

Analysis of Ground Deformations Induced by Tunnel Excavation

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Abstract: In this study, we analyzing the ground deformation response in water-bearing sandstone ground caused by tunnel excavation. Moreover, based on the field monitoring data of Xiang-an subaqueous tunnel in Xiamen, taking a deep research on ground deformations caused by large cross section tunnel excavation. From our research results, during tunnel excavation surface settlement and extensometer settlement may be divided into four stages: slight deformation stage, rapid deformation stage, stable stage and slow deformation stage.

Keywords: Field monitor, ground deformations, shallow excavation method

INTRODUCTION

The national strength of China has increased greatly. Along with enhancement of economy, the city modernization will certainly continue to deepen. Restricted by economy, complicated and diversified stratum as well as special environmental condition, it will be widely used in constructing urban metro tunnel and subaqueous tunnel that the Shallow Excavation Method has strong compatibility to the stratum and high flexibility in the future (Haruyama *et al.*, 2001).

In recent years, the urban underground engineering has developed vigorously and new engineering problems emergence continuously.

During construction period, the influence to the existing facility must be controlled in an allowable level. The broader aspects of the damage caused by settlement are considered in other studies. However, the construction of a large cross section tunnel is a multi-dimensional dynamic process, since it is very difficult to control ground deformation in shallow buried tunnel (Gunn, 1992).

In China, many urban metro tunnels have been constructed in Shallow Excavation Method. After many years, we have made many scientific researches and accumulated rich experience. In fact, excavation especially in the soft soil ground is a complex three dimensional space-time question. If the ground is rich in water, consolidation and hydro-mechanical coupling will be involved, which is more difficult (Mair *et al.*, 1996).

International and domestic scholars have carried on explorations and researches on surface settlement as a result of underground excavation in complex conditions.

Methods for estimating the ground deformations due to tunneling may be classified into three categories: empirical methods, numerical methods and analytical

methods. This study depends on the monitoring data of Xiang-an subaqueous tunnel, taking a key research on the

law of ground deformation in excavating shallow tunnel in weak geology.

BACKGROUND

Xiang-an Tunnel is the first subaqueous tunnel in China. This great sea-crossing project, to our country tunnel construction technology's progress and the development, the reduction and world advanced level's disparity will play the milestone-like the role.

This tunnel connects the Xiamen main island and the Xiang-an District and it has the function of highway and the urban road. Xiang-an tunnel is a three-parallel-tube tunnel. Two main tunnels lie in both sides and an assistant tunnel is in the middle. The tunnel is approximately 5950 m long. Clearance of the main tunnel is designed 5 m high and 13.5 m wide. The tunnel is constructed in water-bearing strongly and completely granite ground. The Profile of the tunnel and general geology is shown in Fig. 1.

The tunnel was constructed in drilling and blasting method. The tunnel was excavated in CRD method with steps 8 to 12 m and core soil 2 m. The excavation: 1, 3, 2, 4 is shown in Fig. 2.

MONITOR SCHEME

According to the peculiarity of the tunnel, engineering practice and the suggestion proposed by design department, the monitoring scheme contents following project:

- Surface settlement
- Extensometer settlement
- Crown settlement
- Ground horizontal displacement
- Pore water pressure
- Ground loading

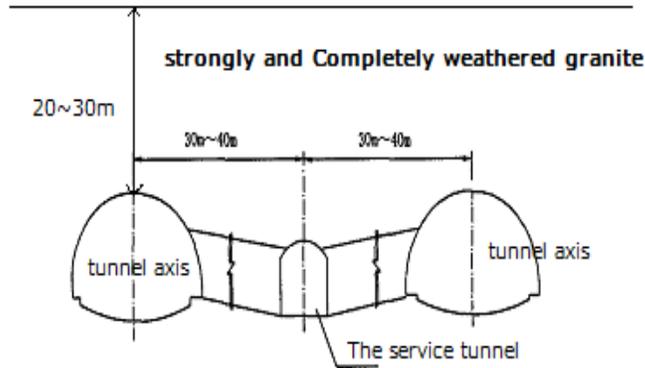


Fig. 1: The profile of Xiang-an tunnel

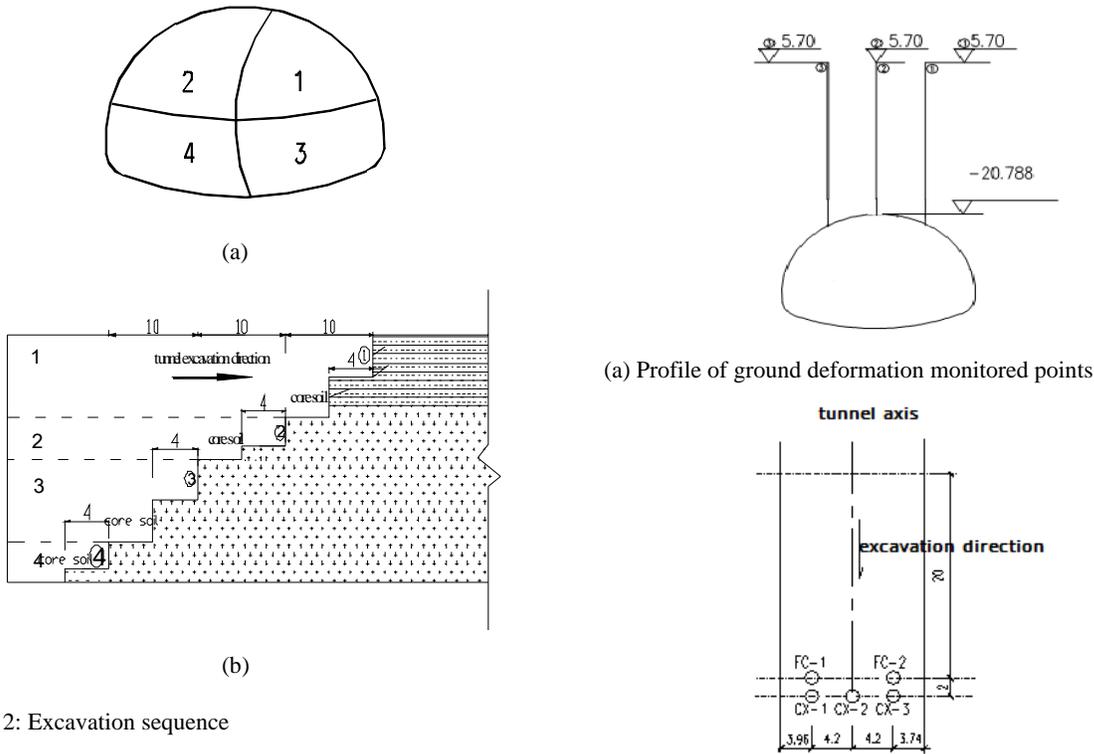


Fig. 2: Excavation sequence

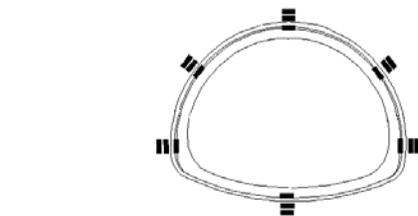
Two measuring sections are placed at ZK11+823 and ZK11+825, about 20 m before the first working face. The monitor points is located around the tunnel wall, as shown in Fig. 3.

Analysis on monitoring data:

Surface settlement: Excavation of a tunnel induces ground movements around the tunnel and at the surface of the ground above.

Recently some attempts have been made to develop simple closed-form analytical solutions for tunneling-induced ground movements in clays. Verruijt and Booker (1996), Strack and Verruijt (2002), Verruijt and Strack (2008) and Bobet (2001) have analyzed different versions

(a) Profile of ground deformation monitored points



(b) plan of ground deformation monitored points

(c) Stress monitored points

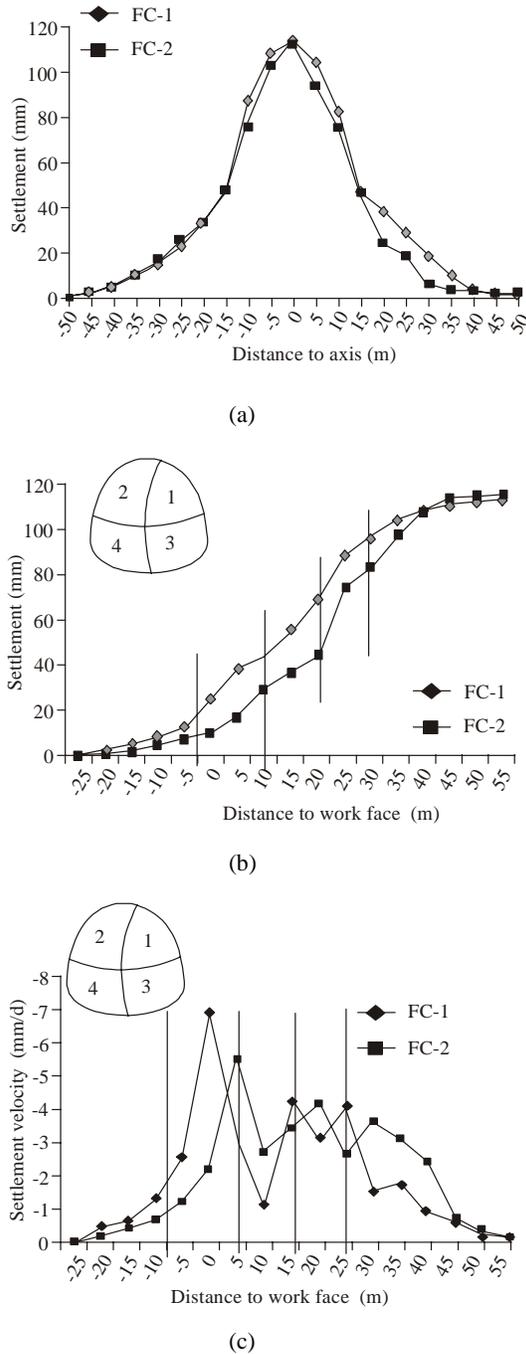


Fig. 4: Surface settlements

of the -Dimensional (2D) version of this problem, treating the stress-strain relationship for the ground as linear. All the solutions are derived with the assumption of a uniform radial ground deformation pattern around a circular tunnel section not considered an oval-shaped pattern and noncircular tunnel section and excavation sequence. The surface settlement curve is shown in Fig. 4.

Surface settlement caused by tunnel excavation may be divided into four stages:

- **Slight deformation stage:** Excavation begins to effect surface settlement when the distances to working face up to -2.0~-3.0 D. In water-bearing sandy stratum the distance may be even surpasses -4D. The settlement in this stage is 5~15% of total subsidence settlement approximately.
- **Rapid deformation stage:** When the distance to working face rang from -2D to 3D, the settlement speed grows rapidly. And the maximum speed appears nearby the working surface
- **Slow deformation stage:** When the distance to working face rang from 3 to 5 D, the settlement slows down in a negative acceleration.
- **Stable stage:** After the distance to working face surpasses 5D, the settlement tends to be stable. The settlement in this stage is 5~10% of total subsidence settlement approximately.

Surface settlements are often estimated using empirical methods such as the Peck method (1969), where it is generally assumed that the surface settlement trough can be approximated by the normal probability curve or error function:

$$S = S_{\max} \exp\left(-\frac{x^2}{2i^2}\right) \quad (1)$$

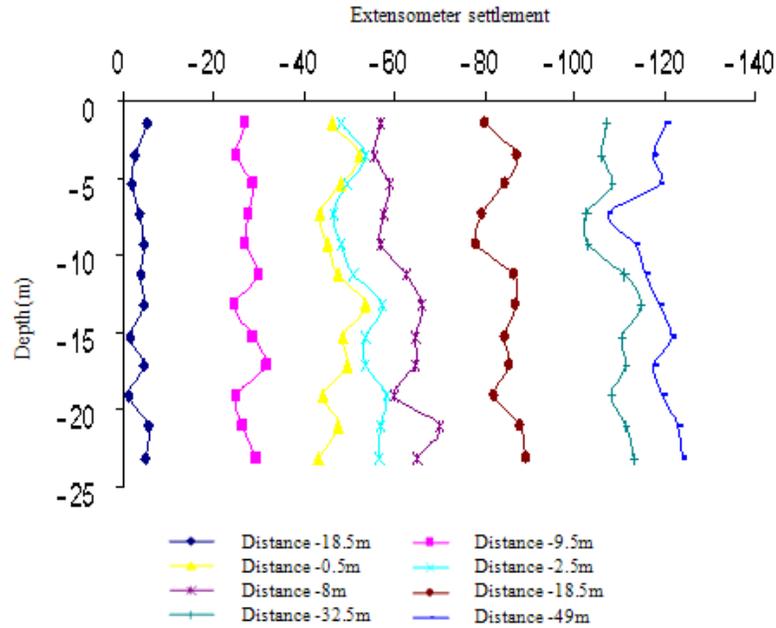
In the equation, S is settlement, S_{\max} is the maximum settlement above the tunnel centerline, x is the horizontal distance from the tunnel centerline in the transverse direction and i is the distance from the tunnel centerline to the inflexion point of the curve. As shown in Fig. 3a, the surface settlement satisfy the Eq. (1) well.

Extensometer settlement: The depths of measuring points are shown in Table 1.

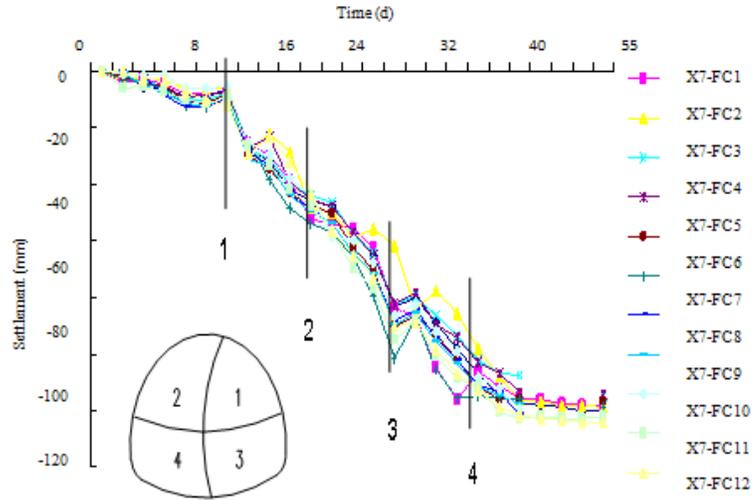
When the working surface was approaching, passing through, leaving the measuring point, the settlement tendency in different depth is similar, which is shown in Fig. 5.

Table 1: Depths of measuring points

X7-FC1	X7-FC2	X7-FC3	X7-FC4
-1.474	-3.473	-5.370	-7.279
X7-FC5	X7-FC6	X7-FC7	X7-FC8
-9.227	-11.237	-13.183	-15.375
X7-FC9	X7-FC10	X7-FC11	X7-FC12
-17.145	-19.09	-21.132	-23.104



(a)



(b)

Fig. 5: Extensometer settlements

The largest settlement appears at 21.5 and 23.5 m depth, respectively. The second largest appears at ground surface. Thus it can be considered that after tunnel excavation, there exists a settlement decrease zone between surface and tunnel roof.

This large section tunnel was excavated by CRD method. As shown in Fig. 1, the settlement caused by excavating 1 has the largest proportion and the next is excavating 2. Therefore, it is important to take actions in

excavating 1 and 2. It will decrease the total settlement effectively.

Crown settlement: As shown in Fig. 6, the vault settlement in two measuring points shows a similar regularity. The curve presents “S”, conforming to the former monitoring data.

Before the settlement became stable, it has experienced the slow deformation stage, rapid deformation stage and finally became stable the stage:

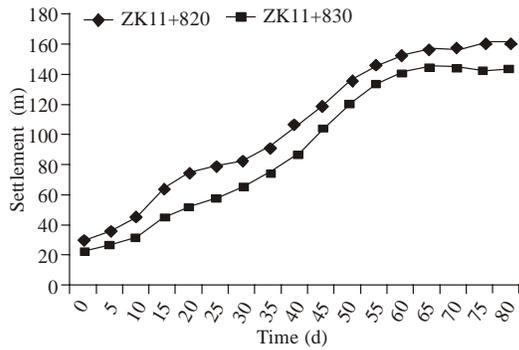


Fig. 6: Crown settlements

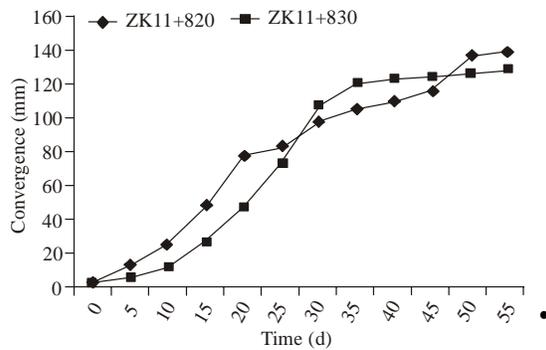


Fig. 7: Horizontal convergence of tunnel wall

The settlement within a scope of 0 to 3 m increases slowly and accounts for 12% of the total vault settlement.

- The settlement within a scope of 3 to 50 m increases rapidly and accounts for 78% of the total vault settlement.
- The settlement within a scope of 50 to 80 m tends to be stable and accounts for 10% of the total vault settlement.
- The settlement experiences a long time, because the tunnel was divided into four guiding adits in excavation. In order to keep working face stable, space between each guiding adit may reach 8~12 m. In extremely weak the space will be larger.

The horizontal convergence of tunnel wall is shown in Fig. 7.

According to the data, the horizontal convergence developed gradually. It can be found that the horizontal convergence has the similar variation discipline compared with the crown settlement.

It shows that removing upside headings impacts the horizontal convergence enormously. The horizontal convergence reaches 98 mm. The values increase slowly during the downside headings excavation the two

sidewall headings and the last value of whole section's horizontal convergence is 133 mm.

According to the monitoring measurement data, the upside headings excavation is a vital step to control the horizontal convergence values of tunnel. It also shows that the horizontal convergence is controlled well, the support structure is reasonable and the blasting vibration has little impact on horizontal convergence.

Horizontal displacements: In Fig. 8, the positive horizontal displacement represents departing from tunnel space and the negative horizontal displacement represents moving towards tunnel space.

Tunnel excavation began to influence on the front ground with a scope of 10 to 15 m, when is bigger than this distance, in the strike departs from the spatial traverse, the stratum is at extrusion condition.

When the working face is approaching and passing through the observation point, the ground move towards the tunnel space and the value is large. And then the displacement changes direction, while the value is quite small. This indicated that the ground transforms from loose into the extrusion tendency.

Along the depth direction, the horizontal displacements near surface and crown are relatively large, which indicates there exist a deformation decrease zone in ground. This is the same with extensometer settlement.

Pore water pressure: Flow behavior around a tunnel is governed by the hydraulic boundary conditions and hydraulic properties of materials involved in the seepage routes such as ground, lining and drainage systems. It has been generally identified that the magnitude of pore water pressure on the tunnel lining is dependent on the relative permeability between ground and lining (Shin *et al.*, 2005).

The pore water pressure may accelerate structural deterioration and consequently increase leakage. In this case, pore water pressures develop between linings and act directly on the secondary lining, which can cause damage to the lining structures.

The liner of impermeable tunnels must support the full hydrostatic pore pressures while the support of a tunnel with drainage around the perimeter of the opening must support the stresses transferred from the ground as well as the seepage forces due to the water flow towards the tunnel (Lee and Nam, 2001; Bobet, 2003). While these two are limit cases, in practice waterproof tunnels may leak resulting in a reduction of pore pressures around the tunnel, or an initially perfectly efficient drainage may loose capacity

The relationship between pore water and time is shown in Fig. 7. When the ground has been excavated and sprayed concrete was not complete, the pore water pressure is zero, because the pore water can flow from the

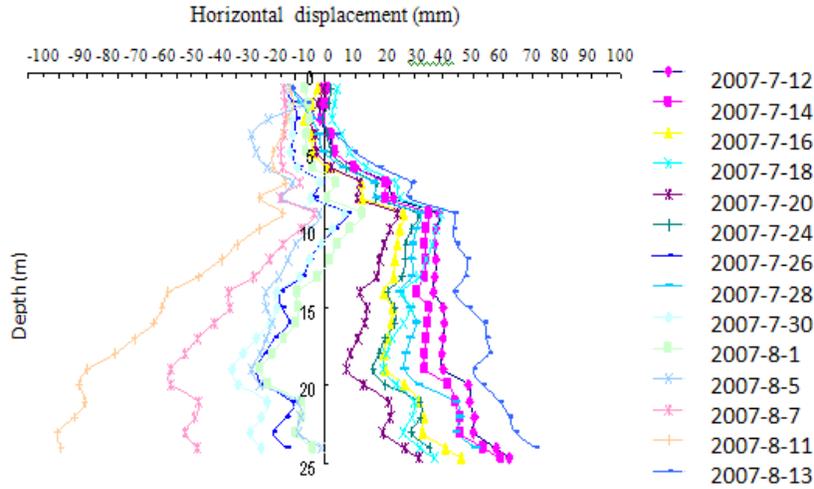


Fig. 8: Horizontal displacements

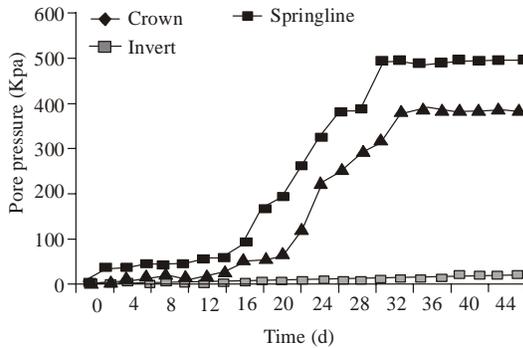


Fig. 9: Pore water pressure

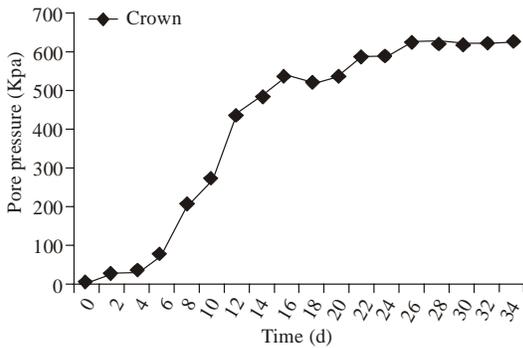


Fig. 10: Ground loading

ground freely. After the sprayed concrete is completed, the pore water pressure developed.

As shown in Fig. 9, the pore water pressure of three positions is monitored. The pore water pressure is similar at crown and spring line. The maximum pore water pressure is reached 531 KPa. While the pore water

pressure at invert is nearly zero, this is because the drain pipe is located there.

The maximum pore water pressure is reached 531 KPa, which is lower than the hydrostatic pressure. Because in this case, the shotcrete lining is permeable, so that discharge takes place. In practice, all amount of inflow should be collected and drained by drainage system. If the drainage system is blocked, the pore water pressure will develop to hydrostatic pressure.

Ground loading: Ground loadings acting on the shotcrete lining are the total stress which consists of effective stress and pore water pressure. And the pore water pressure is the penetrating pressure and the increase in pore water pressure may accelerate structural deterioration and consequently increase leakage. So the pore water pressure is crucial for subaqueous tunnel structures.

The ground loading on the primary lining with time is shown in Fig. 10.

The ground loading developed gradually with time, this related with the sprayed concrete hardening and effective stress increases. The maximum ground loading is 634 Kpa, while the pore water is 531 Kpa. We can see the majority of the ground loading consist of pore water pressure, which is reached 83.7%.

The pore water pressure must be monitored during the life of the tunnel because of degradation of the drainage system. Such degradation has as a direct consequence pore pressure development behind the secondary support.

CONCLUSION

Based on the field monitoring data, analyzing the ground deformation response in water-bearing sandstone

ground caused by tunnel excavation and drawing some meaningful conclusions:

- During tunnel excavation surface settlement and extensometer settlement may be divided into four stages: slight deformation stage, rapid deformation stage, stable stage and slow deformation stage.
- The crown settlement curve presents “S”, conforming to the former monitoring data. Before the settlement became stable, it has experienced the slow growth stage, swift growth's stage, became stable the stage.
- The ground horizontal displacement and vertical displacement reveal essential characteristic of ground response:
 - There exit a certain structural style between surface and tunnel crown to decrease the stratum deformation.
 - During excavation the stratum transform from density to loose and finally in a relative density condition.
- The 83.7% of ground loading is pore water pressure. So it is important to consideration the pore water pressure redistribution in reality.

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REFERENCES

- Bobet, A., 2001. Analytical solutions for shallow tunnels in saturated ground. *J. Eng. Mech.*, 127(12): 1258-1266.
- Bobet, A., 2003. Effect of pore water pressure on tunnel support during static and seismic loading. *Tunnell. Underground Space Techn.*, 18: 377-393.

- Gunn, M.J., 1992. The Prediction of Surface Settlement Profiles due to Tunneling. In: *Predictive Soil Mechanics: Proceedings of the Wroth Memorial Symposium*, St. Catherine's College, Oxford, UK, pp: 27-29.
- Haruyama, K., S. Teramoto, H. Harada and M. Mori, 2001. Construction of urban expressway tunnel with special large cross-section by NATM Metropolitan Inter-city Highway (ken-O-Do) Ome Tunnel. *Modern Tunnelling Science and Technology*, pp: 693-698.
- Lee, I.M. and S.W. Nam, 2001. The study of seepage forces acting on the tunnel lining and tunnel face in shallow tunnels. *Tunnel. Underground Space Techn.*, 16: 31-40.
- Mair, R.J., R.N. Taylor and J.B. Burland, 1996. Prediction of Ground Movements and Assessment of Risk of Building Damage Due to Bored Tunneling. In: Mair, R.J. and R.N. (Eds.), *Geotechnical aspects of UnderGround Construction in Soft Ground*. Proceeding of International Symporiousm, London, 15-17 April, Rotterdam, Balveme.
- Strack, O.E. and Verruijt, 2002. A complex variable solution for a deforming buoyant tunnel in a heavy elastic half-plane. *Int. J. Numer. Anal. Method. Geomech.*, 26(12): 1235-1252.
- Shin, J.H., D.M. Potts and L. Zdravkovic, 2005. The effect of pore water pressure on NATM tunnel linings in decomposed granite soil. *Canad. Geotechn. J.*, 42: 1585-1599.
- Verruijt, A. and J.R. Booker, 1996. Surface settlements due to deformation of a tunnel in an elastic half plane. *Geotechnique*, 46(4): 753-756.
- Verruijt, A. and O.E. Strack, 2008. Buoyancy of tunnels in soft soils. *Geotechnique*, 58(6): 513-515.