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Technical note

Influence of segmental joints on tunnel lining

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ABSTRACT

A simplified method for evaluating the moment carrying of a segmental tunnel liner was proposed using a result from a FEM analysis in which parameters were obtained by calibration against a true scale model test. Influence of segmental joint, number of segment and soil subgrade modulus on the bending moment carrying characteristics of a segmental tunnel was examined. Joint was represented by a series of springs called angular joint stiffness. Based on a set of model tests, practical range of angular joint stiffness was in range of 1000–3000 kN m/rad. It was found that jointed lining carried smaller value of maximum bending moment than the non-jointed one. The reduction in bending moment, represented by the parameter called moment reduction factor, can be simply expressed as a function of angular joint stiffness and number segment.

1. Introduction

One of the most important factors in designing of a segmental tunnel liner is the influence of segmental joints on its overall bending moment carrying characteristics. This is due mostly to the difficulty in providing segmental joints to be as stiff as the main segment. Engineers usually allow segmental joint to be less stiff and undergo more deformation than the main portion, which leads the joint to be the most critical part of the lining. Lining is usually designed using a parameter called flexibility ratio, *F* (Peck, 1972; Einstein, 1979; Son and Cording, 2007) to express the relative stiffness of surrounded soil and lining structure. The flexibility ratio, *F*, is written in the form as shown in Eq. (1).

$$F = \frac{\frac{E_s}{(1+\upsilon_s)}}{\frac{6E_L I_L}{(1-\upsilon_L^2)R^3}} \tag{1}$$

where E_s and υ_s are the Young's modulus and Poisson's ratio of the ground, E_L and υ_L are the Young's modulus and Poisson's ratio of the lining, I_L is the effective moment of inertia of the lining and R is radius of the lining.

Wood (1975) proposed that the effective moment of inertia of the overall lining (I_L) should be reduced to taking into account of its jointed structure as;

$$I_L = \left[\frac{4}{N}\right]^2 I_0 + I_j \tag{2}$$

where I_0 is the moment of inertia of the lining without joint, N is the number of segments and I_j is the second moment area at the joint. The design code of the Japanese Society of Civil Engineering (Koyama, 2003) empirically recommends in its popular simplified design method that segmental joint should be designed to carry only 60–80% of the maximum bending moment carrying by the main segment. Furthermore the lateral confinement from the surrounded soil is also adjusted according to the adopted moment reduction factor. Several model tests and analyses had been carried out to examine the influence of joints on lining behavior. Lu et al. (2006) conducted an experimental study to investigate the load carrying capacity of the full segmental RC lining having outer diameter of 15.0 m. Abundant useful information was obtained, unfortunately the influence of segmental joint stiffness was not explored in detail. Zhong et al. (2006) analytically studied the influence of segmental joint using the finite element analysis program, PLAXIS. In their analysis, segmental joints were assumed to be fully hinged therefore actual construction condition; i.e., joint with partial moment transmitting capacity, was not simulated.

Although quite a few experimental and analytical studies can be found in the literature, their results have not led to any practical design criteria for a segmental lining. The present study therefore aims to simplify the bending moment carrying characteristics of the segmental lining through a set of simplified FEM analysis. Various parameters; i.e. number of joints, joint stiffness, soil stiffness and etc., have been considered.

2. Numerical modeling of shield tunnel lining

A series of three dimensional finite element analysis using SAP2000 were conducted to explore the interaction between joints and the main segment. The main segment of the tunnel was modeled using shell elements, while joint was simulated using an interface element at which its bending moment carrying capacity was

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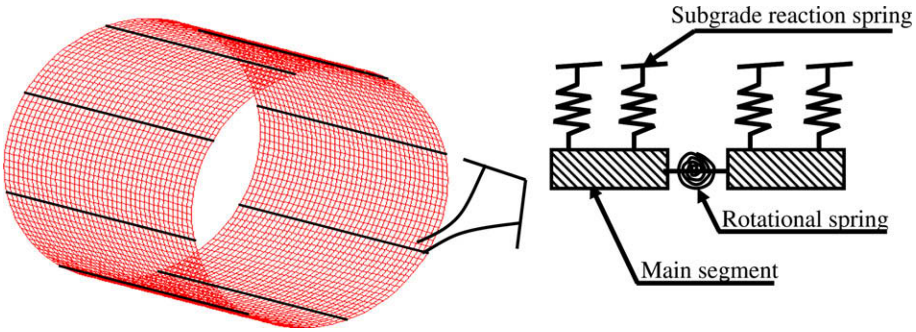

Fig. 1. Cross section of segment model.

Table 1
Summary of lining and soil properties used in the analyses.

Segment and joints	Diameter of tunnel (m)	4–8
	Lining thickness (m)	0.3
	Young's modulus (MPa)	25,000
	Poisson's ratio	0.2
	Angular joint stiffness (kN m/rad)	300–12,000
Surrounded soil	Subgrade modulus (kN/m^3)	3750–56250
	Unit weight (kN/m^3)	20
	Coefficient of earth pressure at rest	0.5

determined by a set of rotational springs as depicted in Fig. 1. The interaction between soil and tunnel lining was also taken into account through a set of normal subgrade reaction springs. The properties and parameters of the lining and the surrounded soil adopted in the analysis are summarized in Table 1. External loads were imposed vertically and horizontally to simulate the action of vertical and horizontal earth pressures (with the coefficient of lateral earth pressure of 0.5) at depth of about 20 m from ground surface.

3. Determination of angular joint stiffness (K_ω)

Model tests were conducted using two connected actual segments used in construction of the water supply network in Bangkok. The test arrangement is schematically shown in Fig. 2. Tested segments were connected by 2 M22 curved bolts of grade 6.8 (f_y = 480 MPa). In order to estimate the practical range of the angular joint stiffness, K_ω, simple FEM analysis using similar configuration as the main analysis was done to simulate the test results. The relationships between the vertical load and deformation obtained from testing and analytical results are plotted together in Fig. 3. The values of K_ω were randomly selected so that the most fitted curves to the test results were obtained. It can be deducted from the figure that the values of the angular joint stiffness should therefore practically be in the range of 1000–3000 kN m/rad. It should be noted that the suggested values may be affected by the curvature nature of the jointed. This curvature effect cannot be taken into account by the present analysis.

4. Influences of the number and orientation of joints

The influences of orientation of segmental joints were examined by rotating the joints along the tunnel's circumferential. The orientation of joints is found to greatly affect the amount of maximum bending moment acting on the lining as can be seen in Fig. 4 where the results obtained from an analytical case are summarized. The variation of maximum bending moment against joint location is sinusoidal in nature, at which its frequency reduces according to the number of joints. The maximum bending moment, which is generally used in design of lining structure, therefore varies within the boundary of oscillation of the sinusoidal curve which gives the upper and lower values of maximum bending moment. The variation can be generally represented a function shown below;

$$M_N = (M_{nonjoint} - 5N) + A\sin(N\alpha - 90) \tag{3}$$

where N is the number of joints in the lining α is the angle of joint position (Fig. 4), A is the amplitude of the sinusoidal curve = $f(N,\ K_\omega,\ k)$, k = subgrade modulus.

For a non-joint case (N = 0), the parameter A should be taken as zero since the maximum bending moment (Fig. 4). This empirical equation is difficult to be normalized to provide a dimensionless representation. Further detail investigation into the analytical results as described in the following paragraphs leads to a more practical representative.

Figs. 5a and 5b show the plots between the upper and lower values of the maximum bending moment against the angular joint stiffness, K_ω. The results shown in Figs. 5a and 5b are obtained from a case where the diameter of the tunnel and subgrade modulus of surrounded soil are 4 m and 15,000 kN/m^3, respectively. When joints are rigid (high value of K_ω), the maximum bending moment, both upper and lower values, of the jointed lining becomes naturally approaching the non-jointed one. However, within the recommended range of the angular joint stiffness (≈1000–3000 kN m/rad), the maximum bending moment decreases to about 0.50–0.95 (for upper value of maximum bending moment) and 0.3–0.90 (for lower value of maximum bending moment) of that obtained from the non-jointed lining. The reduction in maximum bending moment, called herein stiffness reduction factor, η, is also strongly dependent on the number of joints in the lining. Lining with the larger number of joints exhibits larger value of η. The values of η obtained from other analytical cases are summarized in Table 2.

Fig. 6 expresses the influence of the subgrade modulus of surrounded soil on the upper value of maximum bending moment. When a lining is simulated in a stiffer soil (higher value of subgrade modulus), the maximum bending moment acting on the lining decreases. The increase in tunnel diameter also results in increasing in the maximum bending moment as typically shown Fig. 7. Fortunately, the influences of the subgrade modulus and tunnel diameter are equally applied to both jointed and non-jointed cases. As a consequence, the relationship between $\eta \sim K_\omega$ is not affected by the change in stiffness of soil and diameter of tunnel. Similar $\eta \sim K_\omega$ curves as those shown in Figs. 5a and 5b can be obtained from other analytical cases with different values of subgrade modulus and tunnel diameter (Table 2).

Since installation of segmental lining during tunnel construction is random in process, the upper value of maximum bending