Segmental Tunnel Lining Design: Understanding Ground-Tunnel Interactions in Staggered Tunnel Lining

Dr Siti Norafida binti Jusoh

In tunnelling, ground settlement may lead to over-stressing of the tunnel concrete segmental lining. At the same time, stress concentration from the ground around the tunnel may induce lining segment cracking, joints bolts yielding, joint dislocation and joint tendon crushing which can lead to serious slurry or water leakage problems.

It is better to ensure higher flexibility in the tunnel lining rather than higher safety factor in the moment. By maintaining the flexibility, hoop forces induced in the tunnel lining can be sustained and the ground surface will be less susceptible to induced settlement trough.

Therefore, tunnel flexibility is important, especially during tunnel excavation and service, as the soil-tunnel interaction is an uncertainty. Different from the normal construction of buildings, tunnels possess complex interaction as both resisting and supporting forces occur simultaneously.

Tunnel excavation in itself causes relaxation of in-situ stress in the ground, thereby inducing ground movement which is only partially restricted by the insertion of tunnel support. A certain amount of the deformation of the ground will take place at the tunnel depth and this will trigger a chain of movements, resulting in settlements at the ground surface. This becomes more significant with the decrease in the tunnel depth. Concurrently, tunnel lining has to be designed so as not be too stiff as this allows some lining movement to achieve soil-tunnel stability. Having a good understanding of the mechanism of joint interfacing between the segment and ring of tunnel as well as their arrangement, is important to understand the global performance of the tunnel.

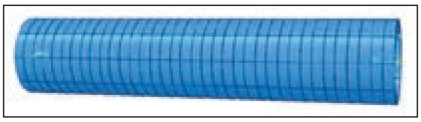


Figure 1: Straight segmental tunnel

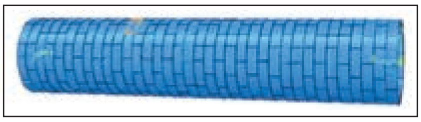


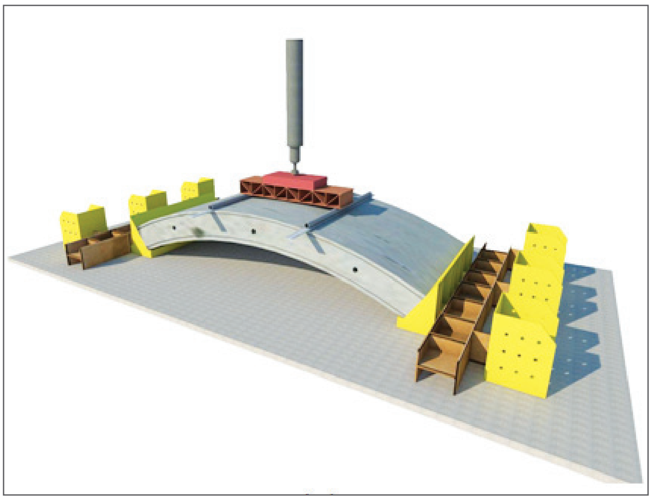
Figure 2: Staggered segmental tunnel

In general, a ring built with straight segment joints will result in high bending moments, which give conservative results (Figure 1). On the other hand, staggered joint lining with larger number of segment types, i.e. having a smaller difference in the reference angles between successive rings, will lead to a significant reduction of the induced bending moment in the lining (Figure 2). This is due to the smaller span of concrete lining affected by the segment joints in the successive rings. As a result, tunnels will have better flexibility in term of the global support structure.

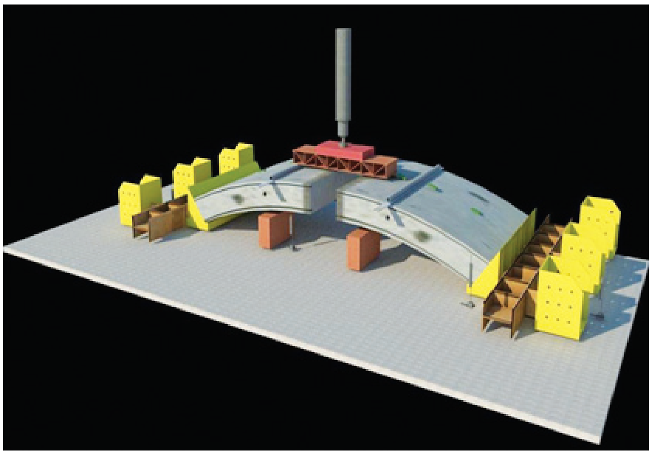
To adopt real tunnel lining response with stress ground redistribution, some researchers have suggested that segmental joints be directly added to the tunnel lining structure by considering a continuous ring with reduced rigidity (i.e. applying a reduction factor to the bending rigidity of the actual tunnel lining).

With this concept, the moment capacity of the joint is less than the moment capacity of the segment body. Joints in a tunnel lining will definitely affect tunnel behaviour, so segmental joints need to be less stiff to allow for more deformation than its main portion. However, flexural joint stiffness, K_θ is highly variable and is dependent on the properties of packer and bolts as well as by geometry of both end rib of lining segments and applied forces. Joints that rotate relatively to one another act as a hinge between the adjoining segments, allowing only a limited angle of rotation between them. The segment has resistance against rotation and hence bending moment is induced. When subjected to a positive bending moment, the value of K_θ is higher than when it is subjected to a negative bending moment. Hence, the factor that most influences the bending moment is the rotational joint stiffness, K_θ.

Therefore, a staggered tunnel lining design, which allows for better stress redistribution and hence maintaining good soil-tunnel stability, is preferred. As far as bending in



(a)



(b)

Figure 3: Laboratory testing schematic diagram showing how two segments response to one another, applied with transversal vertical line load supported with two different boundary conditions used. This corresponding test can obtain moment reduction factor, M_R and angular joint stiffness, K_θ which helps in the understanding of segment joint rotations

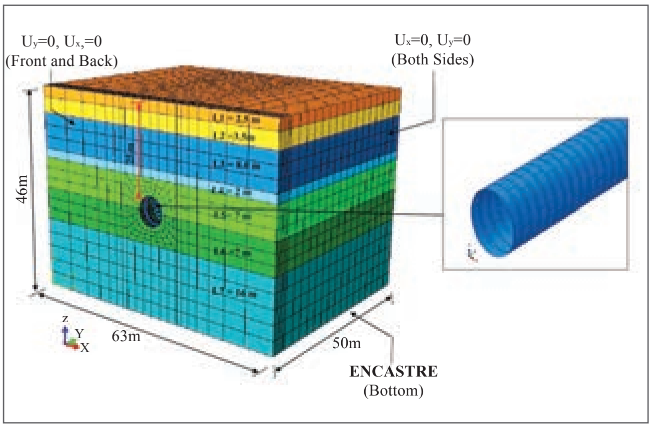


Figure 4: Simulated 3D model of soil-tunnel system with respective boundary condition and meshing. Different colour schemes are used to represent the different types of soil. Staggered tunnel lining model is assembled into the model

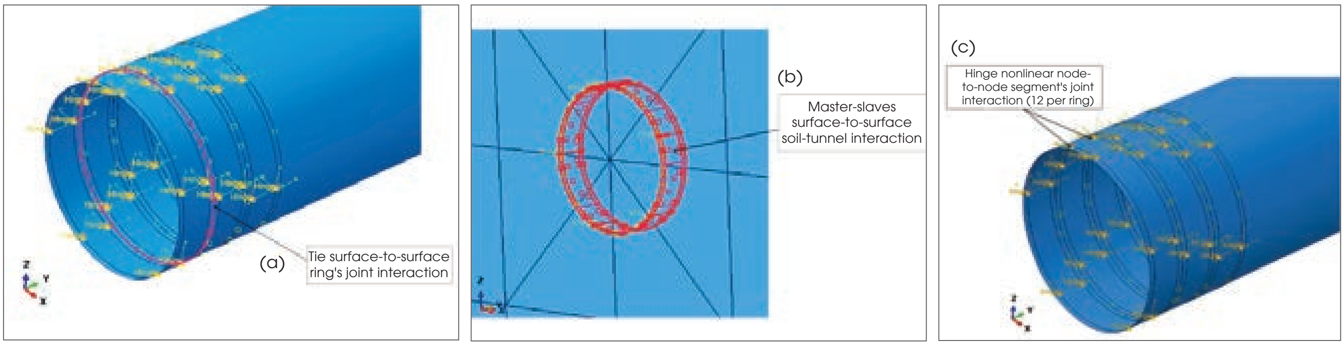


Figure 5: Interaction model in tunnel. (a) Tie constrain of surface to surface type is assigned at the ring's joint. (b) Soil-tunnel interaction "master-slaves" formulation with surface to surface contact algorithm with contact interaction property, penalty friction of tangential behaviour, 'master' is represent by red colour and 'slave' by purple. (c) Segment joint assigned with hinge nonlinear at two different wire link node-to-node position in tunnel lining

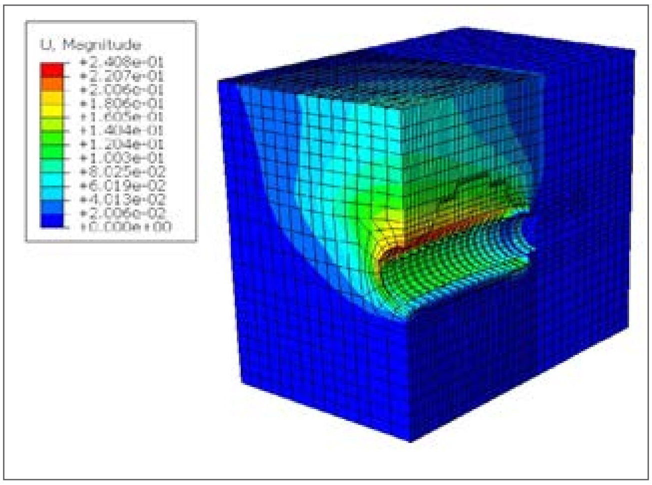


Figure 6: Surface settlement induced by tunnelling

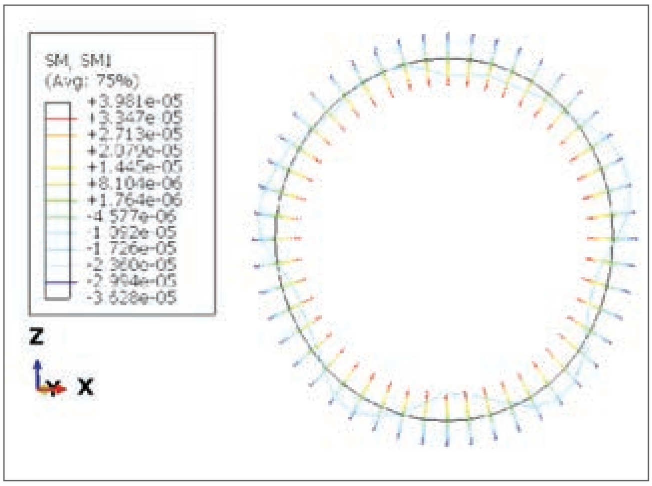


Figure 7: Variation of bending moment in tunnel lining. Note that tunnel distorts at the crown and bulges out at spring line due to the effect of soil-tunnel interaction

tunnel lining is concerned, its bending moment can be influenced by both non-uniform ground pressures and joint eccentricities. By modelling a staggered tunnel model and comparing it with a continuous tunnel lining model, it can be shown that the staggered segmental lining with a larger number of ring types will lead to smaller changes in bending moment. This is due to a shorter span of the lining that is affected by the segmental joints in the successive ring. With variation in lining stiffness occurrence (due to staggered configuration), load (ground) will be transferred from stiffer to softer ring and vice versa. In summary, the global support structure (i.e., tunnel lining) will be more flexible ascribed to the effects of joint configurations, properties and stiffness of the lining in successive ring which is not uniform.

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Author's Biodata

***Dr Siti Norafida binti Jusoh** is a lecturer at the Department of Geotechnics and Transportation, UTM. She is a committee member of TUSTD at IEM.*