Experimental study and application of vacuum preloading for consolidating soft soil foundation

Etude expérimentale et application du préchargement par vide pour la consolidation

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SYNOPSIS The paper described the large scale practical engineering effects obtained by the vacuum preloading method in coastal areas in China in recent years. A new consolidation method that surcharge preloading in the meantime of air-pumping was studied. The paper emphatically introduced its technology, consolidation efficiency and the situation of its application. The processes of consolidated deformation under vacuum was analysed with the aid of centrifugal model test and numerical calculation with finite element method. The paper explained the mechanism of vacuum effects and demostrateo that the consolidation effect can be superposed when vacuum plus surcharge preloading is applied.

INTRODUCTION

At the beginning of 80's, the technique of vacuum preloading for consolidating soft soil foundation developed at our institute has already satisfied engineering requirements with successful consolidation effect. From 1983, in combination with construction projects, field tests for applying and optimizing the consolidation technology on a vast area were carried out, as a consequence , to make this method rapidly reach the stage of engineering application. At the same time the vacuum preloading consolidation in combination with surcharge preloading was developed on the basis of vacuum one, and has achieved success in practical project in 1984. Meanwhile, laboratory tests and theoretical analysis were made for both method in order to estimate the consolidation process of vacuum preloading and vacuum + surcharge preloading and understand the mechanism of vacuum preloading consolidation. By means of improving in-situ construction technology, up to now, unit area covered up with an integral membrane has reached 25,000— 30,000m², vacuum degree could be kept over 650mmHg. Only one vacuum apparatus of 7.5 KW was needed to get vacuum degree of 650mmHg for consolidating 1,500m² each time.Thus, in recent years this method has been widely applying in the construction of soft foundation consolidation in the coastal area in China, obtaining the greatest technico-economic benefits over that of surcharge preloading one.

MECHANISM ANALYSIS OF VACUUM PRELOADING CONSOLIDATION

Concept of Consolidation in Saturated Soil

Pore water pressure u in soil mass can be understood as excess pore water pressure, it can also be considered as the total potential energy of pore water pressure:

$$u = u' + r_w z + r_w \frac{v^2}{2g}$$

in which various terms express pressure energy, energy of position and velocity potential of pore water respectively, a seepage velocity is generally so low that velocity potential can be neglected.

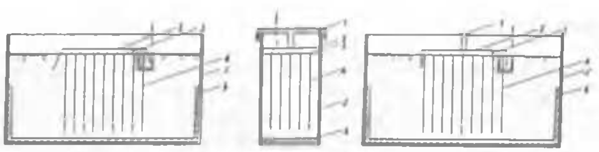
When value u on boundary of soil mass decreases or when unequal increment of u occur in various points in soil mass due to external load, distribution of total potential energy of u between soil mass and its boundaries will be in disequilibrium. If water can be drained from the boundaries the disequilibrium of u will make a part of pore water drain from soil and decrease the value u, correspondingly, the stress will be transferred from pore water pressure to soil skeleton, and this makes σ' increase. Soil mass will be compressed only when σ' increases, deformation will be stabilized until value u in soil mass is transformed into a new equilibrium state adopting to the boundaries,this whole process is called consolidation. It is the disequilibrium of total potential energy of u that is the sole source causing consolidation, which is unnecessary to be caused by external load. Disequilibrium of u , however, is only the necessary condition for consolidation, which doesn't necessarily cause consolidation (for instance, swelling by water absorption), the drainage of poer water from soil and the increasing of σ' are the sufficient conditions for consolidation.

Mechanism Analysis of Vacuum Preloading

Before consolidation, if the soil is normally consolidated, u (potential) on various points are equivalent, there will be no flowing of pore water. Vacuum preloading, shown as in Fig.4, functions in such a way, because the vacuum-pumping doen't change the total stress essentially, but only reduces the value u (potential) in sand drain and sand mat, potential difference of u will be formed in soil mass. Under the action of potentail difference of u, pore water will be drained with seepage flow accordingly thus reduces the potential u in soil .According to Terzaghi's Effective Stress Principle, if total stress σ is not changed, deduction of value of u will be as same as the increment of value of σ'. Thus, the potential u will be further reduced at various points and transferred to further points, as a result, σ' on various points will be increased, soil mass compacted gradually until new equilibrium of u potential forms in soil mass and at boundaries i.e. until deformation becomes stable. This is the whole process of vacuum preloading consolidation.

Discussion on Various Ideas about Mechanism

It was considered by some one that consolidation is produced by pressure difference, P=Pa -Pv, formed between inner (Pv) and outer (pa) sides of sealing membrane when vacuum preloading. Comparative tests of centrifugal model shown in Fig. 1 indicated : P may transfer to the soil through flexible membrane, but P can't transfer to the soil through stiff membrane fixed on the upper edge of the model, but was undergone by the membrane. However the vacuum pumping caused 69cm and 61cm settlement of soil mass respectively. This proved that vacuum preloading is independent of whether there is P on the soil or not, it is different from surcharge preloading caused consolidation by applying external load.



2- plastic sealing membrane
3- 6 same as in Fig. b.

a. Vacuum Preloading Test with Flexible Membrane

1.angle steel 2.stiff sealing 3. sand mat 4.sand drain 5.model salt 6.saturated non-weaven cloth

b. Centrifugal Model Test of Vacuum Preloading with Stiff Membrane

Fig. 1 Comparative Test of Centrifugal Model with Vacuum Preloading

Stress paths for both are different too. TSP(total stress path)line of surcharge preloading is shown in Fig.2 as MB_3, ESP follows from point M to B_3 along the dotted line and generally varis between lines K_o and K_f, in a MC state (ε_b< 0) shown as in Fig.3, so the squeezed deformation begins to appear. For helping shear stress τ_c always smaller than shearing resistance τ_{cf}, load should be applied in steps. TSP will not vary at point M when vacuum preloading takes place. ESP (effective stress path) is MD line. Because it fluctuates between line MG and K_o , in a MD state shown as in Fig.3, so it appears the compression deformation. No stepped vacuum-pumping is needed, because shearing resistance τ_{vf} is getting higher than τ_v more and more.

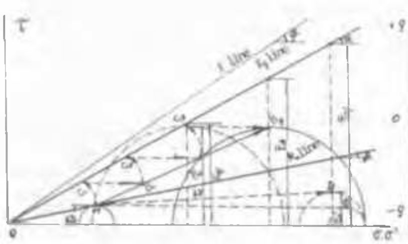


Fig.2 Stress Pathes of Vacuum Preloading and Surcharge Preloading

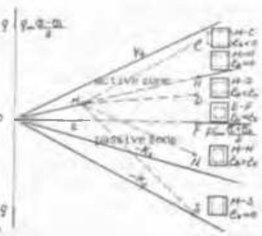


Fig. 3 Stress Pathes Under Different Deformation

When there is potential difference of u in soil mass and seepage flowing field has formed, difference in quantity of water flowing in and out from unit soil mass will exist : When $\partial u/\partial t$< 0, quantity of water decreases, soil mass will be compacted & consolidated; when $\partial u/\partial t$> 0, quantity of water increases, soil mass swells up by water absorption; when $\partial u/\partial t$=0, state & dynamic state will be in equilibrium, no deformation of soil mass will occur. When seepage flow occurs, water produces static pressure (bouyant force) and dynamic pressure (stress of seepage flow) on soil particales. Because the difference in equilibrium relationship of buoyant unit weight and stress of seepage flow and the value of $\partial u/\partial t$, seepage flow can not only densify soil, but also can make soil loose, even can cause pipe gushing and sand running. Stress field of seepage flow certainly results in flowing of water mass, which is the necessary but unsufficient condition for consolidation, the sufficient condition is that $\partial u/\partial t$< 0 and σ' increases. Besides, the direction of seepage flow stress is not definitely coincident with that of consolidation stress. In a word, there is no causality between seepage flow and consolidation.

PRACTICAL EFFECT OF VACUUM PRELOADING METHOD

Consolidation effect of vacuum preloading for drainage depends on vacuum degree beneath membrane (in sand blanket). Improvements were made for several times for the construction technology of that method (see Fig.4) in order to obtain higher vacuum degree beneath membrance, for example, the problem of sealing effects has been solved by development of sealing membrane with fine airtightness, improvement of placement technology and covering water on membrane, vacuum pumping capacity and efficiency have been increased by further improvement of the vacuum apparatus. At present, vacuum degree beneath membrane used in construction may reach above 650 mmHg.Unit spreading area of membrane has been extended to 25,000-30,000m². Power requirement takes only 5w/m², i.e. one set with 7.5KW can control a consolidation area of 1,500m². Hereafter we shall take the foundation construction of container yard in Tianjin Port as an exampl to describe consolidation effect with this method.

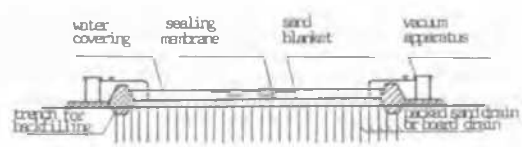


Fig. 4 Technological Arrangement of Vacuum Preloading

Geological conditions of that region are shown in Table 1. It can be seen from the process curves of measured ground settlement after consolidation with vacuum preloading in Fig.5 that consolidation by vacuum preloading is quicker than that by surcharge preloading, for reaching a similar consolidation degree, the former can shorten preloading time by 1/3 (pack drain: diameter=7cm, spacing=1.3m, Length=10m). Calculated values shown in Fig.5 are the results calculated with finite element method, where the deformation of consolidation was estimated as a 2D problem of variable elasticity mode. Ground settlement (see Fig.6) was also larger than that with surcharge preloading. Especially, the observation of horizontal deformation indicated that soil mass produced shrinkage deformation under vacuum action, the vacuum pressure could reach it's maximum value rapidly, which coincident with analyzed results of stress pathes stated in previous chapter. Besides, when he similar vertical deformation ocured, density of soil mass could be higher than that of surcharge preloading.

TABLE I

Indexes of Soil Properties for the Foundation

depth (m)	soil classification	γ (kN/m³)	W (%)	e	I_p
0—2.0	loam	19.6	43	0.97	12
2—5.0	silt mingled with silty loam	16.0	59	1.72	24
5.0—10.0	silty clay mingled with loam	17.6	44	1.24	18
10.0—15.0	silt	16.7	53	1.52	24

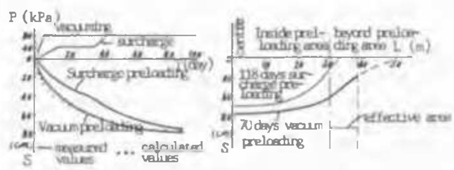


Fig.5 P-S-T Process Curves Fig.6 Settlement Distribution Curves

It was known from the results measured in original location with field vane test and self-boring pressure meter test (see Table 2) : foundation strength after consolidation with vacuum preloading also appeared a distinct increment. Results of static loading tests proved that allowable ground bearing capacity might increase by a factor of 2.

TABLE II

Strength Indexes of Vane and Pressuremeter Tests

depth beneath ground surface (m)	soil classification	vane C_u 1 (kpa)	vane C_u 2 (kpa)	vane C_u 3 (%)	pressuremeter C_u 1 (kpa)	pressuremeter C_u 2 (kpa)	pressuremeter C_u 3 (%)
0—2.0	loam				17	45	165
2.0—5.0	silt mingled with silty loam	12	28	133	10	25	150
5.0—10.0	silty clay mingled with loam	15	27	80	15	29	93
10.0—15.0	silt	23	28	22	21	29	38

notes: 1- before improving ; 2- after improving ; 3- increment rate

For further verifying consolidation effect of vacuum preloading an actual surcharge preloading test was carried out on the foundation consolidated under vacuum of 600mmHg. Mountain mantle was used as surcharge material in 4 steps.Observation of vertical and horizontal deformation of the foundation under each step of loading was made. Inspection results showed that vacuum preloading would achieve its consolidation effect equivalent to 80kpa which might be obtained by surcharge preloading.

CONSOLIDATION METHOD BY VACUUM PLUS SURCHARGE PRELOADING

Distinguishing feature of this method is: surcharge preloading can be applied at the same time with vacuum-pumping, it can not only breakthrough the limit that equivalent load can not exceed 100kpa with vacuum preloading method,but also lower the surcharge height and accordingly reduce the quantity needed with surcharge preloading. Technological arrangement of this method was shown in Fig.7, which was divided into upper and lower part. The lower part was vacuum preloaded first until the vacuum degree beneath the membrane reached above 600mmHg(80kpa) and the strength met the desirement, and then surcharge loaded on the membran, The practical effects were described as follows by taking a test project as an example.

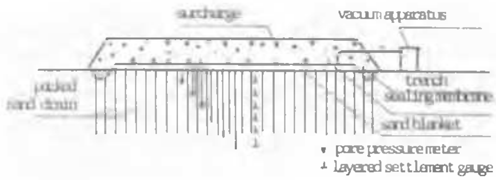


Fig.7 Technology of Vacuum Preloading in Combination with Surcharge Preloading and the Arrangement of instrumentation

The area of test project was 53x60m², preloading pressure increases to be 135kpa defined by engineering requirement. The vacuum preloading could create 80kpa equivalent load, besides, additional load 55kpa should be provided by surcharge preloading. Test results indicated that under the joint action of positive and negative pressure both ground deformation and strength could produce superposed effects.

<u>Observation and Analysis of Deformation</u>

It can be seen from the measured ground settlement process curves shown in Fig.8 that the maximum settlement in the center after vacuum preloading for 78 days was 60.3cm, total settlement amount to 77.7cm,including settlement produced between after installing vertical drain and before vacuum-pumping. Afterward surcharge preloading was applied for 98 days and produced additional settlement of 53.5cm, thus the final settlement was 131.2cm. It shows that when vacuum preloading in combination with surcharge preloading for consolidation was applied, the effects could be superposed.

Calculated values in Fig.8 were obtained with finite element analysis, assuming that the boundary conditions of both vacuum and surcharge preloading would vary simultaneously. It can be seen clearly that calculated values of ground settlement were in rather good agreement with measured ones, which further proved the superposed effect above mentioned. Centrifugal model tests were made in laboratory. The vacuum pumping was operated by a centrifugal machine,

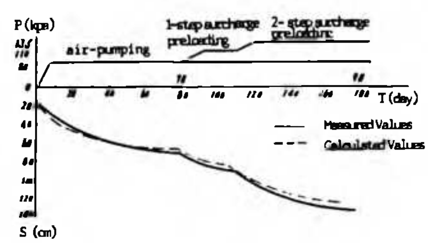


Fig. 8 P-S-T Curves of Vacuum + Surcharge Preloading

at the same time surcharge consolidation on flexible membrane was carried out. It was known that the settlement after combined consolidation with 80kpa vacuum pressure and 40kpa surcharge pressure was approximately equal to the settlement obtained with 120kpa surcharge preloading, which further proved that consolidation stress & consolidation effects created vacuum-surcharge preloading can be superposed.

Increment of Strength

Water content, unit weight & void ratio in foundation soil were greatly improved after combined consolidation with vacuum & surcharge preloading Vane Strength listed in Table 3 indicated that strength achieved after combined consolidation appeared a more distinct increment than that a after vacuum preloading. Static load tests showed: allowable bearing capacity could be improved to 200kpa from 60kpa for natural foundation & from 20kpa foundation improved by vacuum preloading.

TABLE III

A Comparison of Vane Strength Increment in Various Soil Strata Before and After Consolidation

Item / Depth	(1) before consolidation (KPa)	(2) after vacuum preloading (KPa)	(3) vacuum + surcharge preloading (KPa)	$\frac{(2)-(1)}{(1)}$ (%)	$\frac{(3)-(1)}{(1)}$ (%)	$\frac{(3)-(2)}{(2)}$ (%)
2.0—5.0	12	28	40	133	233	43
5.0—10.0	15	27	36	80	140	33
10.0—15.0	23	28	33	22	43	18

For better verifying its consolidation effect actual surcharge test was made. Soil of mountain mantle was used as stacked material in 6 steps. Vertical & horizontal deformation of the foundation at all load levels were obtained. Test results showed that the effect of vacuum preloading (80kpa) in combination with surcharge preloading (55kpa) was as same as that of surcharge preloading(135kpa) alone.

ENGINEERING APPLICATION

In recent years in coastal regions in China, such as Xingang Port of Tianjin, Lianyun Port, Shanghai, Zhenjiang, Ningbo, Wenzhou, Fuzhou & other places,two methods above-mentioned have obtained wide application. The foundation consolidated have been used for constructing cargo storage yards, warehouses, as well as industrial and civil building, reservoirs and etc. Total consolidated area mounted to 1,100,000m². Two case histories using vacuum preloading are given below:

The first case is the foundation soil improvement works of auxiliary construction region on the East Pier,Xingang Port, Tianjin, with an area of 200,000m².

The second case is plastic boards with a length of 12m and a spacing of 1.3m were installed into soft soil with stratum thickness of 16m. After vacuum-pumping for 90 days, ground settlement reached 100cm.

One more example as regard to alkali factory in Lianyun Port located on an alkaline land near beach, where 10m long packed sand drains were installed with a spacing of 1.2m into clay (I_p=30) at the depth of 10m, 150,000m² area was consolidated, vacuum degree beneath membrane was stabilized at 700mmHg, after 4 months vacuum-pumping settlement reached 70cm. Vacuum preloading was carried out first and then pile driving for consolidating foundations of power station and heavy alkali workshop of this factory, resulting in elimination of negative friction of pile.Surcharge preloading, such as the consolidation works of storage yard on the East Pier of Tianjin Port under construction (international tendering invited), where 20m long plastic board was installed with a spacing of 1.3m into extra soft foundation to the depth of 20m for consolidating 200,000m² (another 300,000m² was planned to be consolidated by vacuum preloading) vacuum degree beneath membrane was stabilized at 700mmHg, area covered with an integral membrane reached 26,000 m² and so on.

CONCLUSION

(i) Vacuum preloading is different from surcharge preloading, the consolidation is realized by reducing u (potential) on boundaries and forming potential difference from soil mass and finally resulting in reduction of u and increasing of σ'. When σ remains essentially unchanged,reduction of u is equal to the increment of σ'.

(ii) as a result of three main improvements— pump, membrane and water covering— for vacuum preloading, vacuum degree beneath membrane can be maintained at 650mmHg, corresponding to 80kpa equivalent consolidation load. This method possesses several advantage such as fine effect, low cost, short construction period and need no stacked material, it is an ideal method for consolidating soft clay, especially for extra soft clay.

(iii) engineering practice, centrifugal model tests, finite element calculation and mechanism analysis indicated that consolidation effect of combined method with vacuum and surcharge preloading is the sum of consolidation effect produced by vacuum preloading and surcharge preloading. This method can be used for consolidation works which have higher demand on preloading pressure.

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