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Face Stability Calculation for a Slurry Shield in Heterogeneous Soft Soils

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ABSTRACT: The minimal support pressure needed at the tunnel face can be calculated using a wedge stability analysis. Current methods have been presented only for a homogeneous soil at the tunnel face. This Paper investigates the influence of heterogeneity of the soil on the angle of slip and the minimal support pressure. It is found that the influence of horizontal layer boundaries is significant, especially at the top of the tunnel face. In case of a soft layer over a relatively stiff layer the minimal support pressure is greater than would be calculated by interpolation of the support pressures calculated for the separate layers.

1 INTRODUCTION

In the western parts of the Netherlands a number of tunnels is under construction in extremely soft and heterogeneous soils. In such conditions the control of the tunnel face is one of the more important aspects of the tunnel boring process. To prevent the tunnel face from collapsing, a minimal support pressure is needed. This support pressure can be calculated using several methods, see Krause (1987) and Balhaus (1988) for a comprehensive overview. One of those methods is the wedge stability analysis as proposed by Horn (1961), and adapted by several authors. Although it would be relatively easy to incorporate different soil layers above the tunnel boring machine into the calculation method presented by Jancsecz (1994), none of the methods presented in literature have dealt directly with several soil layers within the tunnel face. And as there is no clear way to obtain an average of the soil properties of the different layers within the tunnel face, these calculation methods can only give a rough indication of the minimal support pressure in a layered soil, which has led to the adaption of large safety factors in the case of the Second Heineoord-tunnel, as used by van der Put (1996). In view of this practise there is a need for more detailed methods to calculate the minimal support pressure.

The wedge stability analysis has a strong resemblance to the stability calculations for slurry filled trenches for diaphragm walls, which have been derived from the same theories. And experiences with such trenches in the Netherlands show that the calculation method for trenches can be extended to accurately describe the stability in multi layered heterogeneous soils. The reader is referred to Walz (1983) for the

theory and to van Tol (1987) for a case study in heterogeneous soft soils. It seems reasonable therefore to extend the tunnel face stability calculations in the same manner. Having obtained such a model we will investigate the influence of heterogeneity on the angle of slip and the minimal support pressure for a simple theoretical case, a soil profile consisting of two layers.

2 WEDGE STABILITY MODEL

The wedge stability model consists of a prismatic soil wedge, see Figure 1, loaded by a soil silo. According to Terzaghi's silo theory the vertical effective soil pressure resulting from the silo and acting on the top of the wedge, denoted as G_s in Figure 1, can be calculated from

$$\sigma'_v(z) = \left(\sigma_0 - \frac{\alpha}{\beta} \right) \exp(-\beta z) + \frac{\alpha}{\beta}, \quad (1)$$

with

$$\begin{aligned} \alpha &= \gamma' - Rc, \\ \beta &= RK_y \tan \varphi \end{aligned} \quad (2)$$

where z the depth, σ_0 a distributed load at $z = 0$, γ' the effective soil unit weight, c the cohesion, φ the angle of internal friction, K_y the coefficient of horizontal earth pressure and R the ratio of the circumference to the horizontal cross section of the soil column considered. This solution is valid for a single homogeneous soil layer, but can be easily extended to a silo in multi layered soil by taking the value of σ_v at the bottom of the first layer as the distributed load σ_0 at the top of the next layer, etc. The total force G_s on the top of the

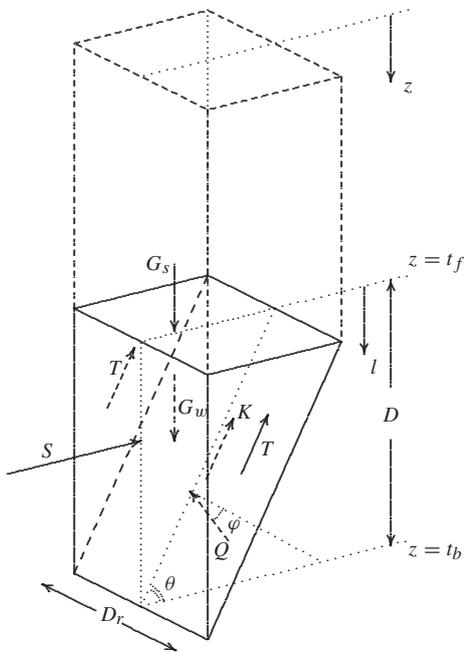


Figure 1. Prismatic soil wedge

wedge can now be calculated as

$$G_s = \sigma'_v(t_f) D_r D \cot \theta \quad (3)$$

where D_r the width of the wedge, θ the angle of slip between the horizontal and the wedge plane and $z = t_f$ the top of the wedge.

The other forces acting on the wedge are obtained easily in the case of a homogeneous wedge. In case of a multi layer analysis however, these forces have to be calculated for the separate layers and will result in a set of equilibrium equations, as given by Walz (1983). Using infinitesimal small horizontal slices this set of equations can, maybe surprisingly, be simplified. First we define the depth of the wedge as a function of depth:

$$w(z) = (t_b - z) \cot \theta \quad (4)$$

for $t_f \leq z \leq t_b$. The total weight G_w is now the integral from $z = t_f$ to $z = t_b$ of

$$g_w(z) = \gamma'(z) w(z) D_r \quad (5)$$

over z , where $g_w(z)$ the weight of an infinitesimal slice of the wedge. In the same manner the forces T and K are the integrals of

$$t(z) = w(z) (c(z) + K_y(z) \sigma'_v(z) \tan \varphi(z)) \quad (6)$$

and

$$k(z) = \frac{D_r c(z)}{\sin \theta} \quad (7)$$

This notation has the advantage that the equations of equilibrium can be combined to

$$E = \frac{G_s (\sin \theta - \cos \theta \tan \varphi(t_f))}{\sin \theta \tan \varphi(t_f) + \cos \theta} + \int_{t_f}^{t_b} dz \frac{g_w(z) (\sin \theta - \cos \theta \tan \varphi(z)) - k(z) - 2t(z)}{\sin \theta \tan \varphi(z) + \cos \theta} \quad (8)$$

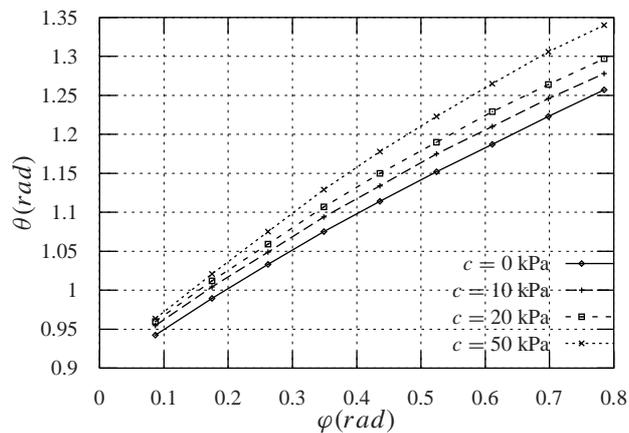


Figure 2. Estimate of the angle of slip for a single layer

with E the resulting earth force. Using this earth force and the water force

$$W = \int_{t_f}^{t_b} dz D_r p(z), \quad (9)$$

with $p(z)$ the piezometric head at depth z , the total slurry force

$$S = E + W \quad (10)$$

can be calculated, using that value of θ for which E and therefore S is maximal. In practise this means that E has to be numerically evaluated for a large range of θ .

3 EVALUATION FOR A SINGLE LAYER

The numerical evaluation of E for a large range of the angle of slip θ can be time consuming. When the angle of slip could be determined directly from the properties of the soil this would shorten the necessary calculations considerably. For a homogeneous cohesionless soil Jancsecz (1994) has shown that the angle of slip depends predominantly on the angle of internal friction of the soil and to a lesser degree on the relative overburden of the tunnel. The Author has made a numerical evaluation of Equation 9 for a wide range of values of the cohesion, the angle of internal friction and the relative overburden, for the case of a soil profile with only a single homogeneous layer. This evaluation has shown that in this case the angle of slip can be estimated from the angle of internal friction and cohesion of the soil only, and that the influence of other parameters can be neglected. The relation between φ , c and θ is plotted in Figure 2 and is valid for an overburden between 0.5 and 3 times D .

These estimates for the angle of slip can be used relatively safely. Numerical analysis shows that even when the estimate of θ is off by 2° the calculated resultant earth force E and the slurry force S , for most practical cases, are correct within the order of 1 promille. Another parameter which has been investigated by a numerical analysis is the wedge width D_r . A

possible choice is $D_r = \frac{\pi}{4} D$, which results in a width times height of the wedge equal to the area of the tunnel face. The other approach simply equates D_r to D . The more narrow wedge generally results in a lower support force, on the order of 3% lower for practical cases. Given the lack of field observations and the minor influence, a value of $D_r = D$ has been used in all subsequent calculations.

4 EVALUATION FOR TWO LAYERS

Compared to a single layer system, the calculation time required for a multi layer system increases considerably. A method to directly estimate the angle of slip is therefore expected to increase the practicality of the model. To this end a numerical analysis has been undertaken for a soil profile consisting of two layers with distinct properties. The properties of the soil layers, the depth of the boundary between the layers as well as the overburden of the tunnel have been varied. It follows that the angle of slip for a wedge which consists of two soil layers with different properties can be estimated from the relative position of the layer boundary and the angle of slip estimated for the separate layers.

Let us define the relative position of the layer boundary as

$$l = \frac{z_b - t_f}{D} \quad (11)$$

with z_b the z -coordinate of the layer boundary, such that $l = 0$ if the boundary is at the top of the wedge, and $l = 1$ if it is at the bottom of the wedge. Using Figure 2 we can estimate the angle of slip θ_f that would occur if the wedge was contained entirely in the upper soil layer. This angle is after all only a function of c and φ . In the same manner θ_b is the angle of slip for the bottom layer. Now we can calculate the angle of slip for the entire wedge from

$$\theta = \theta_f + \zeta (\theta_b - \theta_f) \quad (12)$$

where the factor ζ can be determined from Figure 3, using the relative position l and θ_f .

From Figure 3 it follows that even for low values of l the angle of slip for the entire wedge rapidly approaches the angle of slip for the upper layer. In the same manner the support pressure for the entire wedge rapidly approaches the support pressure calculated for a wedge consisting entirely of the upper soil type. How this effects the minimal support pressure needed at the tunnel face will now be demonstrated for the case of a soft clay layer ($c = 5$ kPa, $\varphi = 15^\circ$) over a stiff sand layer ($c = 0$, $\varphi = 45^\circ$) and the case with the layers interchanged. For both cases the overburden and the diameter of the tunnel are equal to 10 m, and the water table is equal to the ground level.

When the tunnel face lies entirely within the stiff layer the minimal support pressure, at the tunnel axis, is 168 kPa. In the soft layer the minimal support pressure is 197 kPa. The transition between these layers

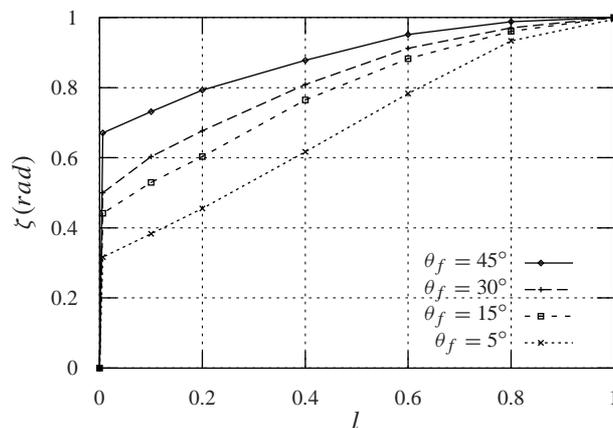


Figure 3. Relative angle of slip for a two layer system

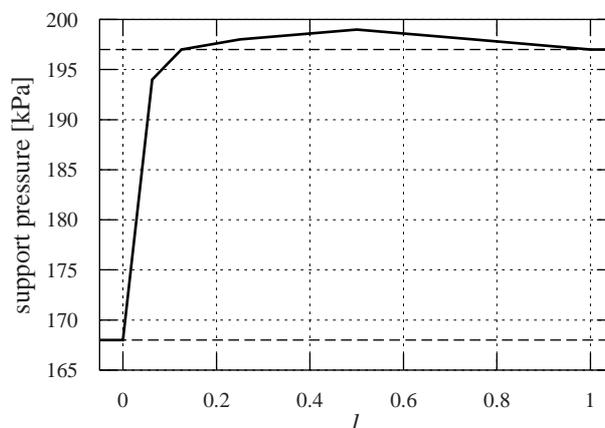


Figure 4. Minimal support pressure for soft over stiff soil

however is of interest. In the case of the soft layer over the stiff layer the minimal support pressure at the tunnel axis is plotted in Figure 4. When the top of the tunnel face enters the soft layer, the required support pressure increases rapidly, reaching a maximum value of 199 kPa for $l = 0.5$. This clearly shows that the support pressure increases in a non-linear way during the transition phase.

For the case of a stiff layer over a soft layer the calculated support pressure behaviour is roughly a mirror image, as plotted in Figure 5. Now another problem shows. To find the minimal support pressure we will, of course, have to calculate the support pressure for all possible failure mechanisms, to check which mechanism needs the highest minimal support pressure. When for this case l is small, it can be easily seen that a slightly smaller wedge, which consists of clay only, will lead to a higher support pressure. Calculations show that in this case the support pressure calculated for such a partial wedge is higher than the support pressure calculated for the entire wedge for all values of $l < 0.55$. This shows that the correct determination of the failure mechanisms remains the controlling influence in a stability analysis.

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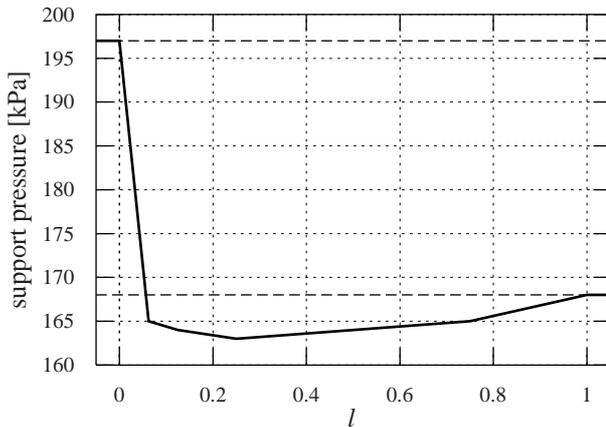


Figure 5. Minimal support pressure for stiff over soft soil

5 CONCLUSIONS

The wedge stability analysis as proposed by Horn can be extended for heterogeneous conditions. Although lacking confirmation from field observations these calculations show the complex interaction between the various parameters of the model, especially the influence of layer boundaries on the support pressure. The strong non-linear behaviour of the model shows the importance of a correct determination of the possible failure mechanisms; an estimate of the support pressure based on the entire wedge or based on average soil parameters will generally lead to an incorrect and possibly unsafe assessment of the minimal support pressure.

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