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SOIL-CEMENT PILES BY DRILLING-MIXING METHOD

Development of the drilling-mixing technology lead to the appearance of the soil-cement piles. It has all advantages of the drilling piles, but it eliminate the problem of the well walls stability. Drilling-mixing technology consist in, that machine with drilling-mixing head loosen soil; impregnated it by laitance; and mixed. Piles are perform from the excavation bottom until design depth. The movable soil-cement mixture feels wells during all the process. Pile has cylindrical form with set sizes in the result of the hardness in 28 days. Soil-cement prism strength this reaching 2 MPa in clay loam and 4 MPa in sand (in clay soil strength is lower) with the amount of cement 20 % from the amount of the dry soil. Soil-cement strength increase twice after one year. Cost of the 1 m^3 of such pile – is 100$ ± 25 % accordingly to the size and conditions of performance. Soil-cement pile feature that it bearing capacity by the soil is much higher than by the pile material. So main purpose of such piles researches – is to find methods for increasing strength of the soil cement. There are identified factors that determine the strength of the soil cement, manufactured by drilling-mixing technology. 1. At the age 28 days with the amount of cement 20 % from the amount of the dry soil higher strength has soil cement manufactured from small sand (up 6 MPa), and lower – from heavy clay loam (1,5 MPa). 2. Increase strength to the 10 MPa is possibly by preliminary soil removing from leading borehole. 3. Steel reinforcement increases the strength of the piles material up to 2 times. 4. Additional water are removing by the mixture vibrating by the deep vibrators. It is increasing soil-cement strength up twice, accordingly to the vibration time and frequency. 5. In the heavy clay loam, soil-cement strength is increasing up to 30–40 % if added sand in the laitance. There are absent researches of the chemical reagents impact on the soil-cement strength. 6. Soil-cement strength is increasing in time, especially if it is manufacturing lower than the ground water table. If it is manufacturing in the dry-air environment part of the strength could be lost. 7. Soil-cement has abnormally high water resistance.

Keywords: poor-bearing soil, pile, soil basement, foundation, soil-cement,mixing technology, strength, settlement, stress-strain state.

Introduction

Drilling piles are replacing precast from the construction market. Its advantages are absence of impact on the existing buildings during construction, wide range of sizes of depth and diameter. Such piles have all advantages of the monolithic structures. Greatest effect is achieved when it used in stable soils above the water table, when elements based on the incompressible soil [1]. Problems occur if piles performing in the unstable dispersed soils under the water table. During drilling and concreting is necessary to provide stability of the well walls. It is release in two ways:

1) there is apply cased pipes during well drilling, pipes are removing and it's used repeatedly; but there are impossible to remove pipes often; 2) drilling with drilling-mixture and underwater concreting. Those factors are increasing cost and term of construction. Development of the drilling-mixing technology lead to the appearance of the soil-cement piles. It has all advantages of the drilling piles, but it eliminate the problem of the well walls stability [2, 3].

1. Equipment for production of the soil-cement piles

Drilling-mixing technology consist in, that machine with drilling-mixing head loosen soil; impregnated it by laitance; and mixed (Fig. 1). Piles are perform from the excavation bottom until design depth. The movable soil-cement mixture feels wells during all the process [4, 5]. Pile has cylindrical form with set sizes in the result of the hardness in 28 days. Soil-cement prism strength this reaching σ = 2 MPa in clay loam and σ = 4 MPa in sand (in clay soil strength is lower) with the amount of cement 20 % from the amount of the dry soil. Soil-cement strength increase twice after one year [6, 7].

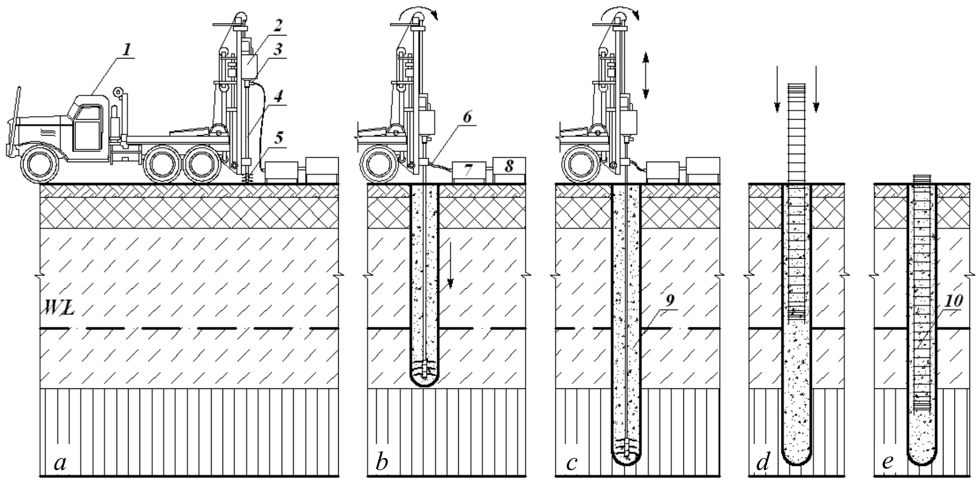

Fig. 1. Soil-cement piles production by the boring-mixing method: *a* – boring equipment; *b* – soil loosening with forcing of water cement mortar; *c* – mixture mixing; *d* – installing of reinforcing frame; e – general view of the soil-cement piles; *1* – automobile with boring equipment; *2* – actuator; *3* – swivel; *4* – boring pipe; *5* – mixer; *6* – supply hose for water cement; *7* – boring supply; *8* – mixture mixer tool; *9* – soil-cement element; *10* – soil-cement pile

General view of such equipment is on the Fig. 2.

Fig. 2. General view of the equipment to produce soil-cement by the boring-mixing technology: *a* – boring workbench; *b* – hiding place for mixers, pump, cement warehouse; *c* – water container; *d* – pressure hose

This equipment includes: boring machine BM-811m at the vehicle "Ural", it is upgraded so that augers replaced with boring rods with a diameter of 100 mm (rods are produced with internal channel to supply the cement slurry; the working body for breaking ground has openings for distributing cement slurry by all section of the well; augers are connected with mortar supplies pressure hoses and swivel; mixer for making cement slurry; pump for pumping the cement slurry to the well. Cement slurry knead in mixer and injected by pump through the swivel in the boring rod and further in the loosen soil. Cement slurry is possible to produce with help of the mixers, which modern industry are producing nowadays, if the homogeneity of the suspension are provided. As slurry pumps use construction or boring diaphragm plunger pumps, which are create pressure not less than 0,5–0,7 MPa. Soil are loosen in the face of the borehole, soil are impregnated by the cement mortar and mix it until mixture will have a homogeneous state of the soil-cement. Mixing quality are essentially depends from the mixer speed of immersion into the soil.

Lower speed of immersion, with constant number of the mixer turns, lead to the thinner soils having. Therefore, it is lead to the mixing higher quality. For the straight immersion of the mixer we should take speed lower than further: in the sandy soils – 0,5 m/min at 60 turns/min, it made shaving with thickness 8 mm; in clay soils – 0,3 m/min at 60 turns/min, it made shaving with thickness 5 mm. Mixer reversal move and repeated cycles "deepening – reverse" is necessary to make with speed lower than 1 m/min at 60 turns/min, it provides vertically displacement of the mixer by one turn on 16 mm. General view of the mixer (Fig. 3), that are used during soil-cement piles production.

a *b* *c*

d *e* *f*

Fig. 3. Mixers (cutting tools) for production of the soil-cements piles:
a – pressure; *b* – impeller; *c*, *d* – auger; *e* – wing; *f* – spiral

Pressure mixer (Fig. 3, *a*) allows reliably regulate the thickness of the soils having, it allows to achieve its smallest thickness. We recommend use it during the work in the heavy loam, light clay. For reliable mixing of the soil-cement mixture needs more repeated cycles "deepening – reverse". Impeller mixer (Fig. 3, *b*) we recommend use during the work in the light loam and sandy loam. It provides best mixing of the soil-cement. Those quality of the mixer could be improved by increasing the number of blades through the height of rod. Auger mixer (Fig. 3, *c*, *d*) we recommend to use during the work in the sandy soils. Wing mixer (Fig. 3, *e*) we recommend to use in the clay soils with low level moistening, during its boring with water to obtain fluid clay soil. Soil saturation by cement and slurry mixing is carried with using of chisel wing.

2. Physical and mechanical characteristics of the soil-cement

Soil-cement pile feature that it bearing capacity by the soil is much higher than by the pile material. This is reducing piles efficiency. So main purpose of such piles researches – is to find methods for increasing strength of the soil cement. For the last 10 years, we have made extensive field and laboratory researches [8]. There are identified factors that determine the strength of the soil cement, manufactured by drilling-mixing technology [9].

Methodic of the soil-cement samples formation was follow. Water and cement in the required amount was mixed manually, until there was obtained homogeneous state "laitance". Cement amount were determined as fraction of the weight of dry soil. After in the mixture was injected additive, if it is necessary.

After in the obtained mixture was injected soil with specific humidity and resulting mixture was mixed to homogeneous mass over 5 minutes. Soil-cement mixture were taught in wooden forms with dimensions 7,07×7,07×7,07 cm and cylinders with dimensions h = 3,0 cm and d = 3,0 cm. Cubes and cylinders was formed by casting method. Cubes was pulled from forms on the second day and it were retained in the water for a specified period of time till the test [7].

Samples test (cubes, cylinders) on compression was performed at the age of 28, 90, 365 and 730 days. It was performed with help of the compression device. On each test was made 6–8 samples from 1 series (with same content of the soil, cement, W/C ratio, time of hardening). External loads was conducted to the destruction of the sample. As a result of the test for each soil-cement sample with different hardening time was obtained values of: density ρ (tons/m^3), humidity W, compression strength R (MPa), deformation modulus E (MPa). Average values of the statistical physical and mechanical soil-cement characteristics.

1. Soils composition, which pile has cut. There are researched loessial clay loam and sandy loam; alluvial quartz sand small and dusty; alluvial floodplain sediments (sand, loam peat). At the age 28 days with the amount of cement 20 % from the amount of the dry soil higher strength has soil cement manufactured from small sand (up σ = 6 MPa), and lower – from heavy clay loam (σ = 1,5 MPa). Graphs show that soil-cement strength (Fig. 4) and deformation modulus reducing with soil plasticity number increasing. Dependences are almost direct (correlation ratio r = 0,94…0,99).

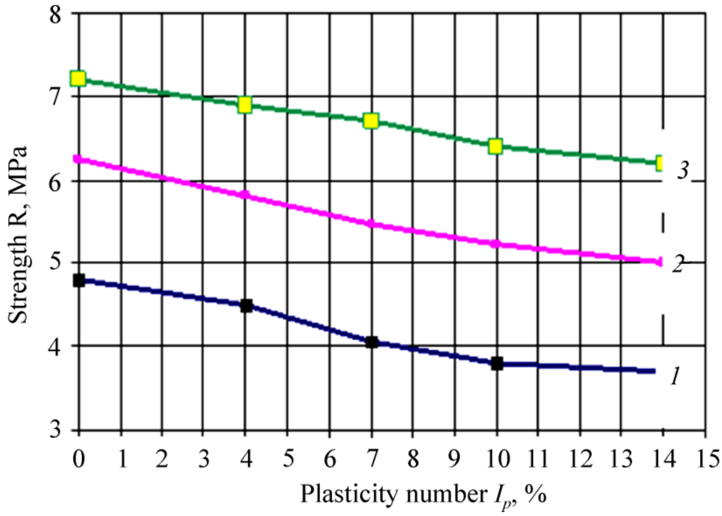

Fig. 4. Soil-cement strength R dependence from plasticity number I_p, % cement content: *1* – 15 %; *2* – 20 %; *3* – 25 %

2. Cement content. Value of the loosened soil in well could take cement less than 20 % by weight of dry soil. Soil-cement strength with constant content of cement increase cements of the high grades, but it is irrational. Increase strength to the σ = 10 MPa is possibly by preliminary soil removing from leading borehole.

3. Steel reinforcement increases the strength of the piles material up to 2 times.

4. Soil-cement piles manufacturing lower than the ground water table lead to the high water-cement ratio of the mixture. It is much increasing material porosity and reducing its strength. Additional water are removing by the mixture vibrating by the deep vibrators. It is increasing soil-cement strength up twice, accordingly to the vibration time and frequency.

5. In the heavy clay loam, soil-cement strength is increasing up to 30–40 % if added sand in the laitance. Soil-cement strength dependences from sand content are on the Fig. 5.

6. Soil-cement strength is increasing in time, especially if it is manufacturing lower than the ground water table. If it is manufacturing in the dry-air environment part of the strength could be lost. Graphs of the soil-cement strength dependence from cement content and hardening period are on the Fig. 6.

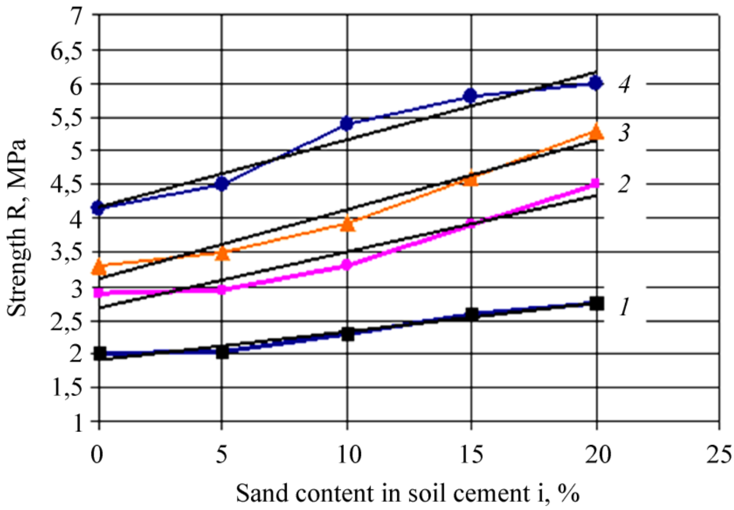

Fig. 5. Soil-cement strength R dependence from sand content for the each hardening period: *1* – 28 days; *2* – 90 days; *3* – 1 year; *4* – 2 years

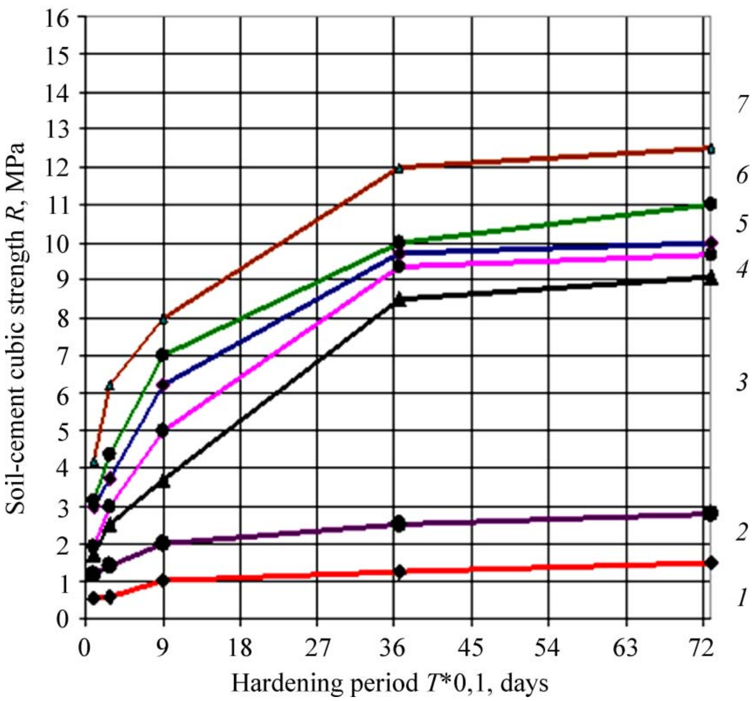

Fig. 6. Soil-cement strength R dependence from hardening period for different cement content: *1* – 5 %; *2* – 10 %; *3* – 15 %; *4* – 20 %; *5* – 25 %; *6* – 30 %; *7* – 35 %

7. Soil-cement has abnormally high water resistance [7]. Without any additives, its water resistance is W8–W12, and for small sand – W6.

3. Field research of soil-cement piles

Experimental site #1. Because there are a lot of close buildings, pile driving is impossible. In terms of geomorphology site is dedicated to Poltava loess plateau. The level of the ground water is 2,2–3,6 m underground. This makes bore-mixing technology efficient method of pile arranging in such conditions. Hydro geological conditions are also favorable for normal soil-cement strength increasing. Because pile is almost below the groundwater level. Soil for piles is clay loam. At the building site arranged 241 soil-cement piles as the foundation for building section, its length is 6 m, and a diameter is 500 mm. Piles reinforcement was carried by welded reinforcement cages hollow.

To provide soil-cement reinforcement were made field test. On the site were made 3 piles groups 2 piles in each series. In the first series concrete bored piles from concrete grade B25, it was control to determine bearing capacity by soil. This piles made from concrete, so its destruction by material is impossible. Second series included piles without reinforcement, its bearing capacity by material is much lower. Therefore, during loading process pile is high probability of its destruction by material, before equality between load and load capacity by soil. Third series include reinforced soil-cement piles. After were made static load test of each 3 series. Summarizing the results of a field experiment we made the conclusions: piles static tests confirm expected effect of soil-cement reinforcement; more appropriate to limit their length during reinforced soil-cement piles design (with taken into account problems of the reinforcement frame deepening); diameter increasing improve bearing capacity at the edge of the pile and conditions of reinforcing frame placing; reinforcement percent of the normal section, frame deepening, length and pile diameter is necessary to coordinate with each other so that the strength of the pile for normal section was secured throughout its length.

Modeling of the soil-cement pile stress-strain state was used Plaxis 3D Foundation. Soil model is elastic-plastic model of the Mora-Coulomb. Pile material – reinforced soil-cement, it is linearly deformed body. Pile diameter is 500 mm, length is 6 m. Piles static test comparison with modeling is on the Fig. 7. Results of the calculations in the graphic form is on the Fig. 8.

Maximal normal tensions concentrated at the top of the pile. Maximum vertical piles displacement is 40 mm. Pile body deformation under loading 500 kN is 2 mm. Pile relative deformation is 0,3 ‰, that is not exceed relative deformation of the soil-cement 1,1 ‰, that is limit of

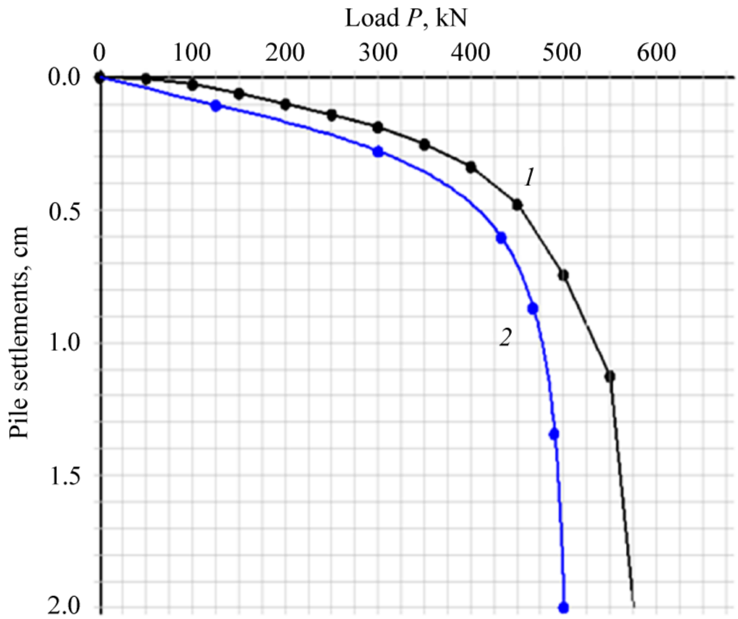

Fig. 7. Pile settlements from load dependence:
1 – static test results; *2* – modeling results

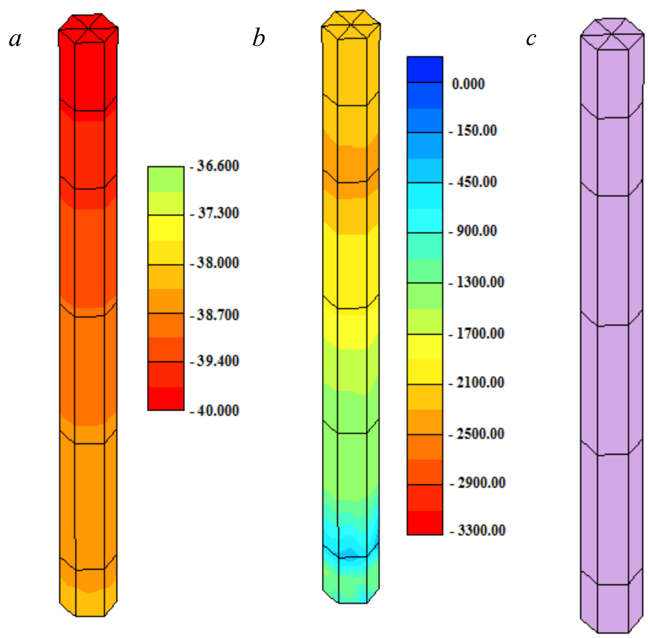

Fig. 8. Modeling of the soil-cement pile stress-strain state:
a – vertical displacement in the pile (mm); *b* – normal stresses in the pile (kPa);
c – deformed scheme of the pile (strain increased in 50 times)

operation of its components. Soil-cement pile is in the elastic work stage, easily seen by its deformation diagram [8]. Normal tensions in the pile body is 2,5 MPa (Fig. 8, *b*), that is exceeding strength of reinforced soil-cement (1,28 MPa) almost 2 times. Specified maximum tension based on cross-sectional area of the pile (0,196 m^2) creates pressure on pile 491 kN.

Bearing capacity is 511 kN, it is provides the strength of reinforced soil-cement pile by material. Therefore, soil-cement pile stress-strain state modeling results has shown bearing capacity 500 kN.

That is consistent with the value of the design load on the soil-cement reinforced piles, which obtained as result of the static load tests. Data analysis modeling allows to assert that the strength of the piles material also provided.

4. Monitoring of the buildings settlements of soil-cement piles

Soil-cement piles were used during house construction in Poltava (site #1). For sections I and II were constructed reinforced soil-cement pile with length 6 m and a diameter 500 mm. Welded reinforcement space frames used for piles reinforcement. Piles in three rows are performed under the middle wall of the building, distance between the rows axes is 1000 mm, distance between the piles axes in the one row is 1000 mm. Piles in three (distance between rows axes is 1000 mm, distance between piles axes in row is 1100 mm) and two three (distance between rows axes is 1000 mm, distance between piles axes in row is 1000 mm) rows are performed under external walls of the building. Under section III arranged root piles. Separating screen between the sections was not found.

As a result of field tests were found that on 02.01.2015 settlements are: first section marks minimum – 29 mm, average – 38,9 mm, maximum – 60 mm; second section marks minimum – 32 mm, average – 45,8 mm, maximum – 67 mm; third section marks minimum (with root piles) – 40 mm, average – 54 mm, a maximum – 70 mm; absolute settlement of all sections, and their relative uneven subsidence less than the ultimate values in requirements; there is tendency to foundation settlement stabilization; sections mutual influence that caused their uneven deformation is not recorded.

Conclusions

Laboratory researches and statically tests of the soil-cement physical and mechanical characteristics were found that: cement content increasing from 5 to 50 % lead to the soil-cement mechanical characteristics increasing by linear dependence, so, structural strength of soil-cement is possible to regulate by cement content even for the complete replacement of soil by cement in mortar; in soil with lower content of clay grains is higher mechanical characteristics, for production strong soil-cement sand with low content of clay grains is most effective; additives (sands and tails) using lead to soil-cement strength R and deformation modulus E increasing, so we recommend to use additives, tails using are more efficiency; soil-cement piles reinforcing by steel frame allows to increase the carrying capacity by material to a value that exceeds the value of their carrying capacity by the soil.

Soil-cement (from silty clay soils or of fine quartz sands) density increasing as result of vibration of liquid soil-cement mixture. Optimal value of vibration intensity were determined, when a specific composition of the mixture reached the maximum density. At greater vibration intensity mixture is stratified. The effect of mixture compaction by vibration occurs due to water and air bubbles displacement from mixture. At higher values of water cement ratio relative strength increasing in the soil-cement higher, but with soil moisture increasing – soil-cement strength falls.

Soil-cement (from light loam) waterproofness due to the “wet spot” method and in the device of the rapid waterproofness determination, cement content is 20 % and W/C = 1, made without additional compression and hydrophobic added, it corresponds for concrete waterproofness grade W14. Soil-cement test on softening show that it doesn’t softening in water, but it also increasing its strength.

Geodesic monitoring of nine-ten stores building (with soil-cement piles in wet loess) have shown that the settlements of its sections is much smaller than the ultimate values in national requirements.

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