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ORIGINAL PAPER

Model test study of land subsidence caused by high-rise building group in Shanghai

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Abstract The paper discusses the influence of a group of high-rise buildings on land subsidence, based on a modeling exercise. The model consisted of five layers of soils typical of the Shanghai area, with the buildings placed on piles set in the upper silty sand horizon. It was loaded to represent the construction sequence of the four buildings. The main settlement was observed to be in the underlying clayey layer. The model demonstrated the increase in pore water pressure with staged loading, its effect on deformation and the increase in effective stress over time. It indicated the largest amount of settlement over time occurs between the buildings.

Keywords High-rise building group · Land subsidence · Model test · Stress superimposition · Shanghai

Résumé L'article discute de l'influence d'un groupe de quatre bâtiments de grande hauteur sur le tassement des sols, sur la base d'une modélisation. Le modèle comportait cinq couches de sols typiques de la région de Shanghai, les bâtiments étant fondés sur pieux sur la couche silto-sableuse supérieure. Un chargement mécanique a représenté la séquence de construction des bâtiments. Le tassement principal s'est réalisé dans la couche argileuse sous-jacente. Le modèle a montré l'augmentation de la pression interstitielle, fonction du niveau de chargement mécanique, l'augmentation des contraintes effectives avec le temps et la déformation des terrains. Le modèle a montré que, dans le cas étudié, l'amplitude maximum de tassement se réalisait entre les bâtiments.

Mots clés Groupe de bâtiments de grande hauteur · Tassement des sols · Modélisation · Contraintes induites · Shanghai

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Introduction

Shanghai was one of the first cities in China to suffer serious subsidence (Xue et al. 2005; Monjoie et al. 1992). Before the 1960s, the main cause was the unrestricted withdrawal of groundwater. Since then, the pumping of groundwater has been strictly controlled in the urban area in Shanghai with the quantity of water recharged into the subsurface always greater than that removed by the pumping.

During the 1990s, a variety of municipal works and high-rise buildings were constructed in Shanghai and land subsidence accelerated again, with the average yearly subsidence increasing to more than four times that of the previous 20 years (Zhang 2002; Lu 2005). Between 1996 and 2003, some 6,783 large scale buildings exceeding eight floors were constructed, of which 2,655 exceeded 18 floors and 587 exceeded 30 floors. In addition, these buildings were tightly packed in a relatively small area. Monitoring data reported by Yan and Gong (2002) emphasized the need to study the engineering-environmental effect of the construction of these high-rise buildings. It is difficult to appreciate the results of monitoring subsidence caused by a large number of high-rise buildings over a long period during which the environment of the site changes as they are affected by many factors, the details of which have often not been recorded. As a consequence, it was considered appropriate to undertake modeling (Xie et al. 2003).

This paper discusses the engineering-environmental effect of a group of high-rise buildings in the typical geological situation of Shanghai, considering the deformation/stress characteristics of different soil layers, the mutual influence of adjacent buildings and the subsidence pattern beneath and around a group of high-rise buildings.

Test model and test method

The model consisted of four high-rise buildings, using a scale of 1–100. The distance between two adjacent buildings was 20 m, in accordance with the *Management of City Planning in Shanghai*. The original plan dimension of each was 20 m × 20 m, with the 22 floors reaching a height of 65 m. The bearing stratum of the pile tip was soil No. 7. The geological and hydrogeological information on Shanghai indicates the soil layers (from the top downwards) are a brown-yellow clay layer, a mucky clay layer, a silty sand layer, a clayey soil layer and a silty sand layer. Figure 1 shows the typical geological section of Shanghai (Tang et al. 2007). The foundation soil of the model test is the grey mucky silty clay of the No. 3 layer, the clayey soil of the No. 5 layer and a silty sand obtained from the site.

In recent years, the evidence indicates that soil deformation related to pumping/recharge has been mainly below a depth of 70 m; that above this level appears to be related to engineering works. The soils affected by the engineering works comprise three thick layers of soft soil with high water contents (Table 1).

The model used pile foundations, as this is the normal type of foundation for high-rise buildings in Shanghai. However, it was not intended to study the characteristics of pile foundations and they are used in the model only to take the building load. In order to simplify the model, organic glass bars were used to make the 46.5 cm model piles and organic glass plates for the 20 m × 20 cm model pile caps.

As noted above, the scale of the model was 1–100 hence the model box was 3.4 m in length, 2.5 m in width and 1.55 m in height. To avoid leakage, the model box was constructed of welded steel plates which were polished to decrease the boundary effect. Recharge holes, holes for measuring water level and discharge holes were placed around the model box at the bottom of two silty sand layers (Fig. 2). Piezometers were installed and in order to study the characteristics of the soil pressure and excess pore water pressure of the different soil layers, highly sensitive soil and water pressure cells were installed under Buildings A and B and also in different soil layers at the mid-point of Line AB. Figures 3 and 4 show the monitoring installed on the pile caps of the buildings and at various points in the foundation soils in order to measure both building and land subsidence as well as deformation of the different soil layers.

Natural soils obtained from the site area were evenly laid in the model box into which the soil and water pressure

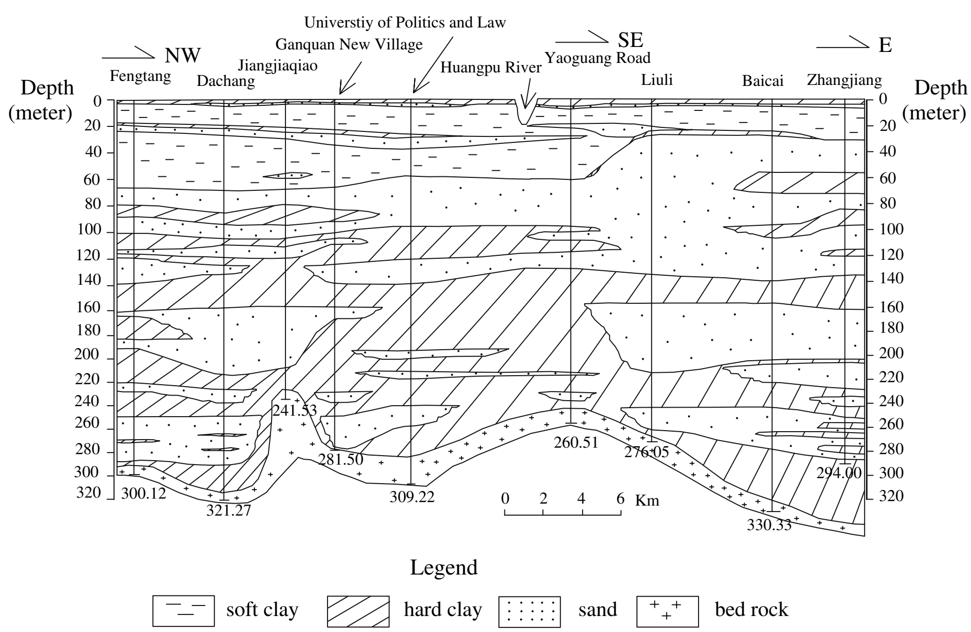

Fig. 1 Hydrostratigraphy along the cross section Fengtang-Yaoguang Road-Zhangjiang

Table 1 Soil properties of model

Soil name	Water content (%)	Weight density (kN/m^3)	Void ratio	Modulus of compressibility (MPa)	Cohesion (kPa)	Angle of internal friction (°)
Grey mucky silty clay	40.6	17.3	1.219	2.704	12.0	22.5
Silty sand,	31.5	18.7	0.965	9.038	57.0	24.8
Clayey soil	38.5	17.9	1.100	3.100	15.8	14.5

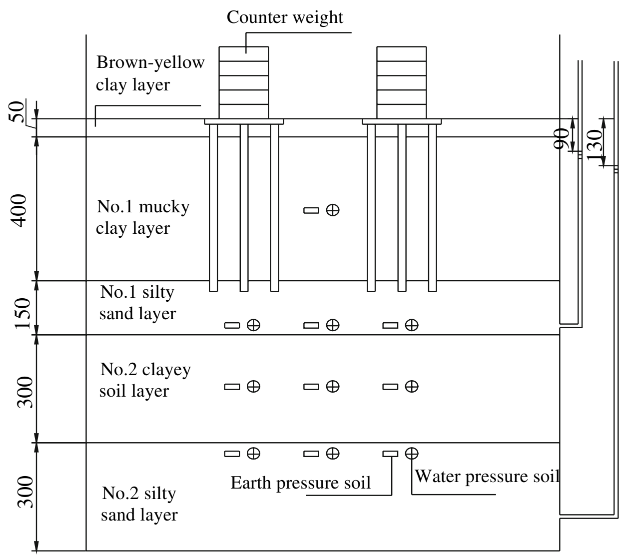

Fig. 2 Section of model and distribution of pressure gauges (length in mm)

cells were embedded. Water was added to the two silty sand layers to simulate the actual water levels in Shanghai, i.e. 9 and 13 m below ground level (see Fig. 2).

Counter weights were used to simulate the building load; the load on a single pile cap being 15 kg. The loading sequence for the buildings was A→B→C, D (C and D were loaded at the same time); the 3 kg counter weights being loaded for every level to simulate the construction sequence. After each loading, data from the monitoring cells were recorded. When each building had been completed, measurements were taken at intervals of 0.5, 1, 2 and 24 h and after all four buildings had been loaded, the measurements were taken every 24 h for 200 h.

Analysis of test results

Data were obtained for five soil layers (Fig. 3):

An upper brown-yellow clay layer,
No. 1 mucky clay layer,
No. 1 silty sand layer,
No. 2 clayey soil layer and
No. 2 silty sand layer.

Comparison of subsidence for different soil layers

The deformation of the individual layers was obtained by subtracting the subsidence recorded in an individual layer from the overall subsidence (Dong and Zhao 1996). Figure 5 shows the relationship curves for deformation and time.

Fig. 3 Model plan and instrumentation layout. Note Points 5–9 in the centre of the model at different layers

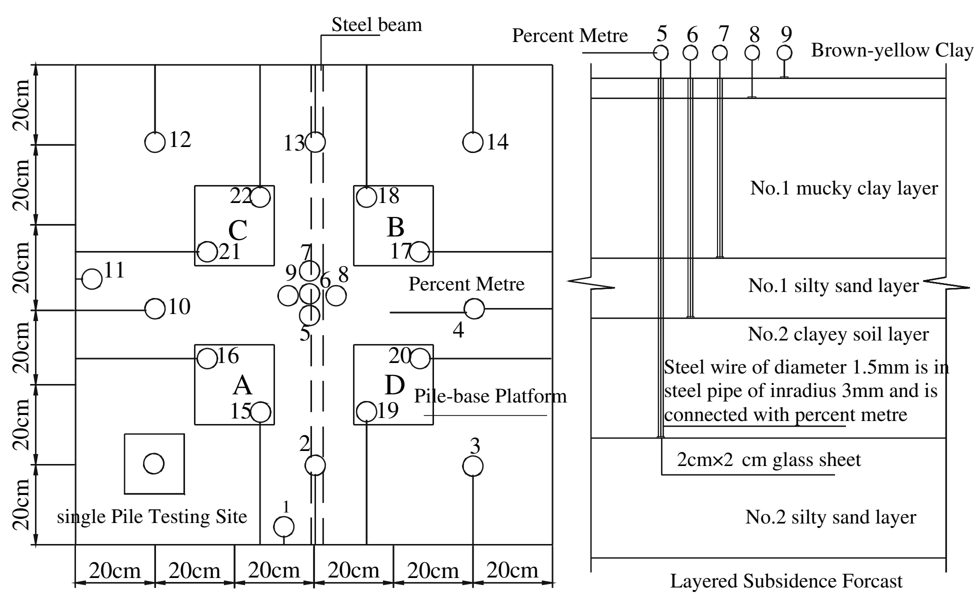

Fig. 4 Layout of the model test

(1) The brown-yellow clay layer is thinner and the soil strength greater, hence the deformation is very small.
(2) The deformation of the No.1 mucky clay layer is smaller than that of the silty sand layers at the initial stage of loading. With increasing load, the deformation value also increases and exceeds that of the silty sand layers. After consolidation, the deformation value continues to increase and the soil shows rheological characteristics. The relationship of this soil type to the pile tips is shown in Fig. 2.
(3) No.1 silty sand layer is the bearing stratum for the pile tip and its deformation is larger. In the course of loading, the deformation fluctuates significantly. The deformation is large after the first loading. After the second loading, the stress at the pile tip changes and the plastic deformation zone around the pile expands. After the loading is complete, the soil consolidates rapidly and is then stable and deformation effectively stops.

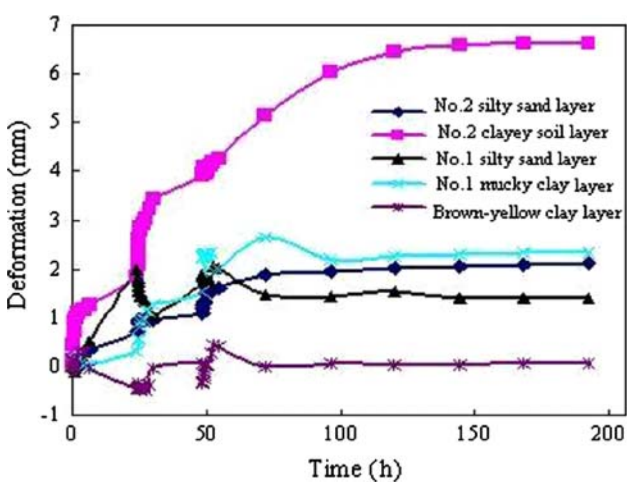

Fig. 5 Relationship of deformation and time

(4) The deformation of the No. 2 clayey soil layer increased rapidly with increased loading, significantly exceeding that of the other layers. The period over which consolidation took place was also longer than that of other layers. This layer, beneath the No. 1 silty sandy layer in which the piles were embedded, experienced the greatest compressibility resulting in the maximum subsidence.
(5) The deformation of No. 2 silty sand layer increased in a stepped manner with increased loading. In the model, this lower silty sand is thicker than the higher (No. 1 silty sand) layer but the monitoring was undertaken towards the top of the No. 2 layer. The soil quickly consolidates, with a value slightly greater than that for the upper (No. 1) layer.

Comparison of subsidence for the four buildings

The subsidence curves for Buildings A–D are compared in Fig. 6. Not surprisingly, Building A was the first loaded and the subsidence was greatest, followed by Building B which was the second to be loaded. Buildings C and D were the last to be loaded (at the same time) and their subsidence was the least.

Comparison of subsidence for points at the same axis

Figure 7 shows the subsidence at various points on the buildings; points 1, 2, 9, 13 and 15 being on the same axis. The subsidence in the central part of the model is significantly larger—ca. 4 times that of the other points. Comparing the subsidence around the building (Fig. 8) with that measured beneath a building (point 15 in Fig. 7) indicates that the area around the building within one width

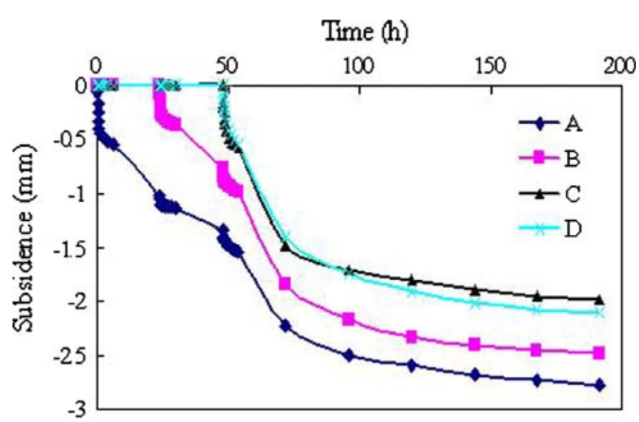

Fig. 6 Subsidence of model buildings

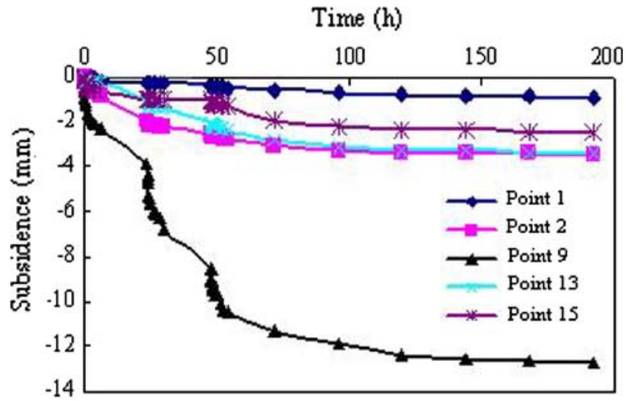

Fig. 7 Subsidence of points on the same axis

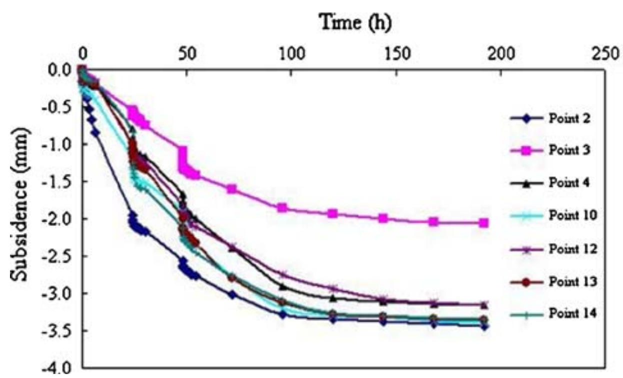

Fig. 8 Subsidence of points around buildings

of the foundation sinks more than that beneath the building itself, while the land subsidence around the building within two times the width of the foundation accounts for about 30% of that the building itself. A number of the settlement curves indicate fluctuation in the early part of the model, with concave and convex trends between the plotted points.

Pore water pressure and deformation of clayey soil layers

Zhang and Lv (2003) observed that the excess pore water pressure of silty sand layers, whilst increasing with the initial load, dissipates quickly. This test therefore mainly studied the excess pore water pressure of the No. 2 clayey soil layer.

Figure 9 shows the relationship between the pore pressures in the No. 2 clayey soil layer beneath Building A, Building B and the central area, for three load and unload conditions.

(a) During the first loading for Building A, the soil beneath Building A experienced the maximum increase in pore water pressure, followed by the central area and Building B. With the unloading, the pore pressure decreased beneath each of the three areas; the main decrease being beneath Building A.

(b) With the second loading, for Building B, the pore pressure under Building B rose very significantly, followed by the central area but there was little change beneath Building A. With unloading, the main decrease in pore pressure was beneath Building B and the central area.

(c) When the third loading, for Buildings C and D, was applied, the pore water pressure in each of the areas rose significantly with that recorded beneath Building A and the central area being very similar while beneath Building B the increase was slightly smaller. With unloading, the pressure beneath Buildings A and B was consistently lower than that in the central area.

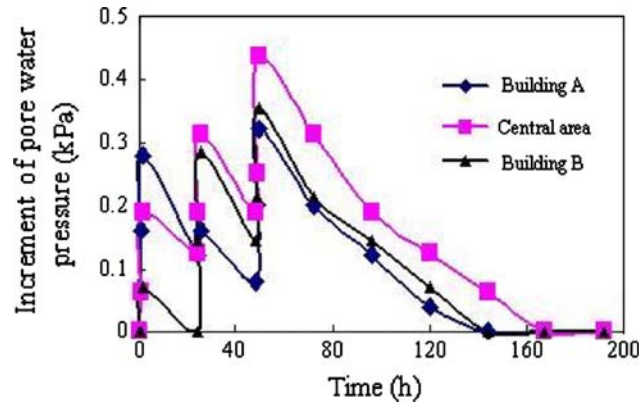

Fig. 9 Change in excess pore water pressure

The consolidation time in the central area was longer than that for Buildings A and B. These results indicate the stress superimposition effect in the central area is the largest and explains why the subsidence is also largest.

Figure 10 shows that as the pore water pressure decreases, the effective stress of the No. 2 clayey soil layer increases. Initially these increases are stepped, although with time they become more consistent. The deformation also rises in a stepped manner initially before a more consistent curve develops with little change in deformation towards the end of the model run.

Soil pressure and subsidence under buildings

Figure 11 shows the distribution of earth pressure at depth beneath Building A. It can be seen that when Buildings C and D are constructed, the pressure increases at the two depths considered (ca. 60 and 80 cm). Figure 12 shows the relationship of soil pressure and land subsidence of No. 1

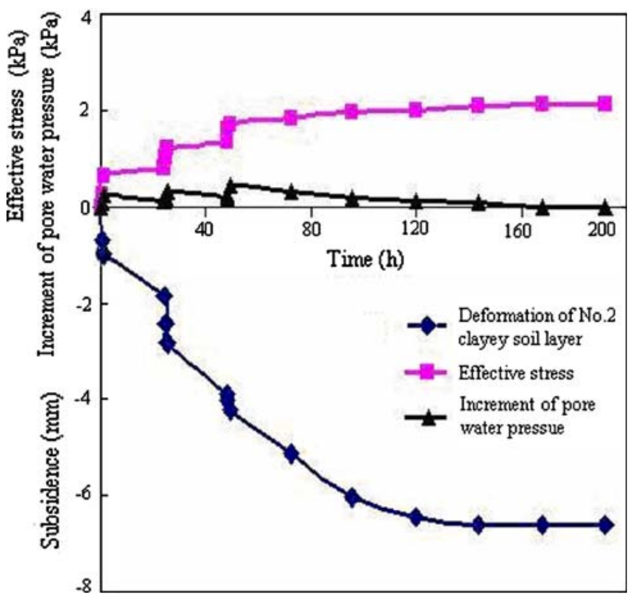

Fig. 10 Effective stress and deformation of No. 2 clayey soil layer

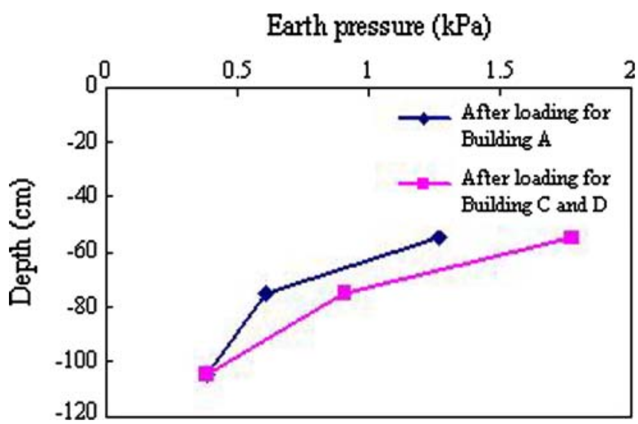

Fig. 11 Distribution of earth pressure at different depths

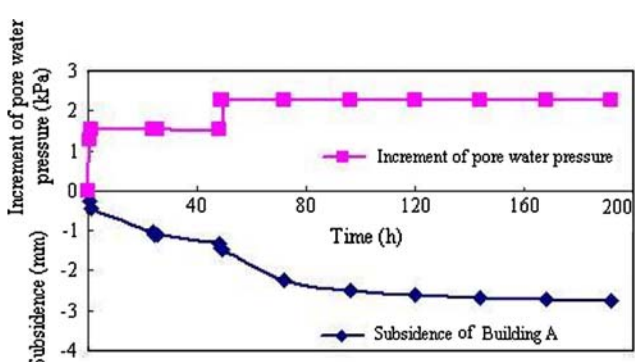

Fig. 12 Change of earth pressure and subsidence of Building A

silty sand layer under Building A. The soil pressure increases in a stepped way related to the effect of the adjacent buildings. Following an initial increase in pore water pressure there is a steady subsidence of Building A. When the pore water pressure is increased a second time, subsidence again commences, although there is little vertical effect. When the pore water pressure remains static, however, the subsidence increases again and then decreases gradually with time.

Conclusions

The paper describes a model set up to simulate land subsidence beneath a group of high rise buildings and in the spaces beneath the buildings in a new, densely developed, area of Shanghai. Five soil layers are used to give a realistic representation of the conditions beneath the city but ignoring the lateral complexities of the soils which are known to exist from boreholes (Fig. 1). Beneath an upper yellow brown clay are two clayey soils and two silty sand bands. The model assumes the piles supporting the high rise blocks are set in the upper (No. 1) silty sand layer. The results show:

(1) The land subsidence caused by high rise buildings is affected by the construction sequence of the buildings. The land subsidence of the points near to the former building is larger than that of those near to the latter building.
(2) The central area of the group of buildings experiences the maximum subsidence. The points within one times the width of the foundation from the centre of the building have the second largest subsidence. The least subsidence is recorded in the area two times the width of the foundation from the centre of the building.
(3) The excess pore water pressure and soil pressure all increase in a stepped way, as do the deformation of soil layers and building subsidence. This can be related to the construction/loading sequence.

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