Design of reinforced soil structures using a two-part wedge mechanism based on AS 4678-2002

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ABSTRACT

The design of reinforced soil structures is divided into two stages: external stability to give the size of the reinforced soil block and internal stability to establish the required layout of reinforcement. The external stability calculation is essentially the same as used to design a gravity retaining wall. This paper outlines a method of internal stability analysis based on a two-part wedge mechanism. The method has the benefit of being based on basic mechanics, with very few assumptions being required to find a solution. In particular, no assumptions are made concerning the critical failure mechanism, and instead a large number of possible two-part wedge mechanisms are searched, including sliding in between layers of reinforcement and sliding over layers of reinforcement. This approach permits important design situations to be modelled in a fundamentally correct way, including connection strength between the facing and the reinforcement, and earthquake loading. The method has been formulated using the recommendations given in AS 4678-2002.

Keywords: retaining wall, MSE, reinforced soil, design, two-part wedge, AS 4678-2002

1 INTRODUCTION

Design of reinforced soil structures is carried out in two stages. Firstly an external stability analysis is carried out, which is used to determine the overall dimensions of the reinforced soil block, namely B as shown in Figure 1. The external stability check is essentially a gravity retaining wall calculation, and is much the same in all codes and guidelines. External stability is not discussed further in this paper.

The second stage of the calculation is to examine internal stability, to ensure that the layout of reinforcement (grade/strength and vertical spacing) is sufficient. The internal stability calculation should also take into account design features such as the connection strength between the reinforcement and the facing, variable design strength and earthquake loading. There are two main methods used to carry out the internal stability calculation: tie-back wedge and two-part wedge. The majority of published design guidelines use the tie-back wedge method, where design is generally based on assuming a single internal failure mechanism, which requires many assumptions to be made as described by Dobie (2011). The purpose of this paper is to give a detailed description of the two-part wedge method of calculation. The final section outlines the partial factors defined by AS 4678-2002 (Australian code for retaining wall design) which may be combined with the two-part wedge to create a comprehensive method for the design of reinforced soil retaining walls (face angle > 70°).

2 TWO-PART WEDGE METHOD

2.1 Outline of the two-part wedge method

The basis of the two-part wedge method of analysis for internal stability is shown on Figure 1. The geometry is typical of reinforced soil structures, but the method of analysis can incorporate all features shown without the need for any simplifying assumptions. The method of analysis is that of limiting equilibrium, but with the important requirement that any mechanism used should be admissible (ie. can actually happen) and that all forces associated with that mechanism should be taken into account.

The two part wedge is defined as follows: fix a distance z_i below the top of the wall, then draw a line at an angle θ_i across the reinforced soil block, defining Wedge 2. Starting at the point where Wedge 2 intersects the back of the reinforced soil block, define a second wedge, Wedge 1 as shown, with the inter-wedge boundary defined as the back of the reinforced soil block (RSB).

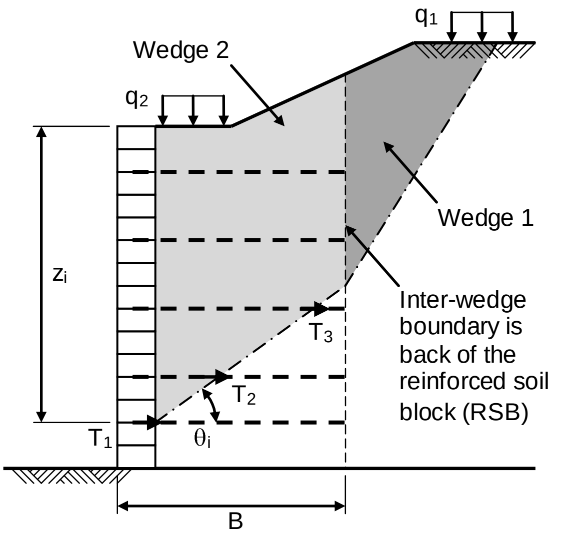

Figure 1. Basis of the two-part wedge method

Wedge 1 is used to calculate the earth pressure forces applied to the back of the RSB, and for simple geometry and conditions, this may be replaced by the Coulomb formula (or Mononobe Okabe for the seismic design case). However for the geometry and isolated surcharge as shown on Figure 1, it is not possible to use the Coulomb formula without making simplifying assumptions. In this situation, to obtain the maximum lateral forces applied by Wedge 1 rigorously, it is necessary to use a trial wedge method in which the angle of Wedge 1 is varied until the maximum lateral thrust is obtained (Culmann wedge method).

The aim of the calculation is to make sure that the resistance provided by the facing and reinforcement which is intersected by Wedge 2 ($T_1 + T_2 + T_3$ as shown on Figure 1) is sufficient to ensure stability of the two wedges.

2.2 Two-part wedge search procedure

In order to find the critical two-part wedge, it is necessary to search through a large number of combinations of wedges. This is normally done as shown on Figure 2 (left). For a specific value of z_i, various values of θ_i are used so that a "fan" of wedges is checked. z_i is then adjusted and the fan of wedges repeated. Normally z_i is chosen starting at the base of the wall (where z_i = H, the total wall height), then at each elevation where reinforcement intersects the facing.

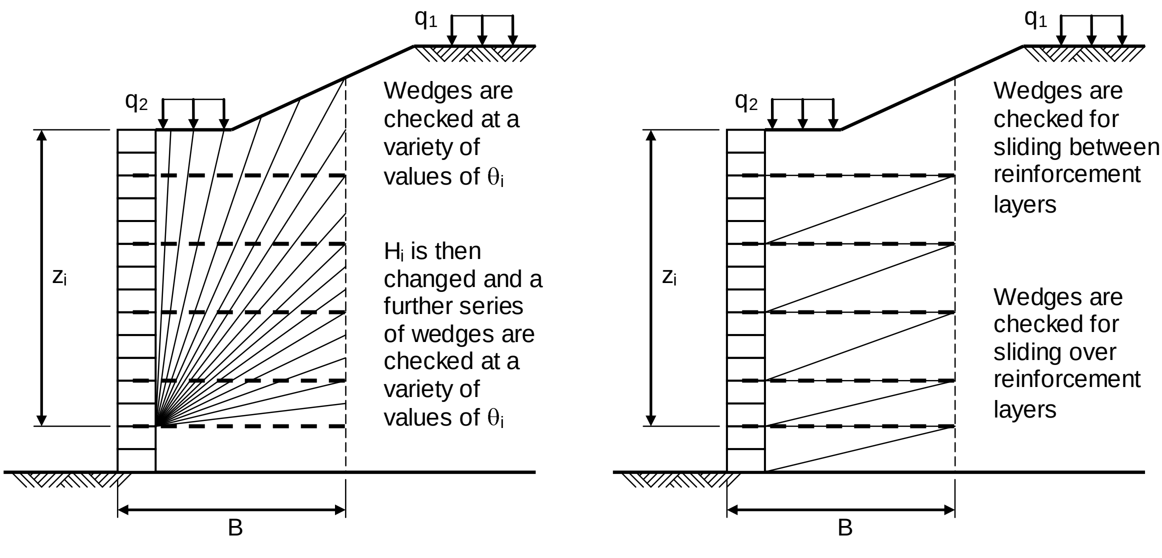

Figure 2. Search routines used with two-part wedge method

Special cases of two-part wedges are checked, as shown on Figure 2 (right). The first are wedges defined by the maximum possible values of θ_i which do not intersect reinforcement. This check is normally carried out between all pairs of reinforcement layers and ensures that vertical spacing does not become too large. Generally the critical case is the lowest wedge, but higher wedges may be critical if vertical reinforcement spacing is increased or large surcharges are present behind the RSB. The second check is sliding over the reinforcement, which is generally critical for the lowest layer of reinforcement especially when the fill/reinforcement combination has a low sliding interaction factor.

Compound wedges entirely inside the RSB are not checked in the method described in this paper, such wedges normally being considered in the design of reinforced slopes (facing angle < 70°).

2.3 Method of calculation

The method of calculation is shown on Figure 3. The principle of AS 4678-2002 is that partial load and material factors are applied to the various components in the stability calculation. In the nomenclature used here, an asterisk (*) indicates a factored force or resistance. Values of the partial factors used are summarised in Section 4 of this paper. The factored total driving force is S* and the factored total resistance is R*. The requirement is that R* > S*, or R*/S* > 1.0 in any calculation.

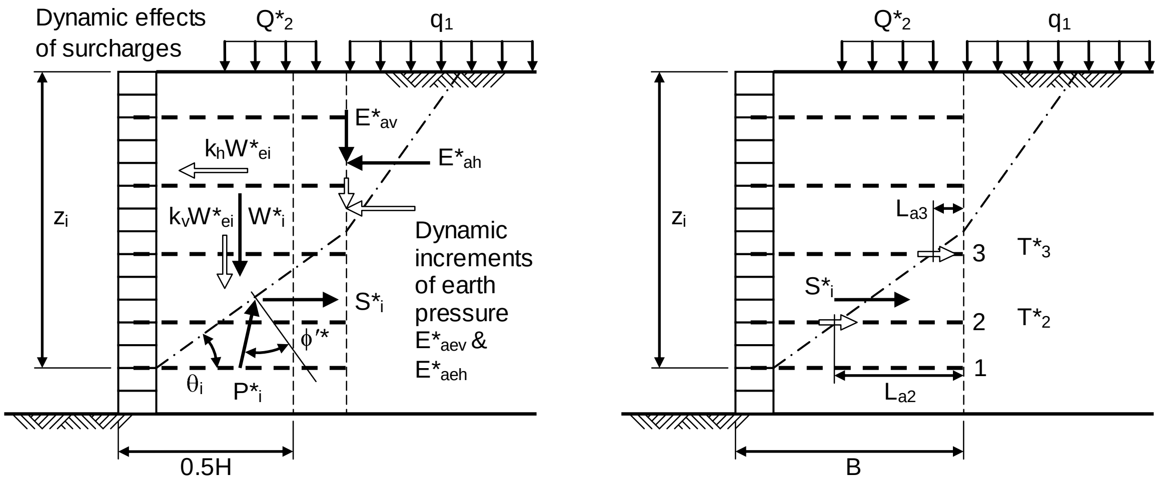

Figure 3. Calculating forces required and available resistance (static and seismic)

Table 1: Forces applied to Wedge 2

Force	**Static**	**Seismic** (subscript "e" denotes seismic force)
E^*_{ah}	Horizontal earth pressure force applied on back of reinforced soil block (RSB)	Additional horizontal earth pressure force applied on back of RSB due to earthquake (E^*_{aeh})
E^*_{av}	Vertical component of E^*_{ah}	Vertical component of E^*_{aeh}
$k_hW^*_{ei}$		Horizontal inertia of Wedge 2_e defined by a width of 0.5H from the front of the facing
W^*_i	Weight of Wedge 2	Vertical inertia of Wedge 2_e either up or down.
Q^*_2	Surcharge applied to the top of the reinforced soil block, live or dead load	Surcharges applied to the top of the reinforced soil block have both horizontal and vertical inertia
P^*_i	Resisting force on base of Wedge 2, equal to $\Sigma V^*_i / \cos(\phi'^* - \theta_i)$ or $\Sigma V_e{}^*_i / \cos(\phi'^* - \theta_i)$	

The various forces applied to Wedge 2 are shown on Figure 3 (left) and are defined in Table 1. The system of forces may be resolved to find S^*_i, the factored driving force which must be resisted by the reinforcement, which is given as follows (ΣH^*_i & ΣV^*_i denote sum of all horizontal & vertical forces):

$$S^*_i = \Sigma H^*_i - \Sigma V^*_i \tan(\phi'^* - \theta_i) \qquad (1)$$

Available resistance from the reinforcement may come from either pull-out or rupture. For layer 3:

$$T^*_3 = \text{smaller of:} \quad 2 \times L_{a3} \times \sigma_v' \times \alpha^*_p \tan\phi' \times (1 \pm K_v) \text{ (pull-out)} \quad \text{or} \quad T^*_{al} \text{ (rupture)} \qquad (2)$$

Where σ_v' is the mean vertical effective stress along L_{a3}, α^*_p is the factored pull-out interaction factor and T^*_{al} is the factored design strength of the reinforcement. This check is carried out for each layer of reinforcement which intersects the base of Wedge 2, with the total given as:

$$\Sigma T^*_i = R^*_i > S^*_i \qquad (3)$$

For sliding on an inclined plane between reinforcement layers (as shown on Figure 2 right), a different approach is used, and the check is carried out as follows (but still related to the forces applied to Wedge 2 as shown in Figure 3 left):

$$R^*_i/S^*_i = (1 - R_f \tan\theta_i) \tan\phi'^*/(R_f + \tan\theta_i) \qquad (4)$$

Where R_f is the ratio of the factored horizontal forces to the factored vertical forces, $= \Sigma H^*_i / \Sigma V^*_i$. Sliding over reinforcement is checked as follows (α^*_s is the factored sliding interaction coefficient):

$$R^*_i = \alpha^*_s \tan\phi' \times \Sigma V^*_i > S^*_i = \Sigma H^*_i \qquad (5)$$

3 TWO-PART WEDGE DEVELOPMENT

3.1 Improving the calculation model

The two-part wedge method as described in Section 2 provides a comprehensive method of analysis of the internal stability of a reinforced soil retaining wall. However as described in Section 2.3, modelling of the contribution of the reinforcement to stability is still restricted to a single value of tensile strength (T^*_{al}) and connection strength with the facing has not been taken into account. This section describes refinements to modelling the contribution of the reinforcement, by taking advantage of the searching procedure used to find the critical design layout. In particular the concept of the "distribution of available resistance" is introduced, which provides the basis for this refinement. To help visualise what might happen when a pair of wedges fail, the mode of failure is sketched on Figure 4.

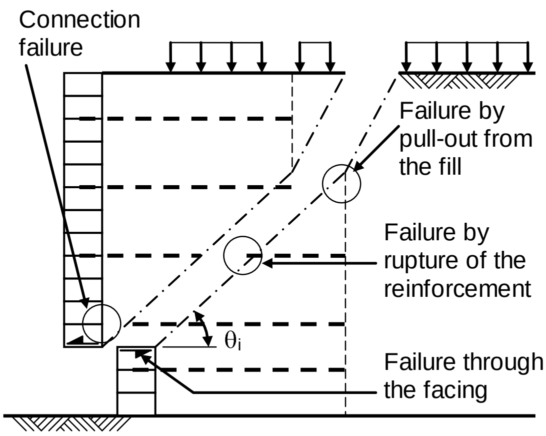

Figure 4. Likely mode of failure of two wedges

As shown on Figure 4, as the wedges slide outwards, three layers of reinforcement are involved, each with a different failure mode:

Upper	Fails due to reinforcement pulling out of the fill
Middle	Fails by rupture of the reinforcement
Lower	Fails by pulling away from the facing combined with pull-out through the fill behind the facing

In addition to the three layers of reinforcement there is also failure through the facing, in this case by sliding between two of the facing blocks, which also provides resistance. However from the point of view of the reinforcement, it is necessary to assess the available resistance at three different locations, with three different failure mechanisms. This can be done by establishing a distribution of available resistance along each layer of reinforcement as outlined in Section 3.2.

3.2 Envelope of available resistance

The envelope of available resistance is developed as shown in Figure 5 (left). This is best described as a series of steps as follows below, where the vertical axis is the factored available tensile resistance, T* (in Figure 5 left, F* as shown = $\alpha^*_p \tan\phi'$):

- Step 1 Starting at right end and moving to the left, T* increases according to the pull-out equation
- Step 2 A maximum value is reached given by the factored tensile design strength
- Step 3 An additional design feature is shown, whereby the section of reinforcement nearest to the facing has a lower factored design strength, due to a higher in-soil temperature
- Step 4 The resistance at the facing is limited to the factored connection strength
- Step 5 Moving to the right from the facing, resistance increases according to the pull-out equation

This process results in an envelope shown by the shaded area, which may be developed for each layer of reinforcement in a structure. Figure 5 (right) shows how these envelopes might appear. For clarity only two layers of reinforcement are shown. The sloping sections of each envelope are steeper for the lower layer of reinforcement because this slope is controlled by the vertical effective stress at the elevation of the reinforcement. This is much higher for the deeper layer.

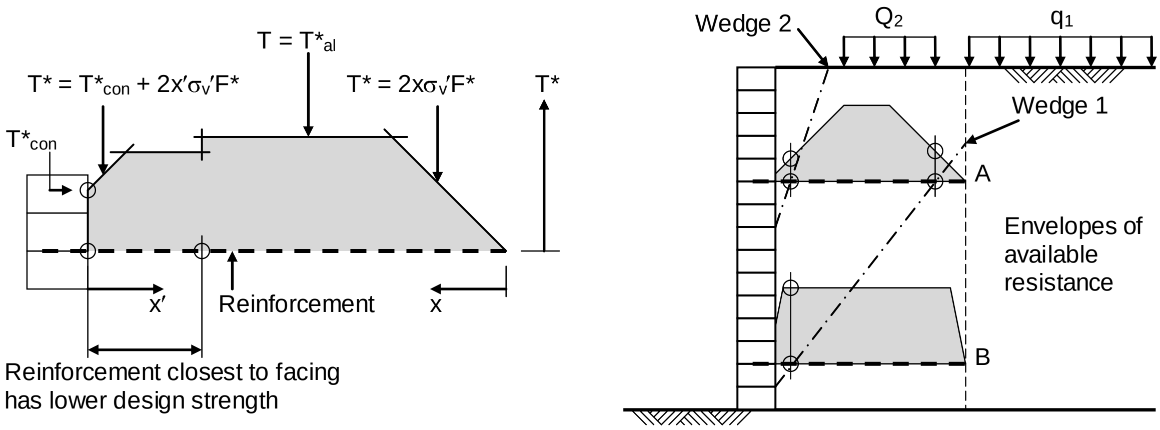

Figure 5. Definition of envelope of available resistance and inclusion in two-part wedge analysis

Two wedges have been added to Figure 5 (right), and the contribution to resistance for each wedge is described as follows:

- Wedge 1 Cuts Layer B near the facing, but reading up to the envelope, full tensile strength is developed. Cuts Layer A close to the buried end so that resistance comes from pull-out.
- Wedge 2 Cuts Layer A at the same distance from the facing as Wedge 1 cutting layer B, but resistance is much smaller due to the lower connection strength and less pull-out resistance through the fill behind the facing

In the case that connection strength is relatively low near the top of the wall, this analysis will result in fans of steep failing wedges near the top, especially severe when seismic forces are added.

4 OUTLINE OF REQUIREMENTS GIVEN IN AS 4678-2002

AS 4678-2002 provides design criteria and guidance for all forms of retaining structure, including reinforced soil structures, in a limit state format. However the standard does not provide a design method (ie. method of calculation). This has provided an opportunity to combine the two-part wedge method described in this paper with the requirements of AS 4678-2002 in terms of general concepts and partial factors. This section summarises the principal factors required to establish the ultimate limit state (ULS). The author's company have developed software to carry out retaining wall design following this approach, which has been in use now for more than 10 years in the ANZ region. Experience gained from using this method has shown that the resulting designs are generally more economical than designs obtained using tie-back wedge methods, with the benefit that potential weak points, such as low connection strength, are thoroughly examined during the design process.

Table 2: Structure classification[A] (ULS)

Classification	Consequence of failure	ULS
C	Significant damage or risk to life	0.9
B	Moderate damage or loss of services	1.0
A	Minimal damage or loss of access	1.1

[A]Applied to reinforcement strength, connection strength and pull-out/sliding interaction

Table 3: Soil strength partial factors (ULS)

Soil or fill conditions	$\Phi_{u\phi}$ (drained)	Φ_{uc} (drained)	$\Phi_{u\phi}$ (undrained)	Φ_{uc} (undrained)
Controlled fill Class I[B]	0.95	0.9	0	0.6
Controlled fill Class II[C]	0.9	0.75	0	0.5
Uncontrolled fill	0.75	0.5	0	0.3
In-situ material	0.85	0.7	0	0.5

[B]γ_d = 98% mean, = 95% min [C]γ_d = 95% mean, = 92% min

Table 4: Reinforcement factors[D] (ULS)

Factor	Purpose	Static	Seismic
$T_u \times \Phi_{rc}$	Tensile strength	Φ_{rc} BBA cert	Φ_{rc} = 1.0
Φ_{up}	Uncertainty factor for the product	0.95	0.9
Φ_{ue}	Uncertainty factor for extrapolation of data	1.0	NA
Φ_{ri}	Reduction factor for installation damage	From BBA Cert	From BBA Cert
Φ_{rt}	Reduction factor for polymer thickness erosion	1.0	1.0
Φ_{rs}	Reduction factor for degrad of polymer strength	1.0	1.0
Φ_{rst}	Reduction factor for temperature	Inc in $T_u \times \Phi_{rc}$	Inc in T_u
Φ_{ud}	Uncertainty factor for degradation, chem, bio, UV	0.95	0.95

[D] based on BBA Certificate 99/R109 "Tensar RE and RE500 geogrids for reinforced soil retaining wall and bridge abutment systems". In absence of independently certified values, AS 4678-2002 gives default values in Appendix K.

Table 5: Soil/reinforcement interaction factors (ULS)

Classification	Consequence of failure	ULS
Sliding	Controlled fill (Class I or II)	0.8
Pull-out	Controlled fill (Class I or II)	0.8
	Natural or in-situ soil	0.75

Table 6: Load factors (ULS)

Load type	Acting	Resisting
Live loads on top of wall (temp surcharges, 5 kPa minimum)	1.5, 0.5 seismic	0
Dead loads on top of wall (permanent surcharges)	1.25	0.8
Earth pressure load (horizontal and vertical components)	1.25	0.8
Earth pressure from live load (horizontal and vertical components)	1.5, 0.5 seismic	0
Water (assessed as worst credible location during design life)	1.0	1.0
Seismic components of load	1.0	0

5 CONCLUSION

A method of calculation is described for checking the internal stability of reinforced soil structures, based on a two-part wedge mechanism, in which a large number of possible failure mechanisms are searched. The method allows connection strength, variable reinforcement strength and earthquake loads to be taken into account. The technique has been combined with the requirements of AS 4678-2002 to create a complete design method, which has been used in the ANZ region for more than 10 years.

REFERENCES

Dobie, M. J. D. (2011). "Internal stability of reinforced soil structures using a two-part wedge method". Proceedings of PIT XV, Conference of the Indonesian Society for Geotechnical Engineering, Jakarta, Indonesia, 61-72.