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SEGMENT'S JOINT IN PRECAST TUNNEL LINING DESIGN

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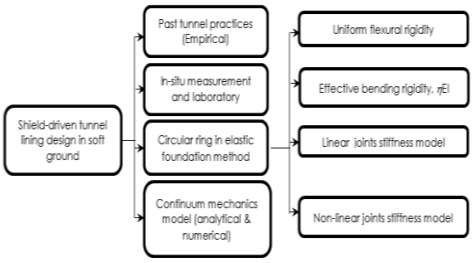
Graphical abstract



Abstract

Tunnel lining design requires an interactive approach as the design is not merely about the strength, but how much the tunnel allows to flexure to overcome the ground movement. When tunnel interacts with soil, stress from the ground is distributed into the structure. In the case of precast segmental bolted tunnel lining, it is critical to investigate the lining joints reaction, as this affects the overall flexural behaviour of tunnel lining. The objective of this paper is to present a discussion on the mechanics response of segmental tunnel lining affected by the segment's joint. A short review on research works conducted in recent day on joint effect in segment's joint in tunnel lining is also presented.

Keywords: Segmental lining, segment's joint

Abstrak

Rekabentuk pelapik terowong memerlukan pendekatan interaktif memandangkan reka bentuknya bukan hanya berkisar tentang kekuatan, tetapi sejauh mana terowong mampu melentur terhadap pergerakan tanah. Apabila terowong berinteraksi dengan tanah, tekanan daripada tanah diagihkan kepada struktur. Di dalam kes segmen konkrit pratuang yang bersambung, ini adalah kritikal untuk menyiasat reaksi penghubung pelapik, kerana ia memberi kesan kepada keseluruhan lenturan pelapik terowong. Objektif kajian ini ialah untuk mempersembahkan perbincangan mengenai sambutan mekanik segmen pelapik terowong yang terkesan dengan penghubung segmen. Ujikaji ringkas mengenai kerja-kerja penyelidikan yang kini dilakukanmengenai penghubung pelapik dalam pelapik terowong juga dibentangkan.

Kata kunci: Pelapik segmen, penghubung segmen

1.0 INTRODUCTION

Design of tunnel lining is not straightforward. It is not independent structural problem, but a ground-structure interaction problem, with the emphasis on the ground [1]. Therefore, lining design process should be approached as iterative process in order to gain an appreciation on how the ground and lining are likely to interact.

Linings are assembled in segmental part connected with bolt, which give effect to the overall structural behaviour. It resist an axial thrust based on the overburden and groundwater pressure at springline, plus bending stresses resulting from an arbitrary percentage distortion of the diameter of the ring.

Japanese Society of Civil Engineering proposed a design code that a lining should carry only 60–80% of the maximum bending moment carrying in the main segment[2].

Large deformation can often be accommodated in the tunnel lining by rotation or shear at the joints between segments inducing high stresses in the linings themselves. When taking in accumulative for both longitudinal and circumferential joint, shield segment damage that occur around segment joint more than once within two to three rings is almost 30% from total occurrences [3]. Cracks are reported mainly to occur near bolt holes and hand holes which affect the overall joint performance [4]. This brings a notion that understanding the behaviour of segmental joint tunnel and carefully design is vital. Klappers *et al*. [5] mentioned that the behavior of joints has to be modeled in a proper way because joints will highly affect the results. Therefore, focusing on bending moment of lining as to gain benefit from designing the lining is a must, in order to obtain more cost effective way and safety of the design.

A discussion on the mechanics response of segmental tunnel lining affected by the segments joint is presented in this paper. An intensive short review on current research works conducted by several authors regarding segment's joint in tunnel lining is also presented. This paper provides the direction of future research field regarding the investigation of the performance in segment's joint connections in tunnel lining.

2.0 IMPORTANT EFFECTS OF SEGMENT'S JOINT DESIGN TO GLOBAL TUNNEL RESPONSE

The most important factors in segmental tunnel lining design is the influence of segmental joints to the overall bending moment carrying characteristics [6]. Jointed segmental precast concrete linings connected by steel bolts are commonly used in most shield-driven tunnels [7]. The stiffness of the tunnel joints can be affected by many factors such as the thrust force level of the segment joints, the remaining longitudinal force and property of the packer material, presenting a non-linear characteristic [8].

Conventional lining design usually take tunnel lining as a uniform rigidity ring model of lining by implying high partial safety factor on bending moment which is over estimated, due to incorrect assumption taken earlier[2]. Lining's bending moment themselves can cause by non-uniform ground pressures and joint eccentricities [9]. In the meantime, under installation and ground static loads, the initial tunnel lining is typically subjected to change of 0.5% of its diameter [10]. Shahrour *et al*. [11] mentioned that the plastic deformations induce an important reduction in the seismic-induced bending moment in the tunnel, while the soil dilatancy moderately affects the bending moment in the lining. The consideration of the elasto-plastic behavior of the soil material leads to a reduction of about 50% in the bending moment. However, some findings are reported by Bilotta and Russo [12] presented internal hoop forces and bending moment using FE model by means beam model and assembly model for four month later after installation stated that in their findings, normal forces, *N* and bending moment, *M* in segmental lining will increase to take into count creep effect of concrete over the time. In addition, staggered segment may lead to the reduction of bending moment was reported by ITA [13]. Moment reported have smaller in magnitude when compared to the moment of the adjacent segment. Engineers usually practice to allow less stiffof segmental joint which lead to more deformation movement and the joint part will be the most critical part of the lining [6]. In the same time, Luttikolt[9] emphasized the influence of joints on the global lining behavior is significant especially when include the interaction between segments, more realistic tunnel lining response can be obtained. Hence, it can be concluded that it is a difficult task to design the accurate bending moment especially at the area of the joint since there arised a lot of uncertainty.

3.0 DESIGN METHOD IN TUNNEL LINING

A working group on tunnel structural design, the International Tunnelling Association (ITA) has summarized the design methods used for shield-driven tunnels in soft ground. Four different design methods are: (a) empirical design methods based on past tunnelling practices; (b) design methods based on in situ measurement and laboratory testing; (c) circular ring in elastic foundation method; and (d) continuum mechanics models including analytical methods and numerical methods [13].

Circular ring in elastic foundation methods most commonly adopted for design purposes, with joints of segments were taken as follows; (a) assuming circular rigidity has uniform flexural rigidity throughout the lining ring (*i.e.*, no reduction of rigidity in lining although joints exist), (b) assuming there is reduction of rigidity due to existence of joint, by taking reduction factor as η ratio to the rigidity of continuous lining structure, (c) lining is simplified as a prefect pins jointed ring with the stiffness of joints is ignored, lining ring is non-redundant structure with surrounding pressures including soil resistance around the lining structure or (d)lining similar with (c) but with joints stiffness where joints are modelled as elastic pin with constant stiffness values.

Regarding the circular ring in elastic foundation method, Lee *et al*.[7] discussed the contribution of each tunnel joint assumption. It is obviously known that first method is the simplest, by assuming circular rigidity has uniform flexural rigidity throughout the lining ring but it may lead to large error in analyses. Due to uniform rigidity, less moment will be predicted thus leading to excessive unsafe design of tunnel lining. Second method seems to be more reasonable, but in

actual, it is hard to obtain the reduction of bending rigidity, η value which previously obtained via empirical relationship for various geological conditions. Koyama [1] stated that it is a practice to assume the value of effective bending rigidity based on the profile of the joint, and also depends on the shape and size of segment involved. A common practice to use reduction factor, η to the flexural rigidity(ηEI)[2,14-20] or to neglect the joint effect in whole tunnel ring (assume continuous lining model).Efforts have been reported via analytical method to propose reduction factor, η, for the flexural rigidity of segment tunnel linings [17,20]. When inspected for ring's joint (with an assumption that segments have similar rigidity), Koyama [2] also found that the effective bending rigidity also changes with the applied load. When taking into account the bending distribution near the circumferential joints (by assuming the additional rate ratio,ζ), the bending moment significantly varies with the bending rigidity of the circumferential joint, which has no basis facts. Therefore, it is still uncertainty on the actual distribution of bending moment calculation by means of this method.

The last method (model the joint as elastic pin with constant stiffness values)is most effective way to investigate the joint stiffness effect on tunnel response especially with various soil resistance pressures in different ground layer conditions [4]. Efforts to estimate the moment and thrust distribution in contiguous tunnel lining due to joint existence in analytical solutions have been started in early of 1960s such as by Morgan [21] and Wood [16] and keep expanding nowadays. The method of closed form solutions gives optimum liner design with good loading cases prediction of preliminary tunnel lining design without the need of complex and time-consuming method such as the Finite Element or Finite Difference. The analytical analysis usually carried out in continuum elastic soil condition and limited their assumptions to linear and multi-linear branch of joint behavior. Assumptions on certain restrain conditions such as adopting the tangential bending moment are known, independent from the bending stiffness of the ring (which is not valid when used in condition of varying bending stiffness – non-linear behavior of longitudinal joints) are usually taken to provide simpler solutions [22]. Joint rotational stiffness magnitudes sometimes are empirically proposed then verified with laboratory tests and/or simplified numerical models. The nonlinear soil behavior and the interactions of soil-tunnel is difficult to be embedded in the analytical analyses. The analytical analyses mostly count a homogeneous rings inelastic continuum soil only [22].

In the meantime, with the growing development of numerical analyses, numerous models had been proposed to examine the influence of joints on lining behavior [23-26]. Various assumptions and models of tunnel joint are presented. Some of the researchers compare and validate their work with in-situ testing or field case study. However, existing solutions do not explicitly account for segment's joint effects developed in tunnel lining. Researchers focus more on tunnel interactions between ring's interstices. Simplified assumptions of segment's joint values are usually taken in those previous researches. Reviews of the related technical literatures also show that the numerical methods often simplify either the detailed structures of the tunnel, or the external loads and boundary conditions. These simplifications are acceptable in most cases but may lead to some inaccuracies. Such as it may underestimate the dynamic stress of the tunnel, and it cannot reflect the joint width variation between tunnel linings.

4.0 CLOSED FORM ELASTIC DESIGN APPROACH IN TUNNEL LINING

A simple design approach by means of empirical formula or design code usually was adopted in designing the segmental tunnel lining. Alternatively, closed form solutions were proposed in designing the tunnel which take into account the lining and soil stiffness. A flexibility ratio in Equation 1 has been proposed which combined parameter between lining stiffness and soil stiffness [27];

$$F = \frac{E_S/(1+v_S)}{6E_L I_L/(1-v_L^2)R^3} \quad (1)$$

where E_S is Young Modulus of soil, $v_S$is Posson's ratio of soil, Young Modulus of lining(E_L), second moment inertia of lining (I_L), Poisson's ratio of lining, v_L and R is radius of lining. However, the proposed solution only covers relations for linear elastic lining and soil stiffness and did not count for the segmental joint factor. Wood [16] adopted segmental joint behavior in tunnel lining as a partial hinges and came out with a moment of inertia of the overall lining, I_e that expressed as in Equation 2;

$$I_e = I_j + I\,(4/n^2) \quad I_j << I \text{ for an expanded and articulating lining} \quad (2)$$

where I and $I_j$are the moment of inertia of the intact lining and segmental joint and N is number of joints in the lining. In much recent attempt, researchers tend to solve using analytical correlation for moment reduction factor in tunnel lining design. Lee and Ge [20] proposed an analytical correlation for moment reduction factor based on the maximum horizontal displacement of a continuous ring. They have included a correlation among the effective segmental lining stiffness, bending moment reduction factor and subsoil reaction.

5.0 MOMENT-ROTATIONS MODEL IN SEGMENT'S JOINT

Numbers of researcher attempt to carry out joint rotational calculation in segment's joints. This is

important task because excellent understanding of joint behavior will lead to an improved understanding tunnel lining in a whole.

Segment's joint interfaces usually taken as a reduced area, which tangential forces are assumed to induce in a concentrated way. Joint that are relatively rotate to each other acting as a hinge between the adjoin segments. The hinge has resistance against the rotation and bending moment is induced. It is crucial to zoom into rotational stiffness as previous researchers have taken that each longitudinal joint treated to have a unique value for the rotational stiffness but in realistic it change non-linearly.

Joints affected the global behavior of lining. Initially, Janssen [28] proposed simple theoretical model to describe moment-rotation behavior of segment joints in linear material properties and full concrete-to-concrete surface contact. Joint has been representing by an equivalent concrete beam between two segment concrete (Figure 1). Rotations and additional curvature occurs from concentrated force applied to the segments.

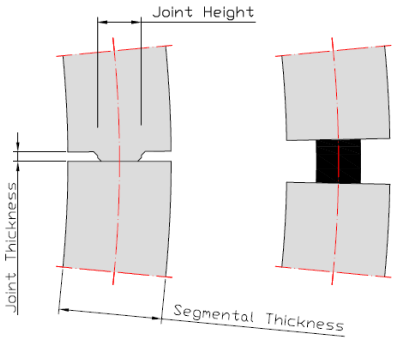


Figure 1 Janssen model (a) reality (b) model simplification [28]

Gladwell [29] improved the moment-rotations relation model by considering the nonlinear stress distribution over the cross-section. In nonlinear condition, it is known that at the edge of contact area the stresses reach infinity. Gladwell discusses the problem in two flat surfaces where the contact stresses concentrated on the edges of the joint (Figure 2). More stiff rotational behavior occur compared to elastic moment-rotation condition. Gladwell took initial stiffness high and lead to longer closed stays joints compared to Janssen. For nonlinear equations of Gladwell, the results approach asymptotical bending moment more quickly.

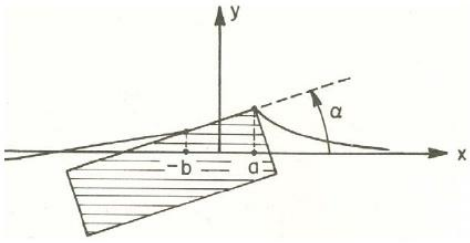


Figure 2 Flat punch pressed unsymmetrical into a half plane[29]

In the interpretation of the analytical models, Blom [22] implemented rotational stiffness in segment's joint and divided into linear and multi-linear models. The rotational stiffness is derived from Janssen theory or an equivalent theory. A linear model is when rotational stiffness is constant when the longitudinal joints are closed. Whilst, rotational stiffness is decreases when the longitudinal joints are opening is called non-linear branch. A model can be combination of both branches named as multi-linear model. If the rotational stiffness is zero, then it means a hinge joint is adopted. Blom [22] also presented discussion on three different stages of non-linear rotational stiffness of segment's joint (Figure 3). Three continual stages are defined based on the bi-linear approach of concrete (elastic part and plastic part). By assuming an increasing rotation in segment's joint at a given normal force, the following stages will be obtained:

i. a constant rotational stiffness until $M>Nl_t/6$: $c_r = \frac{bl_t^2 E_c}{12}$ where l_t =contact area height in the longitudinal joint
ii. rotational stiffness is non-linear, but the ultimate compressive strains are in the elastic branch, until $\varepsilon=\varepsilon'_c$: $c_r = \frac{9bl_t\ E_c M\left(\frac{2M}{Nl_t}-1\right)^2}{8N}$
iii. rotational stiffness is non-linear and the ultimate compressive strains are in the plastic branch, until $\varepsilon=\varepsilon_{cu}$

Blom [22] presents the visualization of three stages behavior of segment's joints for tangential bending moments as a function of the rotation, shown in Figure 3. Stage I is showing that the segment's joint is closed. Tangential bending moment increased rapidly with the rotation increased. Stage II indicates the joint starts to open. Compare to previous phase, when rotation increases, tangential bending moment also increase but in less manner. Stage III presents the existence of concrete plastic stresses. Tangential bending moment in here increases even less when rotation increases. Stage I and II show clear discrepancy. Commonly lining design only consider stage I, more advanced calculations do consider stage II. Stage II has limited validity. However, by using equations of stage II, stage III prediction may lead to just small discrepancies in tangential bending moment and rotations calculations. The fact that reduction of concrete stress in stage III has to be accounted due to concrete plastic stresses conditions. Lack of solution exists for third stage conditions. Blom [22] successfully proposed solutions for linear and multi-linear models; however, Blom's solution only idealized the soil as radial spring and derived the full slip case for soil-lining interfaces.

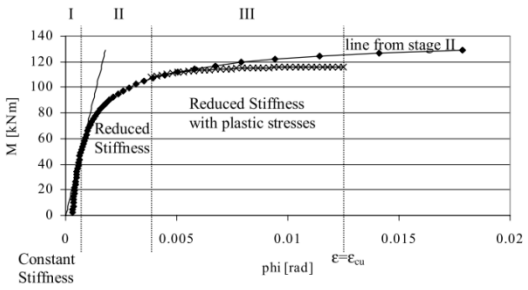


Figure 3 The three behavior stages of segment's joints: Tangential bending moments as a function of rotation in the segment's joints [22]

Luttikolt [9] discussed the behavior of segments joints when significantly affected by the radial forces on the lining. When bending moments are in low range magnitude, the joint experience compression force in the entire cross-section. Only minor rotational joint occur, depending to the joint locations (i.e., height and thickness). However, if the joint height is too small and the joint thickness is relatively large, large rotations may occurred linearly. Gap will introduce once the pressure at the outer side of contact zone become zero, thus lead to extensional segment rotation. Severe rotation may develop when the moment passing the rotational maximum point. Hence, this nonlinear joint response is not well understood and yet to explore further.

From the discussion of rotational phenomena in segment's joint, it can be concluded that non-linear response of segment's joint is not fully explored. Analytical formulations barely could provide proper solutions due to overwhelmed calculations. More extended numerical model and experimental testing are a wise choice to conduct the research and/or to verify the findings.

6.0 RESEARCH ON ROTATIONAL STIFFNESS IN SEGMENT'S JOINT

Smallnumbers of researches focuson segment's jointinvestigations. Analytical, numerical and experiment are the methods used by researchers in their attempt.

6.1 Lee *et al.*

Lee *et al*. [7] proposed an analytical solution by using an equivalence method based on a matching scheme of internal forces and displacements of a jointed segmental tunnel. In this proposed solution, instead of presenting an effective bending rigidity *(EI)*uniformly, the vertical or the horizontal displacementhas been matchseparately in the equivalent continuous tunnel lining. Lee *et al*. [7]proposed the lining rigidity characteristics as joint stiffness, *K*, in set of flexural, axial and shear stiffness (K_θ, $K_\delta$and K_r). Lee *et al*.[6] also introduced a dimensionless parameter called the joint stiffness ratio, λ, relative stiffness of joint ratio to the rigidity of the lining segment. The equation is as follows,

$$\lambda = \frac{K_\theta l}{EI} \quad (3)$$

where E is Young Modulus of concrete, I is moment inertia and *l* is length of lining. Lee *et al*. [7] compared the proposed mechanical behavior of the joints in precast concrete tunnel lining by means laboratory structural testing [30]. Lee *et al*. [7]reported that the flexural joint stiffness, K_θ is highly variable and crucially depends on the properties of packer and bolts, and influenced by the geometry of end rib of lining segments and subjected forces. Lee *et al* also concluded that the joint stiffness, K_θ, is higher when the joint is subjected to a positive bending moment than when it is subjected to a negative bending moment. Researchers brought a good effort in investigating joint rotational stiffness in segmental tunnel lining; however, the nonlinear behavior of longitudinal joints was not explored yet.

6.2 El Naggar and Hinchberger

El Naggar and Hinchberger [18] derived an analytical solution for an inner jointed thin-walled shell and an outer thick-walled cylinder embedded in a homogeneous infinite elastic medium. Inner lining is assumed to have joints that are aligned in the longitudinal direction and situated at $\theta_{=1}$ to $\theta_{=n}$. No slip at full slip at the interfaces of soil and outer lining and outer and inner lining were considered. Analytical solution proposed is based on Airy's stress function. El Naggar and Hinchberger [18] also proposed a joint stiffness coefficient, but in slightly different manner. The closed-form solution is verified by comparing it with FE results and achieved a good agreement. They carried out parametric studies in FE to verify the proposed analytical jointed solution and model the joint stiffness coefficient of λ as 0.1, 0.4, 0.8, 1.0 and 1.5. The joint stiffness coefficient, λ which are taken as:

$$\lambda = \frac{k_\theta}{EI} \quad (4)$$

where $k_\theta$is rotational joint coefficient, *E* is Young modulus and *I* is moment inertia. Tunnel excavation was simulated with the assumption that there was no slip between soil and outer lining. Four, six and eight joint lining configurations had been investigated with two different pattern of joint, started at crown and have interstices angle from crown. Soil-tunnel interactions were simplified and did not represent the real tunnel condition. With verification of FE parametric analyses, analytical jointed solution proposed is proved to helps predict the displacements, moments and thrusts occurred in tunnel lining with reasonable accuracy.

The solution is quite flexible and it can be applied to investigate a wide range of tunnel lining problems and load cases. However, the solution was limited to two

conditions; (i) problems with high large variation of $C_s$exist for the spring line and crown to invert axes and (ii) to the values of λ are less than 0.4. Other than these two conditions, jointed solution might lead to error results prediction. Later in numerical section, the effects of joint stiffness coefficient were discussed in detail.

Then, El Naggar and Hinchberger [19] carried out an approximate evaluation of stresses in degraded tunnel linings. Failure criteria of concrete tunnel lining have been discussed. The lining was modeled as nonlinear elastic reinforced concrete material, with strain softening plastic constitutive model. Joints model started at the crown and situated at 45 intervals. The liner joints were modeled using thin zones of linear elastic elements. Eight joints were considered and the elastic properties were used. Although an effort have been presented to perpetuate research work by introducing nonlinear lining segment, but joint connection are linear and none of construction phase has been taken into account in the modelling.

6.3 Teachavorasinskun and Chub-uppakarn

Teachavorasinskun and Chub-uppakarn [6] focussed on load and displacement in jointed two segmented lining applied with two point load test in laboratory. They validated their partial-scale laboratory with FEM and learned that an angular joint stiffness in the range of 1000-3000 kNm/rad could be adopted for joints to be incorporated in the flexural moment calculations. The simplified FEM analyses using shell element for lining segment and spring to model the joint connections. Effects of joint stiffness, number of segments and soil subgrade modulus were investigated. From the numerical work, they found that the segmental tunnel lining produced smaller maximum bending moment when compared to the non-jointed lining. A parameter called moment reduction factor expressed by a function of angular joint stiffness and number of segment was introduced. Teachavorasinskun and Chub-uppakarn [6]also derived the reduction of bending moment as a stiffness reduction factor as follows;

$$n = \frac{(K_\omega + X)}{K_{ref} + (K_\omega + X)} \quad (5)$$

where $k_\omega$is angular joint stiffness, n is the number of joints in the lining, K_{ref} is the 1650 kNm/rad (from analytical calculation) and $X$is as follows;

$$X = \frac{(4/N)^2}{1-(4/N)^2} \quad (6)$$

In addition, a moment variation equation is represented bythe following:

$$M_N = \left(M_{nonjoint} - 5N\right) + Asin(N\alpha - 90) \quad (7)$$

where N is the number of joints in the lining is a the angle of joint position, A is the amplitude of the sinusoidal curve = f(N, K_ω, k), k= subgrade modulus[6]. In case when $K_\omega$is equal to zero, joint becomes perfectly hinged and $n= (4/N)^2$ is attained [14].Teachavorasinskun & Chub-uppakarn concluded that the maximum bending moment reduction, introduced as stiffness reduction factor, η, iseffected by the total segment used in a tunnel ring, with the larger number of joints exhibits larger value of η. It alsomentioned that the effect of the subgrade modulus and tunnel diameter are similar when applied to both type ofsegments. Therefore, the relationship of η-$k_\omega$is reported to benot affected by the stiffness variation of soil and tunneldiameter [6]. However, it should be noted that a simple manner of soil-tunnel interaction was assigned in their modelling, with straight lines of tunnel's joint configurations; this finding is still yet to be confirmed.

6.4 Do *et al.*

Do *et al*.[25] and Do *et al*.[26]presented a global tunnel development of 2D and 3D numerical modelling by including both longitudinal and circumferential joint model, the construction phases and influences of grouting hardening, respectively. Do *et al*. [25] discussed the influence of joints to the segmental tunnel lining in two dimensional numerical studies using Finite Difference Method on longitudinal joint between segments and also circumferential joint in rings. Joint were modelled as double node connections, with six degree of freedom to represent six springs (rotational, radial and axial stiffness). The bending moment tunnel behaviour with varies K_0lateral earth factor were investigated. It shows that joint rotational stiffness give influence to the bending moment of tunnel in a ring. With decreases of joint rotational stiffness, it has led to negative bending moment. Axial and radial stiffness of joints were reported only giving smaller effect to the global tunnel response.

Then, Do *et al*.[26] extended the tunnel joint discussion into a three dimensional Finite Difference tunnel model in order to evaluate in certain the tunnel lining behaviour and the displacement field surrounding of the tunnel. Lining joint pattern (segmental lining joints and their connections) together with the construction tunnel process (grouting pressure, jacking forces) was taken into account in the proposed model. To model a segment to segment joint, a link of double node connections of six degree of freedom has been model with four different types of connection namely free, linear spring characterized by a stiffness factor, bi-linear spring characterized by a stiffness factor and yield strength and rigid has been developed. The stiffness characteristics of joint connection presented by combination of rotational spring (K_θ), axial spring (K_A) and radial spring (K_R). Axial spring has been approximately proposed to have linear relation of constant coefficient spring based on empirical basis. For radial stiffness and rotational stiffness, bi-linear relation has been characterize by a stiffness factor and maximum bearing capacity base on study that have been presented by Do *et al*.[25].

6.5 Yanzhi*et al.*

Yanzhi *et al*.[8]observed the equivalent lining model's effective elastic constants for the case of segmental tunnel, by means of inverse analysis method, FEM and also parameter optimization. The model incorporated the segment's joints, joints were modeled in local coordinates system described by rotational stiffness K^l_θ, axis stiffness K^l_α, shear stiffness in radial direction K^l_{sr} and shear stiffness in tangential direction K^l_{st}. The segment's joint; the rotational spring stiffness (concrete to concrete surface, 438 mm in height) proposed based on combination of empirical formulas, and real model tests [31]based on Janssen formulation [28] for moment-rotation relationship, lateral spring coefficient (axial and shear spring).

In FEM modelling, researchers had discretized two typical soil deposits of Shanghai soil model into solid element with Drucker-Prager constitutive equation. Soil-tunnel interaction is surface-to-surface contact algorithm. Lateral soil resistance pressure was excluded since long-term equilibrium condition was adopted. Pore water pressure was at the ground surface with fully drained condition. A simple stage of construction phases in accordance to Bobet [32] was adopted in the modelling. The effective rigidity ratio η was 0.68.

Results show good agreement of FE models when compared to the analytical model. However, the equivalent model could only represent the linear tunnel's rigidities with respective joint pattern. It has room of improvement, to try the non-linear response of tunnel sections with details of non-linear segmental model and tunnel's construction parameters (i.e., grouting, face pressure etc.)

7.0 POTENTIAL FUTURE RESEARCH

Pattern of studies show interesting findings on the parameter influences the tunnel lining response. Quite a numbers of researchers presented their findings on joint influences in tunnel by means of analytical solution and numerical modeling. Numerical studies shows great opportunity to be explored but the basis of input data has to further be verified correctly. Do *et al*. [26] also mentioned that experimental studies are important in order to validate the jointed tunnel lining simulation. Only few have carried out laboratory testing to embark knowledge on structural modification and soil surrounding stress redistribution due to joint influences to the segment tunnel lining. In order to gain data accuracy, monitoring tunnel lining during the whole construction process and lifetime is beneficial [33].In addition, nonlinear joint stiffness effect to the global tunnel bending moment is not yet explored in detail with existence of surrounding ground. A new shield-driven tunnel lining design method is proposed by including the nonlinear joint stiffness model for future design method shown in Figure 4. This brief discussion of some literature on the subject is not intended as a comprehensive review and must be considered incomplete. Nevertheless, wide room for improvement to investigate joint influence to tunnel is available to produce a certain way of tunnel lining design. Hence, it can be concluded that, tunnel responses due to jointed tunnel lining are not fully explored. Investigation on this problem is significant to be carried out.

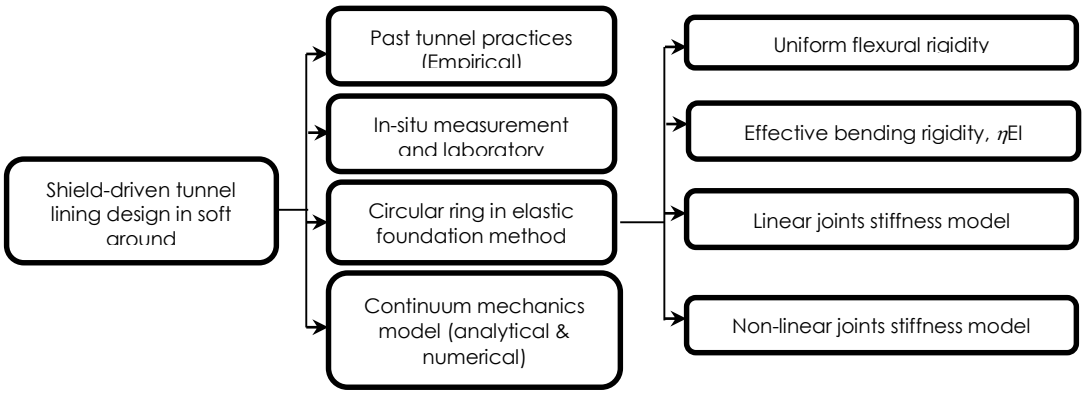


Figure 4 Shield-driven tunnel lining design with segment's joint design method

8.0 CONCLUSION

With precast concrete tunnel lining, the speed of construction and reduced disruption of the site gives local environmental benefits, while the flexibility and adaptability of reinforced concrete structures maximize the economic life of the structure. The structural efficiency of lining and joint leads to resource efficiency. From this overview, the important of segment's joint rotational stiffness cannot be denied. There is a potential research field on structural modification in tunnel lining regarding joint influence is significant to be carried out. Field monitoring on strain measurement, laboratory testing on jointed segment model and fully soil-tunnel numerical modelling with

assured parameters of segments' joint are suggested to be carried out in the future.

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