Experimental study on influence of ground rebound on tunnels caused by groundwater restoration

Takuya Kusaka i), Sokkheang Sreng ii), Hiroshi Tanaka iii), Hitomi Sugiyama iv), Tamio Ito v) and Koji Kobayashi vi)

i) Researcher, R&D Center, Nippon Koei Co. Ltd., 2304, Inarihara, Tsukuba-shi, Ibaraki 300-1259, Japan.
ii) Senior Researcher, R&D Center, Nippon Koei Co. Ltd., 2304, Inarihara, Tsukuba-shi, Ibaraki 300-1259, Japan.
iii) Director General of Technology Headquarters, Nippon Koei Co. Ltd., 4, Kojimachi, 5-chome, Chioda-ku, Tokyo, 102-8539, Japan.
iv) Deputy Director General of Technology Headquarters, Nippon Koei Co. Ltd., 4, Kojimachi, 5-chome, Chioda-ku, Tokyo, 102-8539, Japan.
v) Acting General Manager of Geo-Environment Dept., Nippon Koei Co. Ltd., 2, Kojimachi 4-chome, Chioda-ku, Tokyo, 102-0083, Japan.
vi) Manager, R&D Center, Nippon Koei Co. Ltd., 2304, Inarihara, Tsukuba-shi, Ibaraki 300-1259, Japan.

ABSTRACT

In recent years, regional ground rebound phenomenon caused by the rising of groundwater level has been observed in an urban area in Japan such as Tokyo. This phenomenon might affect the underground structures constructed in those areas. In this study a centrifuge model test was carried out to investigate the fundamental mechanism of tunnel deformation and ground rebound during water rising process. In the centrifuge model test, two model tunnels were installed in different depths of clay ground in order to investigate the influence of ground depth on tunnel deformation. It is found that the relationship between ground surface displacement and elapsed time obtained from centrifuge model test shows similar tendency to the field measurement data. It is confirmed that deformation patterns of the two tunnels were different in the water rising process. This is considered to be due to the difference in deformation and pore water pressure in different layers of clay ground. Detail discussions on deformation mechanism of the two tunnels and pore water pressure distribution in clay are presented in this paper.

Keywords: groundwater level, ground rebound, underground tunnel, centrifuge model test

1. INTRODUCTION

Ground settlement caused by lowering of groundwater level had been a serious social problem in Japan since the middle of last century. This problem was alleviated since the establishment of regulations for environmental pollution prevention to control the use of underground water in the 1960s. Subsequently, groundwater level has been restored in the recent few decades with a rising trend being found in the urban areas of the major cities in Japan such as Tokyo. In contrast to the lowering of groundwater level, rise in groundwater level has caused the ground rebound due to the swelling of clay layer. Since the value of ground rebound is small compare to ground settlement (about one-tenth of the ground settlement), it has not been paid much attention by researchers. However, the maximum value of ground rebound in large cities such as Tokyo was found to be more than 10cm, that cannot be ignored as it might affects the underground infrastructure, and sometimes leads to unexpected deformation.

The authors (Sreng et al., 2009, Kusaka et al., 2011, Kusaka, 2012, Sreng et al., 2014) have presented some related studies on the ground rebound mechanism using centrifuge model tests and their numerical analysis.

In this study a centrifuge model test was carried out to investigate the deformation mechanism of two tunnels in different depths caused by ground rebound during water rising process. In this paper, at first the observed ground rebound distribution in Tokyo city is introduced. Secondly, results of centrifuge model test are presented.

2. SITUATION OF GROUND REBOUND AND DEFORMATION OF SHEILD TUNNEL IN TOKYO

Regional ground settlement caused by the lowering of groundwater level had been occurred especially in east part of Tokyo. Therefore, the observation of ground water level and ground displacement in Tokyo were continuously conducted by the Civil Engineering Support & Training Center of Tokyo Metropolitan Government.

Figure 1 shows an example of relation between groundwater level and ground displacement in Tokyo plotted against time. It can be seen that after the revision of antipollution regulation for control the use of groundwater from 1970 in Japan, groundwater level
has risen year by year. As a result, ground rebound occurred in a wide area of Japan in accordance with the rising of groundwater level. It is noticed that the ground rebound phenomenon was not immediately occurred when the groundwater level began raising in 1970, however after ten years in 1980 ground rebound phenomenon has appeared year by year. This reason is considered that consolidation of clay ground had not finished yet when the groundwater level began rising, and the rising rate of groundwater level was slow.

3. CENTRIFUGE MODEL TEST

3.1 Model preparation and test method

The outline of centrifuge model test is shown in Figure 3. The test was conducted in 70g of centrifugal acceleration to simulate clay layer of the 2.05m height prototype (31.5cm in model scale). As shown in Figure 3, at the bottom of clay layer a 3cm filter layer made of sandy material was setup for drainage function. Clay ground was constructed by conducting self-weight consolidation in 70g of centrifugal acceleration with 49kN/m² preload on clay surface. The clay material used for the model test was slurry material by adjusting 80% of the initial water content. Material used in the centrifuge model test was alluvial clay which was taken from Edo River area at underground level of 15m (GL-15m). The physical properties of the clay material used in the tests are shown in Table 1.

| Parameters                  | Value |
|-----------------------------|-------|
| Soil particle density $\rho_s$ (g/cm³) | 2.679 |
| Liquid limit (%)            | 41.0  |
| Plastic limit (%)           | 25.2  |
| Plastic index               | 15.8  |
| Compression index $C_v$     | 0.260 |
| Swelling index $C_s$        | 0.03  |

In clay layer, nine piezometers were installed to measure the pore water pressure induced inside clay
ground. Ground surface displacement during experiment was measured by a laser displacement gauge setup on the top of soil container. Two model tunnels (lower tunnel and upper tunnel) as shown in Figure 4 were installed in different depth of the clay ground in order to investigate the influence of ground depth on tunnel deformation. The model tunnels were made of acrylic material with 7cm in diameter and 3mm in thickness. Strain gauges were pasted inside and outside the model tunnels to measure bending moment of the tunnels. The initial condition of groundwater level was raised to 43cm in height, which is the same as the water level on ground surface as shown in Figure 3.

Test procedures are as follow:

1. At the initial condition as shown in Figure 5, self weight consolidation process was conducted in 70G of acceleration force field for about two hours to make stability of ground.

2. Water head of filter was lowered in the rate of 0.2 cm/min from the initial condition to filter layer surface. (see process (a) to (b) in Figure 5).

3. Water head of filter was raised back to the initial condition in rising rate of 0.2 cm/min from filter layer surface to the initial condition. (see process (b) to (a) in Figure 5).

Water level on ground surface was controlled in constant by supplying water from a water tank mounted on the top of the model container.

3.2 Experimental results

Figure 6 show the relations of water head of filter and ground displacement plotted against time. It is shown that in dewatering process, ground settles in accordant with the lowering of water head of filter. In water rising process, ground settlement was continuously occurred for a certain period of time even after raised in water head of filter. This phenomenon is considered to be due to consolidation of clay ground was not yet completed at the beginning of groundwater rising process. However, about 400 days after the groundwater rising (at 640days), the ground deformation was shifted to rebound behavior. This result shows the same tendency with field measurement data showed in Figure 1.
7. In the dewatering process, pore water pressure distribution dissipating from hydrostatic pressure condition (start dewatering) to the final stage (after dewatering) as shown in Figure 8(a). It is noted that because the water level on ground surface was kept 8.5cm higher than ground surface, pore water pressure distribution at final stage does not become zero. In the water rising process, pore water pressure distribution increase in accordance with the rising of water head of filter. It is seen that pore water pressure distribution in both processes presents curves shape in depth direction which is similar to curves in consolidation theory.

Figure 9 (a), (b) show bending moment of shield tunnels in dewatering process and water rising process respectively. The left and right figure in figure 9 (a),(b) present bending moment of the lower and upper tunnel respectively.
The bending moment was calculated from bending strain of the tunnels. In dewatering process, it is found that two tunnels (lower tunnel and upper tunnel) were affected by compressive strain of clay ground then deformed in horizontal direction as shown in Figure 9(a). Deformation of lower tunnel was larger than deformation of the upper tunnel. This is considered to be due to the compressive strain in lower part of clay ground was larger than that of upper part. In the process of groundwater rising, from the beginning stage to 136 days, the lower tunnel deformed in horizontal direction caused by compressive strain of clay ground. However, after 136 days the tunnel was affected by swelling strain of clay then deformed in vertical direction. This results show the same tendency with the previous experimental result presented by the authors (Sreng et al., 2014). On the other hand, from the beginning to the end of the water rising process, the upper tunnel deformed in horizontal direction. It is confirmed that deformation types of the two tunnels were different in water rising process. This is considered to be due to the differences in deformation and pore water pressure in different layers.

4 CONCLUDING REMARKS

This study aims to investigate the mechanism of ground and tunnel deformation due to the lowering and rising of groundwater level. A centrifuge model test was conducted to simulate the behavior of ground and the tunnels. The main concluding remarks drawn from the centrifuge model test are summarized as follows.

1) In water rising process, it is confirmed that ground settlement was continuously occurred for a certain period of time, then ground deformation changed to rebound.

2) After water rising, it is shown that pore water pressure in upper part of clay layer decrease for a certain period of time then shift to increase. This phenomenon indicated that the compressive behavior occurred in upper clay layer and swelling behavior occurred in lower part of clay ground.

3) In water rising process, deformation types of the tunnels in different depths in clay were different. This is considered to be due to the differences in deformation and pore water pressure of clay ground.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Prof. Atsushi Koizumi of Waseda University and all members of the Ground rebound study committee of the Kanto branch of the Japanese Geotechnical Society for their advices and discussions during the experimental works.

REFERENCES

1) Civil Engineering Support & Training Center, Tokyo Metropolitan Government (1952-2010): Annual Report on Leveling data.
2) Kusaka, T., Sreng, S., Uzuoka, R., Ito, T. Mochizuki, A. (2011): Study on ground upheaval caused by the rise in groundwater level by centrifuge tests and by numerical simulations, Japanese Geotechnical Journal, Vol. 6, No. 3, 439-454.
3) Kusaka, T. (2012): Effect of Rising rate of groundwater level on Ground rebound, Proceedings of the seventh Asian young geotechnical engineers conference, Tokushima, 227-232.
4) Sreng, S., Li, L., Sugiyama, H., Kusaka, T., and Saito, M. (2009): Rebound Phenomenon in Clay Ground Induced by Rising Groundwater Level, Proceedings of the Fourth Biot Conference on Poromechanics, New York, 106-203.
5) Sreng, S., Kusaka, T., Tanaka, H., Sugiyama, H., Ito, T. (2014): Centrifuge model test of ground rebound caused by the rising of groundwater level and its effect on shield tunnel, Proceedings of Physical Modeling in Geotechnics (ISPMG2014), Perth, 973-978.