

# Influence of Vacuum Preloading of Soft Ground on Surrounding Environment and Nearby Building Considering Unloading Effect

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**ABSTRACT:** Although the vacuum preloading has been widely used in the engineering, the influence area of horizontal deformation is controversial. In order to clarify the influence range and show the deformation of nearby building during loading and unloading of vacuum pressure, a series of finite element analyses are carried out. The horizontal displacement of the ground and the building is shown quantitatively during the application of vacuum pressure. The inclination of the building during unloading is also calculated.

**KEYWORD:** Vacuum preloading; influence area; building deformation; unloading effect

## 1 ENGINEERING BACKGROUND

Vacuum preloading has been one of the most effect and economic ground improvement method for the soft soil. Different to the surcharge preloading, the ground during improvement deforms towards the inside of improved area. Therefore there is no point in worrying about the instability of the ground due to rapid loading rate. However, the influence of the horizontal deformation on the surrounding environment should be specially discussed. (Yu Z.Q. et al, 2001) analyzed the measured data and gave a suggestion about the influence range. (Chen L. Y. et al, 2005) researched the property of isolation piles including depth, stiffness, length and permeability. (Ai Y. B. et al, 2007) calculated the ground crack near the building during the vacuum preloading and discussed the influence factors on the horizontal displacement.

In the practical field, the distance between the edge of the improved area and the building is around 15m. Accord to the previous experience, the horizontal influence zone during the vacuum preloading is over 20m, which would cause significant influence to the foundation of the build. In order to evaluate the possible deformation of the building, it is very necessary to make some calculations before the construction of the vacuum preloading.

## 2 SOIL PARAMETERS

According to the ground exploring and drilling holes, the depth of the soft soil is very thick. The soil can

be classified into six kinds along the depth, including filling, sludge, silty clay, alluvial soil, diluvial soil, completely-weathered moorstone, and the details are described as follows: 1) the depth of filling is between 0-5m, and the number of SPT is between 3-8; 2) the sludge is saturated and in a fluid plastic state; the tip resistance of static sounding is around 0.24-0.39MPa and the number of SPT is usually lower than 2, which is a very soft soil; 3) the silty clay is in a plastic state and the depth is around 17-20m; the tip resistance of static sounding is around 0.9-1.3MPa and the number of SPT is usually between 8-14; 4) the alluvial soil is saturated mixture between sand and clay; the tip resistance of static sounding is around 1.85MPa and the number of SPT is usually between 6-16; 5) the diluvial soil is mainly medium coarse sand under saturated and medium-dense state; the tip resistance of static sounding is around 2.51MPa and the number of SPT is usually between 13-26.

## 3 NUMERICAL MODEL

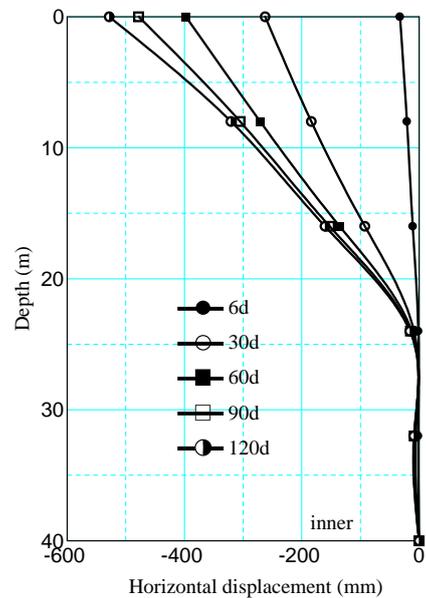
Limited to the space of the text, the relative position between the improved area and the building is omitted. Considering the symmetry of the model, half of the model is used and the simplified plane strain condition is adopted. The width and the depth of the improved area are 24m and 23m respectively. The depth of the sludge and the silty clay are 23m and 17m respectively. At the top of the improved area, the vacuum pressure of -80kPa is applied to form the pressure boundary. The classification of the ground

is divided into sludge, silty silt and silty clay. For other top surface, the atmosphere boundary is adopted. The impermeable boundary is designated to the two side surfaces and the bottom. The height and the width of the building are 18m and 10m respectively. The distance between the improved area and the building is 15m. Considering that the building is a three dimensional structure, the weight and the stiffness of the building should be transferred equivalently to satisfy the plane strain condition.

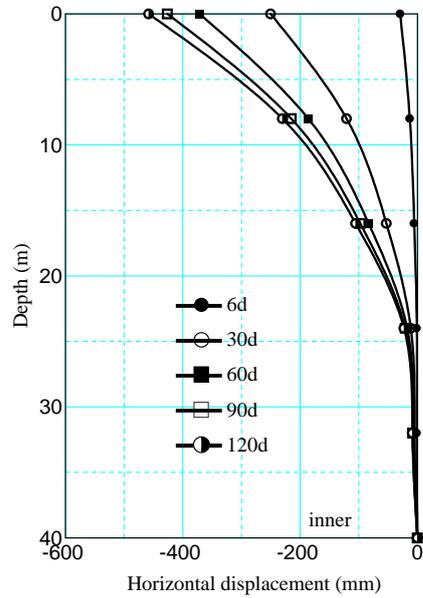
## 4 CALCULATION RESULTS

### 4.1 Horizontal displacement.

According to the relationship between the horizontal displacement and time, the variation of the horizontal displacement along the depth can be obtained, as shown in Figure 1. It gives two horizontal displacement-depth curves when the distance from the borderline is 1m and 5m respectively. As can be seen, there is already certain displacement after 6d vacuum preloading. Until 30d, the displacement rate becomes relatively large. The displacement gradually becomes larger and larger with the duration of the vacuum pressure and the maximum displacement reaches 52.8cm and 45.8cm respectively. In addition, the curve along the depth when the distance is 1m behaves like a straight line, which can be ascribed to the restriction of the cement mixing pile to the surrounding soils.



(1) 1m from borderline of improved area



(2) 5m from borderline of improved area

Figure 1 Relationship between horizontal displacement and depth at different stages

### 4.2 Deformation of building.

In order to observe the deformation of building outside the improved area, the ground settlement at different consolidation time is shown in Figure 2. For the area with horizontal coordinate larger than 15m, the ground deformation decreases significantly and here is just the location of the build. As mentioned above, because the soil parameters at the range of the building have been modified artificially, the settlement would decrease accordingly. In order to clarify the deformation of the building, Figure 2 illustrates the ground settlement at the range of the building. As can be seen, the settlement at the left side of the building is larger than the one at the right side and there is uneven settlement at the bottom of the building due to the vacuum preloading, which results in some inclination of the building. As the duration of the vacuum pressure increases, the uneven settlement becomes larger and larger. Until 120d, the settlement at two corners reaches 11.8cm and 2.9cm respectively and the difference between two settlements is as large as 8.9cm. Taking 10m width of the building, the inclination is 0.0089 and the incline angle is about  $0.51^\circ$ . According to term 5.3.4 of the (Code for design of building foundation GB50007-2011), for the multilayer buildings the entire inclination should be less than 0.004 when the height of the building is less than 24m, according to which it can be known that the computed inclination is larger than the allowable value of the ground.

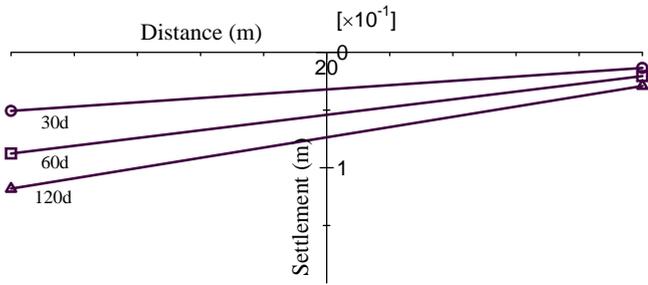


Figure 2 Variation of pore pressure and time at different depths

In order to evaluate the influence of ground deformation including the settlement and the horizontal displacement on the building during the vacuum preloading, Figures 3 and 4 give the settlement and the horizontal displacement of two ends at the top of the building. From Figure 3, we can know that there are significant settlements at both left and right ends with the magnitude of 11.8cm and 2.9cm. The uneven settlement at the top is 8.9cm, which is the same as that at the bottom as shown in Figure 1. An inclination toward the left would occur and the inclining angle is  $0.51^\circ$ . According to Figure 4, the horizontal displacement of the building becomes larger and larger with a maximum of 26.8cm due to the influence of the ground displacement. Because of the huge stiffness of the building, the horizontal displacement of two ends at the top is same. Considering that the height of the building is 18m and that the horizontal displacement at the bottom of the building is 14cm, it can be obtained that the vertical inclination angle is  $0.46^\circ$  and the direction is toward the inside of the improved area.

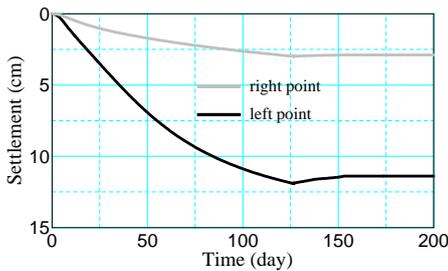


Figure 3 Settlement of the roof at two ends considering unloading effect

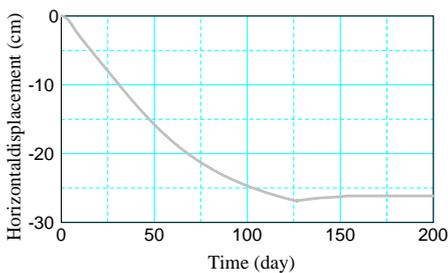


Figure 4 Horizontal displacement of the roof at two ends considering unloading effect

### 4.3 Unloading effect.

In order to consider the influence of unloading on the deformation of the building, another calculation is carried out in which the vacuum pressure is removed at 120d and the following consolidation is kept until 200d. The corresponding settlement and horizontal displacement are shown in Figures 3 and 4. It can be seen that there is slight rebound in the horizontal displacement curve during the unloading process, namely the deformation toward the outside of the improved area. The final horizontal displacement comes to about 26.1cm. The settlements of the building at two ends also become stable at 11.3cm and 2.8cm. In order to comprehend the deformation of the building at both loading and unloading of vacuum pressure, the deformation sketch of the roof is shown in Figure 5. It can be seen that initially the roof is incline and there is successive inclination at the roof toward the improved area due to the uninterrupted vacuum preloading. Here the horizontal displacements at the left and right ends are recorded as  $\Delta x_1$  and  $\Delta x_2$ . The settlements of two ends are recorded as  $\Delta y_1$  and  $\Delta y_2$ . Due to the unloading effect, the deformation of the roof in the reverse direction will occur and marked as  $\Delta x'_1$ ,  $\Delta x'_2$ ,  $\Delta y'_1$  and  $\Delta y'_2$ . The detail values are listed in Table 1 and the solid line represents the final configuration of the roof as shown in Figure 5

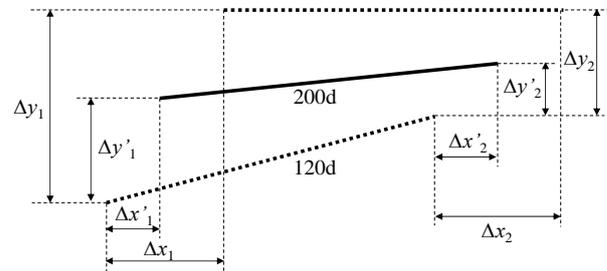


Figure 5 Deformation sketch of the roof

Table 1 Incremental deformation of the roof

Deformation (cm)	Loading	Unloading	Remarks
$\Delta x_1$	-26.8	—	The negative is towards inside of improved area for x, the positive is downwards for y.
$\Delta y_1$	11.8	—	
$\Delta x_2$	-26.8	—	
$\Delta y_2$	2.9	—	
$\Delta x'_1$	—	0.7	
$\Delta y'_1$	—	-0.5	
$\Delta x'_2$	—	0.7	
$\Delta y'_2$	—	-0.1	

## 5 CONCLUSION

A finite element analysis is carried out to investigate the deformation characteristics of building near the improved area using vacuum preloading and unloading.

ing. The horizontal displacement, deformation of build and unloading deformation are displayed respectively and the conclusions are as follows:

(1) When the vacuum preloading has kept for about 120d, there is already significantly settlement at two ends of the roof and they are 11.8cm and 2.9cm. The differential settlement is 8.9cm and the horizontal inclination angle is  $0.51^\circ$ , according to which the horizontal inclination of the roof is 0.0089 which is larger than the allowable value 0.004 defined by (Code for design of building foundation GB50007-2011).

(2) Due to the influence of the horizontal deformation of the ground, the horizontal displacements of the roof and the foundation gradually increase to 26.8cm and 14cm. Considering the height of the building is 18m, the vertical inclination angle is about  $0.46^\circ$  towards the improved area.

(3) After the unloading of the vacuum preloading, the horizontal displacement of the roof decreases 0.7cm and the settlement of the roof at two ends decreases 0.5cm and 0.1cm respectively.

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