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Effect evaluation of lime-soil compaction pile on collapsible loess foundation in a loess site

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Abstract

Due to the increase of load or moisture, collapsible loess can easily cause the damage of building foundation and affect the safety of buildings. In order to effectively eliminate the collapsibility of loess foundation, lime-soil compaction pile was used to treat loess foundation in some sites of the study area. This paper aims at evaluating the effect of the ground treatment. Through on-site drilling, in-situ test and laboratory test, the engineering properties of the treated foundation are evaluated. The results show that the collapsibility coefficient of the site foundation soil treated by lime-soil compaction pile is significantly lower than that of the undisturbed soil, but the local soil still has slight collapsibility. The dry density of the soil between piles increases after compaction, and the properties are improved. However, the minimum compaction coefficient of the layer is between 0.83 and 0.87, which has not yet reached 0.88 of the specification requirements. In this paper, the foundation treatment of the site is also suggested.

Keywords

Collapsible loess, lime-soil compaction pile, foundation treatment, effect evaluation.

1. Introduction

Recent years, with the rapid development of economic construction in the western region, a large number of highways, railways and other buildings have been built in the loess area. Collapsible loess is often encountered in the construction process of these projects. Collapsible loess has high strength and low compressibility when the moisture content is low, while in the case of immersion, the structure of collapsible loess will be destroyed rapidly, and the strength will decrease rapidly, resulting in large subsidence deformation [1-3]. Therefore, when carrying out engineering construction in collapsible loess area, effective treatment measures should be taken to prevent the damage of superstructure and slope instability caused by collapsible deformation of loess.

At present, the treatment methods of collapsible loess mainly include replacement method, cushion method, dynamic compaction method, pre-soaking method and chemical grouting reinforcement method [4-7]. These methods have been applied in foundation treatment engineering practice in collapsible loess area, and each has its advantages and disadvantages.

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The construction technology of lime-soil compaction pile is simple, the construction quality is easy to be controlled, and the construction period is short. The project cost is only 1/3 ~ 1/2 of other pile foundations, and the economic and social benefits are very remarkable. The compaction pile method has been widely used in China since the 1960s, and has achieved useful results.

In order to eliminate the collapsibility of foundation soil, some foundation soil in a self-weight collapsible loess site is treated by lime-soil compaction pile method. In order to evaluate the treatment effect of lime-soil compaction pile and guide the construction of subsequent foundation treatment projects, this paper analyzes and evaluates the engineering properties of the treated foundation soil and the soil between piles through field sampling and laboratory tests.

2. Overview of research sites

The site geomorphic unit belongs to Weibei loess tableland, whose climate is warm temperate continental semi-arid monsoon climate. The research site belongs to the self-weight collapsible loess site, and collapsibility level of the foundation is IV (very serious). The thick of the collapsible loess layer below the site basement is about 20 m. The form of the foundation is an independent foundation, and the average substrate pressure is 300 kPa. In order to eliminate the collapsibility of foundation soil and improve the bearing capacity of foundation, the deep dynamic compaction lime-soil compaction pile (DDC method) composite foundation scheme is carried out in some areas of the site. The lime-soil compaction pile is perforated by impact and immersed tube. The diameter of the hole is 400 mm, and the diameter of the pile after compaction is not less than 550 mm. Under the foundation, the total pile length is 20.50 m, and the effective pile length is 19.80 m. The 2:8 lime soil was used as the pile filler, and the lowest compaction coefficient was 0.97 after compaction. The compaction pile is arranged by equilateral triangle, distance between pile center is 900mm. According to the design requirements, after the completion of the construction, the upper 0.70 m reserved loose layer is excavated, and the 2 : 8 lime soil cushion of 0.50 m is set under the base. The compaction coefficient of lime soil cushion is not less than 0.95.

According to its formation age and origin, the site foundation soil can be divided into Quaternary Holocene artificial fill (Q_4^{ml}), Upper Pleistocene aeolian loess (Q_3^{eol}) and residual ancient soil (Q_3^{el}), Middle Pleistocene aeolian loess (Q_2^{eol}), residual ancient soil (Q_2^{el}), etc.

3. Research program

In order to test and evaluate the treatment effect of lime-soil compaction pile, two exploration wells are arranged in the foundation treatment range to sample the soil between the lime-soil compaction pile and the soil of the pile body. The depth of the exploration well is 25.0 m. Each drilling hole is arranged with a depth of 40.0 m, and the soil between piles is sampled and the engineering properties of foundation soil below the pile bottom are evaluated. At the same time, a borehole is arranged in the untreated area for sampling and testing, aiming to evaluate the engineering characteristics of undisturbed soil and compare with the treated foundation soil.

4. Engineering property evaluation of lime-soil compaction pile for foundation soil treatment

4.1. Basic physical and mechanical properties

According to the results of drilling sampling, the same depth of soil between piles and undisturbed soil were selected and compared, see Figure 1. The change of soil structure can be clearly found. It can be seen from Figure 1 that after the soil between piles was compacted, the engineering properties of the soil changed, and the large pores in the loess disappeared, and a small number of small holes and pinholes were occasionally seen.

a Undisturbed loess in 6.0 m depth

b Soil between piles in 6.0 m depth

c Undisturbed loess in 12.0 m depth

d Soil between piles in 12.0 m depth

Figure 1: Comparison of soil between pile and undisturbed soil at different depths

4.2. Collapsibility of the soil

Collapsibility tests were carried out on the soil samples between piles taken from exploration wells 1, 2 and the drilling, and the collapsibility coefficients were statistically stratified. The statistical results are shown in Table 1.

Table 1: Statistical of soil collapsibility coefficient between piles

Stratification	Exploration well 1#		Exploration well 2#		drilling 1#	
	Range value	Eliminated or not	Range value	Eliminated or not	Range value	Eliminated or not
② loess	<0.015	eliminated	<0.015	eliminated	<0.015	eliminated
③ palaeosol	<0.015	eliminated	<0.015	eliminated	<0.015	eliminated
④ soil	<0.015	eliminated	0.008~0.025	locally eliminated	<0.015	eliminated
⑤ palaeosol	<0.015	eliminated	0.012~0.026	locally eliminated	<0.015	eliminated
⑥ loess	<0.015	eliminated	0.022~0.028	not eliminated	<0.015	eliminated
⑦ palaeosol	<0.015	eliminated	0.030	not eliminated	<0.015	eliminated
⑧ loess	Not collapsible loess					
⑨ palaeosol						
⑩ loess						

According to the soil collapsibility test between piles, the following conclusions can be drawn:

(1) After the foundation soil is compacted, the collapsibility coefficient is significantly reduced compared with the undisturbed soil. The collapsibility coefficient (δ_s) of soil specimens taken from exploration well 1 # and drilling 1 # is less than 0.015, and the collapsibility has been

eliminated. In the exploration well 2 #, the collapsibility coefficient δ_s of loess layer ② and paleosol layer ③ is less than 0.015, and the collapsibility has been eliminated. Foundation soil layer ④~⑦ still has collapsibility locally, the maximum collapsibility coefficient is 0.030, and the collapsibility is slight.

(2) In the exploration well 2#, the collapsibility still exists only in the 4th loess layer layer and the 5th paleosol layer, the collapsibility has been eliminated, and the collapsibility is discontinuously distributed vertically.

(3) The effect of the soil compaction between piles is not uniform, and there are differences in the plane distribution. And in the range of compaction depth, compaction effect of the pile top is better, compaction effect of the lower layer is general.

4.3. Compaction coefficient

According to the compaction test of the field test results, the minimum compaction coefficient of soil between piles is calculated. Layered statistics are performed on the compaction coefficient, and then the average value is calculated. The calculation results are shown in Table 2.

Table 2: Calculation of soil compaction coefficient between piles

Stratification	ρ_d (g/cm³)	Average (g/cm³)	Minimum compaction coefficient of the layer	Average	Meet specification requirements or not
② loess	1.49	1.46	0.87	0.85	no
③	1.42		0.83		no
④ soil	1.49		0.87		no
⑤	1.48		0.87		no
⑥ loess	1.47		0.86		no
⑦	1.47		0.86		no
⑧ loess	1.44		0.84		no
⑨	1.46		0.85		no
⑩ loess	1.44		0.84		no

According to the calculation results of soil compaction coefficient between piles, the minimum compaction coefficient between piles is 0.83 ~ 0.87, with an average of 0.85. According to Standard for building construction in collapsible loess regions (GB 50025-2018), the minimum compaction coefficient of soil between piles should not be less than 0.88. The minimum compaction coefficient of soil between piles in this study site after lime-soil compaction pile treatment did not meet the design requirements.

5. Comparative analyses of undisturbed soil and soil between piles

5.1. Comparative analyses of dry density and void ratio of undisturbed soil and soil between piles

The dry density and void ratio of soil between piles in exploration well 1# and 2# and undisturbed soil are compared, and the change curves of dry density and void ratio with depth are shown in Figure 2 and Figure 3. For the convenience of expression, the soil between piles in exploration wells 1 1# and 2# is abbreviated as E_1 and E_2 respectively, and the undisturbed soil is abbreviated as U_1.

It can be seen from Figure 2 and Figure 3 that the dry density of the soil between piles of exploration wells 1 # and 2 # after compaction is significantly higher than that of the undisturbed soil. The void ratio decreases, and it is much lower than the undisturbed soil. It

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shows that the density of soil between piles after lime-soil compaction pile treatment has been significantly improved.

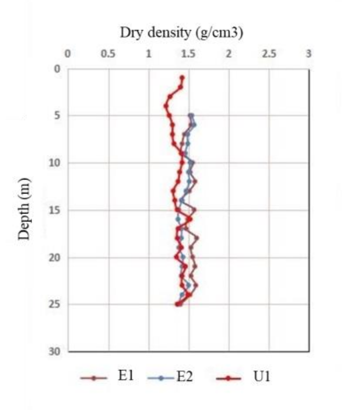

Figure 2: Dry density of soil between piles and undisturbed soil

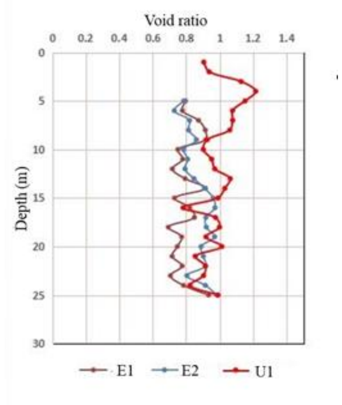

Figure 3: Void ratio of soil between piles and undisturbed soil

5.2. Comparative analysis of soil moisture content between piles and undisturbed soil

The variation curves of water content of soil between piles and undisturbed soil are shown in Figure 4. It can be seen from Figure 4 that the moisture content of undisturbed soil gradually increases with the increasing depth. According to the observation results of exploration well 1 # and 2 #, the moisture content of soil between piles fluctuates greatly with the increase of depth after lime-soil compaction pile treatment, and reaches the maximum at the position of 6.0 m ~ 10.0 m, which is related to the infiltration of surface water.

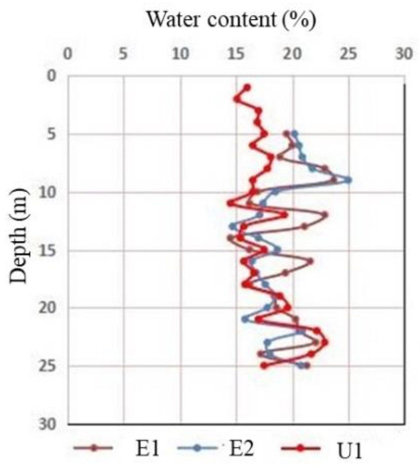

Figure 4: Comparison of water content between soil-between-piles and undisturbed soil

5.3. Comparative Analysis of Shear Wave Velocity Test

Shear wave velocity tests were carried out in boreholes of inter-pile soil and undisturbed soil, respectively. The test depth in two boreholes of inter-pile soil was 40.0 m, and that in undisturbed soil was 25.0 m. The shear wave velocity of each soil layer was statistically stratified, and the stratified shear wave velocity values of undisturbed soil and inter-pile soil were compared. The results are shown in Table 3.

Table 3: Comparison of shear wave velocity values of undisturbed soil and soil between piles

Stratification	Undisturbed soil (m/s)		Soil-between-piles (m/s)	
	Range value	Average	Range value	Average

① plain fill	130.33~243.11	178.21	183.26~230.20	206.92
② loess	168.22~392.63	241.20	228.82~336.12	290.64
③ palaeosol	206.49~305.18	266.68	/	246.34
④ soil	241.18~476.69	322.36	298.11~420.75	347.78
⑤ palaeosol	301.07~375.32	341.36	393.05~467.83	430.44
⑥ loess	262.62~391.71	336.19	376.84~384.82	380.83
⑦ palaeosol	392.92~430.12	411.52	/	402.09
⑧ loess	350.24~430.72	371.87	378.11~464.59	424.54
⑨ palaeosol	263.75~424.08	381.33	/	403.65
⑩ loess	215.21~431.98	351.32	475.42~533.64	504.53
⑪ palaeosol	316.91~451.66	394.52	/	/
⑫ loess	352.22~495.12	460.46	/	/

According to Table 3, it can be concluded that after the soil between piles is compacted, the shear wave velocity values of most strata are significantly improved compared with the undisturbed soil, indicating that the properties of foundation soil are improved.

6. Evaluation of Engineering Properties of Pile Soil

There are four lime-soil piles exposed in the exploratory wells, which are numbered as 1 #, 2 #, 3 # and 4 #, respectively. The variation trend of dry density of pile body in the whole pile depth is shown in Figure 5 and Figure 6.

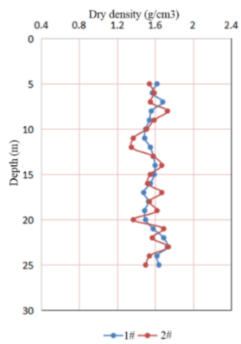

Figure 5: Curves of dry density of 1# and 2# piles

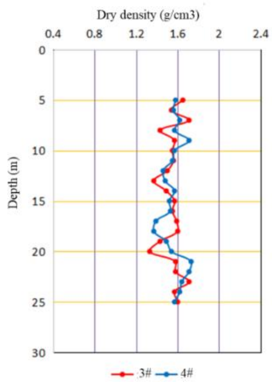

Figure 6: Curves of dry density of 3# and 4# piles

According to the results shown in Figures 5 and 6, the average dry density of each pile is between 1.55 and 1.58. The dry density of the four lime-soil piles exposed in the exploratory well showed a change trend in the whole pile depth range. Among them, the 2 # pile body is 10.0 m ~ 13.0 m and 20.0 m, the dry density of the pile body is small. 3 # pile body in 8.0 m, 13.0 m, 19.0 m ~ 20.0 m, the dry density is small; 4 # pile body in 17.0 m ~ 18.0 m, the dry density is small. It indicates that at this position, the compaction energy is insufficient during construction, and the compaction degree of the pile is small. The dry density of the pile at the top and bottom is slightly better than that of the middle part of the pile, indicating that the compaction degree of the pile is better.

According to the compaction test results, the maximum dry density of lime soil in the site is 1.59 g/m^3, and the average compaction coefficients of piles 1 #, 2 #, 3 # and 4 # are 0.99, 0.98, 0.97 and 0.98, respectively, which meet the design requirements.

According to the testing results of water content, the water content of lime soil of the pile is between 18.6 % and 20.1 %, which is close to the optimal water content of the compaction test of 21.3 %, indicating that the water content of pile is well controlled.

7. Conclusions and suggestions

(1) After the foundation soil is treated by lime soil compaction pile, the collapsibility coefficient is significantly reduced compared with the undisturbed soil. The local soil still has slight collapsibility, and the collapsibility is not completely eliminated.

(2) After compaction, the void ratio decreases, and the properties of foundation soil are improved. However, the minimum compaction coefficient of soil layer of inter-pile exposed in this paper is between 0.83 and 0.87, which has not yet reached 0.88 of the specification requirements.

(3) The average dry density of the four lime-soil piles exposed in the exploration well is between 1.55 and 1.58 g/cm3, and the pile body is mostly hard and dry density is large. Only local dry density and compaction is small. The average compaction coefficient of pile is between 0.97 and 0.99, which meets the design requirements.

(4) In view of the existing compaction coefficient of inter-pile soil has not yet reached the specification requirements, it is suggested that reinforced concrete bored piles should be arranged between the compaction pile to improve the compaction coefficient of the foundation soil, so as to meet the specification requirements of the compaction coefficient. At the same time, after the completion of the construction, the surface waterproof and drainage measures should be done in time to prevent the infiltration of surface water and rainwater.

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