Sensitivity Analysis on Factors of Vacuum Preloading Strengthening Effect

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Abstract. The depth, arrangement mode and the loading mode of plastic vertical drainage (pvd) have great influence on the reinforcement effect. An arrangement mode of vacuum preloading to reduce the impact was put forward. The combination of different depth of pvd and loading modes are used to analyse the effect of vacuum preloading treatment and its influence range. The calculations show that the deformation and the influence distance are smaller by using the 40kPa vacuum loading and 41kPa surcharge load preloading. Reducing the depth of the pvd and vacuum combined surcharge preloading can weaken the influence to the existing highway.

1. Introduction
Vacuum preloading is an effective method for soft soil foundation treatment. In recent years, this method has been widely used in airport, wharf yard, expressway and newly dredged fill foundation treatment [1-3]. Under the action of vacuum load, the soft soil foundation will produce lateral shrinkage deformation facing the reinforcement area, and the adjacent buildings or structures may be seriously affected and even have engineering accidents [4-6]. Therefore, in the design of vacuum preloading, on the one hand, corresponding safety measures should be taken for adjacent buildings or structures in the affected area. On the other hand, it is also necessary to optimize the punching depth and load layout of vacuum preloading. According to the engineering example, the depth and load arrangement of drain boards are studied in this paper.

2. Project overview
A soft foundation treatment site is close to its existing provincial highway and the nearest distance to the road corridor is 7m. This provincial highway is a city main road with 6 lanes in both directions. The highway is treated with CFG piles with a diameter of 40cm. The surface layer of the soft foundation treatment site is backfilled with plain soil, containing some stones, and the burial depth is large, so it is difficult to insert drain boards or carry out mixing wall construction. If excavation and replacement are required within the site before inserting plate construction, some areas need to be excavated 3m deep, and the excavation and replacement construction has certain influence on the existing road corridor, so support treatment is required before excavation and replacement. The support structure adopts high-pressure jet grouting pile, and the continuous wall formed by the support structure can be used as a vacuum preloading sealing wall.
It is necessary to verify whether the isolation and protection measures between the soft foundation treatment site and the existing provincial highway are reasonable and whether the vacuum preloading can ensure that the impact on the highway is small enough and will not cause excessive damage.

The treatment width of the vacuum preloading area is 25m. During the treatment, the site should be leveled to an elevation of 2.2m first, and then a retaining structure should be set up.

Considering the most unfavorable situation, a section with the largest thickness of soft soil layer is selected as the calculation section, and the soil layer parameters of the calculation section are shown in Table 1. Different foundation treatment methods were chosen to compare and analyze the influence of foundation treatment on existing roads under different methods. These treatment methods include: (1) vacuum preloading treatment, short drainage plates with a length of 10m are used near the existing roads and 17m are used in other places; (2) Vacuum combined stacking, vacuum pressure 60kPa, stacking pressure 24kPa, drain plate 17m; (3) Vacuum combined stacking, vacuum pressure 50kPa, stacking pressure 33kPa, drain plate 17m; (4) Vacuum combined loading with vacuum pressure of 60kPa and loading pressure of 24kPa, short drainage boards with a length of 10m are used on the side close to the existing highway and 17m in other places; (5) Vacuum combined loading with vacuum pressure of 50kPa and loading pressure of 33kPa, short drainage boards with a length of 10m are used on the side close to the existing highway and 17m; (6) The vacuum pressure is 400kPa, the stacking pressure is 41kPa, and the drain boards are all 17m.

| Name | depth (m) | Density (g/cm³) | E (MPa) | C (kPa) | φ(°) | K(cm/s) Vertical | K(cm/s) horizontal |
|------|----------|----------------|---------|---------|------|------------------|-------------------|
| 1-1  | 2.16     | 1.72           | 2.06    | 7       | 16.8 | 2.71E-05        | 2.95E-05          |
| 2-1  | 8        | 1.62           | 1.84    | 6.7     | 16.2 | 3.44E-07        | 4.56E-07          |
| 2-2  | 2        | 1.6            | 1.72    | 6.7     | 16.2 | 2.90E-07        | 4.37E-07          |
| 3    | 7.5      | 1.62           | 1.64    | 7       | 16   | 2.56E-07        | 3.38E-07          |
| 6-1  | 4.3      | 1.71           | 2.29    | 8.8     | 16.5 | 7.21E-08        | 7.15E-08          |

3. Simulation calculation

According to the geological data in table 1, a mechanical model as shown in fig. 1 was established using large commercial software FLAC3D.

![FLAC3D 5.00](image)

Figure 1 mechanical model of vacuum preloading

Considering symmetry in the model, only half of the vacuum preloading area and one side of the road are selected. Because CFG piles in the pipe gallery are arranged in a regular triangle with a spacing of 2m, the model thickness is 1m, and the whole model size is 100m×40m×1m. CFG piles are staggered on the front and back of the model, and CFG is 1m deep into the 6 - 1 silty clay layer according to the design requirements. Pile is shown as a retaining structure between the vacuum preloading area and the highway. In the figure, CFG_pile is a CFG pile in the subgrade of expressway, with a pile diameter of 40cm and a pile body entering silty clay of 1m, which is simulated by solid unit.

When long and short drainage boards are combined with vacuum preloading, short drainage boards of 10m will be used within 10m of the existing road side, while drainage boards in other places are 17m.
As they no longer have symmetry, a full-strength model is established. The retaining structure adopts high-pressure jet grouting pile, and the retaining structure on the other side is a clay sealing wall. As can be seen, the maximum settlement occurs on the side of the vacuum zone center away from the 10m short plate. When a 10m short drain board is used within 10m close to the road side, the influence range of foundation treatment on existing roads is 24m, the maximum lateral displacement of CFG piles adjacent to the road corridor is 12.2cm, and the maximum lateral displacement of CFG piles at 15m away from the vacuum area is 6.6cm.

When 60kPa vacuum pressure plus 24kPa vacuum combined with loading treatment, an axisymmetric mechanical model was established, with all drainage plates 17m. Stacking loads in the model are added as surface loads. The vacuum pressure reached 60kPa for 10 days and then remained unchanged. After 15 days, preloading was started. After 10 days, the surcharge reached 24kPa and was unloaded after 110 days.

As can be seen from result, the central surface settlement in the vacuum preloading area is the largest, and gradually decreases toward the surrounding area and the depth of the foundation. There is an obvious boundary between vacuum preloading area and non-vacuum preloading area, and the maximum settlement of the whole model is 2.27m. The maximum lateral displacement occurred near the retaining structure in the vacuum preloading area, and its value reached 0.4m.

When all the long drainage boards are used and the vacuum pressure is 60kPa and the stacking pressure is 24kPa, the influence range of foundation treatment on the existing highway is 20m, the maximum lateral displacement of CFG piles adjacent to the vacuum zone of the existing highway corridor is 8.3cm, and the maximum lateral displacement of CFG piles at 15m from the vacuum zone of the existing highway is 5.3cm.

When the vacuum pressure of 50kPa plus 33kPa is combined with vacuum preloading, the drainage plates in the mechanical model are all 17m, and the foundation treatment is carried out by vacuum combined with preloading, the vacuum pressure is 50kPa, the loading pressure is 33kPa, the vacuum pressure reaches 50kPa for 10 days, and then remains the same, the preloading starts after 15 days, and the preloading reaches 33kPa after 10 days and is unloaded after 100 days.

According to the calculation results, the center surface settlement of vacuum preloading area is the largest, and the maximum settlement of the whole model is 2.23m. The maximum lateral displacement occurred near the retaining structure in the vacuum preloading area, and its value reached 0.44m.

When all the long drainage boards are used and the vacuum pressure is 50kPa and the stacking pressure is 33kPa, the influence range on the existing highway is 5m, the maximum lateral displacement of CFG piles adjacent to the vacuum zone of the existing highway corridor is 5.4cm, and the maximum lateral displacement of CFG piles at 15m from the vacuum zone of the existing highway is 3.3cm.

When the long and short drainage boards are combined with 60kPa vacuum pressure and 24kPa stacking pressure foundation treatment, 10m short boards are used for 10m drainage boards close to the existing highway in the mechanical model, and 17m long boards are used for other places. The vacuum pressure reached 60kPa for 10 days and then remained unchanged. After 15 days, preloading was started. After 10 days, the surcharge reached 24kPa and was unloaded after 110 days.

It can be seen from the results that the maximum settlement of the whole model is 2.17m. When long and short drainage boards are combined with vacuum pressure of 60kPa and stack load pressure of 24kPa, the influence range on existing roads is 1.9m, the maximum lateral displacement of CFG piles adjacent to the vacuum zone of existing road corridor is 5.8cm, and the maximum lateral displacement of CFG piles at 15m from the vacuum zone of existing roads is 2.0cm. The lateral displacement of several CFG piles near the retaining wall is positive and negative, and the pile body is distorted, which is very unfavorable to the stability of CFG pile foundation.

When the long and short drainage boards are combined with the foundation treatment of 50kPa vacuum pressure plus 33kPa stacking pressure, 10m short boards are used for 10m drainage boards on the side of the mechanical model close to the existing highway, and 17m long boards are used for other places. The vacuum pressure reached 50kPa for 10 days and then remained unchanged. After 15 days, preloading was started. After 10 days, the surcharge reached 33kPa and was unloaded after 100 days.
The calculation results show that the maximum settlement of the whole model is 2.17m.

When the scheme of combining long and short plates with vacuum pressure of 50kPa and stacking pressure of 33kPa is adopted, the influence range on existing roads is 8m, the maximum lateral displacement of CFG piles adjacent to the vacuum zone of existing road corridor is -7.7cm, and the maximum lateral displacement of CFG piles at 15m from the vacuum zone of existing roads is -3.1cm. The negative lateral displacement indicates that the soil moves in the direction of the existing highway and several CFG piles near the retaining wall are distorted.

Through the analysis of the results, it can be seen that on the one hand, the combination of long and short plates will easily cause the CFG pile near the retaining wall to twist, on the other hand, the vacuum combined surcharge preloading method will help weaken the adverse effect on the existing roads, and the vacuum pressure and surcharge pressure will have opposite effects on the existing roads. Based on this idea, another treatment method is analyzed: all the long plates will have 40kPa vacuum pressure and 41kPa surcharge pressure.

When 40kPa vacuum pressure plus 41kPa vacuum loading treatment is combined, the mechanical model drain boards are all 17m, the vacuum pressure reaches 40kPa for 10 days and then remains the same. After 15 days, the first stage of surcharge preloading is started, after 10 days, the surcharge reaches 25kPa and remains for 5 days, and then the second stage of surcharge preloading is carried out, after 10 days, the surcharge reaches 41kPa and remains for 100 days to unload.

From the calculation results, it can be seen that the central surface settlement in the vacuum preloading area is the largest, and the maximum settlement of the whole model is 2.17m. The maximum lateral displacement occurred near the retaining structure in the vacuum preloading area, and its value reached 0.37m.

The drainage boards are all made of long plates, with vacuum pressure of 40kPa and stacking pressure of 41kPa, the maximum lateral displacement of CFG piles adjacent to the vacuum zone of the existing highway corridor is 4.3cm, the maximum lateral displacement of CFG piles at 15m from the vacuum zone of the existing highway is 2.5cm, and the lateral displacement of both the corridor and the existing highway is less than 5cm.

4. Comparative analysis of various schemes
The comparative analysis of different drainage plate setting methods shows that reducing the depth of drainage plate setting is effective in weakening the influence of existing highway sides, and has been significantly reduced in terms of the scope and degree of influence. If CFG distortion occurs, it is not conducive to the stability of CFG pile foundation. Therefore, it is not recommended to set up drain boards by combining long and short plates during vacuum preloading.

| condition | (1) | (2) | (3) | (4) | (5) |
|-----------|-----|-----|-----|-----|-----|
| sphere of influence /cm | 24  | 20  | 5   | 1.9 | 8   |
| Maximum lateral displacement of CFG pile near vacuum zone in pipe corridor /cm | 12.2 | 8.3 | 5.4 | 5.8 | -7.7 |
| Maximum lateral displacement of CFG pile 15m from vacuum area /cm | 6.6  | 5.3 | 3.3 | 2.0 | -3.1 |

The comparative analysis of the influence of different pressure loading modes on the highway shows that the negative influence of vacuum combined with surcharge preloading on the highway is generally smaller than that of vacuum preloading, and the closer the vacuum pressure is to the surcharge pressure, the less the negative influence is.

| condition | (1) | (4) | (5) | (6) |
|-----------|-----|-----|-----|-----|

Table 3 Comparison results of different loading mode
5. Conclusion
In this paper, the numerical analysis is carried out for different drainage plate setting depth, layout method and load loading method, and the following conclusions are obtained:

(1) It is effective to weaken the influence of soft foundation treatment on the road by reducing the depth of drainage plate, which has been significantly reduced from the scope and degree of influence;

(2) The foundation treatment method of reducing vacuum load and preloading can effectively reduce the impact on highway pile foundation, and the protection effect is obvious in terms of the scope and degree of impact. Among them, the 40kPa vacuuming load plus 41kPa preloading load is adopted, and the degree and distance of deformation influence are relatively minimum.

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