Geotechnical Aspects of Underground Construction in Soft Ground – Elshafie, Viggiani & Mair (eds)
© 2023 ISSMGE, London, UK, ISBN 978-1-032-40947-4

Long-term behaviour of ground around tunnel due to groundwater level fluctuations

Wei Li
Tokyo Electric Power Services Co., Ltd., Tokyo, Japan

Shigeaki Oka
Tokyo Electric Power Company Holdings, Incorporated, Tokyo, Japan

Alireza Afshani & Hirokazu Akagi
Department of Civil Engineering, Waseda University, Tokyo, Japan

ABSTRACT: The soft clayey soil around fully impermeable segmented tunnels can swell if groundwater table gradually rises in several years. It is analogous to the consolidation of cohesive soil under the influence of gradual groundwater drawdown. Under the gradual rising of groundwater, effective stress in saturated cohesive soils decreases by an increase in porewater pressure and volumetric strain of soil elements increase. Also, the degree of saturation of soils increases and suction forces disappear in unsaturated soils. The new saturated soils may continue to swell until the end of the secondary swelling stage. Because of these events, the loads on the tunnel lining may increase or decrease at different locations. Under the effect of these loads, lining deformation may reach a new equilibrium status. In this paper, a coupled soil-water finite element analysis is employed to study the long-term behaviour of ground and tunnel due to the changes in groundwater level by using an old tunnelling case in Japan. The field measurements are used to support the results of analyses. One-ring model is used to model the lining behavior and interface planes are used between linings and surrounding soils to allow relative movement of soil and lining. The relationship between suction, degree of saturation and permeability ratio are used to model swelling behaviour of unsaturated soils. A series of back analyses were performed to fit the analytical results of ground surface settlement with field measurements by changing the anisotropic permeability of clay and equivalent stiffness of concrete lining. The time-dependent behaviour of diameter changes in one specific tunnel lining and ground surface displacement around the tunnel are investigated numerically.

1 INTRODUCTION

The ground water fluctuation in cohesive soil can cause heave and settlement in the long-term. According to the report of observation on ground surface settlement in Tokyo, the groundwater level in Tokyo fell due to the irrational usage of water by domestic water, industry and higher buildings from the 1920s to the 1960s (TMGBC 2017). The groundwater levels in several of the major cities in the UK and elsewhere in Europe also fell tens of meters by developing the industry from the early 1800s to the 1940s (Wilkinson 1985). The groundwater levels fall as demand increases over and above natural aquifer recharge. The underground structures including tunnels can also be influenced by water table level fluctuations. By lowering the groundwater table in a cohesive soil, consolidation might happen and initially saturated soil may experience the unsaturated condition. It is because effective stress of soils increases with a gradual decrease in pore water pressure. Increase in the amount of effective stress can reduce the void ratio of soil elements and may lead to an increase in loads of the underground structures. To protect the underground water resource and limit the significant settlement of ground surface, the usage of groundwater has been controlled strictly. As a result, there has been a gradual and steady rise in groundwater levels and cohesive soils start to swell up. The swelling behaviour of soils is analogous to the consolidation of cohesive soil under the influences of gradual groundwater drawdown. Under the gradual rising of groundwater, effective stress in saturated cohesive soils decreases by an increase in porewater pressure and volumetric strain of soil elements increase. Also, the degree of saturation of unsaturated soils increases and suction forces disappear in unsaturated soils. The new saturated soils

DOI: 10.1201/9781003355595-77

may continue to swell until the end of the secondary swelling stage. During this stage, the structures on or under the ground surface may heave which leads to an unfavorable structural problem. Therefore, the study of the long-term behaviour of ground and structures due to groundwater level fluctuations is important. In this paper, an aged segmented tunnel in Japan is used for the purpose of this study. Both ground and tunnel behaviour in the long-term have been studied.

In this study, the effect of permeability anisotropy on consolidation and swelling behaviour of cohesive soils around the tunnel is investigated. Table 1 shows some recommended values of permeability ratio r_k (ratio of horizontal to vertical permeability) done by different researchers using laboratory and in-situ tests. For instance, Mitchell (1956) found that the ratio r_k is from 1.0 to 4.0, with an average value of about 2.0 and Chandler et al. (1990) recommended r_k approximately equal 2.0 for London clay by using self-boring permeameter test. The structural stiffness of segmented linings is smaller at the location of joints. If the effect of joints is not taken into account, uniform equivalent stiffness is used in the lining along the tunnel. The effect of uniform equivalent stiffness of lining is also studied on overall ground and tunnel responses.

series of coupled soil-water analyses are performed to study the long-term behaviour of ground and tunnel due to the changes in groundwater level by using the data of an old tunnel in Japan. The field measurements are used to support the results of analyses. One-ring model is used to model the plane-strain condition of the lining. The interface planes between linings and surrounding soils are used to allow relative movement of soil and lining. The relationship between suction, degree of saturation and permeability ratio are used to model swelling behaviour of unsaturated soils. Also, several back analyses were done to fit the numerical results of ground surface settlement with measurement values in the field by changing the anisotropic permeability of clay and uniform equivalent stiffness of lining. The time-dependent behaviour of changes in tunnel diameter and ground surface displacement around the tunnel is investigated numerically.

Table 1. Recommended permeability ratio r_k for different soil types.

Soils type	r_k ratio	Reference
London clay	2.0	Mitchell (1956)
Illite and Boston blue clay	0.9 to 4.0	Olsen (1962)
Marine clay	1.1 to 2.5	Leroueil et al. (1990)
London clay	2.0	Chandler et al. (1990)
Soft clay deposits marine origin	1	Mesri et al. (1994)
Lacustrine varved clay	< 3.0	
Remolded pure clay, synthetic silty clay, and natural clay	1.1 to 3.0	Clennell et al. (1999)
Singapore marine clay	2.0 to 3.0	Chu et al. (2002)
Soft Bangkok clay (at low preconsolidation pressure)	1.0 to 1.3	Seah & Koslanant (2003)
Soft Bangkok clay (at higher stress)	2.8	
Many homogeneous clays	1.2 to 2.5	O'Kelly (2005)
Resedimented Boston Blue Clay	1.2 to 1.9	Adams et al. (2013)

2 A CASE OF AN AGED SEGMENTED TUNNEL

A case of an aged segmented tunnel built in soft clay in Japan is considered here. The tunnel was constructed for electrical transmission in 1983 and since then it experiences significant changes in groundwater level by time. Figure 1 shows the general plan of the site. An observation well for groundwater level measuring and an observation point for measurement of the ground surface settlement are located approximately with a projected distance of 650 m from the tunnel. Therefore, the behaviour of groundwater and ground surface settlement are assumed to be identical at the section of 650 m from the tunnel. The tunnel under study has 191 rings along the tunnel with a total length of 171.9 m.

2.1 *Structural details of the tunnel*

Figure 2 shows the structural details of the lining. There are 6 pieces of reinforced concrete segments in one ring which has a width of 0.9 m, a thickness of 0.25 m, and an inner diameter of 3.5 m, respectively. The segments are connected by segment joints, and the rings are connected by ring joints. The joints are interconnected by steel bolts and sealing rubber.

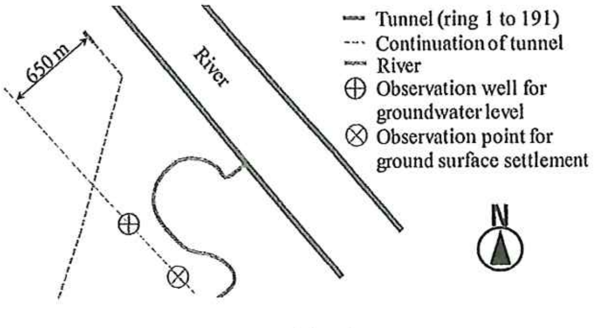

Figure 1. The general plan of the site.

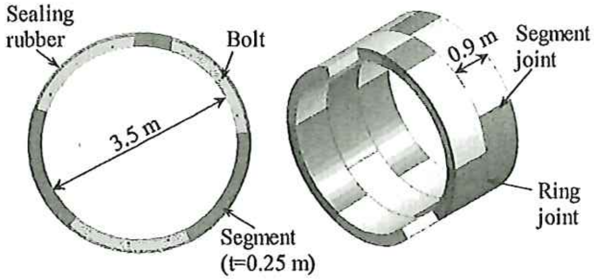

Figure 2. Structural details of the tunnel lining.

2.2 *Long-term behaviour of the ground*

According to TMGBC (2017), the groundwater level dropped significantly in 1961, 1964 and 1971 due to irrational usage by domestic water, industry, and building. This led to a significant settlement of ground surface (see Figure 3). In order to restore groundwater level and limit the ground surface settlement, the usage of groundwater was limited from 1972 which results in a gradual rising of groundwater. Figure 3 shows the recorded groundwater level at an observation well (shown in Figure 1). The field measurement is shown in a blue curve from 1890 to 2016 and the predicted groundwater is shown in the red curve from 1980 to 2040. There is an attempt to predict groundwater behavior from 2016 to 2040, basing on the measured data from 1980 to 2016. The equation is also shown in Figure 3. Here, the data of changes in groundwater from both field measurements and the prediction are used as shown in the black cross marked curve.

Figure 3 also shows measured ground surface displacement recorded from an observation point as shown in Figure 1. It can be seen that the ground surface settles significantly from 1935 to 1975 which is corresponding to the dropping in groundwater level and then it swells from 1975. The maximum value of settlement and swelling of the ground surface is approximately 3.52 m and 0.09 m, respectively.

2.3 *Long-term behaviour of the tunnel*

The changes in diameter of tunnel lining are measured in 2010 by Laser and Station methods. Figure 4 shows the changes in the diameter of the tunnel lining in horizontal and vertical directions. The vertical diameter decreases by a mean value of 20.68 mm, and the horizontal diameter increases by a mean value of 17.08 mm approximately.

3 PERFORMED ANALYSES

3.1 *Numerical model*

A series of three-dimensional coupled soil-water analyses are performed. Figure 5 shows the mesh with a width of 650 m due to the projected distance from the tunnel to observation well and a height of 80 m and one-ring thickness equal to 0.9 m. There are 9,838 nodes and 4,767 elements in the model created by software of Midas GTS NX. Two soft cohesive soil layers (Yc and Yc-lower) are beneath the sandy soil layer (Ys) on the ground surface. The tunnel is embedded in Yc layer which has a very low N-value. This so-called one-ring model demonstrates plain-strain condition of soil and tunnel only at ring No. 99. Because the tunnel is connected to two vertical underground structures at ring No. 1 and 191. At these two connection parts, the deformation of linings is limited, however, between them, the linings can deform freely. The interface elements are also used between linings and surrounding soils to allow relative movement of two different materials.

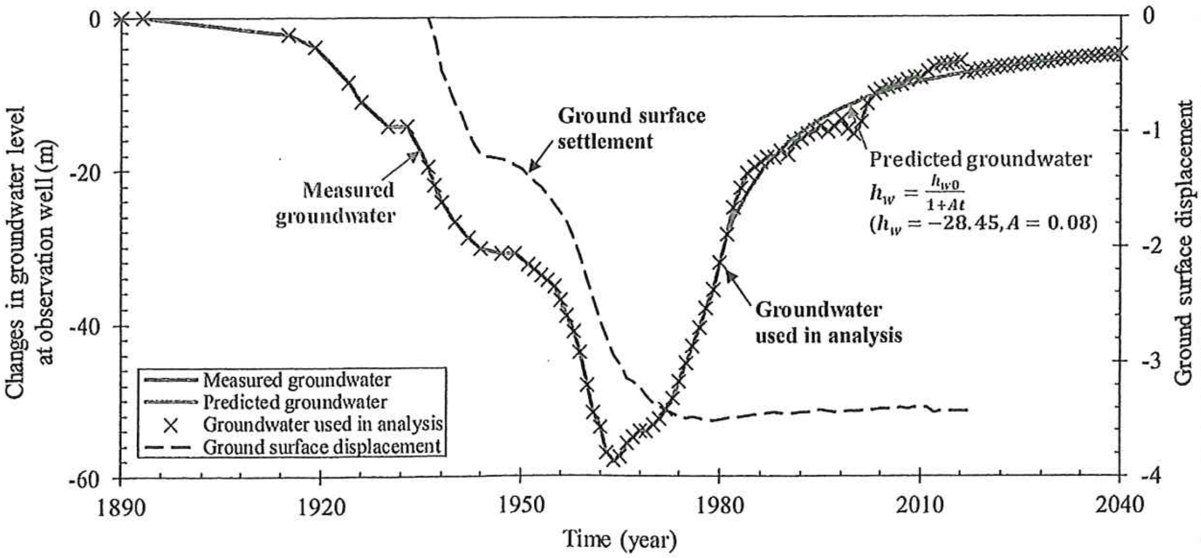

Figure 3. Changes in groundwater level at observation well by time.

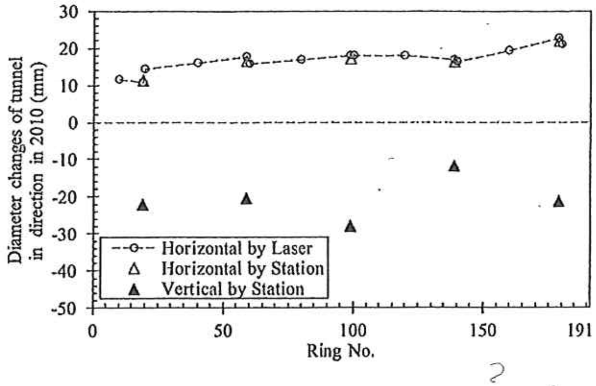

Figure 4. Changes in diameter of tunnel lining in the horizontal and vertical direction by ring numbers.

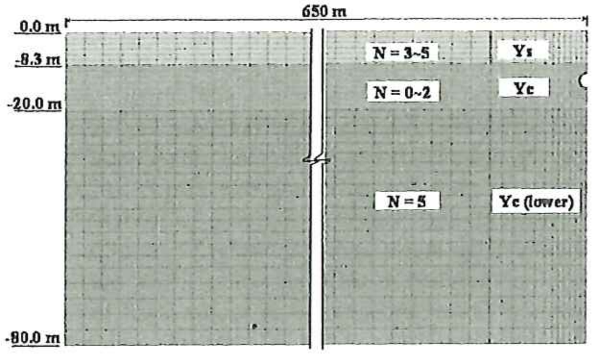

Figure 5. Numerical mesh.

Table 2 shows properties of soils used in the model. The geotechnical tests or used equations to obtain the soil properties are also demonstrated. The elastic model is used for sand and Modified Cam-clay is used for clay soils. The tunnel has been built in very soft clayey soils with low SPT values approximately equal to 1.0. The time-dependent permeability in clay is introduced by C_k parameters with the recommended value of $0.5e_0$ for most soft clay (Terzaghi et al. 1996).

Regarding the boundary conditions, the whole model is constrained in normal direction to the four vertical side surfaces. The bottom of model is fixed and the top surface of model is set to be free. The changes in groundwater level shown in Figure 3 are assumed and applied at the section of observation well, which is 650 m away from the center of the tunnel and at the left side boundary of the numerical model shown in Figure 5.

There are several analysis stages shown in Table 3. First one is for the initial stress condition and in this stage all the elements and gravity loads are applied. Second one is for the initial seepage condition and the changes in groundwater level shown in Figure 3 are applied. Others are the main calculation stages where the analysis are carried out from 1890 to 2040. During October 1979 to May 1983, the tunnel was built in the cohesive soils.

Table 2. Soil properties used in the model.

Parameters	Symbol	Unit	Sand (Ys)	Clay (Yc)	Clay (Yc-lower)	Test method or used equation
Analysis model			Elastic	Modified Cam-clay	Modified Cam-clay	
Depth		m	0~8.3	8.3~20	20~60	
Unit weight	γ	kN/m^3	18.3	16.3	16.3	Physical test
N value	N	—	4	1	5	
Young's modulus	E	kN/m^2	11,200	2,800	14,000	$E = 2800\,N$
Effective Poisson's ratio	ν'	—	0.33	0.35	0.35	Consolidation test for Yc, common values for other layers
Permeability coefficient	k_v	m/sec	1.7×10^{-5}	1.3×10^{-9}	1.3×10^{-9}	In-situ permeability test by boreholes
Void ratio	e_0	—	1.105	1.353	1.353	$e = (\gamma_w G_s - \gamma_{sat})/(\gamma_{sat} - \gamma_w)$
Coefficient of earth pressure	K_0	—	0.5	0.54	0.54	Consolidation test for Yc, common values for other layers
Cohesion	c	kN/m^2	0	—	—	
Frictional angle	φ	deg	25	—	—	
Gradient of isotropic normal consolidation line	λ	—	—	0.284	0.284	Consolidation test (= 0.434Cc)
Gradient of isotropic swelling line	κ	—	—	0.094	0.094	Consolidation test (= 0.434Cs)
Slope of critical state line	M	—	—	1.175	1.175	$M = 6\sin\varphi'/(3-\sin\varphi')$
Dilatancy coefficient	D	—	—	0.069	0.069	$D = \lambda\Lambda/(M + M\,e_0)$ $\Lambda = 1-\kappa/\lambda = 1-Cs/Cc$
Permeability changing ratio	C_k	—	—	0.6765	0.6765	$C_k = e_0/2$

Notes: γ_{sat} is the saturated unit weight of soil, G_s is the specific gravity, C_c is the compression index, C_s is the swelling index, φ' is the effective-stress friction angle, λ is the gradient of isotropic normal consolidation lines (= $0.434C_c$), κ is the gradient of isotropic swelling lines (= $0.434C_s$).

Table 3. Analysis stages in the model.

Stage	Year
Initial-stress	1890
Initial-seepage	1890
Consolidation	1890 to 1964
Swelling	1965 to 1979-09
Tunnel construction	1979-10 to 1983-05
Swelling	1983-06 to 2040

3.2 *Unsaturated behaviour of soil*

The degree of saturation of soil changes by the fluctuation of groundwater level. In unsaturated soil, the soil-water characteristic curves (SWCC) is used which is a relationship between the water energy state and the mass of water (Fredlund 2002a, Fredlund 2006). Japan Institute of Construction Engineering (JISE) proposed SWCC curves for sand and clay by performing laboratory tests. Based on JISE, the relationship between suction (ψ) and degree of saturation (S) is given by curve shown in Figure 6 and relationship between the degree of saturation (S) and permeability ratio (K_r) of soil is given by curve shown in Figure 7. These two curves are employed in numerical analyses to demonstrate unsaturated behaviour of soil.

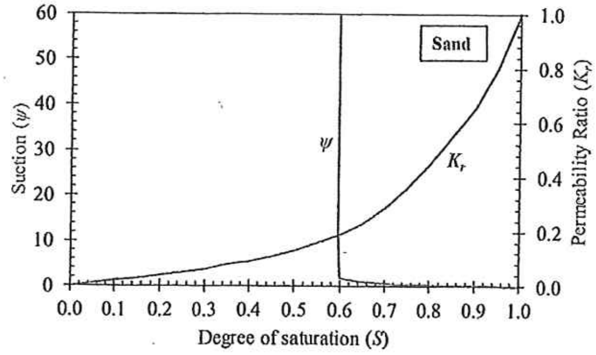

Figure 6. Changes of suction and permeability ratio by the degree of saturation changes in the sand.

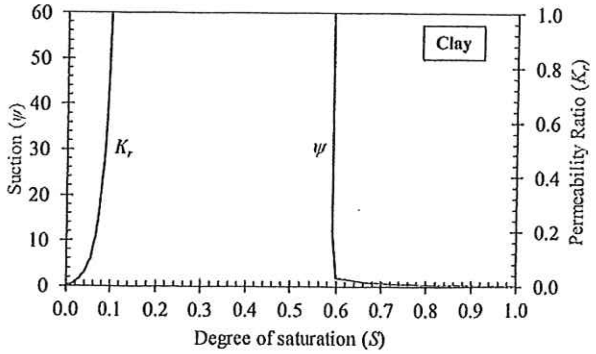

Figure 7. Changes of suction and permeability ratio by the degree of saturation changes in clay.

4 EFFECT OF PERMEABILITY ANISOTROPY AND EQUIVALENT LINING STIFFNESS

4.1 *Permeability anisotropy*

In the real ground, soils have anisotropic permeability. The permeability ratio r_k is recommended to be in a range of 2 to 10 (Look 2014). Using the recommended range for r_k, back analyses are performed to fit measured ground surface displacement with numerical values. The numerical ground surface settlement is read at a node on the ground surface at the section of observation point (650 m away from tunnel).

Figure 8 shows that both measured and calculated values of ground surface displacement. The ground surface settles down firstly due to groundwater dropping and then tends to swell due to groundwater rising. By increasing ratio r_k from 1.0 to 2.0, the maximum ground surface settlement is also increased significantly. It is because the void ratio can be reduced faster by increase horizontal permeability of clay. By increasing the ratio r_k to 2.0, both settlement and swelling increase significantly and the swelling starts approximately 22 months earlier. By the increase in ratio r_k, water flows out or into the soil faster and change in water level influences the effective stress status of elements quicker. The results for ratio r_k of 3.0 and 4.0 are almost identical. Using $k_h/k_v = 2.0$, the close fit between measurement values and calculated results are attainable. So, k_h for clay is set to 2.6×10^{-9} m/s.

4.2 *Equivalent stiffness of lining*

The lining stiffness can be reduced by joint deterioration. Here, the lining is modeled by solid element without considering ring or segment joints and therefore, a reduced equivalent lining stiffness is considered for lining elements. The changes in reduced equivalent lining stiffness are applied by changing the concrete elastic modulus. Using different equivalent lining stiffness, numerical results

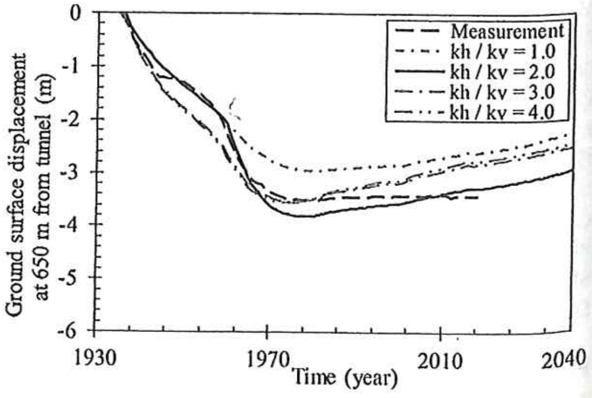

Figure 8. The ground surface settlement at observation point by permeability ratio study.

of the change in tunnel diameter are fit with measured values. Figures 9 and 10 show diameter changes of the tunnel in the vertical and horizontal direction by time, respectively. Figure 11 also shows measured and calculated diameter changes of tunnel lining at ring No. 99 in 2010. The lining deformation increases in the horizontal and vertical direction by decreasing equivalent stiffness of lining. In this way, EI_{eq} = 40% EI is adopted in numerical analyses.

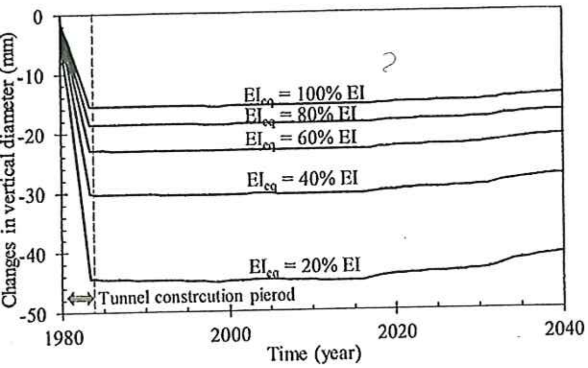

Figure 9. Diameter changes of the tunnel in the vertical direction.

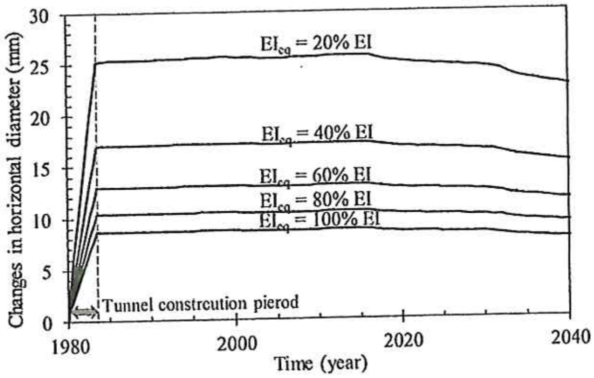

Figure 10. Diameter changes of the tunnel in the horizontal direction.

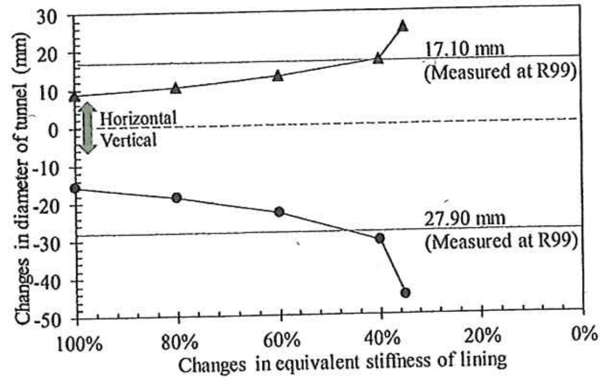

Figure 11. Changes in diameter of ring 99 by changes in equivalent stiffness in 2010.

5 CONCLUSION

The long-term behaviour of ground and tunnel due to the changes in groundwater level was studied and a series of coupled soil-water analyses were employed. Effect of permeability anisotropy of soils and equivalent uniform stiffness of lining on the soil and tunnel behaviour were studied by using the data of an aged segmented tunnel built in soft clay. The conclusions of this study are listed as follows:

Soil permeability anisotropy is an important parameter to study soil behaviour. The ratio r_k of horizontal to vertical permeability is recommended in a range of 2.0 to 10.0 by some researchers, and the proper value of 2.0 can be used for clay in this study. By increasing the ratio r_k to 2.0, both settlement and swelling behaviors of ground soils increases significantly. The ground starts to swell approximately 22 months earlier. Because water flowing into or out of soil voids becomes faster, which influences the effective stress status of soil elements quicker.

The equivalent stiffness of tunnel lining plays an important role to study behaviour of lining, especially when considering the effects of segment and ring joints. In this study, 40% of initial design stiffness of linings has a good agreement with the field measurement. By decreasing 60% in lining stiffness, the diameter of tunnel lining increases 8.5 mm in horizontal direction and decreases 14.9 mm in vertical direction.

However, there are also limitations to this study. For instance, only one specified section of one-ring has been modeled, the behaviour of tunnel lining is limited at this section. For further study, investigations on full tunnel lining are essential. And real equivalent stiffness of tunnel lining calculated by the structural method can also be compared with the percentages obtained in this study.

REFERENCES

Adams, A. L., Germaine, J. T., Flemings, P. B., & Day-Stirrat, R. J. 2013. Stress-induced permeability anisotropy of resedimented Boston Blue Clay. *Water Resources Research*, *49*(10), 6561–6571.

Chandler, R. J., Leroueil, S., & Trenter, N. A. 1990. Measurements of the permeability of London Clay using a self-boring permeameter. *Géotechnique*, *40*(1), 113–124.

Chu, J., Bo, M. W., Chang, M. F., & Choa, V. 2002. Consolidation and permeability properties of Singapore marine clay. *Journal of Geotechnical and Geoenvironmental Engineering*, *128*(9), 724–732.

Clennell, M. B., Dewhurst, D. N., Brown, K. M., & Westbrook, G. K. 1999. Permeability anisotropy of consolidated clays. *Geological Society, London, Special Publications*, *158*(1), 79–96.

Fredlund, D. G. 2002, March. Use of soil-water characteristic curves in the implementation of unsaturated soil mechanics. In *Proceedings of the 3rd International Conference on Unsaturated Soils, Recife, Brazil* (Vol. 3, pp. 887–902).

Fredlund, D. G. 2006. Unsaturated soil mechanics in engineering practice. *Journal of geotechnical and geoenvironmental engineering*, *132*(3), 286–321.

Leroueil, S., Bouclin, G., Tavenas, F., Bergeron, L., & Rochelle, P. L. 1990. Permeability anisotropy of natural clays as a function of strain. *Canadian Geotechnical Journal*, *27*(5), 568–579.

Look, B. G. 2014. *Handbook of geotechnical investigation and design tables*. CRC Press.

Mesri, G., Feng, T.W., Ali, S., & Hayat, T.M. 1994. Permeability characteristics of soft clays. X IIIIC SM FE. 1994. New Delhi. India

Mitchell, J. K. 1956. The fabric of natural clays and its relation to engineering properties. In *Highway Research Board Proceedings* (Vol. 35).

O'Kelly, B. C. 2005, May. Consolidation anisotropy of some natural soft soils. In *Proceedings International Conference on Problematic Soils* (pp. 25–27).

Seah, T. H., & Koslanant, S. 2003. Anisotropic consolidation behavior of soft Bangkok clay. *Geotechnical Testing Journal*, *26*(3), 266–276.

Terzaghi, K., Peck, R. B., & Mesri, G. 1996. *Soil mechanics in engineering practice*. John Wiley & Sons.

TMGBC. 2017. Observation Report on Soil Ground Settlement by Tokyo Metropolitan Government Bureau of Construction.

Wilkinson, B. R. I. A. N. 1985. Rising groundwater levels in London and possible effects on engineering structures. In *Proceedings of the 18th Congress of the IAH, Cambridge* (pp. 145–157).