Determination of δ-value for Reinforced Soil Walls

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Summary The average friction angle mobilised along the soil wall interface and the associated active force acting on a reinforced soil wall was computed using non-linear finite element method. The influence of soil models, soil parameters and wall geometry was also investigated. The results based on polyester reinforcement are compared with those based on steel reinforcement. Generally, for level back-fill walls the emperical method was found to be conservative. The margin of conservatism reduced as the slope of the backfill increased. For walls with high sloping backfill the behaviour was dominated by the slope behind the Reinforced Soil Wall.

1. INTRODUCTION

The thrust acting on a Reinforced Soil Wall, hereafter referred to as RSW, is calculated using classical earth pressure theories such as the Rankine theory or the Coulomb wedge method. One of the confusing issue in the use of classical earth pressure theories is the choice of the average friction angle mobilised along the wall-soil interface, referred to as the δ-value in this paper. In general, the δ-value is less than δ_{ds}, the soil-wall friction angle as measured in a direct shear test because the kinematics at collapse state may not ensure the full mobilisation of frictional resistance. It was recently brought to the authors' attention that the design of geosynthetic RSW δ-value sometimes could have a significant cost impact.

The Rankine theory is based on a set of statically admissible stress state that satisfy the Mohr-Coulomb failure criterion. Only one boundary, the surface of the retained soil, is considered. This leads to $i_a = \beta$ where i_a is the inclination of the resultant active pressure to horizontal and β is the slope of the retained fill. The interface between a retaining wall and the soil, in fact, constitute another boundary condition. In the vicinity of this boundary, $i_a = \beta$ becomes an assumption that needs to be verified. For level retained backfill, Rankine solution will satisfy the boundary condition imposed by a perfectly smooth wall. For a rough wall on sound foundation, the Rankine solution is conservative because of the lower bound theorem. For a sloping backfill, the δ-value along the wall-soil interface constitutes a boundary condition that may be less than i_a. For such a condition, Geoguide 1 (1993) recommends that "Rankine theory should not be applied". For the Coulomb wedge method, the δ-value is explicitly required as an input to the calculation and full shearing resistance is assumed to be mobilised along the planar failure surface through the soil mass. Such a calculation model will yield an upper bound solution since a planar failure surface is assumed. For the condition $\beta=0°$, the Coulomb Wedge method gives good prediction of active force provided an appropriate δ-value is used in the calculation.

For a highly deformable wall (relative to the deformability of the retained soil), the δ-value will be very small and may be approximated as zero. For a RSW using steel reinforcement, the reinforced block is significantly less deformable than the backfill. Hence, a non-zero δ-value is commonly used in the design. For geosynthetic RSW, current design practice (FHWA (1991), BS8006 (1994)) is to assume δ-value as zero despite the wall-soil interface being fully rough. However, the experimental data for supporting such an assumption for RSW using high stiffness geosynthetic such as high tenacity polyester are relatively limited. Wong, Broms and Chandrasekaran (1994), based on tests on model geosynthetic RSWs, concluded that the δ-value may approach the friction angle of the retained backfill. However, the way surcharge was applied to the model walls may not fully represent the field situation.

The broad objectives of this project were to investigate the δ-value, and the associated active force acting on a soil block reinforced with polyester straps using non-linear finite element analysis. The influence of sloping retained backfill was also included in this study. The construction sequence was simulated in the finite element analysis.

2. FINITE ELEMENT ANALYSIS

Non-linear finite element analysis will yield the normal stress, σ_x and shear stress, τ_{xy} acting along the interface between the reinforced block and the general backfill. This interface is commonly referred to as the "virtual back" of the RSW. Thus the active thrust in the horizontal direction and the average mobilised friction angle can be computed as:

$$F_{(fe)} = \int \sigma_x . dz$$

$$\tan \delta_{(fe)} = \frac{\int \tau_{xy} . dz}{F_{(fe)}} \qquad (1)$$

where $F_{(fe)}$ is the active force from finite element analysis, $\delta_{(fe)}$ is the mobilised friction angle from finite element analysis. σ_X is the actice pressure on the reinforced block. τ_{XY} is the shear stress along the interface of general fill and reinforced block.

For such an analysis to be valid, the finite element analysis must be able to capture the following characteristics:

- failure of the soil elements
- deformation of the reinforced block
- deformation of the reinforcement
- effect of construction sequence.

The individual reinforcement layers were modelled as elastic bar elements. The general fill and the selected fill were configured to be be raised approximately at the same rate.

In the context of design for overall stability, the active force and the δ-value are used in Limit Equilibrium calculations for the Ultimate (collapse) Limit State. Hence the wall configuration has to be chosen such that there is adequate translational deformation to enable the development of an active pressure state behind the reinforced block.

3. REFERENCE ANALYSIS

A series of reference analysis were conducted to systematically study the δ-value and active thrust acting on a soil block reinforced with polyester reinforcement. The configuration as presented in Fig.1 allows the systematic study of the influence of sloping backfill. The soil was modelled as an elastic-plastic material based on the Coulomb failure surface as the yield surface. The soil parameters are sumarized in Table 1.

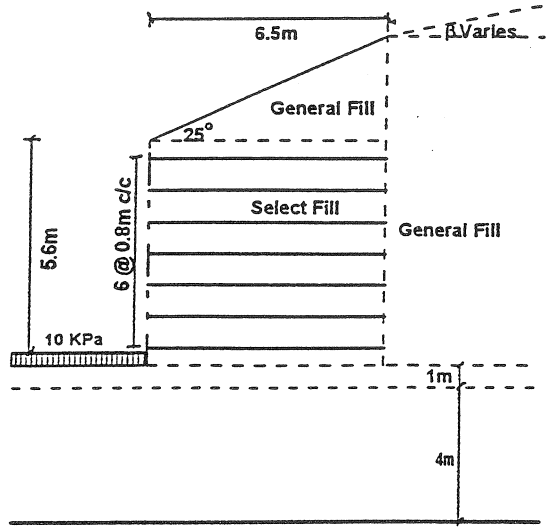

Fig. 1 RSW with Sloping Backfill

Table 1: Properties of soils at different locations

Location	Soil Type	φ°	C (kPa)	E (MPa)	unit wt. (kN/m³)
Reinf. Block	Select Fill	37	0	50	22
above Reinf. Block	General Fill I	33	0	30	22
Backfill	General Fill II	33	5	30	22
Base-top 1 m	in-situ	30	0	50	20
otherwise		30	50	50	20

Two types of soil reinforcements, steel strips and polyester straps, were studied.

(a) Steel strips: The reinforcement was considered to be quasi-inextensible and hence it was only necessary to input an adequately high reinforcement stiffness. A reinforcement stiffness of 40,000 kN per unit strain per reinforcement level, which corresponded approximately to 50 x 4 mm steel strips at 1 m c/c in the horizontal direction, was used.

(b) Polyester strips: The stiffness value was estimated based on Grade-30 Freyssisol straps. A prudent interpretation of the somewhat non-linear load deformation data testing gave 935 kN/unit strain per reinforcement level.

3.1 Results

3.1.1 δ-value

From the stress output using the finite element analysis, the active force acting on the reinforce block was calculated using Eqn. 1. The relationship between $\delta_{(fe)}$ and β for both steel strips and polyester straps reinforced soil wall is presented in Fig. 2. The empirical relationship was also plotted in Fig. 2

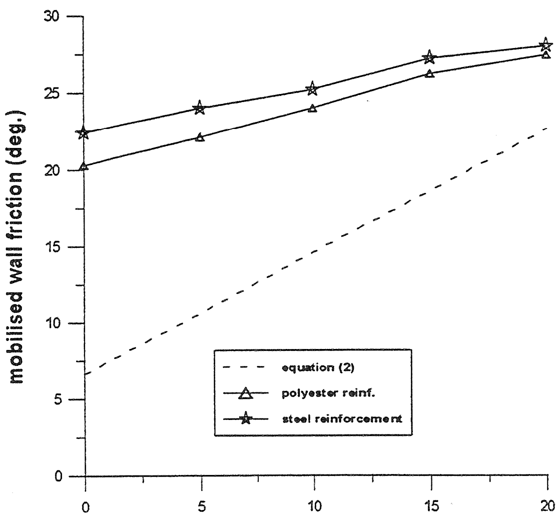

Fig 2. Mobilised Wall Friction for RSW

The pertinent observations are:

(i) The difference between $\delta_{(fe)}$ for the steel system and $\delta_{(fe)}$ for the polyester system was small, about 2° for β = 0° and reduced to less than 1° for β = 20°

(ii) $\delta_{(fe)}$ increased with β.

(iii) The empirical δ-value was always lower than $\delta(f_e)$. However, the emperical relationship gave a higher rate of increase of δ-value with β.

In the design of RSW using steel reinforcement, the following empirical relationship (FHWA 1990) is often used.

$$\delta = \phi\ (1-[1-\beta/\phi].[L/H-0.2]) \qquad (2)$$

Since the wall analysed has an unreinforced soil wedge above the rectangular reinforced block, there is some ambiguity on how the L/H should be calculated. An average L/H value of 1.0 was used. For φ= 33°, the above equation reduces to:

$$\delta = (1-0.8\ [1-\beta/\phi]).33 \qquad (2a)$$

3.1.2 Active Force

The δ-value, in general, affects a design outcome by being an input parameter to the calculation of active force. Hence, $F_{(d)}$, the active force computed with classical design equations, was compared with $F_{(fe)}$, the active force derived from finite element analysis. Four methods were used for calculating $F_{(d)}$.

Method 1: Rankine active pressure equation.
Method 2: Coulomb wedge solution using δ = 0°.
Method 3: Coulomb wedge solution using $\delta_{(fe)}$.
Method 4: Coulomb wedge solution with δ calculated from empirical Eqn (2).

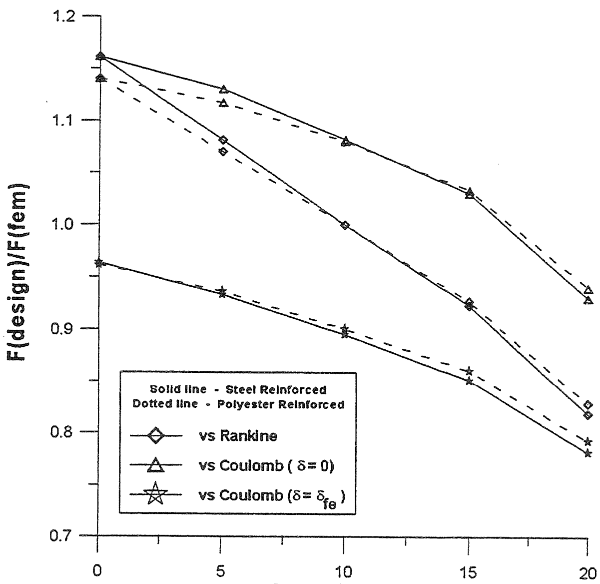

Fig. 3 Active Force on Reinforced Block

The results using these methods, and the influence of β on them, were studied by plotting the force ratio $F(d)/F_{(fe)}$ versus β as presented in Fig. 3. The difference between steel and polyester reinforcement was minimal. Hence subsequent discussion in this section will not differentiate between steel and polyester reinforcement. For β = 0°, the force ratio exceeded unity for methods 1, 2 and 4, thus indicating that the design models were conservative; but the force ratio was marginally lower than unity for Method 3. For all methods, the force ratio reduced with increasing value of β and became less than unity at β=20°. This is because at high β value, the behaviour is dominated by the slope behind the RSW. If the "correct" wall friction of $\delta_{(fe)}$ were used in a Coulomb wedge solution, the resultant $F_{(d)}$ was always less than $F_{(fe)}$. This slight underestimation of $F_{(d)}$, however, is partly compensated by the fact that $F_{(d)}.\tan\delta$, which is a stabilising force for overall stability, will also be underestimated. Thus the overall effect on the stability is likely to be smaller. Furthermore, for high slope angle, the design for overall stability may be controlled by slope stability analysis.

3.2 Influence of Polyester Stiffness

The influence of polyester stiffness was investigated by repeating some of the analyses with the reinforcement stiffness reduced to 400 kN/m per reinforcement level. This reduction in reinforcement stiffness led to about one degree drop in the computed δ-value, and less than 4% change in the computed active force. Hence the findings will not be affected by the variations and uncertainities in the stiffness of polyester reinforcement.

4. PARAMETRIC STUDIES

To investigate whether the findings from the series of reference analyses can be generalised, a parametric study was conducted to test the influence of soil parameters, soil models, and wall geometry. The following additional cases were analysed.

Case 1: The wall configuration and soil models were the same as that adopted for the reference analysis with β = 0°. However, the soil parameters for the general backfill were changed to those for selected fill.

Case 2: The wall configuration was the same as that adopted for the reference analysis. However, a modified Duncan-Chang failure criterion as yield surface instead of the Mohr Coulomb was used. Two sub-cases, β = 0° and β = 10 ° were analysed.

Case3: Same as Case 2 except the soil parameters for the general backfill were changed to those of the select fill.

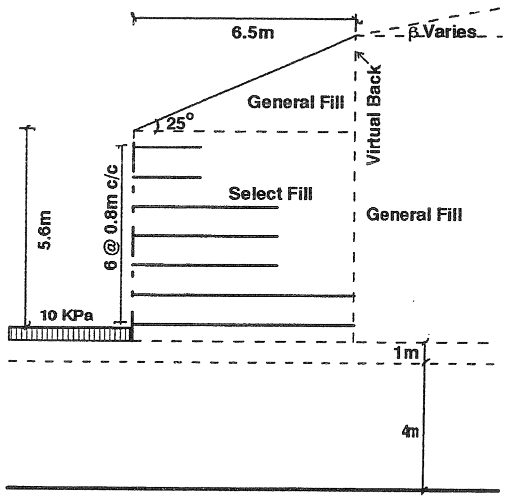

Fig. 4 Step-back Wall Configuration

Case 4: A step-back wall configuration as shown in Fig. 4 was analysed. The soil models and soil parameters, however, were identical to those adopted for reference analysis. Two sub-cases β = 0° and β = 20 ° were analysed.

Case 5: A rectangular RSW as shown in Fig. 5 was analysed. The wall was 8m in height and was relatively slender (width of reinforced zone equal to 4.64m). An elastic-plastic soil model with the Mohr Coulomb failure criterion as the yield surface, but with a non-associative (non-dilatant) flow rule was used. The analysis was conducted using FLAC (1991). The soil paremeters were:

select fill: φ = 40°, C = 0, E = 30 MPa, ν= 0.25
general fill: φ = 40°, C = 0, E = 30 MPa, ν = 0.25

Case 6: A trapezoidal RSW as shown in Fig. 6 was analysed. The base width was 3.2m. The soil model, soil parameters and method of analysis were identical to those of Case 5.

Case 7: Same as Case 6 except the strength parameters of the foundation were reduced, and a water table at foundation level was introduced, to give a safety factor of about 1.1 against bearing capacity failure. Note that the FLAC analysis can handle marginally stable geotechnical structures.

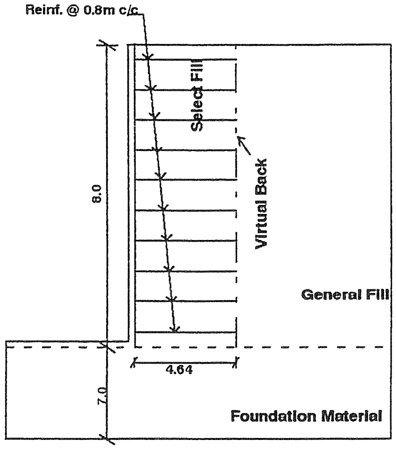

Fig. 5 Rectangular RSW Wall

The above cases examined the influence of soil parameters, soil models, numerical techniques and wall configurations on the computed delta values and active thrust. Both geosynthetic and steel reinforeced RSW were analysed for each and every case. The results are summarized in Table 2.

The pertinent findings are:

- A Duncan-Chang model, relative to the Mohr-Coulomb elastic plastic model, would give a higher $\delta_{(fe)}$ value.
- A slim rectangular wall would lead to an increase in $\delta_{(fe)}$ value.
- A stiffer and stronger general backfill would lead to a reduction in $\delta_{(fe)}$ value.

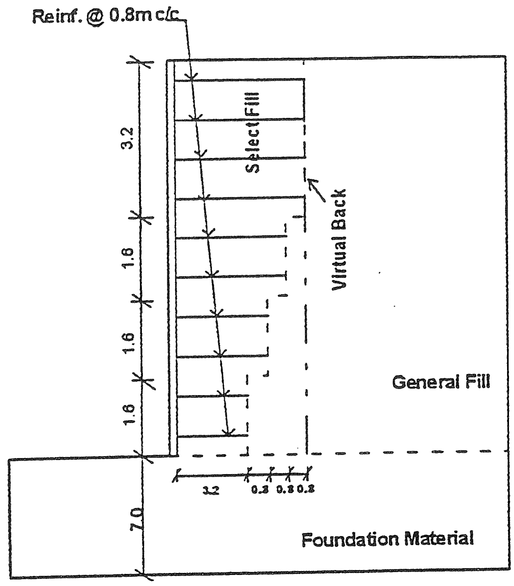

Fig. 6 Trapezoidal Wall

Table 2: Variation of computed $\delta_{(fe)}$

	$\delta_{(fe)}$(deg)		ΣF_{XX} Steel/Polyester Ratio	Wall Configuration	Soil Model
Case	Poly.	Steel			
1 a	13.4	16.9	0.963	Reference $\beta = 0$	MC - A
1 b	20.4	23.1	0.978	Reference $\beta = 15$	MC - A
2 a	24.9	27.1	1.028	Reference $\beta = 0$	DC
2 b	28.5	30.1	1.090	Reference $\beta = 10$	DC
3 a	19.8	26.9	0.936	Reference $\beta = 0$	DC
3 b	23.1	29.6	0.990	Reference $\beta = 10$	DC
4	18.5	19.9	0.980	Step-Back	MC - A
5	28.2	28.0	0.996	Slim	MC - N
6	14.0	14.0	1.000	Trapezoidal	MC - N
7 *	14.6	14.6	0.979	Trapezoidal	MC - N

Notes:

MC - A Mohr-Coulomb elastic plastic model with associative flow rule.
MC - N Mohr-Coulomb elastic plastic model with non-associative (non-dilatant) flow rule.
DC Modified Duncan Chang.
Slim Slim Rectangular Wall H = 8m, L = 4.64m.
* Safety factor against bearing capacity failure about 1.1.

- The value of $\delta_{(fe)}$, for both geosynthetic RSW and steel RSW, was always larger than that predicted by Eqn (2).
- The difference in $\delta_{(fe)}$-value between a geosynthetic RSW and a steel RSW was always small, typically less than 3°, with the exception of Case 3.
- $F_{(fe)}$ for geosynthetic RSW was always close to that of steel RSW.

5. SUMMARY AND CONCLUSIONS

For RSW with sloping backfill, the slope stability mechanism may affect the δ_{fe}-value and F(fe).

The type of reinforcement used in RSW, whether it is steel or geosynthetic, did not significantly influence the δ_{fe}-value or F(fe).

The value of $\delta_{(fe)}$ for both geosynthetic and steel reinforcement in RSW was always larger than that given by Eqn (2).

6. ACKNOWLEDGEMENT

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