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ENGINEERING GEOLOGY AND HAZARD ASSESSMENT OF EXCAVATED CHINA CLAY SLOPES

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Hazard assessment and recognition of slope instability mechanisms is becoming increasingly important in the china clay industry particularly in view of recent implementation of the Quarries Regulations. The engineering characterisation of kaolinised granite is complicated due to the inherent variability of alteration grade within a particular slope. Case examples are used to highlight the wide range of slope mechanisms that may be present within a particular pit as a consequence of variation in alteration grades. A review of proposed approaches to characterisation is given together with suggestions for future design strategies.

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INTRODUCTION

One consequence of implementation of the Quarries Regulations (1999) is that hazard identification, subsequent evaluation and associated risk assessment will become increasingly important in the Extractive Industries. Quarry management will need to identify potential hazards in order to initiate, if required, more detailed geotechnical appraisal of critical areas/slopes that are deemed to pose a significant risk. Hazard identification and an understanding of slope instability mechanisms are therefore considered critical.

Hazard identification within the china clay industry requires appropriate characterisation of altered or kaolinised granite. A considerable number of investigations have been conducted in recent years on the engineering properties of china clay in the south-west of England. In depth description of weathered granites from Hong Kong have also been well documented by several researchers. This paper presents a critical summary of the engineering properties of altered granites together with an appreciation of the difficulties encountered in assigning alteration grades, particularly where alteration can vary both laterally and vertically. The factors controlling the stability of china clay slopes are evaluated with a view to development of hazard and risk assessment procedures. Case studies are used to highlight potential slope failure mechanisms, review the techniques used in stability analysis and highlight suggestions for future design strategies.

ENGINEERING CHARACTERISATION OF KAOLINISED GRANITE

Several researchers including Baynes and Dearman (1978), Dearman *et al.* (1978), Irfan and Dearman (1978) and Hencher *et al* (1990) provided important guidelines on the description and characterisation of kaolinised granite in the south-west of England. Likewise Hencher *et al.* (1984, 1990), Hencher and McNicholl (1995) and Irfan (1996, 1998 and 1999) provided details of the characterisation of the weathered granites of Hong Kong. Of particular importance when undertaking hazard assessment is an awareness of the available approaches for detailed engineering characterisation of weathered or altered granite. Characterisation of weathered or altered rock usually involves categorisation into classes, zones or grades according to readily recognised or simply measured changes in their characteristics, that are perceived to indicate significant changes in engineering behaviour. The available approaches for engineering characterisation are summarised in the description and classification of weathered rocks suggested by the Geological Society Engineering Group Working Party (Anon 1995).

Table 1 summarises typical weathering grades associated with weathered or altered granites. Also included in the table is reference to the zoning method associated with description of Heterogeneous Masses (Anon 1995). The scheme assigns a six-zone weathering classification system for rocks that develop a mixture of relatively strong and weak material in the mass. Irfan (1999) noted that this system is broadly similar to that developed by the Geotechnical Control Office of Hong Kong. Hencher and McNicholl (1995) emphasised that weathered rock could be notoriously variable and unpredictable, making use of any of the suggested methods difficult.

Characterisation of china clay slopes can be particularly complex as they often contain a combination of intensely kaolinised together with relatively unkaolinised granite in varying proportions. The kaolinisation intensity can vary both vertically and laterally along the slope profile. Pine *et al.* (1994) noted that kaolinisation is structurally controlled and generally occurs in association with sheeted greisen, tourmaline and quartz veining. Exley (1959), in study of the St Austell granite, recognised that kaolinised zones were typically orientated parallel to NW-SE and ENE-WSW striking structures. Hencher *et al* (1990) also suggested that the intensely kaolinised zones occurred in association with abundant quartz veins, which tended to be less frequent in the unaltered zones. Alteration was also noted to decrease laterally away from such veins. An example of the distribution of alteration of the coarse-grained biotite granite within the Bodelva China Clay Pit is described by Mueller *et al.* (1999). The completely altered granite was found to be spatially confined within two narrow (50-100m wide) zones. In this particular pit the contacts between individual stages of alteration were normally fairly sharp, and in places spatially related to single quartz-tourmaline or other veins. In some areas, however, variation in alteration was on a smaller scale. Mueller *et al.* (1999) also provided details of mineralogical and textural changes within identified different alteration grades within the biotite granite.

Hencher *et al* (1990) indicated that the kaolinised zones of St. Austell granite show many similarities to tropically weathered granites and can be classified for engineering purposes according to similar criteria. They also noted good correlation between alteration and Schmidt hammer rebound value (Figure 1), feldspar decomposition, field strength and degree of slaking. The hand penetrometer was, however, found not to be useful for differentiating between grades of alteration in the granites of south-

GRADE	DESCRIPTION	CHARACTERISTICS
I	Fresh Rock	No visible alteration. Requires many hammer blows
II	Slightly Altered	Slight discolouration and weakening. Schmidt Hammer 'N' > 45. More than one hammer blow to break.
III	Moderately Altered	Considerable weakening. Penetrative discolouration. Single hammer blow breaks rock. Schmidt hammer 'N' 25-45.
IV	Highly Altered	Large pieces broken by hand. Schmidt hammer 'N' 0-25.
V	Completely Altered	Considerably weakened. Geological Pick penetrates. Original texture preserved. Slakes readily in water. Hand penetrometer 50-250 kPa
VI	Residual Soil	Soil mixture with no rock texture. Penetrometer < 50 kPa

a) Uniform materials

ZONE	GRADE PROPORTIONS	DESIGN ISSUES
1	100% GI-III	Apply rock mechanics principles
2	90% GI-III <10% GIV-VI	Weak materials along discontinuities
3	50 to 90% GI-III 10 to 50% GIV-VI	Rock framework controls strength and stiffness.
4	30 to 50% GI-III 50 to 70% GIV-VI	Rock framework contributes to strength. Alteration products control stiffness.
5	<30% GI-III >70% GIV-VI	Weak grades control behaviour. Corestones very important.
6	100% GIV-VI	May behave as a soil.

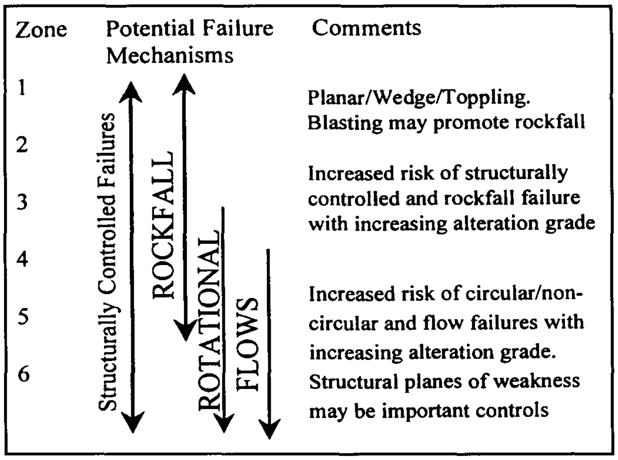
b) Heterogenous rocks

Table 1. *Classification for a) uniform materials and b) heterogeneous rocks (modified after Anon 1995).*

west England because the penetration resistance of the materials was greater that that measurable by the instrument. This led to the development of an alternative knife penetration test (Hencher et al. 1990) for correlation with laboratory shear box tests.

Although the grades in Table 1 provide useful guidelines, Hencher and McNicholl (1995) suggested that misinterpretation is still possible where structural features throughout the mass potentially control the engineering behaviour of the material. It is important, therefore, to establish not only the distribution of different alteration grades but also likely influence of structural features. Once this has been performed the next stage is to delineate engineering zones and to assign parameters to enable engineering slope design.

In the literature there is limited reference to shear strength estimates for varying alteration grade material. This is probably due to difficulties in provision of representative testing over the range of alteration grades; from essentially fresh rock through to residual soil. Dearman et al. (1978) provided useful information relating to shear strength characteristics of varying alteration grade, but comment on the difficulties of providing design shear strength values. They note that the lack of published data is indicative of an unwillingness to prescribe design values, which may be inappropriate. Shear strength parameters for completely altered material have been more widely published. Pine et al. (1994), for example, provided details of the assessment of the risk of failure of a china clay slope in grade V material.



Planar/Wedge/Toppling. Blasting may promote rockfall

Increased risk of structurally controlled and rockfall failure with increasing alteration grade

Increased risk of circular/non-circular and flow failures with increasing alteration grade. Structural planes of weakness may be important controls

Table 2. *Relationship between alteration grade/zone and slope failure mechanism.*

In view of the possible limitations of prescribed zonal weathering/alteration classifications for describing site specific conditions, Hencher and McNicholl (1995) suggested a range of alternative approaches that could be considered for weathered rock. These approaches may have particular application for the china clay industry. The possible approaches are schematically represented in Figure 2 and vary according to the degree to which zones can be regarded as uniform or heterogeneous and intact or discontinuous.

Use of option 2 has been considered for china clay characterisaton using the Geological Strength Index (GSI) concept suggested by Hoek (1998). Sonmez and Ulusay (1999) highlighted the usefulness of the approach for slope stability investigation. Current research at the Camborne School of Mines indicates that the technique shows promise for use in the china clay industry but requires further refinement to include weathered/altered material. The concept is particularly useful when the rock mass is considered as being pseudo-homogeneous. Great difficulty occurs in determining realistic engineering parameters when dealing with heterogeneous rock masses. It is not feasible to test samples, for example, at a scale representative of the rock mass. Back analysis of previous failures in similar material becomes the best source of design data for such cases.

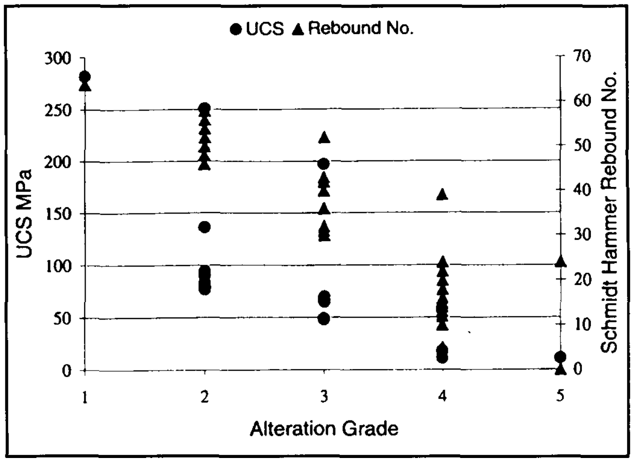


Figure 1. *Effect of alteration grade on strength (based on Hencher* et al. *1990)*

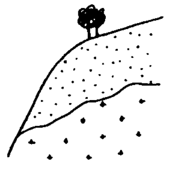
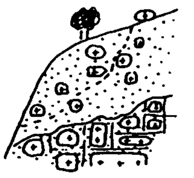
Option	Schematic diagram	Approach
1. Treat as Uniform (continuum)		• parameters from laboratory or in-situ tests considered representative of zone
2. Treat as uniform but mass weakened by discontinuities (continuum)		• allowance made for influence (but not control) of discontinuities on mass properties
3. Treat as heterogeneous (continuum)		• consideration given to influence of strong inclusions
4. Treat as discontinuous due to structural control (discontinuum)		• discontinuity controlled • weathering effects on discontinuity properties to be accounted for

***Figure 2.** Approaches for analysis in weathered zones (after Hencher and McNicholl 1995).*

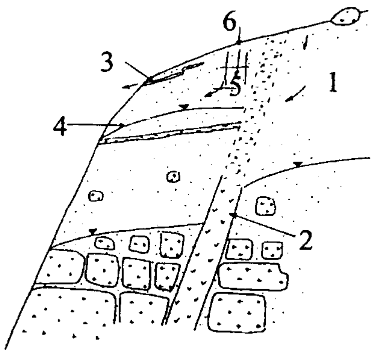
When assessing the possibility of discontinuity controlled behaviour (option 4 in Figure 2) it is important to consider the contribution of relict features within china clay slopes. Dearman *et al* (1978) provided guidelines on typical joint shear strength parameters and suggested that design should be based on these features should they be unfavourably orientated. From the above discussion it is clear that the engineering design of china clay slopes is complex in view of the potential variability of material, both laterally and vertically within any particular slope.

POTENTIAL INFLUENCE OF GROUNDWATER

Hencher and McNicholl (1995) provided a useful discussion of the potential detrimental influence of groundwater for weathered profiles. As illustrated schematically in Figure 3, groundwater distribution and flow can be highly complex in weathered rock masses. Of particular importance is the difficult problem of determining the permeability of slopes containing mixed alteration grades/zones. This may result from behavioural changes with moisture content, piping and associated erosion or build-up of pore water pressures. Effective water management, particularly control of surface run-off during heavy rainfall, is considered essential to avoid any associated slope instability.

SLOPE FAILURE MECHANISMS AND ANALYSIS

Table 2 summarises the potential failure modes likely with different alteration grades within kaolinised granite. As alteration increases there is a transition from rockfall/rock slides to more rotational type failures. The potential controlling influence of discontinuities cannot be discounted throughout the alteration range, particularly where relict features exist. There is also an increasing potential for flowslides within completely altered material.



1. **Permeability may be high or low depending on alteration grade.**
2. **Preferential alteration may cause barriers (high water pressures) or act as conduits.**
3. **Piping along pre-existing fractures.**
4. **Perched water tables due to infilled fractures or differential alteration.**
5. **Fracture flow may dominate, particularly in grades II-III.**
6. **Potential for collapse/slaking due to excessive surface water infiltration.**

***Figure 3.** Structural/alteration controlson groundwater flow (modified after Hencher and McNicholl 1995)*

Hencher *et al.* (1984) highlighted the value of field studies in providing information on the mechanisms that control slope failure in weathered granites. Coggan *et al.* (1998) provided a review of the application of various investigative techniques for analysis of quarry slope behaviour. This included analysis using kinematic, deterministic, probabilistic and numerical modelling techniques. Emphasis was also given to application of both continuum and discontinuum numerical models, together with a need to utilise either two or three-dimensional analysis. Recent back analyses of failures from china clay slopes have utilised both a limit-equilibrium and a numerical modelling approach. Pine *et al.* (1994), for example, used conventional limit-equilibrium techniques to assess the potential for circular or rotational failure in grade V material. This particular slope was further analysed by probabilistic methods to assess the impact of varying input parameters, such as shear strength and hydrogeological conditions, prior to performing numerical modelling with FLAG (Itasca 1995).

An example of the use of numerical modelling, to highlight its

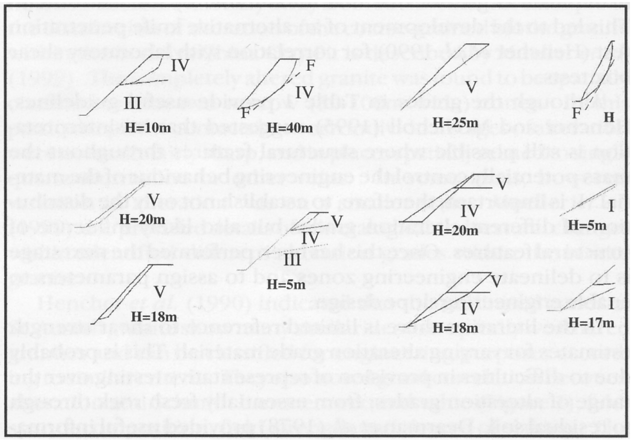


***Figure 4.** Failure mechanisms in recently analysed slopes containing grade IV/V altered granites.*

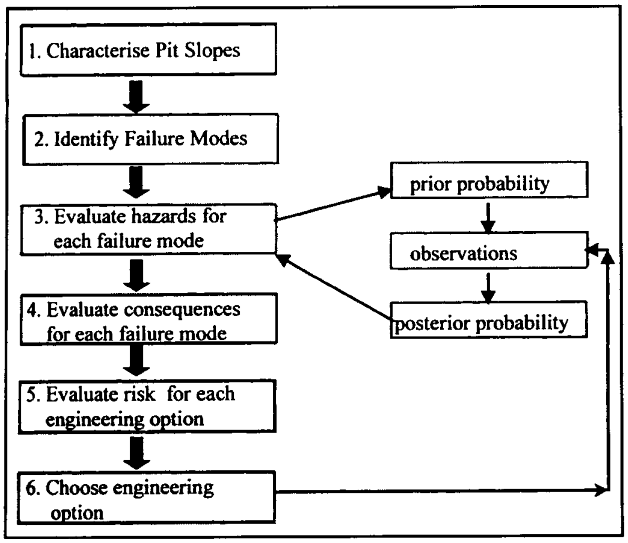


Figure 5. *Decision making process: pit slope design.*

potential application to more complex scenarios that would be difficult to analyse with conventional limit equilibrium techniques, is provided by Coggan *et al.* (2000). The complex scenario analysed included a discontinuity-controlled failure that resulted in a flow slide. Figure 4, based on work by Karim (1987), provides a visual indication of recently analysed slopes from Virginia and Treviscoe china clay pits. Slope heights analysed varied from 5 to 30m. The marked planar failure surfaces frequently observed in-situ suggest a controlling influence of discontinuities on the stability of slopes comprised of mixed alteration/grade material.

HAZARD AND RISK ASSESSMENT

Hazard and risk assessment is important not only as a safety issue but also from an overall economic viewpoint in terms of optimisation of the resource. Hazard and risk can also be evaluated on different scales: either an individual bench or the overall slope. The potential for failure by a variety of mechanisms can then be assessed accordingly. Figure 5 provides a typical flowsheet that could be used within the decision making process associated with pit slope design. This is based on methodologies used for landslide risk assessment (Cruden and Fell 1997). Engineering characterisation of china clay pit slopes allows hazard assessment, risk evaluation and the choice of appropriate design measures. The importance of updating both hazard and risk assessment through observations made during extraction/ mining is emphasised.

It is envisaged that qualitative hazard zonation mapping and increasingly sophisticated quantitative risk analysis techniques (QRA), including fault trees, decision trees and probabilistic analysis will become more familiar to the quarrying industry. An example of the use of probabilistic analysis applied to the china clay industry was given by Pine *et al.* (1994). Techniques, methodologies and approaches developed within landslide risk assessment/hazard zonation have direct application to the quarrying industry. An excellent source of information can be found in Turner and Schuster (1996). Techniques such as 'rockfall hazard rating' (Bunce *et al.* 1997), risk maps, digital elevation models, use of laser profiling and utilisation of a GIS (Geographic Information Systems) approach may become increasingly routine.

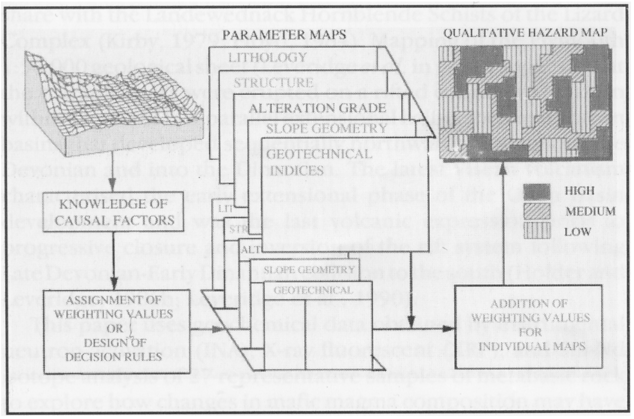


Figure 6. *Use of GIS in slope design (modified after Turner and Schuster 1996).*

Recent work has highlighted the use of a digital elevation model for improved visualisation of a current china clay pit. Improved hazard evaluation has been possible by use of colour-coding within the digital elevation model; an example being use of different colours to represent different slope angles. In view of the potential difficulties of access to existing slopes increased use may also be made of photomodelling techniques (Grainger and Kalaugher 1996). Coggan *et al.* (2000) highlighted the use of laser profiling technology to monitor slope regression. Figure 6, modified after Turner and Schuster (1996), provides an indication of how alternative approaches such as a GIS approach could assist hazard zonation. Clearly the basis for successful implementation of all, or some, of these techniques is sound engineering characterisation of the china clay material and an early identification of likely failure modes.

CONCLUSIONS

The characterisation of kaolinised granite is complex in view of the inherent variability of alteration within a slope. Critical review of previous research suggests that there is still a need to undertake a comprehensive study of alteration of kaolinised granites in the south-west of England from an engineering design viewpoint. A GIS approach could be used to correlate the spatial relationships between lithology, alteration grades, mineralogy, geotechnical parameters and hydrogeology.

The analysis of structurally controlled flowslides in china clay pits is difficult in view of limitations of existing software. Developments need to be made to analyse the whole failure process, from initial trigger through to debris flow. The potential use of debris flow models, such as that described by Ayotte *et al.* (1999), may provide useful analysis of flows to predict potential risk due to associated run-out. There remains, however, a general need for improved coupling of groundwater flow for stability analysis of china clay slopes.

Routine hazard/risk assessment procedures need to be developed in view of the new Quarries Regulations. Management of this system requires development of appropriate databases. Techniques currently used for hazard/risk evaluation within landslide investigation, analysis and mitigation should be incorporated by the Extractive Industries. This includes evaluation of factors such as vulnerability, travel distance (of failed mass), hazard mapping and hazard zonation.

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