at ECS, when without pile-cap, the soil deformation was observed to be larger than that of the pile, resulting in negative skin friction along the entire length of the pile as shown in Fig. 6(a). During PCS, the position of neutral point rose to -8.0 m (the pile length ratio of 0.50). Using pile-caps had some influence on the relative deformation between pile and the surrounding soils. When the pile-caps were used, that the caps can transfer more loads to the pile, the position of neutral point was at -12.8 m (the pile length ratio of 0.80) at ECS accompanied by an increase in the pile-soil relative displacement. During PCS, the neutral point gradually shifted upward to -7.0 m (the pile length ratio of 0.43). Smaller relative displacement in PCS was also observed, which may reduce the bearing capacity of piles. When the pile spacing was increased to *s* = 6D, the neutral point position was at -13.0 m (the pile length ratio of 0.81) at ECS. In PCS, the neutral point position stayed at this depth. One observes that the pile spacing has direct impact on the location of neutral points at ECF, but it does not seem to affect the depth of neutral points when the soil deformation becomes stabilized during PCS.For PGCF, the relative displacement of pile with pile spacing of *s* = 2D, 4D (without pile-cap), 4D (with pile-cap), and 6D was 6.0 cm, 13.0 cm, 4.84 cm and 31.92 cm in the construction stage. While was 6.0 cm, 14.49 cm, 33.38 cm and 41.67 cm separately during PCS.

In summary, for PRSE, the position of neutral point moved deeper with the increase of pile spacing in PCS. For the pile spacing of *s* = 2D to 6D, the pile length ratio varied in the range of 0.22 to 0.63. For PGSE in PCS, the position of neutral point for piles with or without caps both tended to move upward or keep stable. The pile length ratio varied in the range of 0.37 to 0.81 for the pile spacing of *s* = 2D to 6D. For improving the bearing capacity of RPSE and reducing negative skin friction during PCS, measures such as proper drainage system, and waterproof to



(a)

Fig. 7 Positive control measures of foundation settlements of high-speed railway embankments: (a) setting displacement pile between rigid piles in collapsible loess; (b) surcharge preloading or preloading methods in weak foundations



(b)

Fig. 7 Continued

weaken the deformation of soils should be considered as passive countermeasures. In addition we suggest adopting positive control measure such as setting displacement pile above neutral point between rigid piles (see Fig. 7(a)) in collapsible loess foundation and surcharge preloading or preloading methods (see Fig. 7(b)) should be taken into account in other weak foundations such as soft clay foundation. Details of these studies need to be further researched.

3.4 The differential settlements of foundations in different treatment parameters

Differential settlement is also critical for RPSE. Significant differential settlement may cause a serious accident to the trains and other undesirable effects on any structures constructed on the embankment, especially under the high speed. This section mainly discusses the influence of these factors on the settlement of RPSE.

Along the longitudinal direction of a railway, the collapse soils may be treated using different pile spacing in different zones. As such differential settlement tends to take place between these segments. The differential settlement underneath the longitudinal central line of embankment between adjacent zones was treated using different pile structures (see Fig. 2) are shown in Fig. 8. For PRSE at ECS, the total differential settlement between two segments with pile spacing of W1 and W2 was 3.14 cm (W1 = 4D, W2 = 2D), 13.71 cm (W1 = 6D, W2 = 4D) and 16.84 cm (W1 = 6D, W2 = 2D) respectively. In PCS, the total differential settlements of these segments were 4.91 cm, 15.70 cm and 19.71 cm respectively. The controlling abilities of settlement and differential settlement work well in post-construction stage. In the same way, the differential settlement of PGSE in different treatment parameters is shown in Fig. 8. At ECS, total differential settlement between two adjacent segments with pile spacing of W1 and W2 were 13.19 cm (W1 = 4D, W2 = 2D), 2.56 cm (W1 = 4D (pile-cap), W2 = 4D) and 17.42 cm (W1 = 4D (pile-cap), W2 = 6D (pile-cap)) respectively. In PCS, total differential settlements of these were 15.71 cm, 1.21 cm and 22.18

cm respectively. With the increase of pile spacing the differential settlement is enlarging. The pile-cap setting is helpful to reduce the differential settlement and change rate in PCS. Rigid pile structure embankment (RPSE) can control the differential settlement effectively. Under the same pile spacing, PRSE is shown to have better ability of differential settlement control than that of PGSE, however PGSE has the benefits of fast construction and low-cost.

Generally, the designers adopt a single structure of foundation reinforcement using different design parameters to control the settlement both in the embankment zone and the bridge-

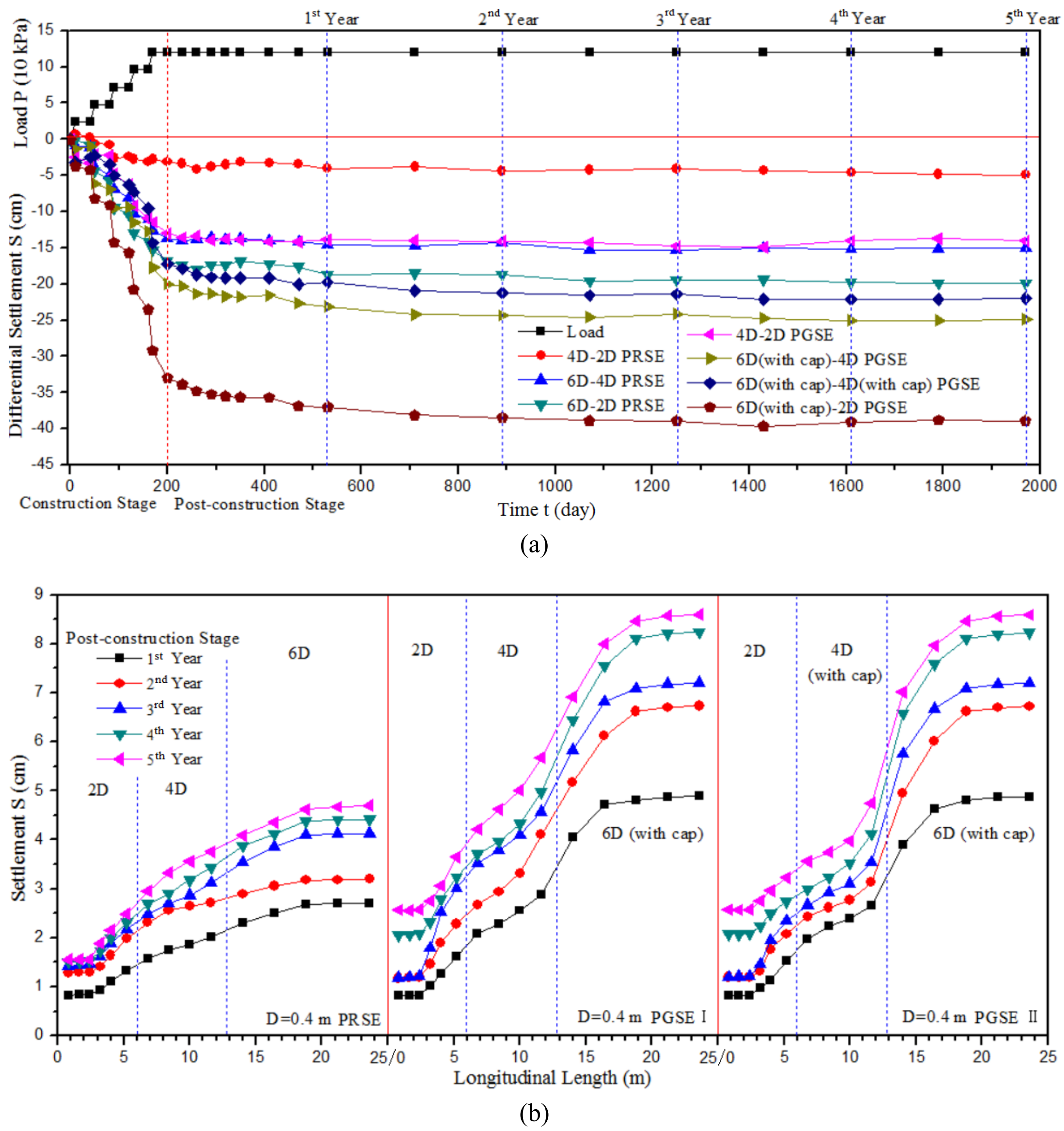
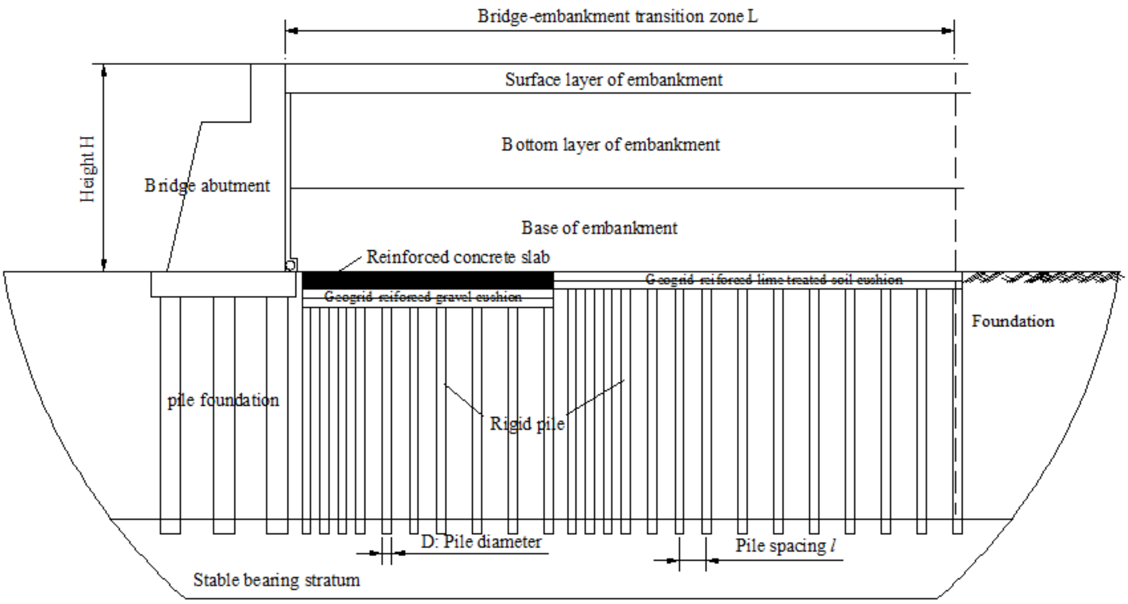
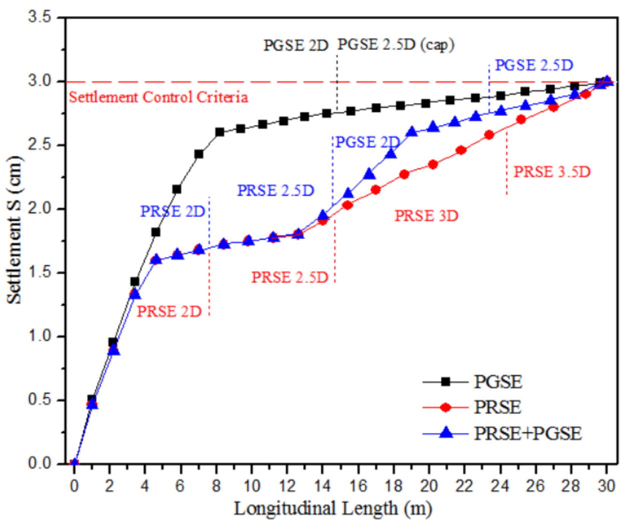


Fig. 8 Differential settlement of PGSE: (a) time effect of differential displacement; (b) time dependent development of differential settlement of central longitudinal section of embankment in the post-construction stage

embankment transitional zone as mentioned above. From a series of experimental results, we suggest that two parts or multi-parts of transition zone forms should be taken into account such as the combination structure of PRSE and PGSE showed in Fig. 9(a). Based on the embankment settlement control criteria of ballasted track for railways design speed of 300 to 350 km/h during PCS in China (see Table 3 above), in bridge-embankment transition zone, maximum allowable



(a)



(b)

Fig. 9 Two types of transition zone forms: (a) two types of transition zone forms as combination of PRSE and PGSE; (b) differential settlement of central longitudinal section of embankment with different foundation reinforcement methods in the post-construction stage settlement is 3 cm and settlement rate 2 cm/year with 1/1000 maximum slope ratio. Furthermore, the length of bridge-embankment transition zone is no less than 30 m. It is assumed that no settlement of bridge abutment occurs. The preliminary experimental results are shown in Fig. 9(b). The combination structure of PRSE and PGSE as bridge-embankment transition zone can meet the requirement of settlement controlling, meanwhile, this structure has good transition line and better economic benefits. Nevertheless, more details about the new combination structure of transition zone should be further investigated.

4. Conclusions

The following conclusions can be drawn from this research:

- Ground reinforcement is required to reduce the post-construction settlement and settlement rate of the embankments. The rigid pile structure embankments (RPSE) are capable of transferring the greater part of the embankment load and surcharge to more competent material at deeper depth due to the arching effect, and a soil layer with high bearing capacity is suggested to be the bearing stratum at pile tip. The PRSE is shown to have better ability for effective settlement control, while the PGSE provides rapid construction as well as cost benefits. The use of rigid piles can substantially reduce the embankment settlement in the construction of embankment on collapsible loess, and the efficiency in settlement reduction is affected by pile spacing.
- Based on the requirements of settlement and settlement rate of different railways design speeds, rational range of pile spacing of PRSE and PGSE are suggested. Rigid pile structure embankment (RPSE) can control the differential settlement effectively. Under the same pile spacing, PRSE can control differential settlement better than PGSE. However, PGSE has the benefits of fast construction and low-cost.
- For PRSE, the position of neutral point moved deeper with the pile spacing increasing in PCS. For the pile spacing of s = 2D to 6D, the pile length ratio varied in the range of 0.22 to 0.63. For PGSE in PCS, the position of neutral point for piles with and without caps both tended to move upward or keep stable. The pile length ratio varied in the range of 0.37 to 0.81 for the pile spacing of s = 2D to 6D.
- For PGSE, pile-caps can effectively reduce the settlement, settlement rate, the differential settlement and the rate of embankment, and transfer more loads to the pile during PCS.
- To improve the bearing capacity of RPSE and avoid the negative skin friction during PCS, measures such as proper drainage system, and waterproof to reduce the compressibility of soils should be considered as passive control means. The positive control measures e.g., setting displacement pile above neutral point between rigid piles in collapsible loess foundation and surcharge preloading or preloading methods, should also be taken into account in weak foundation soils such as soft clay. Two parts or multi-parts of transition zone forms, such as the combination structure of PRSE and PGSE, should be considered for the purpose of settlement control.

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