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Some Considerations for Tunnel Design

Quelques Considérations pour le Calcul des Tunnels

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SYNOPSIS The design of tunnel lining including the effects of the actual shear stresses at the interface between ground and lining can be expected to differ very significantly from more crude approaches.

A set of simplified constitutive laws based on experimental evidence are proposed to model the interface behavior. The results of a Finite Element analysis of a tunnel excavated in a stratified rock mass and subjected to internal pressure is presented.

INTRODUCTION

Previous studies suggest that interface stresses may affect significantly the magnitude and distribution of bending moments in the tunnel lining (Sagasetta, 1976). In order to study analytically this problem the constitutive laws of the interface interaction are required. A set of such laws of a simplified nature are here proposed, and a special purpose Finite Element program was developed to be used in tunnel lining design. The program includes an interface element to model soil-structure interaction.

Several cases were performed to analyze the significance of the various parameters affecting the interface behavior and their influence on the tunnel lining bending moments. Actually, the results of only one case are presented here, because of space limitations. The rest of them will be published elsewhere.

SOIL-STRUCTURE INTERACTION

General Analysis

The relative displacement between adjacent finite elements, as it occurs in the contact surface between the soil and the structure, can be considered using special elements known as joint-elements and interface elements (Goodman et al., 1968; Ghaboussi et al., 1973; Rodríguez Roa, 1977). The simple case of uncoupled interfaces, i.e. where normal and tangential displacements are independent, was considered to be a reasonable model for a number of soil-structure interaction problems.

Proposed Constitutive laws

A commonly used function for representing the behavior of "frictional interfaces", i.e. those with null adhesion, is the so-called hyperbolic law which depends on four independent parameters denoted by R_f , n , K_I , δ (Clough and Duncan, 1971). Figure 1 shows the hyperbolic function

which the previously mentioned authors fitted to direct shear test data on sand-concrete interface behavior for various values of the normal stress, σ_n .

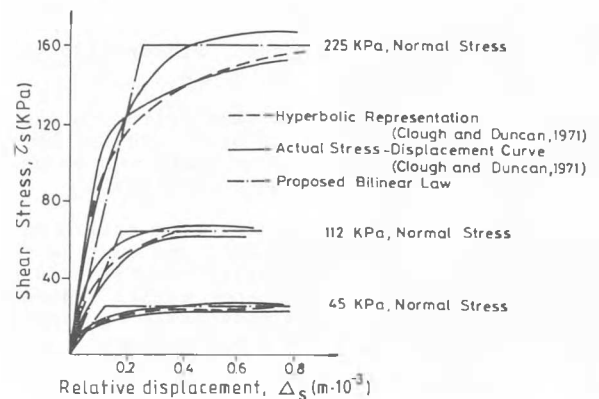


Fig.1. Direct Shear Test Data for Sand-Concrete Interface Behavior.

A simplified bilinear law depending on only three independent parameters, n , K_I , δ , is presented (See Fig. 2). This relationship is sufficiently accurate for most practical applications. Under compressive normal stresses, the tangential stiffness k_s is defined by the following relations:

$$k_s = \text{tg} \theta_f = K_I \gamma_w \left(\frac{\sigma_n}{p_a} \right)^n \quad (\text{for } \tau_s < \sigma_n \text{tg} \delta) \quad (1)$$

$$\text{or } k_s = \text{tg} \theta_f = \frac{\sigma_n \cdot \text{tg} \delta}{\Delta_s} \quad (\text{for } \tau_s = \sigma_n \text{tg} \delta) \quad (2)$$

where:

$$\begin{aligned} \sigma_n, \tau_s &= \text{normal and shear stresses at the interface.} \\ \Delta_s &= \text{relative displacement.} \end{aligned}$$

- δ = peak angle of friction mobilized at the interface.
- γ_w = unit weight of water
- K_I, n = nondimensional parameters.
- p_a = atmospheric pressure.
- θ_i, θ_f = See Fig. 2.

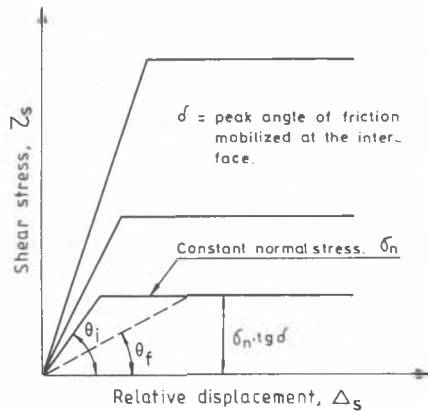


Fig. 2. Bilinear law proposed for frictional interface behavior.

The normal stiffness k_n is commonly taken as a very large value.

Under tensile normal stresses, arbitrarily small values are used for both k_n and k_s .

Figure 1 shows the bilinear law fitted to the experimental results reported by Clough and Duncan (1971). For this particular case, the values $K_I = 33.000$ and $n = 0,75$ were obtained.

In clay soils, the adhesion between soil and structure may not be negligible and must be taken into account (Desai, 1975). Adhesion is due to a physicochemical phenomenon rather than a mechanical one, thus, it is reasonable to expect that its magnitude is independent of σ_n .

Now, as in the case of frictional stresses, interface displacements are required to mobilize adhesive stresses. As the tangential relative displacement increases the adhesive shear stress also increases until it reaches a maximum value " c_a "; beyond this point, the adhesive shear stress gradually decreases with increasing displacements (Uriel, 1980).

Once the interface relative displacement process stops, the soil may, with time, recover its adhesive character. This would be the effect of thixotropic properties.

The proposed simplified constitutive law for an ideal adhesive interface (with null friction) is shown in Fig. 3.

Attempts have been done to estimate the adhesion from the undrained shear strength of the soil (Desai, 1975), however, this procedure may not always be applicable (Burland, 1973).

In order to verify the adequacy of the proposed relations, the results obtained by O'Neill and Reese (1970) for a clay-concrete interface were

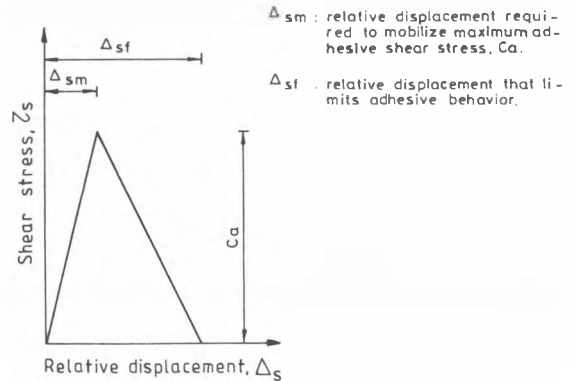


Fig. 3. Constitutive law proposed for adhesive interface.

analyzed (See Fig. 4). Figure 5 shows how the constitutive law, for an interface with friction and adhesion, can be obtained by superposing the functions mentioned above. It is apparent that the proposed relations are consistent with the available experimental evidence. It is also apparent that the softening phenomenon observed in the tests is due to the gradual loss of adhesion with increasing relative displacements.

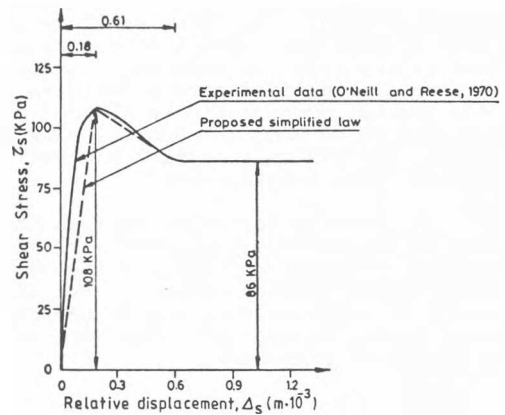


Fig. 4. Direct Shear Test Data for a Concrete-Clay Interface.

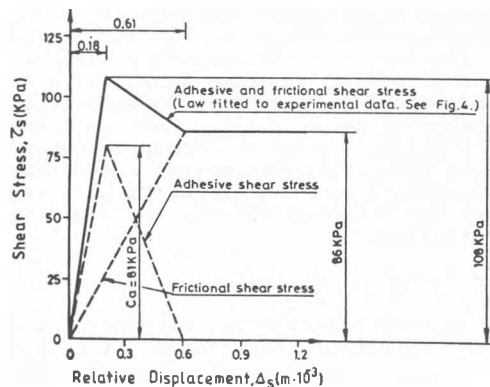


Fig. 5. Constitutive law proposed for adhesive and frictional interface.

In the particular case discussed, the maximum adhesive shear stress is of the order of the maximum shear stress due to friction. On the other hand, the relative displacement required to mobilize the maximum adhesion is about thirty per cent of that corresponding to the maximum friction.

APPLICATIONS

The problem of a tunnel excavated in a horizontally stratified rock mass and subjected to internal pressure was studied. The general dimensions of the tunnel considered are very much the same as those used by Uriel y Sagaseta (1971) in the problem they analyzed.

The rock mass was modelled as a linear elastic anisotropic continuous media. The interface finite element governed by the nonlinear elastic proposed constitutive laws, was assumed to have the properties indicated in Fig. 6. The finite element mesh used is shown in Figs. 7a and 7b.

The stresses on the outward face of the lining obtained from the analysis are presented in Fig. 8. For sake of comparison, the stress pattern obtained by neglecting interface relative displacements, is also shown in the figure.

CONCLUSIONS

The results of the analysis performed show that neglecting interface displacements in modelling ground-tunnel interaction, may lead to significantly different design stresses.

The simplified constitutive laws proposed are shown to fit experimental evidence to a very satisfactory degree. They are very well suited for use in Finite Element analysis.

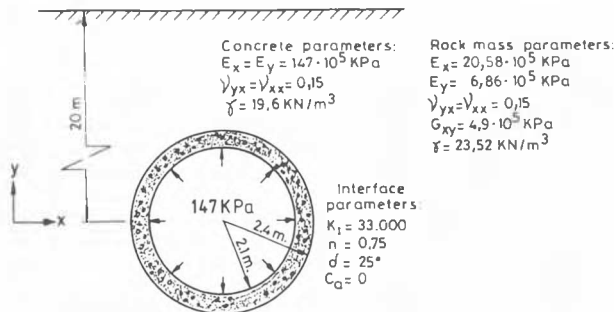


Fig. 6. Problem considered.

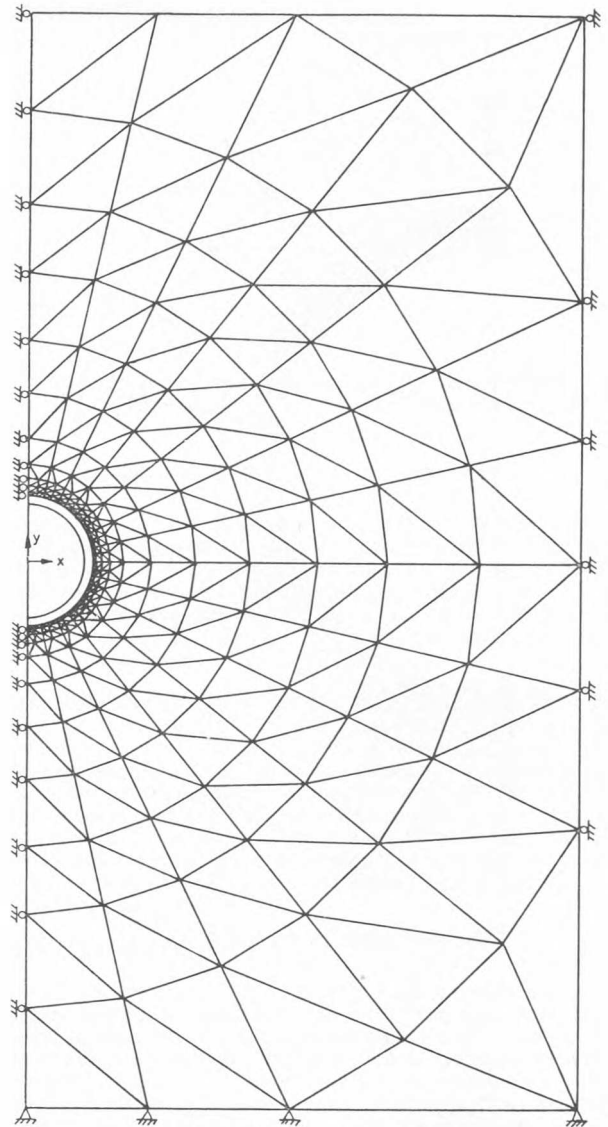


Fig. 7. a) Finite Element Mesh used.

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The work done by the former student Ricardo Rodríguez R. in preparing the computer program, is greatly appreciated.

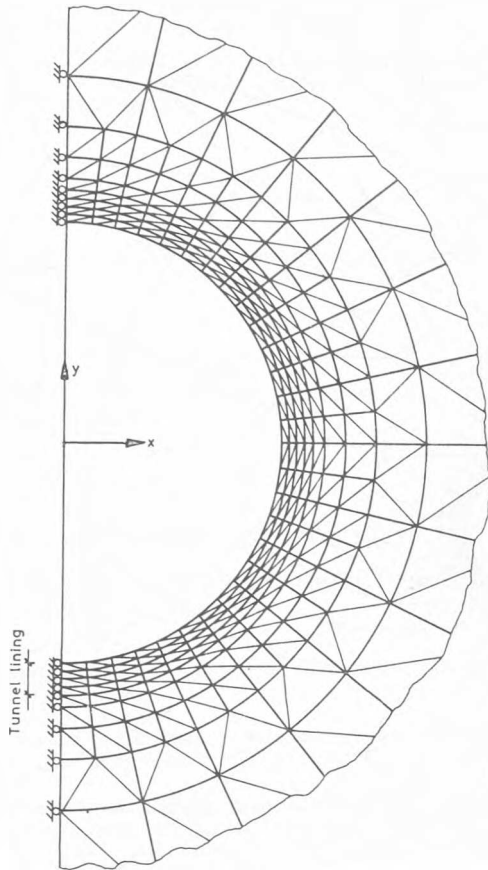


Fig. 7.b) Tunnel lining mesh detail.

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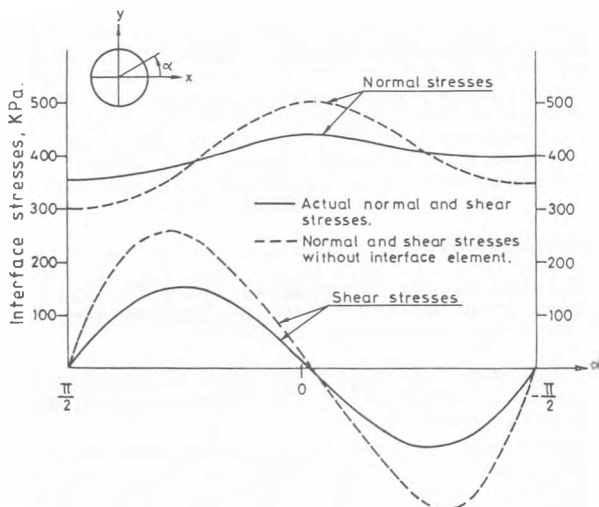


Fig. 8. Results obtained with the model.