Numerical analysis of the influence of soft ground improvement by surcharge preloading method on the underground pipe gallery

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Abstract. The numerical modelling method was used to analyse the influence of surcharging on underground pipe gallery. By simulating the 200-d surcharging process to observe the settlement, lateral displacement and dissipation of porewater pressure in the preloading area, it is found that the vertical displacement of pipe gallery under the influence of the surcharging near the drainage channel is not more than 10 mm, the lateral displacement is not more than 2.4 cm, and the torsion angle of the pipe gallery is not more than 0.18 degree. Therefore, it can be considered that the surcharging has little influence on the adjacent underground pipe gallery.

1. Introduction
The underground pipe gallery project in Hengqin New District, Zhuhai City, Guangdong Province, is the largest comprehensive urban pipe gallery project recently completed in China. It is featured with advanced planning and outstanding integration. It has been built since 2010 and put into use in 2013, with a total length of 33.4 km and an investment of over 2.2 billion Chinese Yuan. The total length of gallery line is 28.8 km, of which the line along Hong-Kong-Macao Avenue is about 7 km long⁴⁻⁵.

Hengqin New District was built alongside the mountain and had been also planned with a number of flood drainage channels for flood control and flood prevention. The No. 1 flood drainage channel is located south of Hong-Kong-Macao Avenue, starting from the No. 19 flood drainage and ending at the No. 2 flood drainage channel. The No. 1 flood drainage channel is the only flood drainage channel running through the east and west with a total length of 6782.27 m. This channel is also planned in parallel with the Hong-Kong-Macao Avenue. The channel bottom ground has been improved by surcharge preloading with band drains. The surcharge preloading method is a common method for improving soft soil ground with a quick dissipation of excess porewater pressure caused by surcharge loading through the inserted band drains, resulting in large settlement and deformation of the ground, thus improving its bearing capacity. But this method also results in a large lateral deformation outside the improved area⁴⁻⁵. This paper intends to study the influence of surcharge preloading method on the underground pipe gallery of Hong-Kong-Macao Avenue through numerical simulation.
2. Project overview

2.1 Geologic information

According to the Geotechnical Engineering Investigation, the whole site for flood drainage channel is divided into 9 engineering geological layers and 23 sub-layers. The surface layer is backfill soil, with silt and muddy clay below, sanded with some gravel layers, and granite at the bottom. The typical soil layers are as follows:

I layer, backfill (Q₄ml): Uneven soil quality, consisting of argillaceous fine sand, cohesive soil, granite crushed stones and boulders, loose to slightly dense, with crushed stones and boulders 5 cm to 100 cm in diameter. The distribution of this layer is discontinuous, the thickness of the layer varies greatly, and the composition varies greatly.

II-2 layer, silt (Q₄m): The soil quality is relatively uniform, with a thin layer of sand locally. This layer is basically distributed continuously, with an average thickness of 5.08 m, and with low strength, high compressibility and poor engineering geological properties.

III layer, silt (Q₄m): The soil quality is relatively uniform, with a small amount of shell debris locally. The layer is distributed basically continuous, and the layer thickness changes greatly, with an average thickness of 6.60 m, and low strength, high compressibility and poor engineering geological properties.

V-1 layer, silt (Q₄m): The soil quality is relatively uniform, and a small amount of humus is mixed locally. This layer has a discontinuous distribution and a great variation of thickness, an average thickness of 8.02 m, and low strength, high compressibility and poor engineering geological properties.

VI-1 layer, silty clay (Q₄alk+ps): Plastic, locally hard plastic, uneven in soil quality and mixed with more sand grains. The distribution is discontinuous and the layer thickness changes greatly, with an average thickness of 3.71 m. This layer has medium compressibility, general engineering geological properties.

IX-1 layer, fully weathered granite (2(3γγγ): The original rock structure is still discernible, feldspar is basically weathered into soil, exposed locally, and has good engineering geological properties.

2.2 Reinforcement Scheme for Foundation of Flood Drainage Channel

The treatment width of No. 1 flood drainage channel in the north of China is about 37 m, the junction with the plot and the built box culvert is locally narrowed, and the preloading area is 39,521 m². The plastic band drills are arranged in a square shape with a spacing of 1.0 m. The influence length of the band drains is about 25.0 m. The drainage channel ground was improved by the following procedures:

(1) The site is treated with a combine of band drains and surcharge preloading;
(2) The current site is levelled to an elevation of 1.0 m, and the band drains are installed after laying a sand cushion of 0.5 m;
(3) The inserted band is arranged in a regular triangle with a spacing of 1.0 m, and the penetrating silt layer is not less than 0.5 m. It can be seen that the depth of the band drains in the preloading area is penetrated into but not through V-1 layer;
(4) Preloading soil thickness is 4.0 m;
(5) The full preloading time is not less than 200 d;
(6) Calculate the post-construction settlement from the settlement observation data, and determine the unloading time of preloading soil in combination with the measured settlement rate. The measured settlement three-point method or Asoka (shallow hillock) method is required to calculate the degree of consolidation to meet the design requirements, and the settlement rate is required to be less than 3 mm/d during ground improvement.

The section of underground pipe gallery is 61.5 m long, 39 m high and 21 m wide, and 31.5 m wide for the left and right small pipe galleries, respectively. These galleries were placed in concrete C40. In addition, there are 4 concrete mixing piles under the pipe gallery. On the right side of underground pipe gallery, there are also a rainwater pipe gallery (square) and a sewage pipe gallery (square), with cross-sectional dimensions of 2.1 m×1.2 m and 1 m in diameter, respectively.
3. Numerical analysis model

The surcharge preloading influence was numerically simulated by FLAC\textsuperscript{3d} finite difference calculation software. FLAC 3D can simulate the failure of rock and soil materials and the mechanical behaviour of plastic flow, and is more suitable for analysing progressive failure and simulating large deformation.

In this simulation, the three-dimensional problem is simplified to the two-dimensional plane strain one, and a numerical simulation of the impact of 200 d to 300 d loading on the surrounding environment is carried out by taking half of the construction section according to the principle of symmetry. The calculation method proposed by Chai Jinchun was used to simulate the influence of band drains to surrounding soft soils, and the soil property was modelled by Mohr-Coulomb elastic-plastic model. The soil mass is simulated by zone which is different from that of finite element method.

After the geometry model was established, it is restrained at the left and right side boundary in the horizontal displacement, and is restrained at the bottom boundary in the vertical displacement. To simplify calculation, it is considered that the water table is located on the upper surface of the surcharge fills. Combined with geotechnical investigation report and geotechnical statistical information\textsuperscript{[1-2]} of Hengqin area, the soil parameters are determined as follows:

| Soil layer       | Dry density (g/cm\textsuperscript{3}) | Bulk modulus (MPa) | Shear modulus (MPa) | Effective cohesion (kPa) | Effective friction angle | Porosity |
|------------------|----------------------------------------|--------------------|---------------------|--------------------------|-------------------------|----------|
| Backfills        | 1.38                                   | 3.63               | 1.49                | 5.0                      | 28°                     | 0.48     |
| II-2 silt        | 0.90                                   | 15.0               | 9.45                | 2.6                      | 24.8°                   | 0.67     |
| III silt         | 0.96                                   | 1.95               | 1.17                | 5.6                      | 24.1°                   | 0.65     |
| V-1 silt         | 1.00                                   | 28.6               | 1.47                | 22.2                     | 28°                     | 0.65     |
| VI-1 silty clay  | 1.46                                   | 54.8               | 1.96                | 27.0                     | 30°                     | 0.46     |

For the gallery concrete, take the density to be 2500 kg/m\textsuperscript{3}, the bulk modulus to be 21.67 GPa, and the shear modulus to be 13 GPa according related Chinese concrete structural specification. According to the linear elastic model, the density of the pile foundation under the gallery is 2000 kg/m\textsuperscript{3}, its bulk modulus is empirically taken as 0.4167 GPa, and shear modulus 0.0892 GPa.

The calculation process is as follows: the sand cushion is laid on the first day, and surcharges are loaded on the following 8th, 31st and 61st day, with the surcharge thickness of 1.5 m, 1.5 m and 1 m, respectively, totally 4 m surcharge thickness; then the surcharge preloading influence of 200-d duration is calculated. In order to facilitate comparative analysis, the actual calculation was carried out up to 250-d surcharge preloading. The whole geometric model is 32m high and contains 29,088 zones and 34500 nodes.

4. Analysis of calculation results

4.1 Ground settlement

Figure 1 shows the settlement contour of the calculated section after 200-d surcharge preloading. It can be seen that the maximum settlement occurred at the center of the channel and is about 1.8 m. The surcharge preloading also causes settlement deformation in the near area, which is more obvious in the right slope area. The deformation of the soil under the right road can be neglected because it has been improved in advance.

Figure 2 shows the settlement curve of the channel surface layer every 3m from the center to the right during the 200 d surcharge preloading. It can be seen that the channel surface layer immediately has obvious settlement deformation for each stage of surcharge preloading, and then the settlement deformation trend slows down. At 200 d of surcharge preloading, the settlement at the center of the channel is at most 1.8m, while at the edge of the channel, due to boundary constraint, the settlement is 0.8m. In the area of channel edge and channel center, the settlement is between the settlement deformation value and the settlement deformation value.
4.2 Porewater pressure

Figure 3 shows the variation of porewater pressure at the depths of 3 m, 9 m, 15 m and 21 m below the center of channel bottom during 200-d surcharge preloading.

It can be seen that for each surcharge preloading, the pore pressure in the ground improvement area rises abruptly (due to the surcharge preloading is applied in one procedure) and then gradually dissipates. At the end of the surcharge preloading period, the pore pressure dissipation was basically completed at 3 m, while residual excess pore water pressure was still not completely dissipated in deeper areas, indicating that the time required for the excess pore pressure caused by surcharge preloading to dissipate completely may be more than 200 d.
4.3 Displacement of pipe gallery caused by surcharge preloading

Figure 4 shows the vertical displacements of the left, central and right monitoring parts of the top of the pipe gallery during the 200-d surcharge preloading. By taking downward direction as positive, it can be seen that the pipe gallery is mainly displaced upward during the surcharge preloading process. At 200 d, the vertical displacements do not exceed 10 mm, indicating that the gallery is less affected by the improvement. The difference between left and right settlement is only 5 mm, resulting in a torsion angle caused of not more than 0.15°. Since it is very small, the torsion influence can be ignored.

Figure 5 shows the lateral displacement of the pipe gallery under the influence of surcharge preloading; these three curves represent the lateral displacements of the top, center and bottom monitoring points near the left side of the pipe gallery. By taking the rightward direction as positive, it can be seen that at 200 d, lateral displacement ranges from 2.0 cm to 2.4 cm. If the unfavourable condition of instantaneous loading is considered, the maximum lateral displacement ranges only 3.2 cm to 3.8 cm. However, the actual displacement should be smaller than this displacement because the application of surcharge loading is not instantaneous. When the surcharge load reaches 200 d, the lateral displacement difference is very small compared to the 4-m height of gallery, resulting in a torsion angle of only 0.18°. It can be considered that there is almost no torsion deformation of the pipe gallery.
5. Conclusions
By simulating the 200-d preloading consolidation process of the ground for No. 1 flood drainage channel in Hengqin New Area, the influence of preloading on underground pipe gallery of Hong-Kong-Macao Avenue is analysed. The result shows that the vertical displacement of underground pipe gallery is not more than 10 mm, the lateral displacement is not more than 2.4 cm, and the torsion angle of the pipe gallery is not more than 0.18º under the influence of the surcharge preloading on the soil ground for adjacent flood drainage channels. Therefore it can be considered that the surcharge preloading practice has little influence on the adjacent underground pipe gallery.

References
[1] He, J. (2015) Construction Practice and Thinking of Underground utility tunnel in Hengqin New District. *Installation*, 10:18–20
[2] Liu, Y. (2017) Research on construction, operation and management of urban underground utility tunnel in Hengqin New District of Zhuhai City. *Urban Road Bridge and Flood Control*, 2:166–9+20
[3] Chen, J. R. (1994) An example of application of foundation settlement and drainage consolidation theory. *Harbor Engrg. Tech.*, 4:51–6
[4] Guo, Z. P. *et al* (1994) Comparative Study on Deformation of Soft Foundation by Different Preloading Methods *Water Trans. Engrg.*, 1:1–5+48
[5] Yan, S. J. and Wang, X. Y. (1992) Discussion on Preloading Effect of Soft Soil Foundation. In: *Proc. 4th Conf. on National Engrg Geol.*. Beijing, China
[6] Zhu, X. G. and Pan, Q. Y. (1992) *J. Study on Deformation of Foundation after Overload Removal*. Zhejiang Univ (Natural Sci. Ed.), 2: 121–31
[7] Peng, L. C. *et al* (2016) Statistical Analysis of Physical and Mechanical Indexes of Soft Soil in Hengqin New Area of Zhuhai. *Guangdong Water Conser. & Hydro.*, 4: 29–32
[8] Wang, W. *et al* (2015) Comparative statistical analysis of mechanical properties of soft soil before and after vacuum–surcharge preloading treatment in Hengqin new area of Zhuhai. *Guangdong Civ. & Archi.*, 10: 27–9