

# Design of the secondary tunnel lining using a ground-primary support-secondary lining interaction model

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**Abstract:** It is the common practice to reinforce excessively the secondary tunnel lining due to the lack of rational insights into the ground loosening loads. The main load of the secondary lining for drained-type tunnels is the ground loosening. The main cause of the load for secondary tunnel lining is the deterioration of the primary support members such as shotcrete, steel ribs, and rockbolts. Accordingly, the development of the analysis model to consider the ground-primary supports-secondary lining interaction is very important for the rational design of the secondary tunnel lining. In this paper, the interaction is conceptually described by the simple mass-spring model and the load transfer from the primary supports to the ground and the secondary lining is showed by the characteristic curves including the secondary lining reaction curve for the theoretical solution of a circular tunnel. And also, the application of this model to numerical analysis is verified in order to review the potential tool for practical tunnel problems with the complex conditions like non-circular shaped tunnels, multi-layered ground, sequential excavation and so on.

## 1. Introduction

The load for the design of the secondary tunnel lining is generally determined by empirical methods from a few rock mass classification methods such as Terzaghi's, RMR or Q-system. The loads calculated from these conventional methods are too conservative and simple to consider the complex ground condition and tunnelling works. However, there are no guides or specifications enough to the design model of the secondary tunnel lining to consider rationally the complex conditions such as the too many properties of the ground, the primary lining, and their equilibrium state.

This paper proposed the secondary tunnel lining model for the rational design that is based on the interaction with the ground and primary support members after the secondary lining installation. The main loads for the secondary lining are resulted from the deterioration of primary support members. A simple mass-spring conceptual model described the load transfer mechanism from the primary support members to the secondary lining and the ground. The theoretical validation and the practical application of this proposed model were verified by the closed form solution and the numerical analysis for the circular tunnel.

## 2. Conceptual Model of Secondary Tunnel Lining

The simple mass-spring model of Fig.1 shows conceptually the sequential interaction of the ground, the primary support, and the secondary lining. The initial state before tunnel excavation is the equilibrium state like Fig. 1(a). It is assumed that the fictitious space excavated is supported by the ground spring. The load of the initial ground,  $mg$  ( $g$ ; gravity acceleration), is balanced to  $k_g u_0$  as followed equation (1) when  $m$  is the mass of ground,  $k_g$  the ground spring, and  $u_0$  is the initial displacement.

$$mg = k_g u_0 = F_g \quad (1)$$

Once tunnel excavation and primary support installation trigger the secondary equilibrium state to balance the ground reaction loss from excavation with the additional reaction due to the installation of the primary support (Fig 1b). The deterioration of the primary support members such as the corrosion of rockbolts and wiremesh, and the alkali-reaction of shotcrete may reduce the stiffness of the primary supports, which causes the incremental load for the secondary lining (Fig. 1d).

This interaction mechanism can be understood by the displacement-force curves of Fig. 2. And then, it can be summarised in the mathematical forms as followed;

- (a) Initial state, the same as equation (1)  
(b) Excavation and support ( $\alpha < 1$ )

$$mg = \alpha k_g u_o + (\alpha k_g + k_s) \cdot \Delta u_1 = \alpha k_g (u_o + \Delta u_1) + k_s \cdot \Delta u_1 = F_g' + F_s \quad (2)$$

- (c) Lining Installation (Equilibrium condition is not changed because the lining self weight is much less than ground)  
(d) Deterioration of support ( $k_s$  is reduced to  $k_s'$ , where  $k_s' < k_s$ .)

$$\begin{aligned} mg &= \alpha k_g u_o + (\alpha k_g + k_s') \cdot \Delta u_1 + (\alpha k_g + k_s' + k_l) \cdot \Delta u_3 \\ &= \alpha k_g (u_o + \Delta u_1 + \Delta u_3) + k_s' (\Delta u_1 + \Delta u_3) + k_l \cdot \Delta u_3 = F_g'' + F_s' + F_l \end{aligned} \quad (3)$$

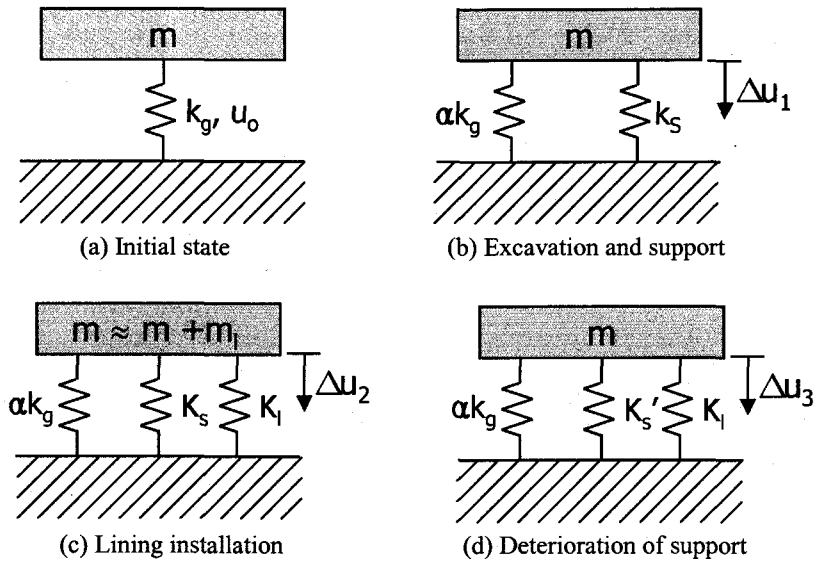


Fig. 1. Structural behaviour of concrete lining as a mass-spring model.

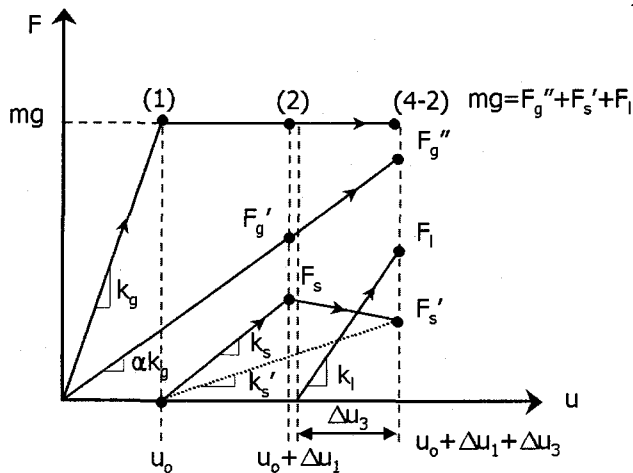


Fig. 2. Displacement-force curves for sequential loading stages.

### 3. Ground-Primary Support-Secondary Lining Interaction Model

The proposed model for the structural analysis of the secondary lining in this paper is developed to consider the load transfer mechanism from the primary support to the ground and the secondary lining due to the deterioration of the primary support members.

The magnitude and mode of the load acting on the secondary lining is highly dependent on the equilibrium condition of the primary support and the ground. In this condition, when the primary support loses its supporting capacity totally or partially, the ground and the secondary lining share the load which occurred by the disturbance of the equilibrium condition. The relative stiffness of the secondary lining to the ground determines the portion of the load generated from losing the capacity of the primary support. The stiff secondary lining covers the high portion of the load. Accordingly, the structural analysis for the rational secondary lining design is required to consider the equilibrium condition of the ground and the primary support members and the stiffness of the ground and the secondary lining.

This proposed model couldn't be considered in the conventional methods such as the frame analysis because the load for the secondary lining cannot be explicitly calculated. For this reason, the numerical analysis method such as FEM(Finite Element Method) or FDM(Finite Difference Method) is used in the practical analysis because it can model the sequential analysis for the stages of the tunnelling work such as the excavation, supporting, lining installation and the deterioration of the primary support members.

In the numerical analysis, the deterioration of the primary support members is modelled by removing the structural elements as shotcrete and rockbolts. The equilibrium condition of the primary support and the ground before the lining installation is achieved by the general method for the tunnel stability analysis. This analysis can be done just by one more stage analysis for the secondary lining installation and the primary support member removal after the final stage of the general tunnel stability analysis because the initial condition of this model is the last stage of the general tunnel stability analysis.

### 4. The proposed model verification by the theoretical analysis

The theoretical analysis for the circular tunnel under the uniform stress field (Fig.3) was executed to verify the proposed model. Kirsch's and Salencon's equation was used for the theoretical elastic and elastic-plastic solution, respectively (Goodman, 1980, O'Rourke, 1984). The material properties of the ground, the primary lining, and the secondary lining are followed as Table 1 and 2.

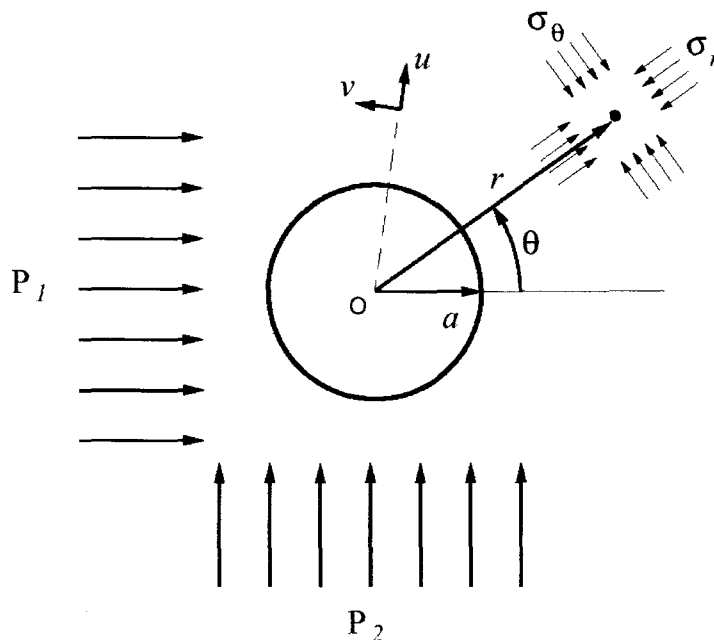


Fig. 3. Cylindrical hole in infinite elastic medium.

Table 1. Ground properties.

Elastic Modulus (MPa)	Cohesion (MPa)	Poisson's Ratio	Frictional Angle (degree)	Initial Stress (MPa)
500	0.5	0.2	30	8

Table 2. Lining properties.

Lining	Elastic Modulus (MPa)	Thickness (m)	Uniaxial Strength (MPa)	Inertia Moment (m <sup>4</sup> )
Primary	15,000	0.2	30	0.00667
Secondary	21,000	0.4	35	0.00533

Fig.4 shows the theoretical support pressure-displacement curves of the ground, the primary lining, and the secondary lining due to the tunnel excavation. In case of the unsupported condition, the ground support pressure decreases linearly in the elastic region and in the non-linear manner in the plastic region. When the primary lining installed before the convergence of the ground displacement, the ground displaces to the first equilibrium position at which the ground support pressure is equal to the passive pressure of the primary lining due to the ground displacement. If the primary support loses its support pressure after the installation of the secondary, the ground moves to the secondary equilibrium position that the ground support pressure is equal to the passive pressure of the secondary lining due to the ground displacement increment. From this point of view, the load of the secondary lining is less than the load of the primary lining because the ground shares the part of the load.

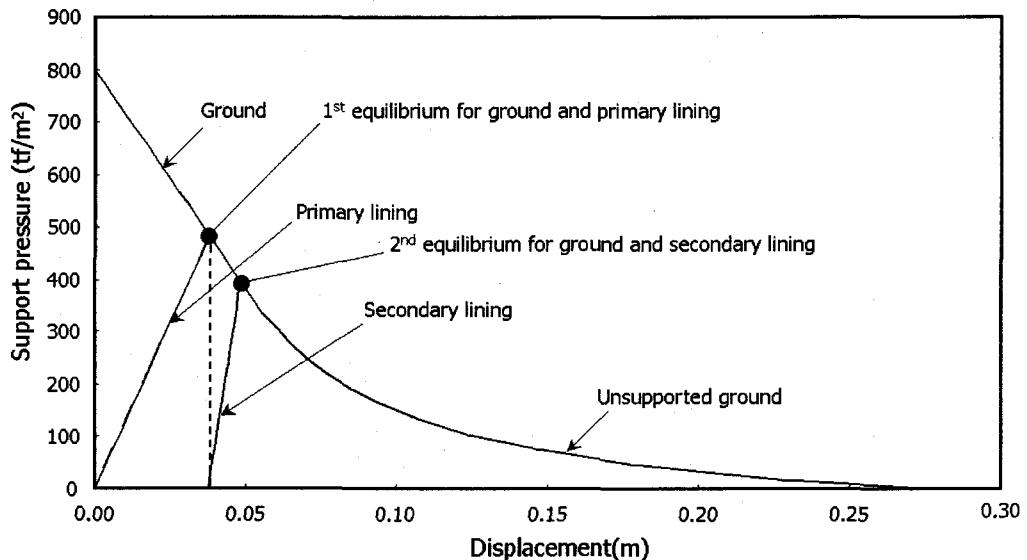


Fig. 4. Ground-primary lining-secondary lining interaction curves by the theoretical analysis.

## 5. The proposed model application to the numerical analysis

Numerical analysis was executed by the FLAC(Itasca, 2000) for the condition as Table 1 and 2. Fig.5 shows the numerical model and the finite element mesh.

First, the elastic and Mohr-Coulomb model for the unlined tunnel were analysed to see the ground characteristic curve. Fig.6 shows the ground reaction curves for the two models. Mohr-Coulomb model make a large non-linear displacement relative to the linear elastic model for the plastic deformation of the ground.

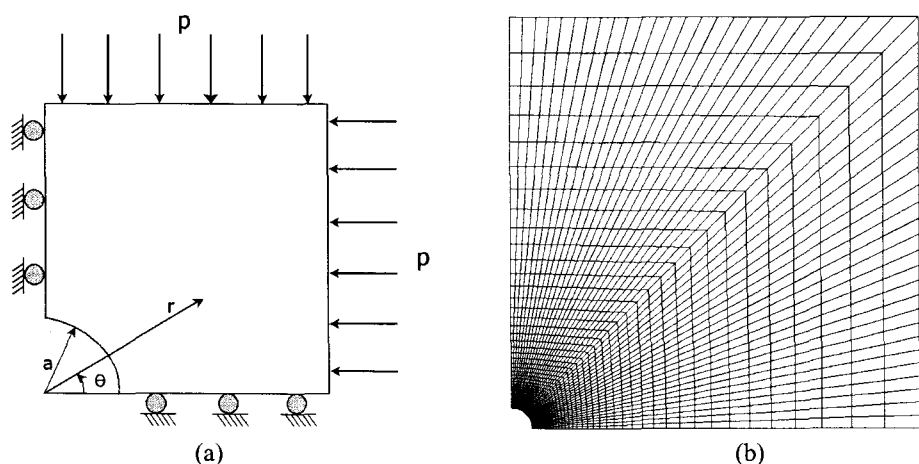


Fig. 5. Model and mesh for numerical analysis.

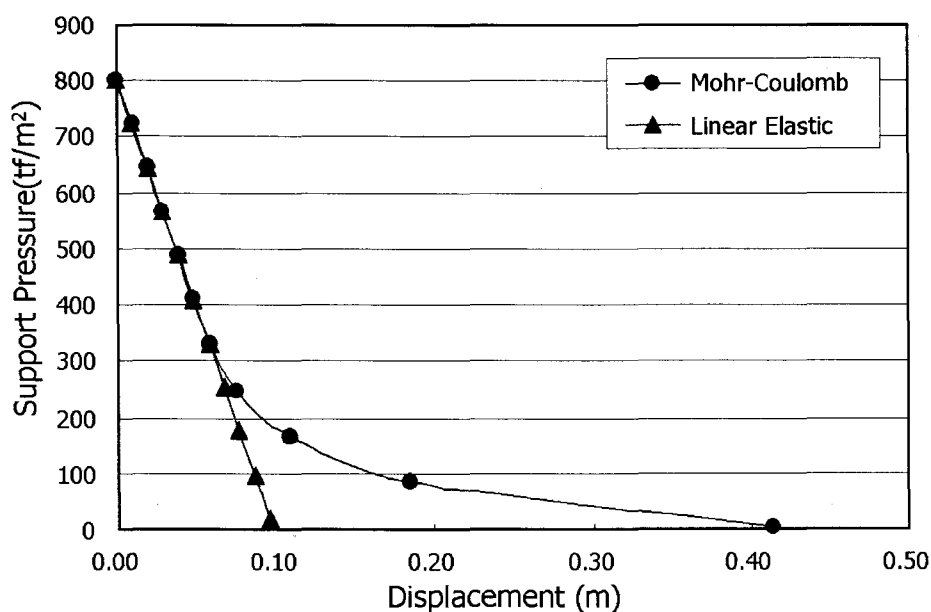


Fig. 6 Ground reaction curves for the unlined tunnel by numerical analysis.

Fig.7 is the result for the sequential analysis of the excavation and lining installation in the same condition. It is assumed that the primary lining is installed at the same time as the tunnel excavation. Solid lines and dashed lines show the theoretical and the numerical results each. The numerical results fit in well with the theoretical results. Very little difference was caused by the modelling method of the lining considered as beam elements in numerical analysis.

## 6. Conclusions

This paper proposed a ground-primary lining-secondary lining interaction model for the rational design of the secondary lining. The concept of the proposed model was described by a simple mass-spring model. This model is proven to be valid theoretically through the theoretical analysis for a circular tunnel. And also, its application to the numerical analysis was verified by comparing the theoretical results.

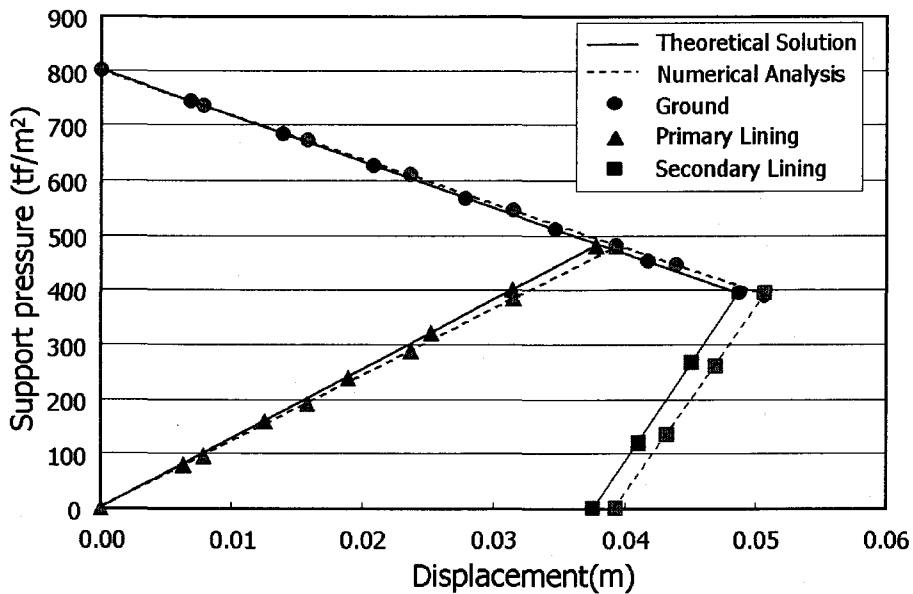


Fig. 7. Ground reaction curves for lined tunnel by analysis.

There are two major advantages to use this model for the practical design works. The first is to consider the mechanical condition of the ground and the primary lining before the installation of the secondary lining. The second is to use the existing numerical analysis process because only two stages of the secondary lining installation and removing are just added after the tunnel excavation and support stages.

It is well known that conventional design methods using the frame analysis have a trend to reinforce the secondary lining too excessively. Accordingly, it is expected that this model can be attributed to the more rational and efficient secondary lining design than the any conventional design model.

## References

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