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Numerical Analysis of Cross Passage Opening for TBM Tunnels

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ABSTRACT: Building railway and road tunnels calls the need to construct cross passages between adjacent TBM bores and connection in order to access shaft to provide a safe means of emergency egress for commuters. Construction of cross passages in soft ground under high groundwater table on TBM tunnels proves to be a challenging task. In order to improve buildability of the cross passage, the application of special precast segment with provision of shear bicones and drilling windows for ground treatment, and the use of temporary support for tunnels are unavoidable. This paper introduces techniques that are utilized to create opening in segmental lining in the modern tunnelling industry, and the findings present an integrated design approach using the software PLAXIS^{2D} and Oasys GSA^{3D} for a large cross passage opening in TBM tunnel. The effect of ground treatment at opening and shear bicones at ring joints, and the use of temporary steel hamster cage to support the opened rings inside the tunnel were assessed numerically. The actual performance of the opened rings has also been evaluated against the design prediction through assessment of the field measurements from convergence monitoring.

RÉSUMÉ: La construction de tunnels ferroviaires et routiers appelle la nécessité de construire des passages croisés entre les alésages TBM adjacents et la connexion afin d'accéder à l'arbre pour fournir un moyen sûr d'évacuation d'urgence pour les navetteurs. La construction de passages transversaux dans des sols souterrains sous une nappe phréatique élevée sur des tunnels TBM se révèle être une tâche difficile. Afin d'améliorer la construction du passage transversal, l'application d'un segment préfabriqué spécial avec la fourniture de bicônes de cisaillement et de fenêtres de forage pour le traitement au sol, et l'utilisation d'un support temporaire pour les tunnels sont inévitables. Cet article présente des techniques qui sont utilisées pour créer une ouverture dans le revêtement segmentaire dans l'industrie de tunnels modernes et les résultats présentent une approche de conception intégrée à l'aide du logiciel PLAXIS^{2D} et Oasys GSA^{3D} pour une large ouverture de passage traversant tunnel TBM. L'effet du traitement au sol aux bicônes d'ouverture et de cisaillement au niveau des joints annulaires et l'utilisation d'une cage de hamster en acier temporaire pour soutenir les anneaux ouverts à l'intérieur du tunnel ont été évalués numériquement. La performance réelle des anneaux ouverts a également été évaluée par rapport à la prévision de conception par l'évaluation des mesures de champ à partir de la surveillance de convergence.

KEYWORDS: Cross passages, opened rings, shear bicones

1 INTRODUCTION

The precast concrete segmental lining systems currently in use in TBM tunnel are made of reinforced concrete, fibre reinforced concrete or combinations thereof. The tunnel lining is assembled from rings each containing a certain number of precast concrete segments. Segments are normally formed in either a rectangular, trapezoidal, or rhomboidal arrangement. The last segment to be inserted in a ring, known as the keystone, has tapered sides to facilitate sliding it into place. The precast concrete segmental lining in typical rectangular configuration can be seen in Figure 1. The particular feature of a segmental lining is the high degree of jointing. The joints can be differentiated into the radial joint between the segments in a same ring, and the circumferential joint between the successive rings. Segments of the new ring are temporarily bolted to each other and together to the previous ring, in order to prevent movement during ring building as a result of accidental removal of TBM thrust rams. Adjacent rings are rotated by either one-third or half of the segment arc length to create a staggered joint pattern, and thereby avoid cruciform joint which is the most common location for leaks. The radial joint will be closed which results in a fixed outer diameter. The annulus space between the lining and the surrounding ground is backfilled with appropriate annulus filling material to ensure proper bedding of the segments.

In any railway and road infrastructures, cross passage is provided at regular intervals for TBM tunnels as a safe means of egress in the event of an emergency. The cross passage is a connecting structure between the twin-tube TBM tunnels or between the TBM tunnel and the shaft structure. On the single-pass (one layer) lining system, the segmental lining provides the immediate initial ground support for the excavation and, at the same time, serves as the inner lining for final tunnel support. Formation of an opening on the single-pass lining for TBM tunnel in soft ground with high groundwater table poses significant risks and challenges to the tunnel engineers, as the reinforcing steel between segments are not structurally connected to each other.

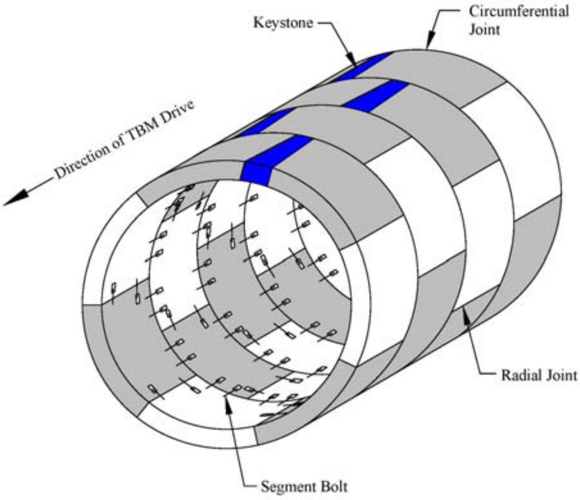

Figure 1. Precast segment in rectangular configuration.

During the design of opening for cross passage, the load in tunnel lining from which the segments are removed, is transferred to the adjacent fully enclosed rings, as illustrated in Figure 2. For a small opening, the transfer of this load is unlikely to overstress the adjacent fully enclosed rings if adequate factors of safety have been used in the design of segment. For opening exceeded two segmental rings, however, the use of special segment in conjunction with temporary steel bracing and interface shear bicones on tunnel lining to enable load transfer to more fully enclosed rings on each side of the opening become unavoidable. This paper introduces techniques that applied to create opening in TBM tunnel in the modern tunnelling industry, and presents the key aspects of ground-structure interaction and their effect on the design of openings and supports. It also includes a case study on the numerical analysis of a large cross passage opening on TBM tunnel involving partial removal of segments on five consecutive rings, as well as evaluation of the structural response of the opened rings from the measurements of convergence monitoring.

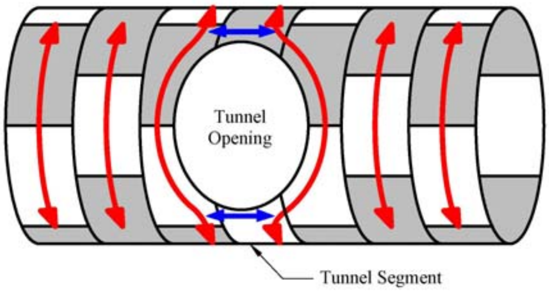

Figure 2. Stress distribution around opening in segmental lining.

2 OPENING ON TBM TUNNEL

2.1 *Design considerations*

Creating opening for cross passage at TBM tunnel would result in permanent disruption to the structural response of segmental lining and change in effective stress of the soil mass in close proximity to segments where the cross passage is to be built. The structural disruption implies that the built-in stresses on opened rings, will need to be transferred to other structural elements. During excavation of the cross passage, there will be a temporary stage of reduced ground support to the tunnel lining. The excavation will also affect the state of stress in soils surrounding the tunnel. If the stresses developed on the opened rings are found to be excessive, temporary steel bracing will be installed inside of the tunnel to provide support mitigating ring ovalization resulting from opening and cross passage excavation. The internal support will maintain the structural integrity of segments ensuring a safe design.

In the permanent condition, the impact of reduction in ground support to the stability of tunnel will be improved since the completed cross passage structure provides lateral restraint to tunnel avoiding further movement, which will otherwise occur during the load transfer to the opened rings after removal of the temporary steel bracing. Therefore, the segments for opening of the cross passage must be designed to withstand all load cases and combinations which they will be subjected during their design life. This requires thorough investigation and assessment of the stresses on tunnel and of the deformations of the lining. The latter is of important in case of external influences, such as construction activities at nearby to the TBM tunnel.

In deciding upon the type of the temporary opening support system that is best suited under the prevailing ground conditions, it is important to examine, among other things, the geology of the site carefully. Whether the ground is soft or hard may either favour or preclude the use of certain types of the temporary support system. Softer and looser soils with high groundwater table that are likely to generate high earth and hydrostatic pressures may warrant stiffer and stronger opening supports capable of withstanding such pressures. Where the ground may be firm and stiff with lower groundwater table, earth and hydrostatic pressures are likely to be relatively low. Under such geological conditions, a relatively flexible opening support system appears to be adequate.

Besides, the choice of the temporary support system is also dependent upon many other factors such as the need to minimize interference with the TBM operations; local expertise and the availability of plant and technology; consequence and the risk balance and the required design life of the system; whether and to what extent of ovalization in the opened rings is acceptable; and inevitably, the considerations of construction programme and cost. The list of the factors influencing the choice of support systems discussed here is by no mean exhaustive. However, these factors needs to be gone into thoroughly as the very minimum before one can expect to home in on the most effective and practical choice. Furthermore, it is also imperative to ensure that any other constraints, which may be peculiar and specific to a given site environment and likely to influence the choice, are not overlooked.

2.2 *Opening support systems*

There are a number of methods available to create an opening on the precast concrete segmental lining. They are essentially producing a structural beam above and below the opening. Of these, the more commonly used system in modern tunnelling industry are given as follows:

a. Steel lintel and sill beams – They are a strong structural steel member, which placed horizontally across the opening between the adjacent fully enclosed rings. The temporary lintel and sill beams will take the hoop load from the opened rings and transfer it through a shear connection to the adjacent fully enclosed rings, until the permanent collar and cross passage lining are completed. The shear connection can be established by using either anchor bolts or cast-in elements. The anchor bolts are simply post-installed by drilling the fixing holes in segments. The alternative cast-in elements by means of steel connection plates can provide a more robust solution. The steel plates are bolted to the side of the precast segments during fabrication, and subsequently attached to the back of the lintel and sill beams by welding. The load transfer mechanism of this temporary support system can be improved by using steel props. In the railway project in Hong Kong as shown in Figure 3, steel lintel and sill beams in conjunction with steel props were used for cross passage construction in TBM tunnel.

Figure 3. Steel lintel and sill beams in conjunction with steel props in Kowloon Southern Link Tunnel in Hong Kong.

b. ‘Half-moon’ support frame – This temporary support frame is typically made up of bolt-on lintel and sill beams with jambs running between them. The implementation of jambs helps to transfer hoop load around the opening optimizing the size of lintel and sill beams, and reduce squatting effect associated with the removal of soil from behind the lining during the excavation of cross passage. Similar to the previous system, additional support can be provided by fixing steel props to the lintel and sill beams on either side of the opening. The steel props in combination with the jambs would act as a rigid compression member, which improve the overall structure stiffness around the opening (Figure 4). The magnitude of the load on the internal support frame is a function of the relative stiffness to the adjacent fully enclosed rings, and shall be duly assessed and allowed for in the design.

Figure 4. 'Half-moon' support frame in A86 Socatop Tunnel in France.

c. 'Full-moon' support frame – This temporary internal support system is a methodology capable to deal with the heavier loads, which provides support for a full 360 degrees of the tunnel. The structural steelwork comprises a series of ring girders and cross beams in the form of a hamster cage to support the opened rings and transfer the loads around the opening. Prior to ring opening, the temporary steel cage will be tightly packed against the inner surface of the segmental lining, so that the loads on tunnel lining associated with ring opening and cross passage excavation can be effectively distributed to the temporary steel cage without jeopardizing the structural integrity of the segments. The robustness and effectiveness of the entire system can be further improved by introducing the steel props. This method provides complete internal support across the opened and the adjacent fully enclosed rings, as shown in Figure 5. After the cross passage is completed, the temporary steel cage will be removed.

Figure 5. 'Full-moon' support frame in Express Rail Link Tunnel in Hong Kong.

d. Rectangular frame of steel segments – They are the special segments that fabricated by steel to replace the standard precast concrete segments in the tunnel lining. These permanent steel segments are put in place together with the precast concrete segments using the TBM erector. Opening can then be made relatively easily and quickly by unfastening the central steel segment. The purpose made steel segments will act as a portal frame supporting hoop load from the opened rings with minimal effect on adjacent fully enclosed precast concrete rings. Provision of drilling windows for ground treatment can also be allowed in the steel segment design. The rectangular frame of steel segments may be used in conjunction with the steel props to alleviate squatting effect associated with spoil removal from behind the lining while constructing the cross passage. The application of steel segments has considerably simplified the procedures for cross passage construction in confined environment. However, the prefabricated steel segment are more costly than the standard precast concrete segment. Figure 6 shows the prefabricated steel segments around a cross passage opening in TBM tunnel in the UK.

Figure 6. Prefabricated steel segments in Channel Tunnel in the UK.

2.3 *Recent developments*

Developments in the segment fixtures have revolutionized the utilization of shear recovery bicone system. These interface shear bicones were first used on the A86 Duplex Tunnel in France to ease the creation of opening in the precast concrete segmental lining by minimizing the amount of temporary supports required during the cross passage construction, but have quickly been adopted on other projects around the world including a number in Hong Kong. Bicones in circumferential joint not only serve to improve the precision of ring installation, but also help to transfer the interface shear forces between the opened and the adjacent fully enclosed rings, as illustrated in Figure 7. Bicones are suited for all segment geometries, but can only be used in circumferential joint. It is important to note that bicones keep segment installation tolerance low; however, subsequent ring offset to compensate for imperfections is not possible.

The bicone with a diameter of 79-100mm is fastened on one side by means of an epoxy resin. Depending on the inherent strength of the precast concrete segment, the bicone may provide an allowable shear resistance of the order of 150-375kN per unit run of the ring. Usually, bicones are used in combination with guide rods in the radial joints; however they can also be used in combination with segment bolts which are required to hold segment in place provisionally during assembly and to ensure compression of the gaskets. The material and the dimensions of the bicone should be such as to prevent the buildup of constraining forces in closed joint before the cross passage construction. The edge of the recess should be properly bevelled on both sides of the ring in order to facilitate fastening of the bicone in the recess. The allowable installation tolerance depends on the performance of epoxy resin and the necessary compression of gasket, and has to be verified separately.

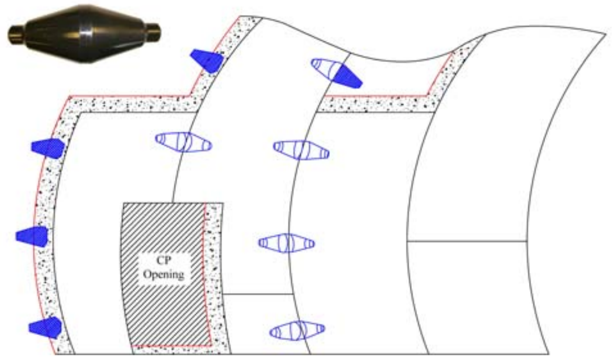

Figure 7. Illustration of shear bicones in circumferential joint.

3 CASE STUDY

3.1 *General description*

It is obvious that creation of openings in segmental lining alters the simple lining behaviour to a more complex one. Due to an abrupt change in the cross-sectional dimensions of the ring, the areas around opening are subject to high stress concentration which may lead to wide cracking that is unacceptable from aesthetic and durability viewpoints. The reduced stiffness of the ring may also give rise to excessive ovalization under service load and result in a considerable redistribution of internal forces and moments in the lining. These will require strengthening of the lining, but in order to design the strengthening works, the stress concentrations and ring distortions resulting from the opening shall be quantified.

The critical stage of the lining design is when the opening is made for the breakout of cross passage from the TBM tunnel. The hoop loads have to divert around the opening, resulting in higher compressive stresses to either side of the opening, and flexural stresses above and below in the opened rings. In the design of lining with cross passage opening, usual acceptance criteria for structural members shall apply. These are basically the strength and serviceability requirements. An accurate assessment of ultimate strength is necessary to provide adequate safety against possible collapse. Serviceability, in general, requires that the ovalization produced under working loads be sufficiently small and cracking, if any, be controlled with maximum crack width not exceeding some tolerable limits.

However, due to the provision of openings, the conventional design procedures for precast concrete segmental lining by using the closed form solutions as described by Muir Wood (1975), Curtis (1976) and Duddeck & Erdmann (1985), and the 2D plain strain analyses to calculate the internal forces and moments are not applicable to the design. The only way to determine the compressive and the flexural stresses around an opening would be to simulate the tunnel lining in a 3D manner. A case study from a railway project in Hong Kong that involved partial removal of segments on five consecutive rings, has been chosen to give an overview of the integrated design approach combining the 2D finite element and the 3D bedded beam spring modelling techniques for design of tunnel opening at connection to cross passage.

3.2 *Lining geometry*

The example described here concerns the construction of cross passage for connection between the TBM tunnel and the shaft structure. The tunnel was excavated by an articulated closed face slurry shield TBM. The tunnel is lined with a single-pass, precast concrete segmental lining system. All segments are conventionally reinforced. Each ring comprises 6 segments plus a keystone. Each segment is provided with an all-round seal by elastomeric compression gasket which prevents groundwater entering the tunnel. The tunnel lining has an outer diameter of 7.1m and an inner diameter of 6.5m. The ring has been standardized to 1.5m wide, except on the sections of tunnel required to negotiate the driving of curve and the changes of gradient using tapered rings. The thickness of lining is 300mm with a 28-day concrete strength of 50MPa. Table 1 shows the details of geometric characteristics of the precast concrete segmental lining.

Table 1. Geometric characteristics of the precast segmental lining.

Parameter	*Value*
Internal diameter	6,500mm
Lining thickness	300mm
No. of segment per ring	7 (6 segments + 1 keystone)
Ring width	1,500mm (standard)
Concrete strength	50MPa
Ring connections	Bolts with provision of shear bicones at cross passage locations

The opening on the lining was sized to provide a 4.5m high and 6.3m wide clear passageway for connection to the shaft structure. This required partial removal of segments from five consecutive rings. The section of the tunnel where the opening to be formed, was located in the saturated granitic saprolite, which is overlain by a 1.5m thick blanket of variable fill with a total ground cover of 22m above the tunnel crown. Before excavation, the soil was improved by grouting to increase soil stability, soil bearing capacity and prevent the water seepage which may cause the ground bulging into TBM tunnel during the break-out.

3.3 *Method of analysis*

For such a large cross passage opening, the lining was designed to be supported by a temporary steel hamster cage with shear bicones at the circumferential joints of the opened rings to transfer the hoop load around the opening limiting the internal forces and moments in segments to the acceptable levels. The evaluation of the loads acting on the temporary steel cage, the shear bicones and the permanent lining requires the solution capable to resolve a relatively complex stress-strain problem.

Given the 3D nature of the problem, there was no doubt that the numerical analysis should be performed by using finite element model. This model permits the simulation of the entire excavation and construction processes that lead to the completion of the opening. It provides complete information on the stress-strain conditions of the tunnel, the surrounding soil mass and nearby structures. However, due to the limitations of simulating the complex steel structure and the special interface elements in the commercial 3D finite element software, an integrated design approach based on a 2D finite element model in conjunction with a 3D bedded beam spring model was adopted in the analysis.

The ultimate goal was to use the 2D finite element model to verify the earth pressure taking into account of the ground-structure interaction, and apply it into the 3D bedded beam spring model to assess the effect of opening to the segmental lining and determine the stress distribution for design of the temporary steel hamster cage and shear bicones.

3.4 *2D analysis*

The 2D finite element analyses were performed in plain strain mode by using the software PLAXIS^{2D}. 15-noded triangular elements were used for the mesh with a width of 100m and a height of 62m. The boundary was restrained in the horizontal plane at both sides and in both planes at the base. The soils were assumed to behave linear elastic perfectly plastic and characterized by the Mohr-Coulomb model. Some engineering properties of the soil materials are shown in Table 2. The groundwater level is at the ground level. The tunnel lining has been modelled linear elastically, using plate element with a flexural rigidity of 36.7MNm^2 and a normal stiffness of 8670 MN, and a lining weight of 25kN/m^3. The flexural rigidity has been reduced to account for the presence of joints between segments. Following the recommendation by Muir Wood (1975), a reduction factor of four has been applied to the flexural rigidity of the lining in the analysis.

Table 2. Design soil parameters of the Mohr-Coulomb model.

Parameter	*Fill*	*Granitic saprolite*		
-	-	Medium dense	Dense	Very dense
N (SPT)	N=20	N=20	N=20-50	N=50-100
$\gamma_{saturated}$ [kN/m^3]	20	20	20	20
ν [-]	0.3	0.2	0.2	0.2
E [MPa]	20	9.5-17	19-45	57-141
c' [kPa]	0	7	7	7
□’[°]	35	39	39	39
K_0 [-]	0.43	0.37	0.37	0.37

The excavation and construction of tunnel was simulated by using the convergence-confinement method (Panet & Guenot, 1982; Kielbassa & Duddeck, 1991; Potts & Zdravkovic, 2001). The ground reaction curve for the convergence-confinement method was determined taking into account the stress relaxation of the ground, the subsequent installation of the lining, as well as the effect of load sharing between the ground and the lining. This method is used to represent 3D tunnelling effects. It provides a convenient way to bring this 3D problem to a 2D one for which to determine the earth pressure on the lining as a function of deformations. In order to achieve the desired amount of ground loss, it was assumed that stresses had been reduced by a factor of 0.35 at the time that lining was installed. The resulting internal forces and moments on lining which calculated from the PLAXIS^{2D} analysis as shown in Figure 8, were then resolved to derive an equivalent earth loading applied together with the groundwater pressure to the 3D bedded beam spring model.

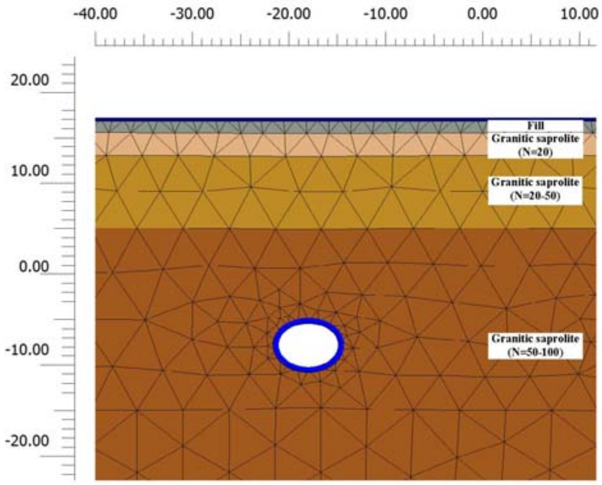

Figure 8. Plane strain model for tunnel by PLAXIS^{2D}.

3.5 *3D analysis*

The 3D bedded beam spring model was created to replicate the tunnel lining using the software Oasys GSA^{3D}. The tunnel lining was modelled as a monolithic ring with no radial joints comprised of a grid of quadrilateral shell elements. The ground medium was represented by a set of radial and tangential springs. Ground springs under tension were ignored and therefore no reaction was imposed on the segmental lining. The stiffness of the radial springs was calculated using the linear load deformation relationship according to Duddeck & Erdmann (1985). The stiffness of the tangential springs is difficult to derive, however, the empirical relationship with respect to the radial springs as suggested by USACE (1997) was adopted in the analysis.

The single ring model was used to establish a base case for design. This model was calibrated against the PLAXIS^{2D} analyses to ensure that the structural response of the tunnel lining was compatible with the 2D finite element model prior to commencement of the 3D analysis. This was followed by a full 3D model incorporating the opened and the adjacent fully enclosed rings, as well as the temporary steel hamster cage. At the interface between the adjacent rings, rigid links have been used to simulate the action of shear bicones. These links have been connected with compression only springs to allow separation to occur and so allow joint rotation. ‘Cut-off’ has been specified to the spring forces and interaction factors representing the bicone behaviour. The ‘cut-off’ pressure was obtained from the results of the direct shear test on bicones in the laboratory, and imposed on the beam spring calculation process.

Load combinations and factors of safety were considered in accordance with the national codes and standards. The design loads that included the earth loading as determined from the PLAXIS^{2D} analysis were applied directly on the tunnel lining under different load combinations. The resulting internal forces and moments from the 3D model were used to undertake the structural assessment for the rings and the temporary steel hamster cage design. Figure 9 shows the full 3D model which was used for design of the opening at temporary stage during the cross passage construction. Finally, a separate full 3D model was developed to simulate the tunnel lining at the permanent condition. This was used to assess the structural response of the rings after completion of the permanent collar and cross passage lining, and removal of the temporary steel hamster cage.

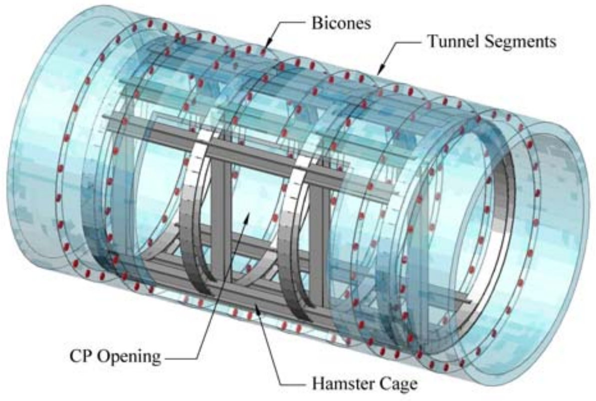

Figure 9. Full 3D model for tunnel opening by Oasys GSA^{3D}.

3.6 *Evaluation of field measurements*

During the cross passage construction, the opened rings would deform while the stress redistribution took place. Ovalization to the opened rings is a major concern when opening is made in the segmental lining. The opened rings are generally deformed until the loads are carried in the ring thrust. It is important to know when the ovalization has stabilized and whether the field measurements are compatible with the design estimations, such that the temporary work design can be reviewed if continued ovalization is leading to overstress of the opened rings. Therefore, the use of instruments to assess the deformation in transverse section of the tunnel serves as a key to checking such situation.

In this project, measurements of ring ovalization by means of convergence arrays within the tunnel was carefully used to gather and provide routine data for stability assessment of the opened rings. The deformation of the rings was monitored by the conventional levelling survey method using the total station. Special reflex targets were installed via supporting bolt-studs on the opened rings. The coordinates of each array were derived from the infra-red light beam which transmitted from the total station. The individual movement of array and the relative movement between the arrays were then calculated using the method of trigonometry.

The predicted ovalization of the opened rings from the 3D analyses can be seen in Figure 10. Evaluation of the ring deformation from the convergence measurements was carried out for the opened rings. The monitoring data that used in the evaluation, have been assessed and adjusted to eliminate the movements associated with the ring building. Results of the evaluation showed that the measured ring ovalization agreed well with the design prediction from the 3D model, as shown in Figure 11.

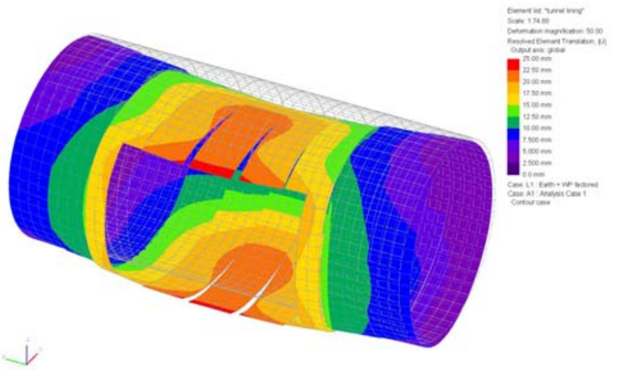

Figure 10. Oasys GSA^{3D} output of estimated displacements.

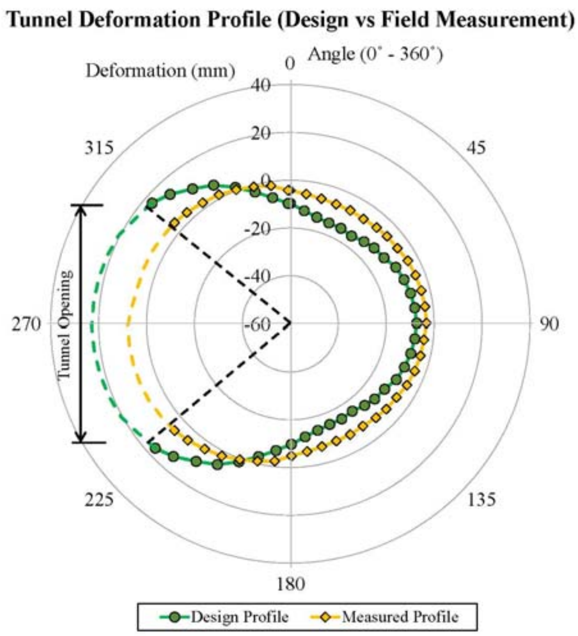

Figure 11. Evaluation of ovalization on the opened rings.

4 CONCLUSION

Building railway and road infrastructures calls for the need to construct cross passage at regular intervals between the twin-tube TBM tunnels or between the TBM tunnel and the shaft structure to provide a safe means of egress in case of emergency. Details of various construction techniques that used to create opening in TBM tunnel in the modern tunnelling industry and the newly developed shear recovery bicone system have been discussed.

Creation of openings in segmental lining alters the simple lining behaviour to a more complex one, as the reinforcing steel between segments were not connected to each other. The critical stage of the lining design is when the opening is made for the breakout of cross passage from the TBM tunnel. The hoop loads have to divert around the opening, resulting in higher compressive stresses to either side of the opening, and flexural stresses above and below in the opened rings. This has to be assessed in a 3D manner.

In order to address the limitations of simulating the complex temporary structural steelwork and the special interface elements in the 3D commercial finite element software, an integrated design approach combining the PLAXIS^{2D} and the Oasys GSA^{3D} analyses was introduced for design of the cross passage opening. The evaluation of the monitoring data for ring ovalization for a large cross passage opening in a railway project in Hong Kong was presented, which demonstrates good agreement between the results of this integrated approach and the actual performance of the opened rings.

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