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A partial factor approach for reinforced fill slope design in Hong Kong

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ABSTRACT: This paper presents a partial factor approach that has been adopted, since its introduction in 1993, for the design of new reinforced fill slopes built in public works projects in Hong Kong. The design methodology and recommended partial factors are explained. Administrative arrangements for the introduction of the design approach and a criterion for the demarcation between reinforced fill slopes and walls are described.

1 BACKGROUND

In 1989, the Geotechnical Control Office (GCO) (renamed Geotechnical Engineering Office, GEO, in 1991) of the Hong Kong Government published a model specification for reinforced fill structures (GCO, 1989) to provide guidance on the design and construction of reinforced fill walls with a near-vertical face. At the same time, an Endorsement Certificate System was introduced by the GEO for the prior approval of proprietary reinforced fill products intended to be used in Hong Kong (Pang, 1991; Man & Pang, 1992 & 1994).

The design requirements for different geotechnical features in Hong Kong are summarised in Table 1. The design method of GCO (1989) is essentially a lumped factor approach, in that the earth pressure calculated from the use of unfactored soil shear strength parameters is multiplied by a lumped factor to derive the design loading, which should be within the resistance available from the reinforcing elements (Pang, 1991).

This method is widely adopted in reinforced fill wall design in Hong Kong. It is, however, not considered suitable for reinforced fill slopes. An alternative design method for reinforced fill slopes based on the use of the partial factor approach was formulated in 1993. It has several advantages over the lumped factor approach, which include :

(a) Achievement of a more reliable and consistent margin of safety. In reinforced fill walls, relatively large earth pressures are developed and a reasonable safety margin can be obtained by applying a lumped factor to the earth pressures calculated from unfactored soil shear strength. However, for

Table 1 - Design Requirements for Different Geotechnical Features in Hong Kong

Type of feature (Reference)	Consequence category	Groundwater condition	Minimum factor of safety (FOS)		
			Soil strength	Interface strength	Strength of reinforcement
Cut and fill slopes (GCO,1984)	High	10-year	1.4 (3)	-	-
		1000-year	1.1		
	Low	10-year	1.2 (3)	-	-
	Negligible	10-year	1.1	-	-
Soil nailed slopes (Powell & Watkins, 1991)	High	10-year	1.4 (3)	2.0	1.8
	Low	10-year	1.2 (3)	2.0	1.8
Retaining walls (GEO, 1993)	Not classified	Worst credible (1000-year)	1.2	-	-
Reinforced fill walls (GCO,1989)	High	10-year	1.0	1.8 (5)	1.7 (6)
	Low			1.5 (5)	1.4 (6)

Notes :

(1) The FOS are applied to reasonably conservative 'best-estimate' parameters (i.e. selected values).

(2) FOS on soil strength and interface strength are applied to c' & tan ϕ' and c'_b & tan ϕ'_b respectively, where c'_b & ϕ'_b are shear strength parameters for the interface between reinforcement and fill.

(3) For stabilisation works to existing slopes, FOS of 1.2 and 1.1 are acceptable for high and low consequence respectively.

(4) Selected values of dead load and live load are adopted in design, except that factored values of live load (using a partial load factor of 1.5) are used in retaining wall design.

(5) The FOS are for design against pull-out failure. For rupture along a reinforcing element surface and rupture through selected fill material, 1.5 and 1.2 are adopted for high and low consequence respectively.

(6) The FOS are for steel strips that comply with GCO (1989). For other proprietary products, the required FOS are specified in Endorsement Certificates.

reinforced fill slopes, the calculated earth pressure is comparatively small, and an adequate and consistent safety margin is difficult to achieve with the use of the lumped factor approach.

(b) More rational consideration of variability in loading and resistance parameters - uncertainties in the parameters are managed directly with the use of different partial factors.

(c) Provision of a framework for future development and improvement in design - it is also compatible with GEO's recommended standards for retaining wall design (GEO, 1993).

2 DESIGN PRINCIPLES

The proposed partial factor design approach for reinforced fill slopes involves the examination and control of the relative magnitude of two key elements : loading and resistance. The purpose is to ensure that it is sufficiently unlikely that a reinforced fill slope would fail to satisfy any of its performance criteria, i.e. occurrence of limit states. The following are the main design principles :

(a) Two types of limit state are considered in design, viz. the ultimate limit state and serviceability limit state. The ultimate limit state involves the formation of failure mechanisms and loss of equilibrium, hence leading to uncontrolled deformation and slope failure. Six possible modes of internal instability (Figure 1) and four modes of external instability (Figure 2) are examined in design against the occurrence of the ultimate limit state.

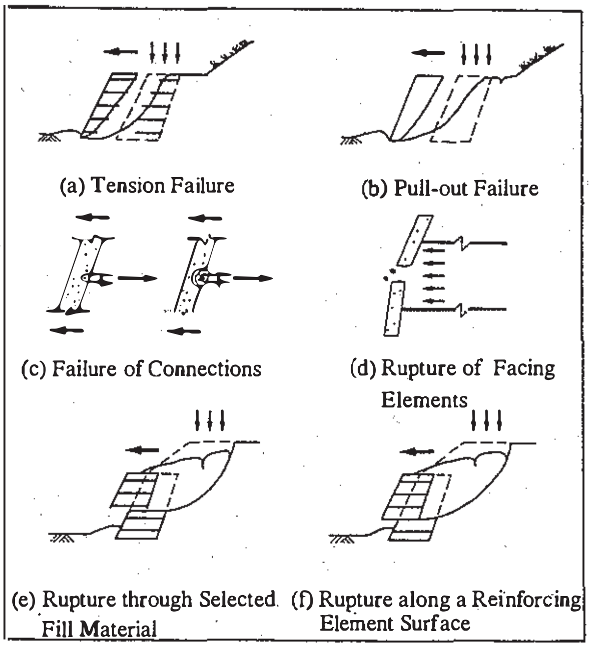


Figure 1 - Ultimate Limit State of Internal Instability

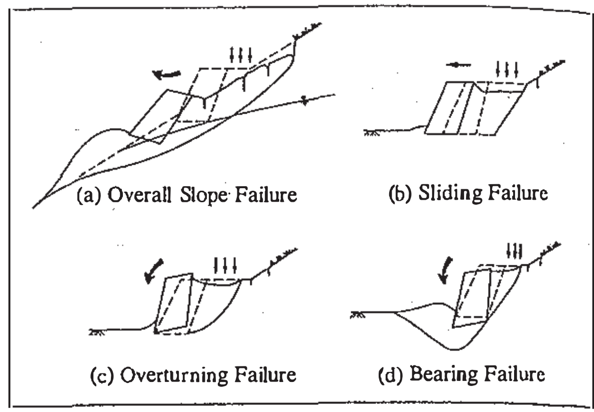


Figure 2 - Ultimate Limit State of External Instability

The serviceability limit state concerns deformation which may affect the performance of the slope, such as appearance and tolerable settlement.

(b) Different limit states are considered separately in design, and their occurrence is either eliminated or is shown to be sufficiently unlikely by requiring that the design loading does not exceed the design resistance. Design loading and design resistance are derived from the use of design values of the relevant loading parameters and resistance parameters (Table 2).

(c) Except for the case of water pressure, design values are obtained by factoring the selected values of the corresponding loading and resistance parameters :

$$L_d = L_s * \gamma_l \qquad (2.1)$$
$$R_d = R_s / \gamma_r \qquad (2.2)$$

where L_d, R_d = design values of loading parameter L and resistance parameter R respectively; L_s, R_s = selected values of loading parameter L and resistance parameter R respectively; selected values are reasonably conservative 'best-estimate' values, and guidelines on their determination are given in GEO (1993); and γ_l, γ_r = partial load factor for loading parameter L and partial resistance factor for resistance parameter R respectively.

The recommended minimum partial load and resistance factors are given in Table 3.

(d) For water pressure, prescribed groundwater condition is adopted as design value. This involves the use of the 10-year groundwater condition (GCO, 1984) in design against overall slope instability and the worst credible groundwater condition (GEO, 1993) against other modes of ultimate limit state. According to GCO (1989) and GEO (1993), where adequate sub-soil drainage is provided, zero water pressure within the 'compacted fill' may be taken as the worst credible groundwater condition.

Table 2 - Loading and Resistance Parameters

Type of loading	Loading parameters	Partial Load Factor
Dead load	Weight of soil, reinforcing elements and water	γ_{dead}
Live load	Surcharge, traffic load, wind load, structural foundation load (including both structural live and dead load) and compaction-induced stress	γ_{live}
Water pressure	Groundwater condition prescribed for design	Not applicable

Type of resistance	Resistance parameters	Partial Resistance Factor
Shear strength	Shear strength parameters tan ϕ' of 'compacted fill'.	γ_{fill}
	Shear strength parameters c' & tan ϕ' of 'ground'	γ_{ground}
Tensile strength of reinforcing elements	Characteristic strength of steel strips that comply with GCO (1989), and endorsed tensile strength of proprietary reinforcing elements	γ_m
Friction/ interaction	Coefficient of friction/interaction (i.e. μ) between reinforcing elements and 'compacted fill'	γ_μ

Notes :
(1) 'Compacted fill' refers to the fill placed for the construction of a reinforced fill slope. According to GCO (1984), c' of 'compacted fill' is taken as zero.
(2) 'Ground' refers to the material in the ground against which a reinforced fill slope is constructed.

Table 3 - Recommended Minimum Partial Factors

Limit state		Partial load factor		Partial resistance factor			
		γ_{dead}	γ_{live}	γ_{fill}	γ_{ground}	γ_m	γ_μ
Internal instability	All modes	1.0	1.5	1.2	1.2 (2)	1.05(3)	1.2(3)
External instability	Overall slope failure	In accordance with requirements of GCO (1984), see Table 1					
	Sliding	1.0	1.5	1.2	1.2 (2)	-	-
	Bearing	1.0	1.5	1.2	1.2 (2)	-	-
	Overturning	No calculation required if there is no 'tension' at the base of reinforced block					

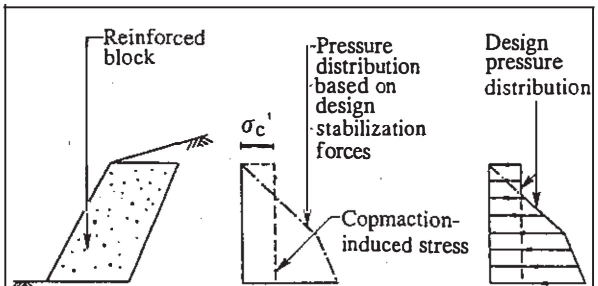
Notes :
(1) Worst credible groundwater condition is adopted for all modes of ultimate limit state except overall slope failure.
(2) For soil modelled as cohesive material, $\gamma_{ground} = 2.0$ is applied to undrained shear strength.
(3) The partial factors are for steel strips that comply with GCO (1989). The values of γ_m & γ_μ are specified in Endorsement Certificates for other proprietary products.

3 DESIGN STABILISATION FORCE AND PRESSURE DISTRIBUTION

The design stabilisation force is the sum of the required tensile forces in the reinforcing elements to maintain the slope in equilibrium given that the relevant loading and resistance parameters are at their design values. Reinforcing elements are normally embedded horizontally in the 'compacted fill' and hence the tensile forces act in the horizontal direction. Where the reinforcing elements are inclined to the horizontal, it is assumed that only the horizontal components of the tensile forces are effective in maintaining the slope in equilibrium.

The design stabilisation force may be calculated by rigorous methods of limit equilibrium analysis. In applying limit equilibrium analysis, sufficient number of potential failure surfaces should be tried to obtain the 'worst' case, i.e. maximum force, for design. Curved or multi-part wedge failure surfaces should normally be adopted, as the use of planar failure surfaces may seriously underestimate the force. The analysis should be applied at different depths to obtain the design stabilisation forces at different depths and hence the corresponding pressure distribution with depth.

Reinforced fill slope construction may result in compaction-induced stress in the 'compacted fill' and such stress may constitute a considerable portion of the design loading. General principles on the assessment of compaction-induced stress are given in GCO (1989).



Design value of compaction induced stress $\sigma_c' = r\sqrt{\gamma_{live} Qp}$

γ_{live} = partial factor for live load (Table 3)
Q = intensity of effective line load induced by compaction plant
p = soil unit weight
r = 0.45 for 'extensible' reinforcing elements (i.e. $\varepsilon_d > 1\%$), 0.9 for 'inextensible' reinforcing elements (i.e. $\varepsilon_d \leqslant 1\%$)
ε_d = short term strain of the reinforcing element when loaded to the design tension

Figure 3 - Simplified Method of Assessment of Compaction-induced Stress

A simplified method of assessment is shown in Figure 3. For internal instability due to tensile failure of reinforcing elements, failure of connection and rupture of facing elements, where deformation before failure is limited, increase in lateral stress due to compaction should be included in assessing the design pressure distribution for these modes of failure. For other modes of internal instability, where the deformation would be sufficiently large for relaxation of the compaction-induced stress, compaction-induced stress may be neglected. Compaction-induced stress may also be neglected in the design for external stability.

4 ULTIMATE LIMIT STATE OF INTERNAL INSTABILITY

The design against the occurrence of the ultimate limit state of internal instability is carried out to provide an adequate margin of safety against all possible modes of internal instability (Figure 1).

4.1 Tension failure of reinforcing elements

The design tension T_d at each level of the reinforcing elements is calculated from the design pressure distribution, as illustrated in Figure 4. The design tensile resistance of a reinforcing element, which is given by factoring the selected tensile strength of the reinforcing element by γ_m, should not be less than T_d.

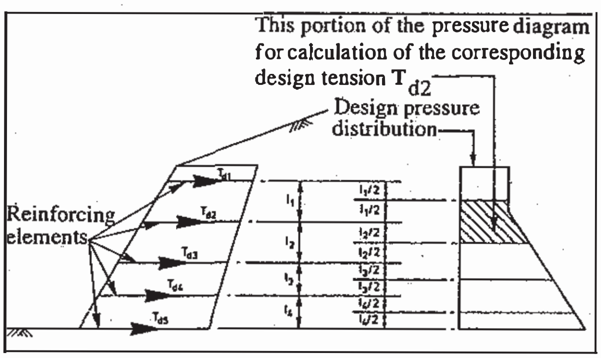


Figure 4 - Calculation of the Design Tension T_d

For steel strips that comply with GCO (1989), γ_m may be taken as 1.05 and the selected tensile strength is given by :

selected tensile strength
$$= \sigma_y \, (B - 2\,t_s)\,(t - 2\,t_s) \qquad (4.1)$$

where σ_y = 95% characteristic yield stress of steel; B, t = width and thickness of steel strip respectively; t_s = sacrificial thickness allowance specified in GCO (1989).

For other endorsed proprietary products, the selected tensile strength of the reinforcing elements and the required partial resistance factor γ_m are specified in the relevant GEO Endorsement Certificates.

4.2 Pull-out failure of reinforcing elements

For checking against pull-out failure, the effective bond length of a reinforcing element is taken as that protrudes beyond the potential failure surface under consideration. The potential failure surface corresponding to the maximum design stabilisation force may not necessarily be the critical failure surface in checking against pull-out failure. Hence, sufficient number of potential failure surfaces should be checked to ensure that the pull-out resistance is adequate in all cases.

The design pull-out resistance of a reinforcing element is given by :

Design pull-out resistance
$$= 2B * L_e * \sigma_{ve}' * \mu \,/\, \gamma_\mu \qquad (4.2)$$

where μ = selected value of coefficient of friction/interaction between the selected fill material and the reinforcing element specified in GEO Endorsement Certificates; B, L_e = width and effective bond length of reinforcing element respectively; σ_{ve}' = average normal stress acting on the effective bond length; and γ_μ = partial factor on μ (Table 3).

4.3 Failure of connections

Where facing elements are provided, the connection between a facing element and a reinforcing element is designed to withstand the design tension T_d. For bolted connections, all modes of failure including shear and bearing failure should be checked. The requirements of relevant local structural standards should be observed in the design. In addition, the selected strength of the connection should exceed that of the reinforcing element, in order to avoid brittle failure at the connection.

4.4 Rupture of facing elements

Where facing elements are provided, their structural design is based on the design pressure distribution incorporating compaction-induced stress. The requirements of relevant local structural standards should be observed in the design.

The limit states of failure of connections and rupture of facing elements are not relevant where no structural facing is provided. However, the possibility of inadequate bond length of a reinforcing element within the zone in front of a potential failure surface should be checked, particularly in case of a shallow failure surface. Adequate measures should be provided to ensure local stability at the face and to protect it from surface erosion. This may consist of wrapped around geosynthetic facing with short secondary reinforcements for steep (say, 45° to 70°) slopes, and geosynthetic erosion mat for less steep (say, less than 45°) ones. Fire hazard and its effects on the integrity of the facing and the reinforcing elements should also be considered.

4.5 Rupture through selected fill material and rupture along a reinforcing element surface

Shearing failure of the selected fill material along any plane parallel to the reinforcing elements and along the surface of any layer of the reinforcing elements should be checked. Rigorous methods of limit equilibrium stability analysis may be adopted. The feature is deemed to have adequate stability against these modes of failure if the factor of safety calculated with the use of the design values of the relevant loading and resistance parameters is not less than unity.

5 ULTIMATE LIMIT STATE OF EXTERNAL INSTABILITY

The design against the occurrence of the ultimate limit state of external stability is carried out to provide an adequate margin of safety against all possible modes of external instability (Figure 2).

5.1 Overall slope failure

The requirements given in GCO (1984) for slope design in Hong Kong, summarised in Table 1, are followed in the design against overall slope failure.

5.2 Instability of the reinforced block

The reinforced block (i.e. the reinforced portion of 'compacted fill') should be designed to ensure that it does not translate, rotate or unduly subside as a monolith. The reinforced block is treated as a gravity retaining structure and the requirements given in GEO (1993) for retaining wall design in Hong Kong are adopted in checking against sliding, overturning and bearing instability.

A trapezoidal distribution of ground bearing pressure over the base of the reinforced block may be assumed. The 'width' of the foundation to be used in the ultimate bearing capacity calculation is taken as the length of the reinforcing elements in the bottom layers of the reinforced block or the height of the reinforced block, which ever is the lesser dimension. In case of negative eccentricity, it is not necessary to check bearing instability.

The reinforced block should be proportioned to ensure that the ground bearing pressure does not fall below zero under any load combination. It is not necessary to check overturning failure if there is no 'tension' along the base.

6 SERVICEABILITY LIMIT STATE

Reinforced fill slopes could generally tolerate a fair degree of deformation without significant adverse effects on their performance. Given that the serviceability condition of a reinforced fill slope is not sensitive to slope deformation and due account has been taken of the allowable long term strain of the reinforcing elements in assessing their design resistance, an explicit check against serviceability limit state is not required.

Where serviceability limit state check is needed, the guidelines given in GCO (1989) should be followed and selected values of the relevant design parameters should be adopted.

7 DEMARCATION BETWEEN REINFORCED FILL WALLS AND SLOPES

For the purposes of defining the range of application of the partial factor approach, a calibration study was carried out to compare the outcome of design using the proposed approach and the lumped factor approach of GCO (1989). Details of the calibration and the findings are described in Wong (1993). It was found that the lumped factor approach of GCO (1989) would result in unsafe design when the angle of inclination of the front face of the reinforced fill structure exceeds 20° from the vertical. Hence, where the angle is greater than 20°, the structure is treated as a reinforced fill slope and designed with the use of the proposed partial factor approach.

This demarcation criterion permits the application of the comparatively simple design method of GCO (1989) to the majority of the reinforced fill structures which are intended to serve as a retaining wall, while the partial factor approach is adopted in the design of reinforced fill slopes, which are comparatively lightly reinforced, to achieve a consistent safety margin against different modes of failure.

8 ADMINISTRATIVE ARRANGEMENTS

The allowable properties of proprietary products to be used in reinforced fill wall design based on the lumped factor approach of GCO (1989) are specified in Endorsement Certificates issued by the GEO. With the introduction of the partial factor approach, the Endorsement Certificate System was revised so that the relevant properties of the endorsed products for use in reinforced fill slope design are also specified. These properties include :

(a) Selected value of reinforcing element tensile strength and the corresponding partial resistance factor γ_m - for proprietary polymer reinforcing elements, the reasonably conservative 'best-estimate' 35°C & 10^5-hour strength is adopted as selected value. γ_m should cover the effects of material variability, construction damage, environmental effects and other special factors including stress rupture and inaccuracy due to synergy among the factors and extrapolation of data.

(b) Selected value of the coefficient of friction/interaction between reinforcing elements and compacted fill and the corresponding partial resistance factor γ_μ - guidelines on the determination of the selected value of the coefficient of friction/interaction are given in GCO (1989) and GEO (1993).

Following consultation with the government Departments involved, it was decided in 1993 that the partial factor approach should be adopted for the design of all new reinforced fill slopes built in public works projects in Hong Kong. The approach was also promulgated to practitioners in the private sector, through the issue of a GEO report (Wong, 1993) which describes the methodology with worked examples incorporated, as a recommended standard of good practice for the design of reinforced fill slopes in Hong Kong.

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