Ground treatment of sea embankment by vacuum preloading with PVDs

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Abstract: Vacuum provides an alternative in reducing the length of preloading period for soft soil consolidation. In this method, soft clay foundation is preloaded by reducing the pore-water pressures through the application of vacuum pressure in combination with surcharge preloading. A full scale and fully instrumented test embankment was constructed. A drainage pattern system combined with 22 m prefabricated vertical drains (PVDs) length was used with triangular pattern of 1.2 m spacing. Among the foundation instrumentation, piezometers were installed in the foundation subsoil at varying depth to measure the pore-water pressures. After 6 months of vacuum pressure application at 80 kPa, the test embankments were raised to a maximum height of 5.5 m. The effect of vacuum preloading was investigated by the field conditions, maintaining higher vacuum pressures, and unloading vacuum. The results are demonstrated the efficiency of combined vacuum and surcharge preloading.

Key words: soft soils; vertical drains; vacuum preloading; embankment; ground improvement

Sea embankments are constructed to protect the land area from the disastrous flooding of rivers. They are almost the world's oldest hydraulic engineering structures as evidenced in all centers of ancient culture, especially in China, Egypt and India. However, even though the long history of this type of construction contributes to the progress in this particular field of civil engineering, neither modern scientific knowledge about soil mechanics, hydrogeology and hydrology, nor even experiences in modern construction technology are sufficiently taken into account when designing a sea embankment. The sea embankment at Wenzhou district coast of China is chosen as a case of study shown in Fig.1. The embankment is constructed on the deep and extensive soft soil foundation. For the optimum design and to get insight into the deformation, pore water pressure and consolidation, an in-situ test was conducted during construction. The maximum height of the embankment is 5.5 m.

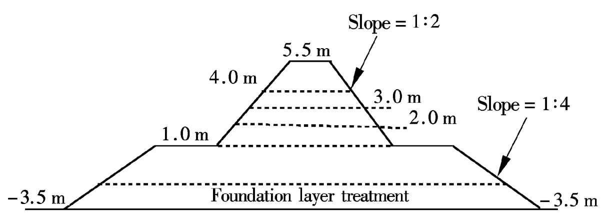

Fig.1 Sea embankment

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1 Technique of Vacuum Preloading

Vacuum consolidation was proposed by Kjillman who first introduced the principle of vacuum preloading[1]. The technique has been studied and applied quite extensively in Asia since the 1980's for consolidation of soft, highly compressive soils[2-6]. The vacuum combined surcharge preloading method has an obvious consolidation effect on soft soils[7]. Also the combination of vacuum and surcharge preloading is effective on the surrounding environment's soil inside the improving zone; the surrounding soils have inward lateral movement at the stage of vacuum preloading and then move outward at the stage of vacuum-combined surcharge preloading[8]. The vacuum preloading method is one of the techniques for improving soft soil foundation. In this method, the surface of treated soil is covered with a sealing membrane. In China, this method has become popular in recent years. The area of soft foundation treated by this method has reached in excess of 3 000 000 m^2. Through a vacuumizing apparatus, a negative pressure, which serves as a heap load, is established in a sand cushion beneath the sealing membrane and in the vertical drains set up in the treated soil[9]. When a vacuum is applied to a soil mass, it draws down the soil-pore water pressure. When the total stress remains unchanged, the decrease in the pore water pressure generates an increase of the effective stress in the soil-occurring consolidation of the soil. A diagram of the vacuum preloading method is shown in Fig.2. The fill must be free from stones or sharp objects to minimize the risk of punch holes in the membrane[10]. The initial total stress in the ground and pore-water pressure is induced due to conventional surcharge and vacuum pressure applied at the ground surface assuming 100% efficiency (vacuum pressure of 100 kPa)[11]. At the site of the proposed area, is the presence of more than 22 m thick, weak, and compressible soft clay. Soil improvement is designed with the vacuum assisted consolidation with prefabricated vertical drains (PVDs) application as depicted in Fig.2. The test site is set up at K32 + 281 to K32 + 910 and the vacuum design of the facial drainage system is shown in Fig.3.

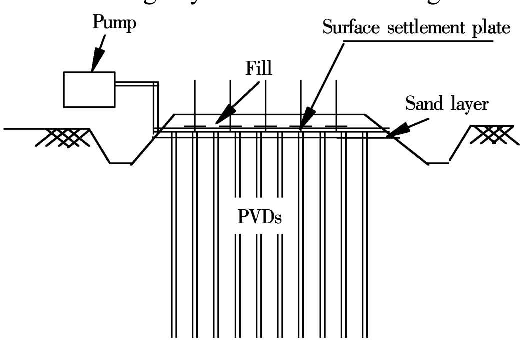

Fig.2 Typical layout of vacuum assisted consolidation with PVDs

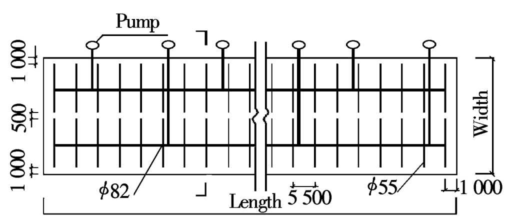

Fig.3 Vacuum design of horizontal drainage system (unit: mm)

For economic utilization of the proposed site, ground improvement techniques are necessary. In this regard, ground improvement with PVDs is studied; successfully using conventional surcharge, vacuum-assisted preloading can be a viable alternative. In this method, besides the increasing of effective stresses in the soil mass by increasing the total stresses, vacuum preloading relies on increasing the effective stresses by decreasing the pore-water pressures. Thus, vacuum preloading combined with surcharging can shorten the consolidation period considerably without endangering the stability of the test embankment. Preloading using a fill surcharge was not feasible as it is difficult to build a fill embankment several meters high on soft soil. Sand drain and more recently prefabricated vertical drains are used with vacuum loading to distribute the vacuum and dissipate the pore water pressure. Experiments have shown that for an appropriately designed scheme, using the vacuum preloading method for the equivalent load, the vacuum preloading method has been shown to be cheaper and faster. According to a comparison made by Ref.[12], the cost of soil improvement using vacuum preloading is only two-thirds that of by fill surcharge.

2 Soil Investigation of the Proposed Area

The soil profile at the site can be divided into sub-layers as shown in Fig.4. It consists of 1.0 m thick fill overlaying soft clay which extends from 1.0 m to 4.0 m depth. Underneath the soft silty clay a 9.0 m thickness of soft silty clay, the soft silty clay layer can be encountered at 20.5 m depth. From 20.5 m to 23.0 m depth, silty clay is found. Gravel and sand can be encountered at a depth of 28.0 m. The ground water level was recognizable at the ground surface. The initial piezometric level is lower than the theoretical hydrostatic pressure below 22.3 m depth due to the excessive withdrawal of ground water that caused ground subsidence.

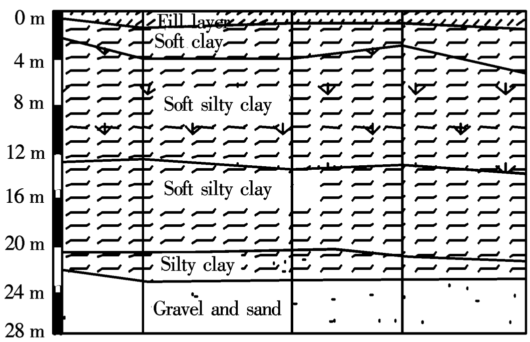

Fig.4 Soft soil section profile at K32 + 281 to K32 + 910

3 Full Scale Test Embankment

The drainage system was constructed on the area with PVDs as shown in Fig.3. A drainage system with 22.0 m of PVDs length was used. The working platforms, which also served as drainage blankets, were constructed with a thickness of 0.30 m for the embankment. The PVDs were installed in a triangular pattern with 1.2 m spacing. The parameters related to the interaction behaviour of PVDs and soft soil are listed in Tab. 1 and Tab. 2 in which the soil is classified as low-to-medium plasticity silty clay. On the top of the drainage system, a water and air tight geomembrane liner was placed. The geomembrane liner was sealed by placing the edges at the bottom of the perimeter trench and covering it with 30 cm layer of sand bentonite and submerging it under water.

Tab.1 Physical properties of the soft soil under treatment

Depth/m	Water content/%	Dry density/($g \cdot cm^{-3}$)	Void ratio	Liquid limit/%	Plasticity index/%	Liquidity index	$C_v/(mm^2 \cdot s^{-1})$
1.2 – 1.5	25.6	1.61	0.691	39.7	17	0.17	0.129 0
2.7 – 3.0	32.8	1.43	0.894	37.3	14	0.68	0.272 0
4.6 – 4.9	38.4	1.32	1.061	36.2	13	1.17	0.327 0
6.4 – 6.7	52.8	1.11	1.439	50.3	21	1.12	0.380 0
8.2 – 8.5	37.4	1.35	1.020	42.3	20	0.76	0.779 0
10.8 – 11.1	43.9	1.23	1.211	42.9	19	1.05	0.205 0
13.3 – 13.6	42.5	1.25	1.170	37.3	13	1.40	0.080 0
15.6 – 15.9	46.4	1.18	1.302	39.2	17	1.42	0.093 9
17.6 – 17.9	29.7	1.41	0.907	24.4	6	1.88	0.786 0
20.2 – 20.5	45.7	1.21	1.243	39.3	16	1.40	0.094 0

Tab.2 Mechanical properties of the soft soil under treatment

Depth/m	S_r/%	G_s	P_c/kPa	E_s/MPa	$K_v/(nm \cdot s^{-1})$	$K_h/(nm \cdot s^{-1})$	C_c	C_s
1.2 – 1.5	100	2.72	135	5.68		0.368	0.15	0.016
2.7 – 3.0	99	2.71	123	5.58	1.31		0.17	0.021
4.6 – 4.9	98	2.73	79	2.98		7.64	0.24	0.021
6.4 – 6.7	100	2.72	93	1.58	6.95		0.47	0.065
8.2 – 8.5	100	2.72	76	3.19		1.63	0.23	0.025
10.8 – 11.1	99	2.72	95	1.92	1.37		0.36	0.036
13.3 – 13.6	98	2.71	76	2.23		3.66	0.32	0.032
15.6 – 15.9	97	2.72	169	2.59	3.89		0.55	0.046
17.6 – 17.9	88	2.69	176	7.44		32.5	0.15	0.012
20.2 – 20.5	100	2.71	122	2.69	1.02		0.37	0.043

Note: S_r is the degree of saturation, G_s is the specific gravity, P_c is the preconsolidation pressure, E_s is the elastic modulus, K_v is the vertical hydraulic conductivity, K_h is the horizontal hydraulic conductivity, C_c is the compression index, and C_s is the swelling index.

4 Ground Treatment Work

Treatment of the soft soil has been made under the controlling conditions of a minimum bearing capacity of 80 kPa. The average degree of consolidation was greater than 85% under a surcharge of 120 kPa, which can be estimated as[13]

$$1 - U = (1 - U_v)(1 - U_r) \tag{1}$$

where U is the average degree of consolidation, and U_v is the degree of vertical consolidation.

$$U_v = 1 - \sum_{m=0}^{\infty} \frac{8}{\pi^2 (2m+1)^2} \exp\left[-\frac{\pi^2}{4}(2m+1)^2 \frac{C_v t}{H^2}\right] \tag{2}$$

U_h is the degree of horizontal (radial) consolidation, it can be estimated as[14]

$$U_h = 1 - \exp\left[\frac{2C_h t}{r_e^2\left(\ln\left(\frac{r_e}{r_w}\right) - \frac{3}{4}\right)}\right] \tag{3}$$

where C_v is the coefficient of consolidation due to vertical flow, C_h is the coefficient of consolidation due to horizontal (radial) flow, $n = r_e/r_w$ is the ratio of the radius of well influence to the radius of the drain well (assuming that the PVD cross section dimension of the well drain's section is a circle).

After applying the vacuum pressure for 6 months, the embankment is raised in stages up to a height of 5.5 m. The stage loading diagrams with time are shown in Fig. 5. The average settlements for a constitutive 45 d period at the center of section K32 + 325, K32 + 415, K32 + 625, K32 + 695, K32 + 795 and K32 + 870 were less than 8.0, 15.0, 7.0, 7.0, 6.0 and 6.5 mm/d, respectively. The results are shown in Tab.3.

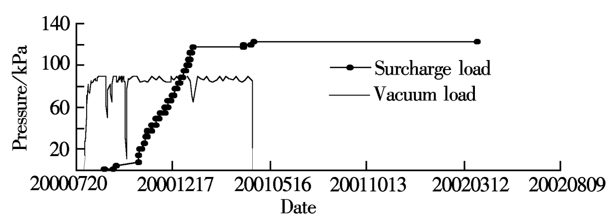

Fig.5 Diagram of vacuum and surcharge loading curve

The PVDs were installed on a triangular grid with a spacing of 1.2 m to a depth of 22 m. Corrugated flexible pipes 85 mm diameter (main pipes) and 55 mm diameter (tributary pipes) were laid horizontally in the sand blanket to link the PVDs with the main vacuum pressure line. The pipes were preformatted and wrapped with a permeable fabric textile to act as a filter layer. Three layers of thin PVC membrane were laid to seal. Vacuum pressure was then applied using vacuum pumps. The water collection system was connected to a vacuum pump capable of continuously supplying 80 kPa vacuum pressure.

Tab.3 Results of rate of settlement and final settlement

Location		Date	Total settlement/cm	Rate of settlement/(mm · d^{-1})
K32 + 325	Center	20020212	213.2	8.0
	Left	20020212	170.2	
	Right	20020212	173.3	
K32 + 415	Center	20020128	235.4	15.0
	Left	20020128	175.1	
	Right	20020128	183.3	
K32 + 625	Center	20020205	171.9	7.0
	Left	20011201	150.4	
	Right	20020205	130.2	
K32 + 695	Center	20020205	150.2	7.0
	Left	20020205	114.8	
	Right	20020205	134.6	
K32 + 795	Center	20020210	167.5	6.0
	Left	20020210	132.9	
	Right	20020210	143.2	
K32 + 870	Center	20020210	154.1	6.5
	Left	20020210	111.5	
	Right	20020210	106.3	

5 Field Instrumentations

The field instrumentations for monitoring of embankment behaviour include surface settlement plates, subsurface multipoint extensometers, piezometers, pore water pressure gauges, and inclinometers. The instrumentations include standpipe piezometers, surface settlement plates or benchmarks, and observation wells. The surface settlement plates were placed directly on top of the geomemebrane liner. The inclinometers were placed at the edges of the embankment. In the area of the project, observation wells, standpipe piezometers and a benchmark were also installed.

6 Measurement Data

The settlement at the embankment area was monitored during vacuum preloading. Curves of the monitored settlement with time are presented in Fig.6,

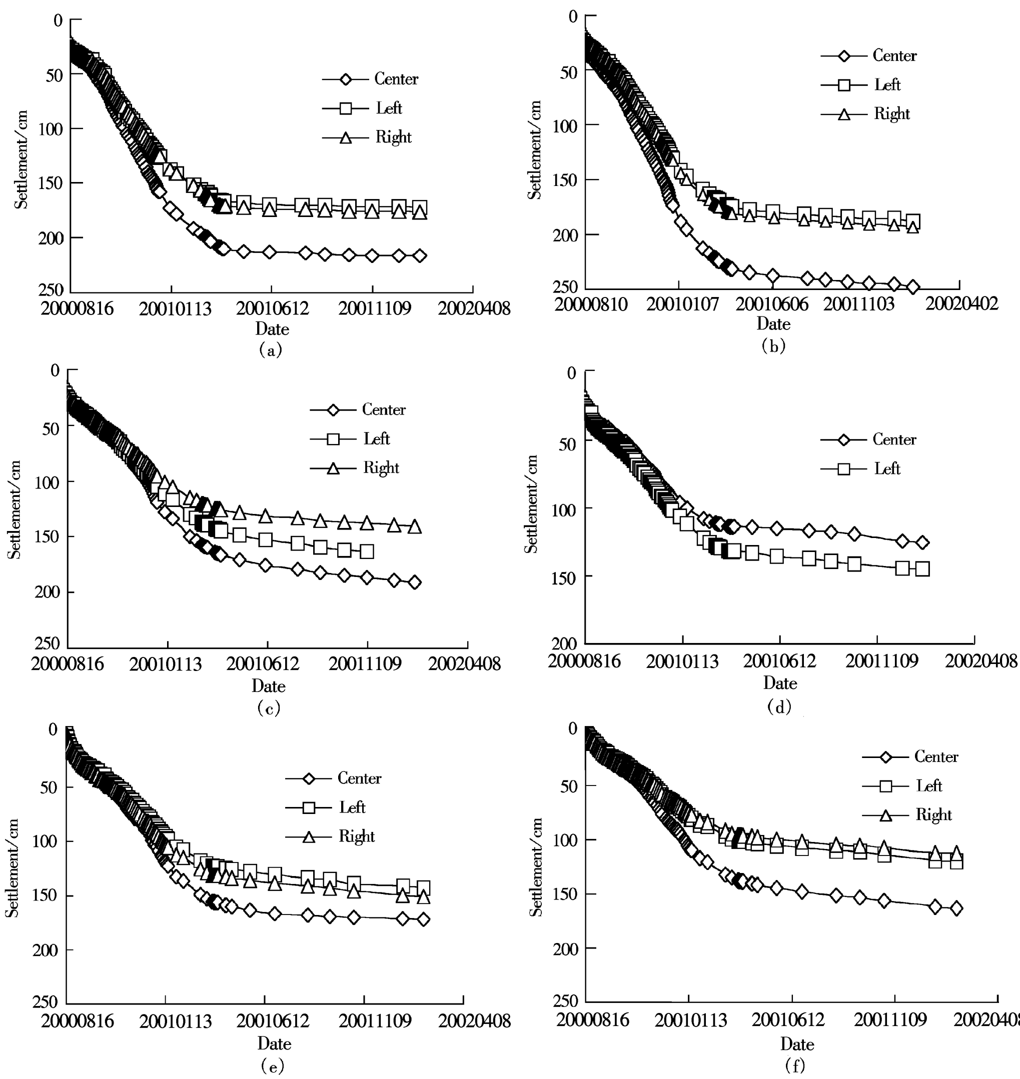

Fig.6 Settlement vs. time. (a) At section K32 + 325; (b) At section K32 + 415; (c) At section K32 + 625; (d) At section K32 + 695; (e) At section K32 + 795; (f) At section section K32 + 870

in which settlements were more at the centers of sections than left wards or right wards of the observed embankment sections for all sections except section K32 + 625 where the settlement at the embankment center was less than the left side, that, depicted in Fig.6 (d), may be due to the mistakes of settlement observation. The rate of surface settlement is shown in Fig.7 where it was about 0.2 to 2.25 mm/d at the beginning in all sections and decreased to be about 0.12 mm/d after 9 months loading. The surface settlement at the end of preloading was 1.063 m to 2.132 m, so, settlement was very high within short time and without shear failure of the soil. All these observed data reveal that the vacuum preloading method was very effective, especially in the cases of combination with surcharge pressure to consolidate and consequently improve very soft soils. The vacuum load caused an inward lateral displacement of about 20 to 25 cm in the soil. The lateral displacements were monitored at various depths with elapsed time, see Fig.8.

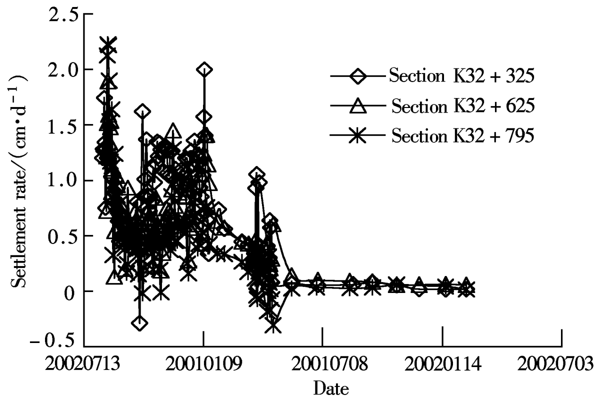

Fig.7 Settlement rate vs. time

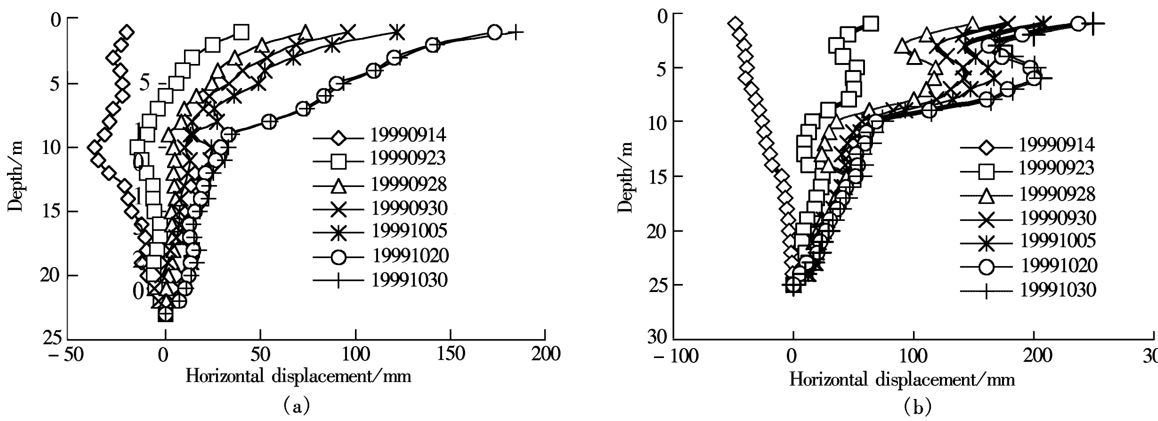

Fig.8 Horizontal displacement vs. depth. (a) At section K32 + 415 right side of the embankment; (b) At section K32 + 695 right side of the embankment

7 Pore Water Pressure

Under vacuum load, the pore water pressure in the soil was reduced. The reductions in the pore water pressure at different depths are plotted against time as shown in Fig.9. In general, the pore water pressures at various depths approached constant after 40 d of vacuum application. The final pore water pressures throughout the full depth indicate that vacuum preloading is very effective.

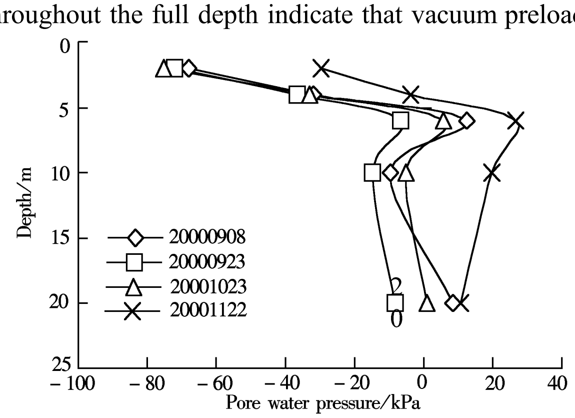

Fig.9 Reduction of pore water pressure at different depths

8 Conclusions

The application of vacuum preloading consolidation of the sea embankment has been described. Ground improvement has performed to prevent damages that occur according to excessive settlement under static and dynamic loading on the sea embankment. Based on the measurements and analyses, the conclusion of the study can be enumerated in the following points:

1) The vacuum preloading method can be used with confidence in ground improvement of sea embankment soft soils foundation.

2) The vacuum preloading can be effectively used for the treatment of very soft clays, which are difficult to treat using surcharge only.

3) For this sea embankment, the lateral displacement was at maximum 25 cm inward; indicating that the vacuum is very effective.

4) The vacuum distribution — a prefabricated

vertical drains system design in a triangular pattern of 1.2 m spacing, PVDs dimensions are 100 mm width and 4 mm thickness, and 22 m depth together with horizontal PVC 82 mm and 55 mm diameters corrugated flexible collector pipes —was effective in distributing the vacuum pressure. A vacuum pressure of 80 kPa was maintained throughout the whole 22 m depth of soft clay.

5) A combined vacuum pressure of 80 kPa and 120 kPa of surcharge achieved more than 85% average degree of consolidation during 6 months.

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真空预压技术加固海堤深厚软基原型试验研究

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摘要: 真空荷载提供了一种减少堤坝软土地基固结时间的选择.本文开展了一个海堤全断面的试验及原型观测研究.试验堤高 5.5 m, 22 m 深且三角形布置的塑料排水板作为竖向排水通道, 现场布置了水平测斜和沉降仪等观测仪器, 埋设在不同地基深度的孔隙水压力计用来量测真空-堆载联合荷载下的地基中超静孔隙水压力的变化.通过场地条件分析、高真空度维持和真空卸载, 得到了系统的沉降变形和孔隙水压力资料, 试验结果验证了真空-堆载联合预压加固海堤软土地基的效果.

关键词: 软土; 垂直排水井; 真空荷载; 海堤; 地基处理

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