FACTORS INFLUENCING DESIGN OF SLOPES IN RESIDUAL SOILS: AN OVERVIEW

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SUMMARY

The key to understanding the stability of slopes in residual soils lies in recognising the influence of the weathered profile, relict discontinuities, shear strength parameters, and groundwater conditions. These factors would need to be carefully considered while preparing a site investigation programme to establish the information required for a stability analysis.

INTRODUCTION

Cut slopes in residual soils are increasingly encountered in present-day engineering projects, and often prohibitive construction and maintenance costs arise from their instability. Instability manifests itself dramatically as landslips, landslides and mudflows. The inability to assess the stability of these slopes is often attributed to the "wide range of complex factors involved". The factors influencing slope stability in residual soils are:

1. slope height and slope batter;
2. any imposed loads;
3. geology;
4. shear strength parameters;
5. soil suction;
6. groundwater condition;
7. appropriate factor of safety;
8. surface protection of slope.

This paper examines only factors 3 through 7, though some interesting concepts relating to remainder of the factors will emerge.

GEOLOGICAL FACTORS

A number of studies on the development of natural slopes and slope instability in residual soils have concluded that:

- landslides are the predominant method for the development of natural slopes in tropical regions where deep residual soil profiles occur;
- landslides are associated with the characteristics of the weathered profile;
- maximum landslide activity is associated with periods of intense rainfall;
- shallow slides are the most common mode of instability, but deep slides which involve movement of a block of soil along relict discontinuities are also frequently encountered.

Discussions on the above are presented in the following subsections.

Characteristics of the Weathered Profile

The weathered profile is the sequence of layers of materials which have developed in place over fresh, unweathered rock due to the weathering processes of chemical decomposition and physical disintegration. These layers possess significantly different strength and permeability characteristics. A typical weathered profile for igneous rocks, proposed by Deere and Patton [2], is shown in Figure 1. Deere and Patton [2] have also dealt with typical weathered profiles in other rock types.

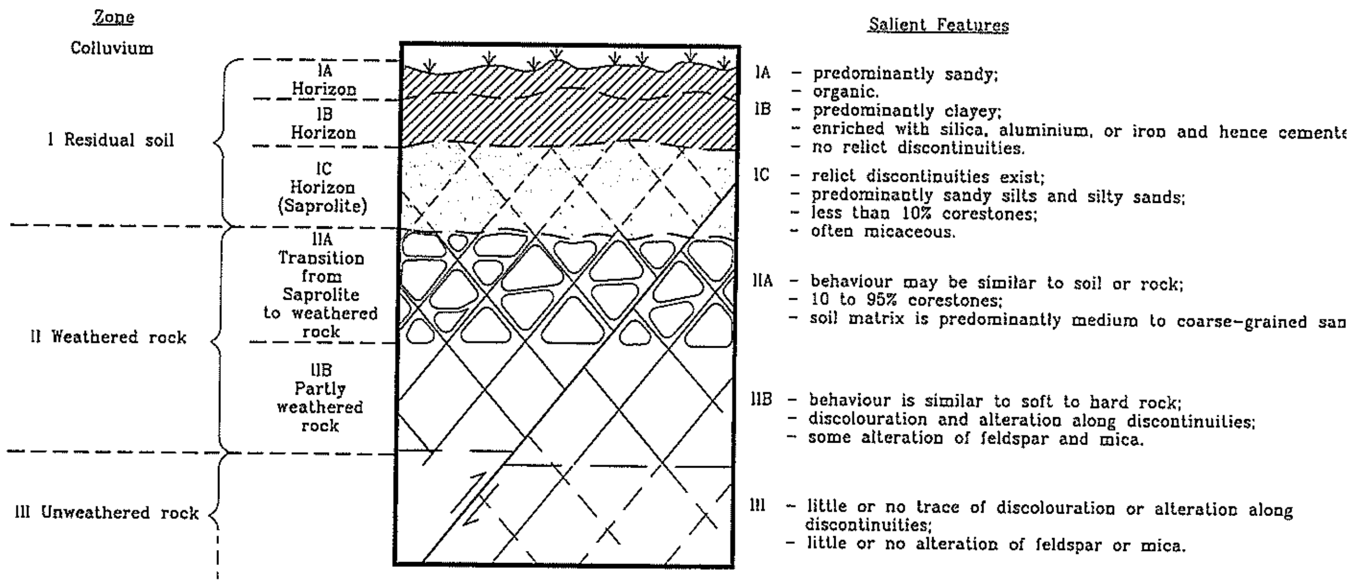


Figure 1 Typical weathered profile for intrusive igneous rocks (Deere and Patton [2])

Residual soils are considered to be the products of chemical decomposition and a combination of weathering factors influence the resultant soil profile (Townsend [10]):

- climatic conditions during weathering, with rainfall controlling the supply of moisture for chemical reactions and the leaching of soluble constituents of the minerals, while temperature influences reaction rates;
- properties of the parent rock material and rock mass;
- topography and drainage conditions during weathering, which govern the moisture intake by the parent rock and the leaching of soluble constituents of the minerals;
- period over which weathering has been active.

Obviously, the above factors are optimised in rolling, gently sloping terrain in tropical regions, where deep residual soil profiles (up to 50 m) exist.

The colluvium (or slope wash and slide debris) mantling residual soils is a product of physical disintegration, which involves the processes of mechanical abrasion, erosion, etc.

The weathering processes result in a dramatic alteration in the strength and permeability characteristics of the parent rock slope so as to increase its susceptibility to failure. Relict discontinuities, such as bedding planes, joints, foliations and faults, which are inherited from the parent rock mass further reduce the stability of the slope. Although apparently stable under normal conditions, instability frequently occurs during periods of intense rainfall or during excavation.

Rainfall-landslide relationships have been established in different geological and meteorological settings, but that established in Hong Kong by various authors, including Lumb [6], Brand et al. [1] and Kay et al. [5], are considered as models in many countries.

Common Modes of Slope Instability

The modes of instability are closely associated with the geological settings, which may be broadly divided into two classes (Deere and Patton [2]):

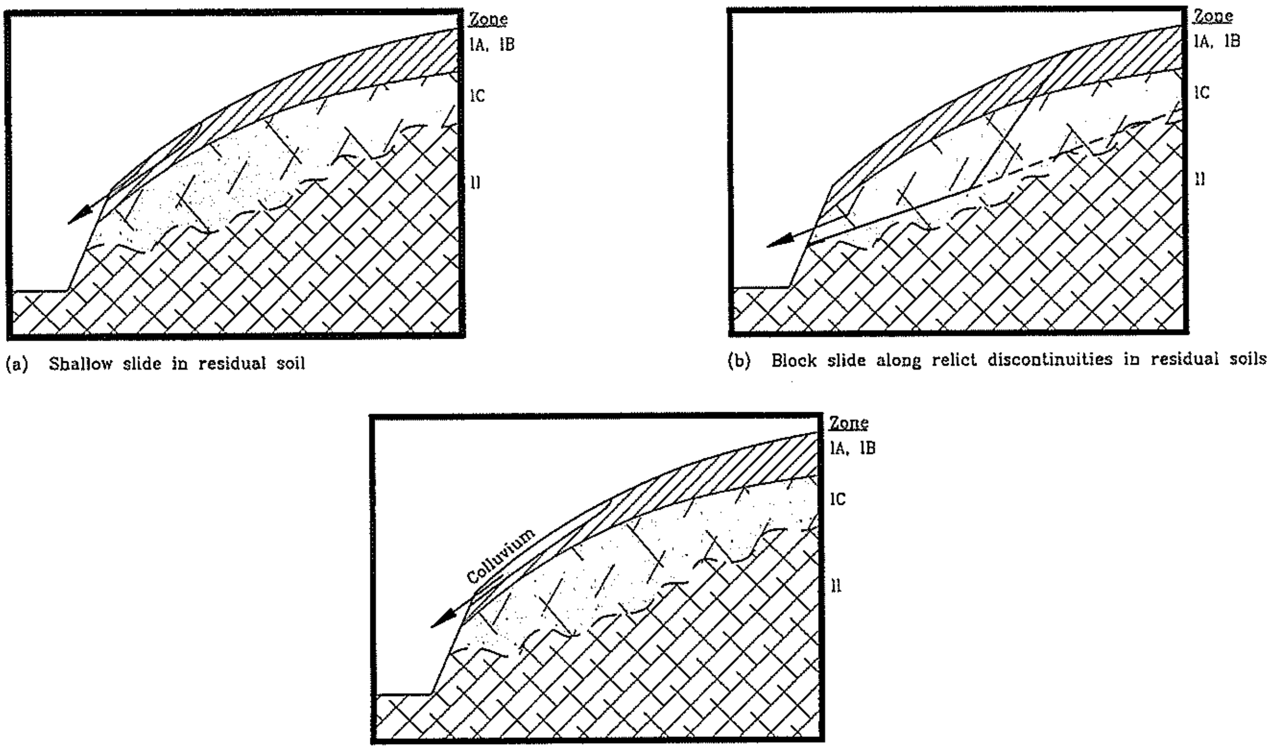
- **massive homogeneous rock**, such as granite, gneiss, thick-bedded sandstone, etc.;
- **anisotropic rock structure**, characterisedby schist, slate, thin or interbedded shale and sandstone, etc.;

As highlighted previously, the residual soil profiles in the above geological settings are different and each may be mantled in colluvium.

In a geological setting consisting of massive homogeneous rock, adversely orientated relict discontinuities are not frequently encountered. Therefore, the most common mode of instability comprises shallow slides, as shown in Figure 2a. These slides frequently occur during periods of intense rainfall.

By comparison, in areas where anisotropic rock structure predominates, adversely orientated relict discontinuities invariably exist. Therefore, the most common mode of instability comprises block slides along relict discontinuities, as shown in Figure 2b. Such slides may occur as the slope is excavated or during periods of intense rainfall, and are the principal consideration during slope design.

Slides in the colluvium, as shown in Figure 2c, are also common following a period of intense rainfall.



(a) Shallow slide in residual soil

(b) Block slide along relict discontinuities in residual soils

(c) Ravelling of thin colluvium

Figure 2 Common modes of instability in residual soils and colluvium

SHEAR STRENGTH PARAMETERS

A number of studies on the stability of slopes in residual soils and the shear strength characteristics of residual soils have concluded that:

- the only type of stability analysis that is valid is an effective stress analysis;
- rational selection and grouping of samples for effective stress shear strength testing is important;

- effective stress shear strength testing should be undertaken in the stress range appropriate to the particular slope stability problem;

- residual soils are typically partly saturated and the resultant soil suction (i.e. negative pore-water pressure) contributes to an increase in the shear strength and hence slope stability;

- the influence of relict discontinuities on the bulk shear strength of residual soils is important.

Discussions on the above are presented in the following subsections.

Effective Stress Analysis

The use of an effective or total stress analysis depends upon whether the stress change likely to cause failure is imposed under conditions which allow only negligible or rapid dissipation of the excess pore-water pressure. The principal factor governing the likely drainage condition is the coefficient of consolidation (c_v) which is given by the expression:

$$c_v = k/m_v\gamma_w \qquad (1)$$

where k denotes the coefficient of permeability, m_v denotes the coefficient of volume compressibility, and γ_w denotes the unit weight of water.

Since residual soils are the products of leaching under high rainfall, they exhibit relatively high bulk permeabilities, ranging from 10^{-6} to 10^{-7} m/s (Townsend [10]). They also exhibit relatively low compressibility due to cementation. Therefore, based upon equation (1) residual soils have high c_v values which will result in rapid drainage, and hence only an effective stress analysis is valid.

Rational Selection and Grouping of Samples

For the laboratory measurement of shear strength under controlled drainage conditions, we are largely dependent upon triaxial compression tests on undisturbed soil samples. The effective stress shear strength parameters, i.e. cohesion (c') and angle of internal friction (ϕ'), may be determined from either a consolidated-drained (CD), or a consolidated-undrained test with pore-water measurements (CUP). The CUP test (multi-stage or series of single-stage tests) is commonly used, being a quick test.

It is common to see the test results plotted on a t-s' diagram (or a q-p' diagram) with a large scatter of the results about the best fit failure envelope. The scatter is largely due to the lack of attention to variations in strength in the residual soil profile. The selection of samples for testing and grouping on t-s' diagrams (or q-p' diagrams) should be undertaken based upon strength indicators such as SPT N values, void ratio (or moisture content) measurements, or visual examination (i.e. 'thumb test'). The author has found that the above procedures generally reduce the scatter considerably and typical results are presented in Figure 3.

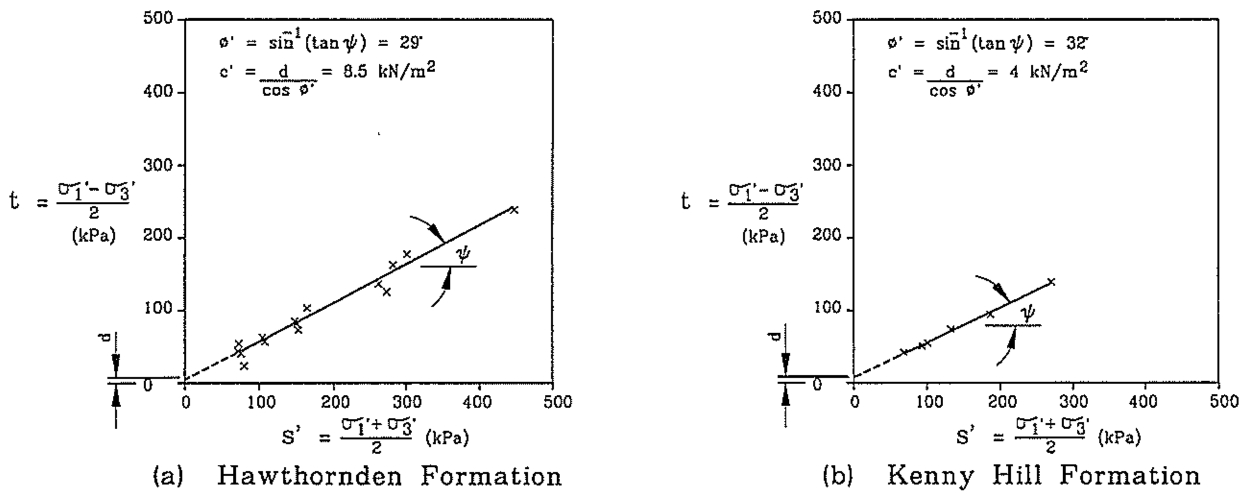


Figure 3 **Shear strength data for residual soils in Kuala Lumpur, Malaysia, obtained from CUP triaxial tests**

Stress Range for Testing

An important aspect of effective stress strength testing in relation to slope stability is the choice of the appropriate stress range, due to the non-linear nature of the failure envelope. As highlighted previously, shallow slides are the most common mode of instability, and therefore triaxial tests should be undertaken at low effective confining pressures, representative of those existing along shallow potential failure surfaces. A typical failure envelope for residual soils in Hong Kong is shown in Figure 4, where at low stress levels, ϕ' increases but c' reduces. However, since a long extrapolation to the ordinate axis is not required, measured c' values may be regarded as reliable.

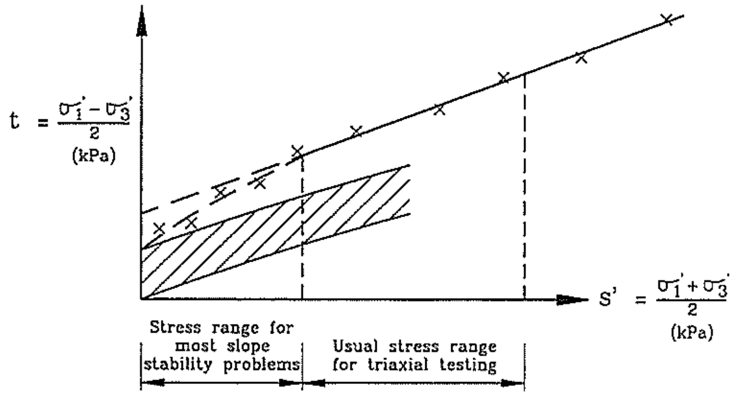


Figure 4 Appropriate stress range for triaxial testing (Sweeney et al. [9])

In selection of these stresses for CD or CUP triaxial tests, the slope of the stress path should be taken into account, as shown in Figure 5.

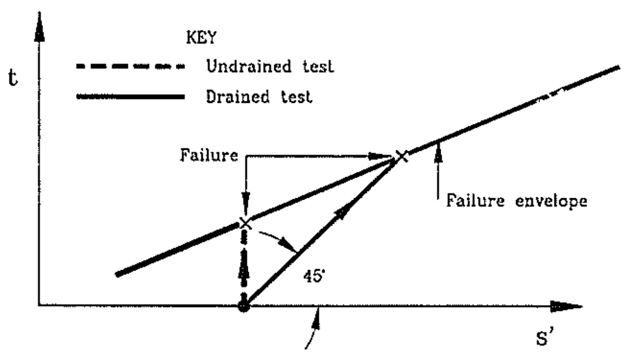


Figure 5 Stress paths for triaxial tests

Soil Suction

Typically, residual soils are partly saturated and the resultant soil suction (i.e. negative pore-water pressure) contributes to an increase in the shear strength of the soil, and hence slope stability. The shear strength equation for saturated soils is given by the expression:

$$\tau_f = c' + (\sigma - u_w) \tan\phi' \qquad (2)$$

where τ_f denotes the maximum resistance to shear on any plane, σ denotes the normal total stress, and u_w denotes the pore-water pressure.

By comparison, the shear strength equation for unsaturated soils, proposed by Fredlund et al. [3], is given by the expression:

$$\tau_f = c' + (\sigma - u_a) \tan\phi' + (u_a - u_w) \tan\phi^b \qquad (3)$$

where u_a denotes pore-air pressure, and ϕ^b denotes the angle of internal friction with respect to change in matric suction, i.e. (u_a-u_w).

For convenience, equation (3) may be rewritten by grouping terms independent of normal stress as:

$$\tau_f = C + (\sigma - u_a) \tan\phi' \qquad (4)$$

where C denotes $c' + (u_a-u_w) \tan\phi^b$.

Therefore, the influence of soil suction can be considered as an increase in the cohesion of the soil (Fredlund et al. [4]) which in turn contrbutes to slope stability. Soil suction can be determined by field measurements using a tensiometer, or in a laboratory by testing soil samples at their natural degree of saturation.

However, soil suction is generally discounted in stability analysis because the well-developed internal drainage of residual soils is conducive to water infiltration (Townsend [10]), with subsequent reduction in soil suction, soil strength and stability with time. This emphasises the importance of surface protection of slopes against water infiltration by such methods as a layer of "chunam" (soil-cement and lime plaster) and thick vegetation.

Effect of Discontinuities on Shear Strength

As highlighted previously, relict discontinuities such as bedding planes, joints, foliations and faults are frequently encountered in the residual soil profile, and their influence on the bulk shear strength is important. In a series of tests, Skempton and Petley [8] demonstrated that the formation of discontinuities resulted in the total loss of the cohesive component of shear strength (i.e. $c' = 0$), with the ϕ' value remaining unaltered. However, the bulk shear strength may exhibit a considerable cohesive component, although the magnitude would depend upon the spacing of discontinuities.

It should be noted that where past shear deformation has occurred along a discontinuity, the angle of internal friction assumes a residual value.

GROUNDWATER CONDITION

As highlighted previously, the only type of stability analysis that is valid is an effective stress analysis. To undertake an effective stress analysis, it is essential to obtain a best estimate of the equilibrium value of the pore-water pressure which will act on potential failure surfaces, which in turn requires an appreciation of:

- the change in groundwater table due to excavation;
- the rise in groundwater table during periods of intense rainfall;
- perched water table.

Discussions on the above are presented in following subsections.

Change in Groundwater Table Due to Excavation

To evaluate the stability of cut slopes, it is essential to estimate the drawdown in the groundwater table resulting from the excavation of the slope, and after steady state conditions are achieved. General solutions for estimating the drawdown are not available, but a solution for incompressible material with drainage occurring from the voids within the soil as the groundwater table lowers, has been proposed by Nguyen and Raudkivi [7]. The soil properties required are the coefficients of permeability (k) and voids storage (S_v).

Rise in Groundwater Table

Pore-water pressures in slopes are likely to change substantially with changes in rainfall if the c_v value of the soil exceeds about 0.1 m^2/day (Wesley [11]), which is so for residual soils. Typically, the groundwater table is low during dry season, but rises significantly during periods of intense rainfall. A rise in the groundwater table influences slope stability by:

- increasing the pore-water pressure on potential failure surfaces, and consequently reducing the effective stress and shear strength (significant effect);

- reducing the soil suction, and consequently shear strength (potentially significant effect);

- increasing the weight of the sliding mass due to an increase in the bulk unit weight (minor effect).

The combination of factors results in slope instability, and therefore, it is essential to predict the rise in groundwater table due to the "maximum possible precipitation" (or "probable maximum precipitation") during the design life of the relevant project. This requires an appreciation of the following hydrogeological factors:

- the residual soil profile and variations in permeability;

- the intensity and duration of rainfall;

- the regional topography;

- surface protection of slope.

Perched Water Table

Considerable variations in permeability are frequently encountered within the residual soil profile. The sequence of a relatively high permeability layer overlying an impermeable layer frequently results in a local build up of pore-water pressure, or perched water table, and consequently instability. However, the scale of instability is likely to be small.

For example, the colluvium is often more permeable than the underlying layers, resulting in perched water tables during periods of intense rainfall, and consequently the ravelling of colluvium.

APPROPRIATE FACTORS OF SAFETY

In slope design, the factor of safety is defined as the ratio of the actual strength available and that mobilised, with the mobilised shear strength being equal to the destabilising force. Conventionally, this is incorporated in design as a single factor of safety. The purpose of a factor of safety is to take account of significant uncertainties and the appropriate value for design depends upon:

- the nature of the site investigation programme to establish the characteristics of the weathered profile, probable mode of instability, appropriate shear strength parameters along potential failure surfaces, and groundwater conditions;

- risk of reduction in shear strength due to an increase in pore-water pressure after intense rainfall;

- risk of increase in the destabilising force due to removal of the slope toe (either by geomorphological, or man-made processes), or "live loading" at the head of the slope (by construction plant, earth fill stockpile, etc.), or seismic loading;

- necessity to limit ground deformation;

- limitations of existing methods of analysis.

Two distinct approaches frequently adopted in determining an appropriate factor of safety are:

1. **Most probable** shear strength parameters, groundwater conditions and loads are selected, and a generous factor of safety, between 1.3 and 1.5, is considered;

2. **Most unfavourable conceivable** shear strength parameters, groundwater conditions and loads are selected, and a lower factor of safety is considered.

Regardless of the approach adopted, a sensitivity study to develop an appreciation of the relative importance of the various factors influencing slope stability is essential.

CONCLUSION

The advent of computers has made methods for the analysis of potential circular and non-circular failure surfaces very simple. However, there are many problems associated with the application of these methods for the design of slopes in residual soils due to significant uncertainties regarding the characteristics of the weathered profile, the probable mode of instability, appropriate shear strength parameters along potential failure surfaces, and groundwater conditions. This paper has examined the above factors which would need to be carefully considered while preparing a site investigation programme for slope design. Important points include:

- a sound understanding of the geological setting is required to establish probable modes of instability;
- the site investigation must determine the variation in the strength and permeability characteristics within the residual soil profile;
- the site investigation must identify any relict discontinuities within the residual soil profile;
- the only type of stability analysis that is valid is an effective stress analysis;
- effective stress shear strength testing should be undertaken in the stress range appropriate to the problem;
- the influence of relict discontinuities on the bulk shear strength of residual soils is important;
- groundwater observations to develop an appreciation of hydrogeological influences is important;
- a sensitivity study to develop an appreciation of the relative importance of the factors influencing slope stability is essential.

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