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Limit analysis of ground anchor forces

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Abstract

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Limit analysis of ground anchor forces

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An anchored sheet wall is commonly used in retaining deep excavations. Anchor force is one of the critical design parameters in practice. Based on the kinematical admissible failure mechanism, a limit analysis approach to determine the anchor force is presented. The explicit formula for the anchor force is given, which makes it easy to calculate using a simple calculation program such as MS Office Excel. Anchor force is mainly influenced by seven parameters: the internal friction angle; cohesion of the soil; wall friction angle; surcharge on the ground surface; dip angle of the anchor; penetration depth of the wall; and depth from the anchor force action point on the wall to the ground surface. The relevant quantitative calculation can be performed by the proposed method. In addition, the design anchor force under a specified design safety factor and the anchor forces of multiple rows of anchors are also illustrated in this paper. To verify that the method is reasonable, the predicted and measured anchor forces are compared in two classical soil-nailed wall experiments. The result shows that the presented method is applicable.

Notation

C_P	calculation coefficient of work rate of lateral resistance on penetration part of wall
c	cohesion of soil
c_r	mobilised cohesion of soil considering shear strength reduction coefficient
E_c	internal energy dissipation rate
F	anchor force; subscripts 1, 2, 3 represent the first, second and third row of anchors, respectively
F_p	passive resistance acting from the left side (see Figure 1) of the penetration part of sheet wall
F_s	factor of safety or shear strength reduction coefficient
f_i	derivation coefficient of gravity work rate, $i = 1, 2, 3$
h	total height of anchored sheet wall
i	index of number
k_p	coefficient of passive earth pressure
n	total number of anchor rows
q	surcharge on ground surface
r	radius of any point on a log-spiral slip line, where subscripts 0, h stand for the starting and ending points, respectively
S_H	horizontal spacing between adjacent soil nails
S_V	vertical spacing between adjacent soil nails
s	distance from intersection between the slip line and ground surface to the wall
W	work rates of external forces, where subscripts F, G, P, q stand for anchor force, gravity, passive earth pressure and surcharge on ground surface, respectively
z	depth of anchor force action point on the wall (below ground surface); subscript i stands for the i th row of anchors
z_p	penetration depth of anchored sheet wall
z_s	sum of depth z of each row of anchors

β	dip angle of anchor; subscript i stands for the i th row of anchor
γ	unit weight of soil
δ	wall friction angle
θ	rotation angle of any point on a log-spiral slip line, and subscripts 0, h denote the starting and ending points, respectively
ξ_i	ratio of anchor force of the i th row over the row nearest to the ground surface
ϕ	angle of internal friction of soil
ϕ_r	mobilised internal friction angle of soil considering shear strength reduction coefficient
ω	angle acceleration of kinematical soil body

1. Introduction

An anchored sheet wall is a typical structure applied in deep excavation engineering. In practical design, anchor force is one of the critical parameters. Whether a practical engineering design is safe enough or not depends to a great extent on the rational determination of anchor force. The classical Rankine's earth pressure theory is a method for calculating the force. However, because moment equilibrium is ignored, sometimes the related calculation results are not rational. Variational calculus can be reasonably used to solve the problem (Puła *et al.*, 2005), and its computation results are suitable for practical engineering. From the perspective of convenient application in engineering design, however, it has two defects, namely, no explicit formula for anchor force and the complicated process of numerical computations.

Limit analysis is a method available for finding a relatively simple solution to the slope stability problem (Chen, 1975; Florkiewicz and Kubzdela, 2013; Han *et al.*, 2014; Li *et al.*, 2009; Nian *et al.*, 2008; Yang and Pan, 2015). Stability

Using an integration method (Chen, 1975), the internal energy dissipation rate can also be derived as

$$8. \quad E_c = \frac{cr_0^2}{2 \tan \phi} \{e^{2(\theta_h - \theta_0) \tan \phi} - 1\} \omega$$

Substituting Equations 3–8 into Equation 2, the force F is deduced as

$$9. \quad F = \frac{\gamma r_0^3(f_1 - f_2 - f_3) + q \left[(r_0 \cos \theta_0)^2/2 - (r_h \cos \theta_h)^2/2 \right] - C_P - (cr_0^2/2 \tan \phi) [e^{2(\theta_h - \theta_0) \tan \phi} - 1]}{\cos \beta (r_0 \sin \theta_0 + z) - \sin \beta (r_h \cos \theta_h)}$$

The maximum F is obtained using the first derivatives of F with the angles θ_0 and θ_h (see Figure 1)

$$10. \quad \left. \begin{aligned} \frac{\partial F}{\partial \theta_0} &= 0 \\ \frac{\partial F}{\partial \theta_h} &= 0 \end{aligned} \right\}$$

Given multiple rows of anchors and identical anchor force of each row, the F can be deduced as

$$11. \quad F = \frac{\gamma r_0^3(f_1 - f_2 - f_3) + q \left[(r_0 \cos \theta_0)^2/2 - (r_h \cos \theta_h)^2/2 \right] - C_P - (cr_0^2/2 \tan \phi) [e^{2(\theta_h - \theta_0) \tan \phi} - 1]}{\sum_{i=1}^n \cos \beta_i (r_0 \sin \theta_0 + z_i) - \sin \beta_i (r_h \cos \theta_h)}$$

Alternatively, provided that the ratio of anchor force ξ_i for the i th row over the first row (nearest to the ground surface) is specified in a practical design, the following can be obtained

$$12. \quad F_1 = \frac{\gamma r_0^3(f_1 - f_2 - f_3) + q \left[(r_0 \cos \theta_0)^2/2 - (r_h \cos \theta_h)^2/2 \right] - C_P - (cr_0^2/2 \tan \phi) [e^{2(\theta_h - \theta_0) \tan \phi} - 1]}{\sum_{i=1}^n [\cos \beta_i (r_0 \sin \theta_0 + z_i) - \sin \beta_i (r_h \cos \theta_h)] \xi_i}$$

Equations 9, 11 or 12 are readily resolved using Solver Macro (of MS Office Excel 2010) by way of a spreadsheet. The anchor force F is usually determined in several iterations. The authors also obtained the anchor force by developing a computer program in Microsoft Visual C++ 2008.

3. Two engineering examples

An anchored sheet wall was proposed to retain deep excavation in cohesionless soil with a unit weight γ of 19 kN/m³ (Puła *et al.*, 2005). The wall system is characterised by $\beta = 0^\circ$, $\delta = 0^\circ$, $h = 12$ m, $z = 2.5$ m, $z_p = 3.0$ m and $q = 0$ kPa. With respect to angles of internal friction ϕ ($=27^\circ$ to 32°) of the soil, the values of anchor force F (kN/m) are determined (see Table 1) using the newly proposed limit analysis method. The associated slip lines are shown in Figure 2. Table 1 indicates that the values of the anchor force and some geometric features of the slip line obtained by the proposed method are in good

agreement with the variational calculus, despite the differences at $\phi = 27^\circ$, 34° and 35° . At $\phi = 30^\circ$ to 33° , the anchor forces obtained by the proposed method are also similar to those obtained from the limit equilibrium method (without considering moment equilibrium) based on Rankine's pressure theory. The impact of the shape of the slip line (log-spiral in the current method, see Figure 2) is limited on the force F as against the latter based on a linear slip line. This is especially

true at a large internal friction angle (e.g. $\phi > 32^\circ$) as the corresponding log-spiral slip line approaches closely to a straight line and exhibits the sliding mode of a coarse soil slope. Overall, the proposed method is acceptable in most cases.

Next, an anchored sheet wall is adopted to retain deep excavation engineering in cohesive soil (Puła *et al.*, 2009). The clay has a unit weight, γ , of 20.11 kN/m³, cohesion, c , of 30 kPa and internal friction angle, ϕ , of 17° . The wall system has the features of $\beta = 0^\circ$, $h = 15$ m, $z = 3.0$ m and $z_p = 3.0$ m. Given the

conditions of no surcharge, q ($=0$), on the upper and lower ground surface, and smooth wall (with a friction angle $\delta = 0^\circ$), the current limit analysis method offers an anchor force, F , of 177.041 kN/m. This force agrees well with $F = 164.3$ kN/m and 174 kN/m estimated using the classical limit equilibrium method and variational calculus, respectively (see Table 2). Figure 3 shows similar curved slip lines between the proposed method and variational calculus, but both are different from the straight line determined using the classical limit equilibrium method.

4. Parameter study and discussion

Based on Equation 9, 11 or 12, the effects of related parameters on the anchor force are further analysed for the above-mentioned example problems.

Figures 4, 5, 6 and 7 provide the dimensionless $F/(0.5\gamma h^2)$ for typical internal friction angles of the soil, ϕ , plotted against

Table 1. Computation results of anchor force for the cohesionless soil example using three methods

Internal friction angle: degrees	Limit analysis (proposed method)		Limit equilibrium		Puła et al. (2005)	
	F: kN/m	s: m	F: kN/m	s: m	F: kN/m	s: m
27	366.748	2.949	286.03	7.35	338	4.95
28	287.166	4.596	257.07	7.21	287	4.83
29	241.077	5.555	228.24	7.07	241	5.62
30	203.957	6.168	199.5	6.93	203	6.13
31	171.552	6.900	169.14	6.8	170	6.74
32	142.481	6.461	142.06	6.65	142	6.75
33	113.56	6.516	113.26	6.52	115	6.93
34	84.018	6.088	84.32	6.38	90	7.01
35	54.549	6.300	55.20	6.24	67	7.06

Figure 2. Slip lines in the case of various internal friction angles for cohesionless soil

Figure 3. Slip lines for the cohesive soil example

Table 2. Computation results of anchor force for the cohesive soil example using three methods

Limit analysis (proposed method)		Limit equilibrium		Puła et al. (2009)	
F: kN/m	s: m	F: kN/m	s: m	F: kN/m	s: m
177.041	10.29	164.3	11.10	174	10.27

wall friction angle, δ , dip angle of anchor, β , normalised cohesion, $c/(\gamma h)$, or surcharge, $q/(\gamma h)$, and z/h or z_p/h , respectively. Figure 4 indicates that $F/(0.5\gamma h^2)$ reaches the maximum value for a frictionless wall ($\delta=0$), and the associated anchor force is on the conservative side. Figure 5 shows that the influence of the dip angle of the anchor on $F/(0.5\gamma h^2)$ depends to a great extent on the internal friction angle, ϕ , of the soil. At $\phi > 29^\circ$, the $F/(0.5\gamma h^2)$ shows slight increase with the dip angle;

Figure 4. Relationship between $F/(0.5\gamma h^2)$ and wall friction angle δ ($h = 12$ m)

Figure 5. Relationship between $F/(0.5\gamma h^2)$ and dip angle of anchor β ($h = 12$ m)

Figure 6. Relationships between $F/(0.5\gamma h^2)$ and dimensionless factors $c/(\gamma h)$ and $q/(\gamma h)$ ($h = 12$ m): (a) $F/(0.5\gamma h^2)$ plotted against $c/(\gamma h)$; (b) $F/(0.5\gamma h^2)$ plotted against $q/(\gamma h)$

Figure 7. Relationships between $F/(0.5\gamma h^2)$ and dimensionless factors z/h , and z_p/h ($h = 12$ m): (a) $F/(0.5\gamma h^2)$ plotted against z/h ; (b) $F/(0.5\gamma h^2)$ plotted against z_p/h

otherwise at $\phi < 29^\circ$, the increase is remarkable. An increase in $c/(\gamma h)$ reduces the $F/(0.5\gamma h^2)$ (see Figure 6(a)); and increasing $q/(\gamma h)$ causes a linear increase in $F/(0.5\gamma h^2)$ (see Figure 6(b)). The ratios z/h and z_p/h greatly influence $F/(0.5\gamma h^2)$ (see Figure 7). The $F/(0.5\gamma h^2)$ decreases with increasing z/h , but the trend is not distinct at $\phi > 29^\circ$. In contrast, the $F/(0.5\gamma h^2)$ decreases with increasing z_p/h for the internal friction angles investigated.

The effects of essential parameters β , q , c , z , z_p and F_s on anchor force are illustrated in the following subsections.

4.1 Dip angle β of anchor

Under various dip angles of the anchor, the anchor force obtained by the proposed method is shown in Figure 8, together with those obtained by variational calculus (Puła *et al.*, 2005). There is a small difference between the two methods at $\phi = 35^\circ$. The overall comparison is satisfactory; in

Figure 8. Effects of dip angle of anchor on anchor force

particular, the presented method is much more readily calculated than the variational calculus.

4.2 Surcharge q on the ground surface

As shown in Figure 9(a), the anchor force increases 'linearly' with increasing surcharge.

4.3 Cohesion c of soil

According to Equations 9, 11 and 12, it is clear that a higher cohesion of the soil reduces the anchor force. This reduction is generally non-linear, as is evident from Figures 9(b1) and 9(b2). Figure 9 also shows that the forces obtained by the proposed method are larger than those calculated using the limit equilibrium method (ignoring the moment equilibrium on the wall) based on Rankine's pressure theory. The latter estimation is not safe for practical engineering. Figure 9(b3) demonstrates that the log-spiral slip line under the condition of $c = 5$ kPa also gradually approaches a straight line with an increasing internal friction angle of the soil.

Figure 9. Effects of cohesion c and surcharge q on anchor force: (a) F plotted against q ; (b1) F plotted against c ($\beta = 0^\circ$); (b2) F plotted against c ($\beta = 15^\circ$); (b3) slip lines for cohesive soil

4.4 Depth z of anchor force action point on the wall

Figure 10(a) shows that the anchor force gradually decreases with increasing depth of the anchor force action point on the wall (below the ground surface). The decreasing rate is high at $\phi < 29^\circ$, otherwise the rate is small.

4.5 Penetration depth z_p of the wall

Figure 10(b) indicates that the anchor force decreases approximately linearly (at a similar rate) with increasing penetration depth of the wall when the internal friction angle is higher than 30° .

4.6 Design safety factor F_s

The anchor force as discussed above is for the critical state of soil. In practice, determining design anchor force in a working condition of soil (with a factor of safety, F_s) is of much greater significance. According to the shear strength reduction method (Zienkiewicz *et al.*, 1975), the design

safety factor, F_s , is defined as

$$13. \quad F_s = \frac{c}{c_r} = \frac{\tan \phi}{\tan \phi_r}$$

Equation 13 is recast into

$$14. \quad \left. \begin{aligned} c_r &= \frac{c}{F_s} \\ \phi_r &= \arctan(\tan \phi / F_s) \end{aligned} \right\}$$

The design anchor force for a safety factor, F_s , is determined by simply substituting c_r and ϕ_r for c and ϕ in Equations 9, 11 or 12. Figure 11 (for instance for one row of anchors) shows the design anchor force grows non-linearly as the design safety factor increases for both cohesionless soil and cohesive soil.

Figure 10. Effects of anchor depth z and penetration depth z_p on anchor force: (a) F plotted against z ; (b) F plotted against z_p

Figure 11. Effects of design safety factor on anchor force

Figure 12. Relationship between sum of depth of anchor force action point on the wall and anchor force

4.7 Multiple rows of anchors

In retaining deep excavation, multiple rows of anchors are commonly adopted. Given identical anchor force and identical dip angle of each row of anchors (see Equation 11), it is safe to say that anchor force depends mainly on the sum, z_s , of the anchor depths (e.g. z_1 and z_2) of all rows and is not directly

influenced by the specific depth of each row. The anchor force decreases as the sum z_s increases (see Figure 12). The rate of the decrease is negligible at $\phi > 30^\circ$, and the anchor force is nearly independent of the anchor depth. Alternatively, the ratio of anchor force of each row over the first row (nearest to the ground surface) is assumed as 1:1:1, 1:0.9:0.8 and 1:1:1:0.9.

Figure 13. Relationship between sum of multiple rows of anchor forces and dip angle of anchor in the case of a specified ratio for anchor force of each row over the first row: (a) $\phi = 27^\circ$; (b) $\phi = 29^\circ$; (c) $\phi = 31^\circ$; (d) $\phi = 33^\circ$. (e) Sketch map of multiple rows of anchors. I, II, III represents case number

The resulting sum of anchor forces of each row is obtained using Equation 12 and is shown in Figure 13. This result indicates that the ratio has negligible effect on the sum except for

the conditions of $\phi = 27^\circ$ and $\beta \geq 15^\circ$ (see Figures 13(a)–13(d)), and the anchor force of each row can be regarded as identical in practical design under these conditions.

Figure 14. Comparison of anchor forces between the predicted and measured results: (a1) CEBTP wall ($h = 7$ m); (a2) CEBTP wall ($h = 5$ m); (a3) CEBTP wall ($h = 3$ m); (b) Davis wall ($h = 9.2$ m); (c) diagrammatic sketch of the CEBTP wall; (d) diagrammatic sketch of the Davis wall

5. Comparison between theoretical predictions and experimental results

The proposed method is here compared with the tests on two classical soil-nailed walls: a Centre d'Expertise du Bâtiment et des Travaux Publics (CEBTP) wall in sand soil (Plumelle, 1986) and a Davis wall in cohesive soil (Shen *et al.*, 1981). The relative ratios of anchor force of each row over the first row are prescribed in advance as unity and as identical to measured data (termed 'Calibrated'), respectively, in order to calculate the anchor force of each row. First, taking an identical anchor force among different rows, the predicted (tensile) anchor force of a soil nail is approximately equal to the measured maxima in the CEBTP wall experiment at a wall height of 7 m or 5 m (see Figure 14). The predictions, however, overestimated the measured maximum by 12% and 18% for the 3 m-high CEBTP wall and the Davis wall, respectively. Next, the ratios of anchor force of each row over the first row are taken as the experimental ratios for the CEBTP wall, the (tensile) anchor forces in the soil nails were re-estimated, and are plotted in Figures 14(a1), 14(a2) and 14(a3) as 'Calibrated' force. As expected, the 'calibrated' tensile anchor forces for all rows follow a similar trend to the measured data. They are slightly higher than the measured values owing to the proposed method being underpinned by the upper bound theorem of limit analysis.

6. Conclusions

For an anchored sheet wall, the limit analysis method based on a kinematically admissible displacement mechanism is

depends greatly on the internal friction angle of the soil and is distinctive when the friction angle is smaller than 30° .

- (c) Based on the design safety factor defined by shear strength reduction, the anchor force increases non-linearly with the safety factor for both cohesive and cohesionless soil.
- (d) Whether the soil is cohesionless or not, the log-spiral slip line gradually approaches a straight line with increasing internal friction angle of the soil. In addition, the anchor force obtained by the limit equilibrium method (without considering moment equilibrium) based on Rankine's pressure theory is not conservative for practical engineering, when compared with the proposed method.

Appendix

In Figure 1, there is the following geometric relationship

$$15. \quad \frac{h}{r_0} = e^{(\theta_h - \theta_0) \tan \phi} \times \sin \theta_h - \sin \theta_0$$

$$16. \quad s = r_0 \cos \theta_0 - r_h \cos \theta_h$$

According to the concept of the gravity work rate, the coefficients of the gravity work rate can be expressed as follows

$$17. \quad f_1 = \frac{(3 \tan \phi \cos \theta_h + \sin \theta_h) e^{[3(\theta_h - \theta_0) \tan \phi]} - 3 \tan \phi \cos \theta_0 - \sin \theta_0}{3(1 + 9 \tan^2 \phi)}$$

suitable for analysing the anchor force, and an explicit formula for the force can be obtained. The proposed method is easily applied. The following conclusions can be drawn.

- (a) The internal friction angle and cohesion of the soil and the depth of excavation have major effects on the anchor force. The surcharge on the ground surface and the penetration depth of the wall also significantly affect the anchor force. Relatively speaking, the depth from the anchor force action point to the ground surface has a minor impact on the anchor force. The wall friction angle affects slightly the anchor force and its calculation result is conservative if the angle is assumed to be zero degrees. For multiple rows of anchors, the anchor force is linked much more closely with the sum of the depth of each row of anchors than with the specific depth of each row.
- (b) On the one hand, the anchor force gradually grows with the increasing dip angle of the anchor. Thus, the dip angle of the anchor should perhaps be as small as is practically possible. On the other hand, the influence

$$18. \quad f_2 = \frac{1}{3} \frac{h e^{2(\theta_h - \theta_0) \tan \phi}}{r_0} \cos^2 \theta_h$$

$$19. \quad f_3 = \frac{s}{6r_0} \left[\cos \theta_0 + e^{(\theta_h - \theta_0) \tan \phi} \times \cos \theta_h \right] \times \sin \theta_0$$

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