Jurnal
Teknologi

Full Paper

INVESTIGATION ON THE MECHANICS OF PRECAST SEGMENT TUNNEL LINING

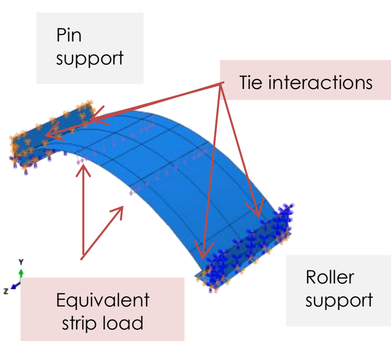
Siti Norafida Jusoh[a*], Hisham Mohamad[b], Aminaton Marto[a], Nor Eliza Alias[c,d], Muhammad Azril Hezmi[a], Rini Asnida Abdullah[a], Nor Zurairahetty Mohd. Yunus[a]

[a]Department of Geotechnics and Transportation, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak
[c]Department of Hydraulic and Hydrology, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[d]Climate Change Research Group, Resource Sustainability Research Alliance, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
18 January 2016
Received in revised form
8 March 2016
Accepted
18 March 2016

*Corresponding author
snorafida@utm.my

Graphical abstract



Abstract

Tunnel lining design is an interactive problem, which is not merely about the strength, but how much the lining could deform to accommodate the ground movement. When tunnel interacts with soil, stress from the ground is distributed onto the structure. In precast segmental tunnel lining, it is critical to investigate the lining reaction when applied with load, as this affects the overall flexural behaviour of tunnel lining. The objective of this paper is to understand the basis of tunnel lining mechanical behaviour response. A series of conducted flexural bending laboratory testing and developed numerical models presented here in order to discuss on the mechanics of segmental tunnel lining. By having two different support mechanisms, variation trend in load-deflection and moment bending curve depicted. Mirror trend of pin-pin support can easily be spotted in the results indicated segment lining affected by the load and support design.

Keywords: Segmental lining; segment's joint; flexural test; numerical model

Abstrak

Rekabentuk pelapik terowong adalah masalah interaktif, di mana ianya bukan semata-mata berkisar mengenai kekuatan, tetapi setakat mana pelapik dibenarkan untuk melentur bagi menampung pergerakan tanah. Apabila terowong berinteraksi dengan tanah, tekanan dari tanah akan disebarkan kepada struktur. Di dalam segmen pelapik terowong konkrit pratuang, adalah kritikal untuk menyiasat tingkahlaku lenturan apabila dikenakan beban memandangkan ia akan memberi kesan kepada keseluruhan tingkahlaku lenturan pada terowong. Tujuan kertas kerja ini ditulis ialah untuk memahami asas tingkahlaku mekanik pelapik terowong. Siri ujian makmal lenturan yang telah dijalankan dan pembangunan model berangka dibentangkan untuk membincangkan mekanik segmen pelapik terowong. Dengan dua jenis mekanisma sokongan yang berbeza, perubahan bentuk beban-pesongan dan lengkung momen lentur diperolehi. Bentuk cerminan sokongan pin-pin mudah dilihat dalam keputusan menunjukkan pelapik segmen terkesan dengan beban dan reka bentuk sokongan.

Kata kunci: Pelapik segmen; penghubung segmen; ujian lenturan; model berangka

1.0 INTRODUCTION

The evolution of construction techniques and trend towards integrated use of structure design nowadays are to promote reliable and economic construction. Lining tunnel is one of its kinds. Lining assemble in segmental part connected with bolt, resist an axial thrust based on the overburden and groundwater pressure at spring line, plus bending stresses resulting from an arbitrary percentage distortion of the diameter of the ring. Large distortion can often be accommodated in the tunnel lining by rotation or shear at the joints between segments inducing high stresses in the linings themselves especially when interacts with ground surroundings [1]. When tunnel interacts with soil, stress from the ground is distributed onto the structure. When taking in accumulative for both segment's and ring's joint, shield segment damage that occur around segment joint more than once within two to three rings is almost 30% from total occurrences [2]. While bending strength and stiffness of structural linings are reported small compared with those of the surrounding ground [3]. Japanese Society of Civil Engineering empirically recommends in its popular simplified design method to suggest a lining should be designed to carry only 60–80% of the maximum bending moment carrying by the main segment [4]. The concern on how much bending moment carrying capacity in lining brings a notion that understanding behaviour of segmental joint tunnel and carefully designs it is important. Understanding the segmental behaviour is important to optimize the design of lining, lead to cost effective production and maintain the good services during its design life.

Considerable research on movement and stresses for a single and multiple tunnels has been undertaken [3, 5-7]. However, lack of investigation exists for extreme details conditions of structural response (i.e., flexural bending moment in tunnel lining) and the behaviour of the joints condition; both in longitudinal and circumferential joints. Research has been carried out via numerical analysis, laboratory and full-scale test that included the joint tunnel response but not in specific [1, 3 and 8-10]. Researchers concluded that longitudinal joint is crucial to investigate but the analysis is complex to fulfil [3,8]. Thus, these indicate the importance of understanding on tunnel behaviour, how much tunnel lining allowed to bend and to understand their load-displacement curve.

Intensive review on previous flexural test both in numerical simulation and laboratory testing on tunnel have been presented in Jusoh [11,12]. The direction of future research regarding on the performance in tunnel lining joint connections and the importance of laboratory testing are also mentioned earlier [11]. Laboratory testing of point load test have been developed to imitate flexural behaviour of segmental tunnel lining condition in real [12].

Previous numerical modelling was accomplished that involved segment's modelling [3,8,9,13]. The behaviour of segment connections of southern high-speed line of "Green Heart" shield driven tunnel have been investigated via ANSYS finite element software [3] via contact element. Simulation mentioned that the lining stresses measured in the field construction are not uniformly distributed in radial, axial and tangential directions [3]. In reality, axial normal forces found tend to have eccentricity and sectional forces and moment are measured twice higher compared with conventional models [3]. Results showed tangential stresses along the lining did not changed much because of the hardening of grout, but distribution in a ring lining did change [3]. However, the range of how much stress distribution changed in lining is not mention in exact amount/ percentage.

Similarly, influence of packing material configurations, their thickness and stiffness and width and thickness of concrete segments to the critical contact deficiencies in tunnel using DIANA 9.3 also investigated via contact element [8]. Researchers concluded that the packing stiffness, the width and the thickness of segment do influence the critical contact deficiency [8].

Simplified FEM analyses using shell element for lining segment and spring to model the joint connections have been compared with a true scale model test [9]. In the numerical work, it was found that the jointed lining produced smaller magnitude of maximum bending moment than the non-jointed one [9]. A parameter called moment reduction factor expressed by a function of angular joint stiffness and number of segment was introduced. Based on the model test, accepted practical angular joint stiffness is in the range of 1000-3000 kNm/rad [9]. However, only "fixed-fixed" conditions were considered here in. Whereas, segment's connection in partially fix or hinge were still not fully understood.

Numerical modelling simulated an in situ testing of slender tunnel of new Line 9 (L9) of the metro of Barcelona have been developed to investigate the performance of rings placement [13]. Segment's joint were simulated as shell interface elements [13]. Three hydraulic flat jacks embedded at the extrados of the loaded ring. From the simulation, nonlinear tensile stresses behaviour of joint was depicted at the extrados side of segment joint and concentration of compression stresses occurred in intrados side [13]. Concentrated rotation occurs in segment's joints. These resembled behaviour of joint in full-scale test [14].

One can see that abundant useful information was obtained from previous researcher; unfortunately the mechanics of segmental lining was not explored and discussed in great detail. Therefore, an investigation of the mechanics of segmental tunnel lining is crucial. In this paper, current research works performed by the authors on mechanics behaviour of precast segment tunnel lining are presented. A series of flexural bending laboratory testing conducted presented here in order to discuss on the mechanics of segmental tunnel lining. Numerical models also developed to simulate laboratory experiment and understand more certainty on the structural response and deformations.

2.0 METHODOLOGY

This research involve two major parts of work; one is laboratory testing and another is simulation using numerical methods. The results from numerical shall be used to compare data obtained from the laboratory experiments.

In particular, testing was carried out to analyse the complex lining joint behaviour in longitudinal direction and to understand the structure response with more certainty. Support mechanisms were designated at first place to resemble the joint behaviour in lining. Two support mechanisms are introduced namely; Pin-Pin support (Phase 1 and 3) and followed by Pin-Roller support (Phase 2 and 4). This paper is focus on discussions of the single intact segment testing results only.

2.1 Laboratory Testing Work

Flexural bending test using segments taken from nearby factory has been carried out. The segments configurations have been mention earlier in [12].

As segment is not perfectly half of rounded shape, support systems were developed to make sure the edge of segment lies comfortably in the testing area. The support system was fabricated using combination of simply supported steel beam to form triangular shape (Figure 1). In the first experiment (Phase 1), one of the supports, i.e. 1.4 m long of three steel rollers (i.e., roller support on the right) was designed in such way that it could slide horizontally while the other end (on the left) is bolted to the floor to function as a pin support. The roller steel was applied with grease roller (to ensure none friction will occur) to function as a roller support. At the left support is a steel box with 2 m anchored steel bolted to the floor. The triangle steel beam also supported laterally with H-beams to eliminate the triangular beam translation during the testing. To attach segment to the triangular steel beam, specially designed wall plug of 220 mm length and 50 mm thread with diameter of 25 mm were used to help fixed the segment in position and to the hole of triangle steel beam support system.

Testing was carried out using a Dartec hydraulic ram with a load-controlled system. A two-point vertical load (using a frame extension redistribute as strip loading), imitating the localised ground static load was applied to the middle of the segment. A 200 tonne of load cell are attached with computerized system used to verify the applied load from hydraulic ram of system. The strain gauges were properly mounted onto extrados and intrados of segment test specimen. At the same time, LVDTs were mounted at locations with higher anticipated movement. Translation readings at the support system were also being monitored.

Tests were performed initially within the elastic region. In reality, a full ring of tunnel would consist of 5 to 8 segments jointed together. The joints allow tunnel either to flex inward or outward, thus allowing tunnel to stay in a good service. In the first stage, the first tunnel segment were laid as Pin-Roller and applied with load system (i.e., later known as non-jointed pin-roller test, NJPR) shown in Figure 1. In pin-roller testing, a triangle steel support of one side was allowed to move to imitate hinge joint interaction. Three different load series, beginning within "elastic" loading (i.e., Test 1), continued with double the amount of initial loading stage (Test 2) and finally loading to failure (Test 3).

In Phase 2, a non-jointed pin-pin test (NJPP) was performed. For NJPP test, a triangle steel support of one side (which previously allowed to move) was then fixed with bolted floor anchor and H-beam. This was carried out to imitate almost rigid ground condition surrounding the tunnel. Similarly, incremental loading has been applied up to 130 kN (Test 1) ("elastic" loading) and 300 kN (Test 2) and the performance of segment was investigated. Strains at intrados and extrados of segment surface were measured. Both of the results are presented in the results and discussion section.

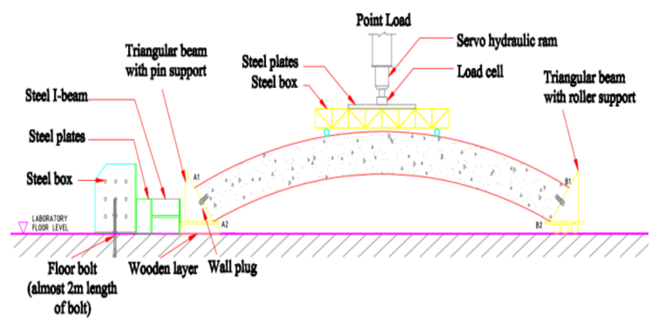


Figure 1 Test arrangement of pin-roller support for single segment [12]

2.2 Numerical Modelling

Numerical modelling of segmental tunnel lining via ABAQUS 6.10 has been carried out. At first, simple segment model were performed by means beam element and verified successfully with analytical method; Unit load Method. Then, simulations effort was continued. As the experimental segments' response did affected by the designated support systems in laboratory testing, therefore, a model of support designation is developed in numerical model to get more realistic results.

Figure 2 shows the arrangement model of phase 1 testing. A pair of triangular steel beam element was introduced at two ends to simulate the complicated boundary condition of segment's joint (support system). Tie constraint node-to-node interaction was introduced to model wall plug function that attached the support system to the segment.

A total of 12870 number of shell elements (SR4) was assigned to mesh the model with the reference surface was at shell mid-surface (mid of segment's thickness). Tie interactions was used to represent join connection between segments and support systems. Bias meshes were assigned at critical stress area and very finer mesh approximation is generated at the interaction regions to make sure interactions node can be assigned appropriately (Figure 3).

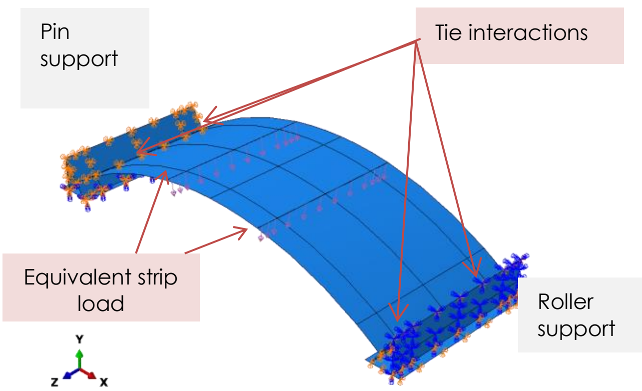


Figure 2 Phase 1 numerical model

Figure 3 Mesh generation for segment and support designation

Concrete damage plasticity model (CDP) has been assigned to the segment with properties of 2400 kg/m^3 for density, Young Modulus, E_c of 33 GPa and Poisson's ratio of 0.2. More details properties are presented in table 1. While for support, steel supports were assigned with density of 7800 kg/m^3, Young Modulus, E_s of 207.5 GPa and Poisson's ratio of 0.32.

An equivalent two strip load pressure applied to the partitioned surface in the range of 0.5 meter from mid-span of segment at both side. Incremental of load imitating the experimental loading were used in the modelling. Pin and roller support assigned respectively onto the outer surfaces of the support model.

Table 1 Plasticity material parameter used in CDP model

Dilation Angle, ψ	Flow potential eccentricity, ϵ	f_b/f_{c0}	K_c	Viscosity parameter, μ
15	0.1	1.16	0.666	0.01

3.0 RESULTS AND DISCUSSION

In general, loading caused compression strain at the extrados and tensile strain at the intrados of segmented lining. Load versus segment's deflection for both Pin-Roller and Pin-Pin support condition are plotted in Figure 4. As expected, the deflection measured at the mid-section of segments showed that the pin-roller segment lead to more deflection compared to pin-pin support condition.

Using the data inferred from the strain gauges, the flexural moment versus segment's span of selected load range were plotted in Figure 5. An inward moment is represented by negative flexural moment. Symmetrical curve of outward bending moment were depicted for Pin-Pin support system which generally true for rigid tunnel condition. Whilst, for Pin-Roller support system, higher moment embraced at the mid span segment followed with imbalance distribution of flexural moment occurred; lower moment occurred at pin side and higher moment measured at quarter roller support side followed with sudden drop of moment magnitude. In Pin-Roller, which purposely carried out to imitate jointed hinge longitudinal condition, the moment of structure shows higher in magnitude when came to middle position and decreased dramatically at edge of roller side as segment try to response to interactions occurs. In conclusion, Pin-Roller support mechanisms (i.e., hinge jointed segment's connection) gave more room for tunnel to flex thus leading to lower mid span deflection.

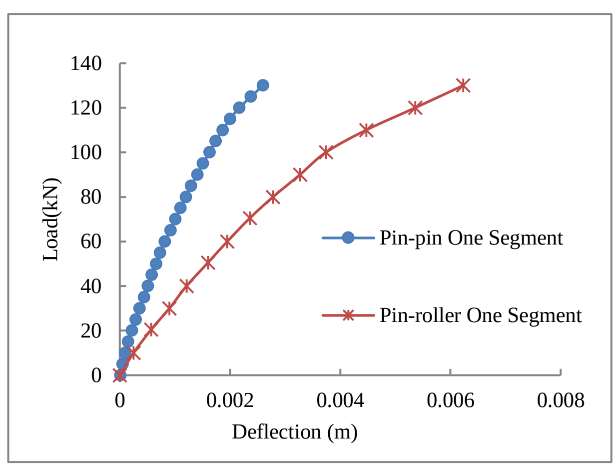


Figure 4 Load vs deflection at mid-section of segment

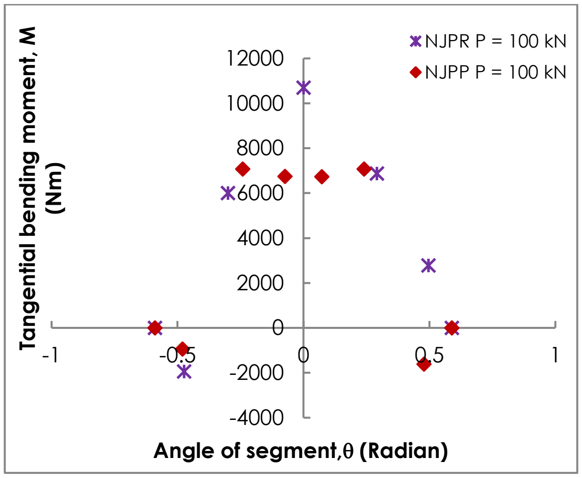


Figure 5 Bending moment for non-jointed pin-roller test (NJPR) and non-jointed pin-pin test (NJPP) of single segment

Figure 6 compares the results of bending moment diagram calculated using numerical model and the laboratory data of non-jointed single segment with pin-pin support (NJPP) for load of 100 kN. Numerical model showed continuous plotted moment diagram for segment in whole segment's span which gave more accurate moment reaction when compared to laboratory results (i.e., only few points measured). It is also found that the triangle support model of segments in laboratory did gave affect to the overall results. Therefore, appropriate model of support and material properties modelled have been carefully adopted in numerical to represent the real laboratory settings condition.

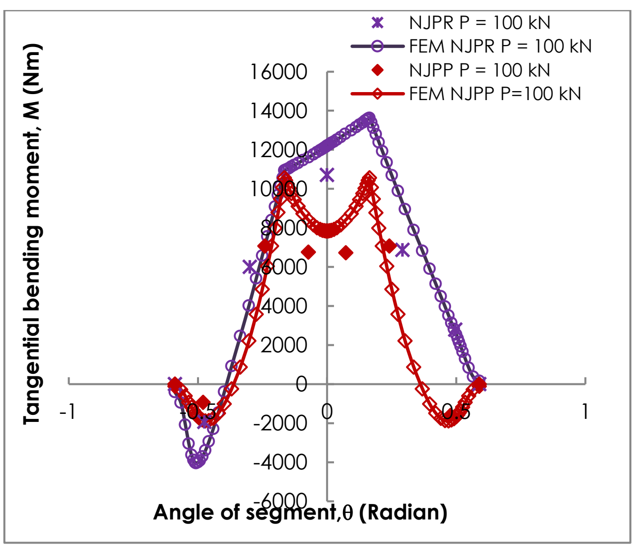


Figure 6 Tangential bending moment for non-jointed pin-pin support condition (NJPP) and non-jointed pin-roller (NJPR) with respectively numerical modelling result (FEM-NJPP and FEM-NJPP) at load P=100 kN

4.0 CONCLUSION

Investigation on the mechanics behaviour of precast segmental tunnel lining was presented. A series of laboratory testing of segmented tunnel lining had been carried out to conduct a flexural test. The load was applied on an arch configuration of tunnel lining to record the movements of the segment in elastic-plastic range and to understand the flexural moment deflection response in tunnel segments. In addition, numerical modelling has been carried out to understand the structural response and deformations in more certainty. The overall approach was to conduct computational simulations by means of finite element analyses.

Results showed that by having two different support mechanisms, variation trend in load-deflection and moment bending curve depicted. Mirror trend of pin-pin support can easily spotted in the results indicated tunnel behave simultaneously according to the support design.

Further research is needed to be carried out to understand the appropriate characteristics of tunnel response especially related to segment's joint interactions and also to predict the ground load surrounding - structure effect, which are essential for long-term safety measurements. This could give more understanding on the ground-tunnel interactions in more certainty.

Acknowledgement

This research was made possible, thanks to the support provided by MTD ACPI Engineering Bhd., responsible of the design and supplying segment tunnel for Construction and Completion of Singapore Beduk Reservoir and Tunnels for Downtown Line Stage 3. The authors also would like to thanks the financial support from UTM Research University Grant Scheme (RUGS), Vote #06H71 and the Ministry of Higher Education (MOHE), Malaysia through the Research Commissioner and Exploratory Research Grant Scheme (ERGS), Vote #4L061.

References

[1] Chen, J., Mo, H., .2009. Numerical study on crack problems in segments of shield tunnel using finite element method. Tunn. Undergr. *Space Technol*. 24 (1): 91–102.
[2] Sugimoto, M. 2006. Causes of shield segment damages during construction. *International Symposium on Underground Excavation and Tunnelling*. Bangkok, Thailand.
[3] Blom, C., Van der Horst, E., Jovanovis, P. 1999. Three-Dimensional Structural Analyses Of The Shield-Driven ''Green Heart'' Tunnel Of The High-Speed Line South". *Tunn Undergr Space Technol.* 14(2): 217–224.
[4] Koyama, Y. 2003. Present status and technology of shield tunneling method in Japan. *Tunn. Undergr. Space Technol.* 18 (2/3), 145–159.

[5] Loganathan, N. & Poulos, H.G. 1998. "Analytical Prediction For Tunneelling-Induced Ground Movements In Clays". J. Geotech.Geoenviron. Eng. 124(9), 846-856.

[6] Park, K.H. 2004. Elastic Solution for Tunneling-Induced Ground Movements in Clays. *International Journal of Geomechanics*. 4(4): 310.

[7] Liao, S.M., Peng, F.L., Shen, S.L. 2008. Analysis of shearing effect on a tunnel induced by load transfer along longitudinal direction. Tunnelling and Underground Space Technology 23: 421–430.

[8] Cavalaro, S, & Aguado, A. 2011. Packer behaviour under simple and coupled stresses. *Tunn Undergr Space Technol* . 28:159–173.

[9] Teachavorasinskun, S. and Chub-uppakarn, T. 2010. Influence of Segmental Joints on Tunnel Lining. *Tunnelling and Underground Space Technology*. 25(4): 490–494.

[10] Wang, L.Z., Wang, Z., Ling-ling Li, L.L., & Wang, J.C., 2011. Construction behaviour simulation of a hydraulic tunnel during standpipe lifting. *Tunnelling and Underground Space Technology*. 26, 674–685.

[11] Jusoh, S.N., Mohamad, H., Marto, A., Yunus, M.N. 2015. Segment's Joint In Precast Tunnel Lining Design. *Jurnal Teknologi (Sciences & Engineering)*. 77(11): 91–98.

[12] Jusoh, S.N., Mohamad, H., Marto, A. & Yunus, M.N. 2015. Point Load Testing Of Flexural Behavior Of Segmented Tunnel Lining. *Malaysian Journal of Civil Engineering.* 27(1): 81-92.

[13] Arnau O. & Molins C. 2011a. Experimental And Analytical Study Of The Structural Response Of Segmental Tunnel Linings Based On An In Situ Loading Test. Part 1: Test Configuration And Execution. *Tunn Undergr Space Technol* . 26: 764–777.

[14] Arnau O. & Molins C. 2011b. Experimental And Analytical Study Of The Structural Response Of Segmental Tunnel Linings Based On An In Situ Loading Test. Part 2: Numerical simulation. *Tunn Undergr Space Technol*. 26: 778–788.

[15] Nishikawa K. 2003. "Development Of A Prestressed And Precast Concrete Segmental Lining". *Tunnelling and Underground Space Technology.* 18: 243–251.