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Investigation by centrifuge modelling of the effects of the vertical geosynthetic reinforcement on the stability of steep slopes in clay

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ABSTRACT: Vertical geosynthetic reinforcement has been installed in a number of slope stabilisation schemes in the UK and brief details are given. A centrifuge model study has been undertaken in an attempt to quantify the possible benefits of such vertical reinforcement in steep, uniform slopes of compacted clay as a precursor to attempts to model some of the field situations.

1. INTRODUCTION

The stabilisation of existing slopes by the use of geosynthetics surrounded by cohesionless backfill, placed in narrow vertical trenches normal to the slope surface has been demonstrated by Barker et al. (1989, 91). This paper gives brief details of further field examples of such vertical reinforcement and then presents the results from the first stage of an experimental investigation into these techniques using a centrifuge modelling approach.

2. FIELD WORK

A total of five projects incorporating vertical reinforcement have been completed and two further projects have been taken to tender stage in the UK in the period 1984 to 1996. All the completed projects have been carried out using an hydraulic excavator digging the entire length of the trenches and rapidly installing the geosynthetic reinforcement and base drain and backfilling with crushed stone drainage media.

Of the two projects not constructed, one is currently due to commence and the other was not proceeded with, despite offering considerable savings. These have been planned to be installed using different techniques from each other and from the other group of projects: one in Crockham Hill, Kent has long trenches dug by excavators in 5m sections, installing and backfilling with granular backfill in stages a continuous length of reinforcement the length of the trench; the other near Godstone, Surrey using a large chain-and-bucket trenching machine installing a continuous length of reinforcement into granular backfill the length of the trench. This latter method is likely to provide the quickest and least cost slope stabilising installations once it has been refined. Because this type of project and method of installation is likely to be the most important application of the technique the Godstone project will be used as a prototype for the second stage of the centrifuge research project outlined in this paper.

Brief details of the projects referred to above are as follows:

- Larkfield Car Park Site Formation, Maidstone, Kent in clay cut and site won fill: 1.5m deep in 1.5m high 200m wide 45° slope at 2m centres using Tensar SS2 polypropylene geogrid connected to surface laid geogrid - constructed 1984.
- Frindsbury Peninsular Flood Bund, Rochester, Kent in surplus site won materials: 1.75m deep in 3m high 120m wide 30° slope at 2m centres using Geolon 70 woven polypropylene

geotextile reinforcement connected to surface laid geogrid over erosion control matting - constructed 1988.

- Bayley's Hill Tennis Court Cut Slopes, Sevenoaks, Kent in Atherfield Clay: 1.75m deep in 5m high 30m wide 18° slope at 5m centres using Rehau Raugrid 55/30-15 pvc-coated polyester geogrid reinforcement - constructed 1990.
- Affydown Phase 2, Toys Hill, Kent in site won Atherfield Clay fill: 1-1.75m deep in 25m long trenches in 50m wide 15-30° slope at 10m centres using Rehau Raugrid 55/30-15 pvc-coated polyester geogrids either side of unreinforced counterfort drains installed in Phase 1 - Phase II constructed in 1992.
- M25 Motorway Slope Failure near M25 Interchange, Godstone, Surrey in Gault Clay: 5.5m deep 55m long trenches in 300m wide 10° slope at 12.5m centres using pvc-coated polyester geogrid reinforcement Fortrac 110/100-10 - priced by the Contractor with a saving of £50-70,000 on a total project cost of £300,000 in 1993.
- Cobden Gardens Slope & Toe Wall, Southampton, Hampshire in London Clay: 1.75m deep connected to a 3.5m high 10m long 80° geotextile reinforced lightweight fill wall at 2.4m centres using Rehau Raugrid 35/20-15 pvc-coated polyester reinforcement - constructed 1993/94.
- Crockham Hill Village Hall Slope Retention, Edenbridge, Kent in Atherfield Clay: 3.5-1.5m deep 10-15m long trenches in 20m wide section of 10° slope at 5m centres behind 3m high Rehau Raugrid 35/20-15 geogrid reinforced soil wall and 1.5-3m deep in 5-10m long trenches in adjacent 30m wide 15-20° regraded slopes using UCO SG100/100 polyester geotextile reinforcement - construction due May-June 1996.

3. CENTRIFUGE MODEL WORK

The technique of centrifuge modelling in geotechnical engineering is now well established - see reviews in Craig et al (1988), Corte (1988), Ko and MacLean (1991) and Leung et al. (1994). There has been some work in the area of modelling geotextiles, e.g. Ovesen & Krarup (1983), Porbaha & Goodings (1994), but no previous models of vertical geotextile reinforcement have been reported.

In an ideal model of a given field situation, a prototype reduced by a linear scaling of 1/N should be subjected to a sustained centrifugal acceleration N times greater than the earth's gravitational acceleration, so that all self-weight stresses are identical to those in the field. This is a prime requirement in modelling with geotechnical materials where behaviour in shear is critically dependent upon the ambient pressure conditions - this is true in both tension and compressive zones. Once subjected to this increased acceleration regime, engineering processes can be simulated at the reduced scale.

Since excavation of narrow trenches, the placement of small scale reinforcement and of trench backfill cannot be simulated aboard the centrifuge at present a simplified approach has been adopted to assess comparative performance of models with different degrees of reinforcement. A simple 60° clay slope above a stiff cohesionless base layer has been adopted. Vertical trenches have been excavated, reinforced and backfilled on the laboratory floor, under unit gravity conditions, and then subjected to steadily increasing accelerations, in a consistent manner for all models, aboard the large geotechnical centrifuge in Manchester University described by Craig & Rowe (1981). As the accelerations were built up in stages the slopes became more heavily stressed and greater proportions of the available shear resistance were mobilised until the slopes ultimately collapsed. Comparison is possible in terms of the mechanisms of failure observed and the levels of acceleration sustained.

Two clay materials have been used, a remoulded glacial till, Cowden clay (PI = 23) and a more plastic Derwent clay (PI = 31). Each was mixed to a uniform moisture content. Minor variations between clay strengths in different models are taken into account, below, by the use of dimensionless groupings in the analysis of performance.

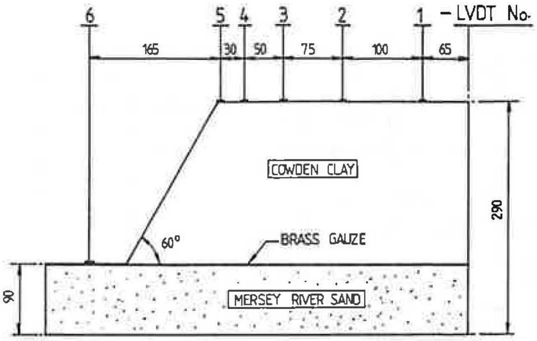


Figure 1 Cross-section through models

This is a common approach in model testing.

4. DESCRIPTION OF MODELS

The basic cross section of each model was as shown in Figure 1, with a 200mm high, 60° clay slope cut into an initially uniform bed of clay compacted in 30mm layers into a model container, 545mm square internally, above a 90mm basal layer of dense sand with a wire mesh at the interface to prevent the clay punching into the sand on initial compaction. The presence of this strong lower layer ensured that only toe failures occurred - preliminary tests with softer foundations had shown deep seated slip failures. Post compaction excavation showed that the clay beds, as prepared, were fully homogenised. Wooden formers lining the sides of the soil container allowed the trimming of the slope to the desired profile.

Trenches for reinforcement were cut, using a purpose made tool, at various spacings,T, across the model width. These trenches were 5mm wide and divided the model into equally spaced bays across the 520mm soil width.

Precut sections of nominally 1:25 scale Tensar SS2 reinforcement were placed in the trenches across the full clay cross-section shown in Figure 1, with the longitudinal members horizontal and the transverse members vertical - in one model only this orientation was reversed. The reinforcement was pressed to one side of the trench prior to backfilling with dry sand. This placement technique, has been adopted in some, but not all of the field constructions - in others the reinforcement has nominally been central to the trench.

In order to obtain a visual indication of the soil distortion within the individual bays vertical columns of dry spaghetti were inserted on the centre line of the bays, in a line perpendicular to the crest at a regular spacing of 20mm. After two or three hours in place the spaghetti softened and subsequently distorted with the clay. The model surfaces were marked with water-based paint to show the formation of cracks and the general pattern of surface deformation on television monitors as the models were rotating in the centrifuge.

Installation of the model box in the centrifuge was a simple matter, with the model central axis parallel to the vertical axis of centrifuge rotation - thus the model 'vertical' actually rotates in the horizontal plane as the centrifugal acceleration is radial and horizontal. There are minor errors in the analysis associated with the radial nature of the centrifugal acceleration field and with the presence of the natural gravitational field normal to the centrifugal acceleration. However these are of second order effect for models of this size in a centrifuge with operating radius of 3m and operating accelerations in excess of 25g and will not be considered here.

Model instrumentation was limited to an array of six displacement transducers (LVDTs) measuring the settlements and heaves of the model surface, as shown in Figure 1. Each LVDT was attached to a 30mm x 10mm plastic footing bearing on the soil surface and had a maximum operating travel of 20mm, i.e 10% of the slope height, H. Two solid state television cameras monitored the model performance during each test - one showing a plan view as seen from the axis of rotation and the other, showing a closer, oblique view of part of the slope face.

Output from the instrumentation was passed through slip-rings to an analogue/digital converter in the centrifuge control room and to a standard PC logging program. Readings were taken every 10 seconds throughout the test running time.

5. RESULTS FROM MODELS

A standard centrifuge speed/time profile was used. From an initial start up to 20rpm (1.3g) the speed was increased by 10rpm

Table 1 - Details of models tested

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
Slope Material (Clay Type)	Cowden Clay	Cowden Clay	Cowden Clay	Cowden Clay	Cowden Clay	Cowden Clay	Derwent Clay	Derwent Clay	Derwent Clay
Model Slope Height (H)	200mm	200mm	200mm	200mm	200mm	200mm	200mm	200mm	200mm
Slope Inclination (β)	60	60	60	60	60	60	60	60	60
Number of Vertical Reinforcements	0	3	5	3	3 Unreinforced Trenches	7	7	0	5
Reinforcement Orientation	N/A	Normal	Normal	Transverse	N/A	Normal	Normal	N/A	Normal
Length of Reinforcement (L_g)	N/A	310mm	310mm	310mm	N/A	310mm	310mm	N/A	310mm
Reinforcement Spacing (T)	N/A	174mm	105mm	174mm	174mm	65mm	75mm	N/A	105mm
Slope Height to Trench Spacing Ratio (T/H)	∞	0.87	0.53	0.87	0.87	0.32	0.37	∞	0.53
Undrained Shear Strength	40	41.3	33.3	34.6	33.5	27	14.2	15.3	15.3

every 100 seconds to 120rpm and thereafter by 5rpm every 100 seconds. Visual observations were recorded in terms of observed cracking at the upper clay surface and bulging of the toes of the clay bays between reinforcements. Once the majority of the LVDTs showed movements beyond their working range, the model was deemed to have failed and the centrifuge was brought to a halt and the model removed for dissection.

Details of the nine tests carried out using the two soils are given in Table 1.

Figure 2 shows model 3, divided into 5 bays after testing and gives an indication of the ultimate overall deformation observed, with bulging of the clay at the slope toe between the trenches and considerable tension cracking at the upper surface.

For the same model Figure 3 shows the time history of measured settlements from the six LVDTs. This is typical of each test. There is in the later stages a clear change in displacement in each 100 second step, but complete equilibrium was not reached. It was decided that rather than wait after each speed change for deformation of the clay to stop, it was better to continue with the speed changes and limit the amount of drainage from the clay bays into the trench sand.

Using the measured deformations and converting from rotational speed to centrifugal acceleration, Ng, the settlements can be expressed in terms of the effective height of the slope. This is defined as the product of the initial model height multiplied by the acceleration factor, N. Such a plot is shown in Figure 4 for the same model. Model failure can be defined in various ways, e.g. by the first formation of surface tension cracks, by the attainment of a specified settlement, or by a total collapse of the slope. Since there was no sudden collapse in any of the models, a limiting settlement criterion might best be used. One basis for comparison between models is to utilise the stability number ($S = c_u/\rho.Ng.H$) or its inverse. This allows a comparison between models in which the undrained shear strength, as measured after the test (from points in the model remote from the partly drained areas close to the trenches) on strip down, varies a little. Also it takes direct account of the increasing unit weight of the soil ($\gamma = \rho.Ng$).

Comparing the settlement for one displacement transducer, position 3, behind the slope crest in each model, the effect of the different reinforcement patterns can be seen in Figure 5.

The data for six models in Cowden clay cover a range from no reinforcement ($T/H = \infty$), to three, five and seven bays ($T/H = 0.87, 0.53, 0.37$). The data for Derwent clay cover zero, five and seven bays. It is clear that in both materials the presence of trenches and reinforcement has allowed the models to sustain a greater level of loading. This can be assessed more directly by comparison of the stability number at identical limiting displacements, Figure 6

The classic value for the stability number at collapse, for a 60° slope in saturated undrained clay is 0.191 (Taylor

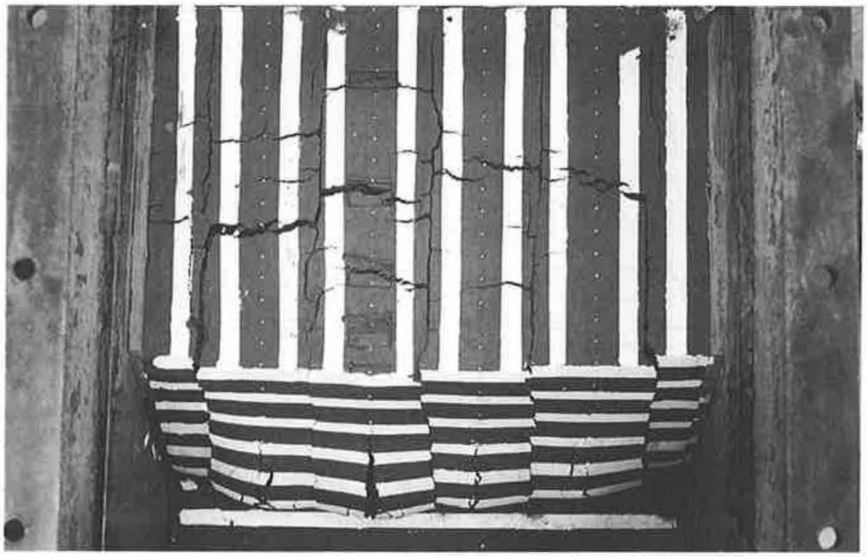


Figure 2 - Model 3 after test

1948), giving an inverse of 5.24. This compares with the values for the unreinforced slopes of 5-7 for Derwent clay at different settlement criteria and 4.3-6.2 for Cowden clay.

The effect of increasing reinforcement is more marked at higher displacements, indicating that some displacement is required to mobilise the reinforcement effect. The group of models in Cowden clay, each with three trenches, but with different reinforcement orientation in two and no reinforcement at all in the third (sand backfill only), show noticeable improvement with the inclusion of transversely orientated reinforcement as against sand alone and further improvement with longitudinal reinforcement. It is clear that part of the improvement in stability is due to the counterfort action of the sand filled trenches in this rather soft clay, with the remainder directly attributable to the geosynthetic grid.

Figure 7 shows a cross section through the spaghetti in one bay of model 7 in Derwent clay. From this the rupture surface in the clay is clearly seen. It should be noted that in all models the geogrid remained anchored in the sand in the trenches and showed no tension failures but only limited shear distortion. In effect the models failed by the clay shearing between the trenches with bulging at the toe in each bay - Figure 2. In the area of the toe the transverse tensile stresses induced at the soil surface by the bulging have caused tension cracks to open along the line of the spaghetti markers. Such cracks might well form in the field, but are accentuated in the models by the stress concentrations associated with the inclusions. Figure 8 shows the change in position of the rupture planes observed in the three Derwent clay models. There were minor variations in position at the different sections in any model, but the pattern is clear - more reinforcement leads to failure in the clay closer to the slope surface. There was more scatter in the Cowden clay models but the overall trend was similar.

6. FUTURE MODEL PLANS

The modelling of vertically reinforced slopes is continuing with the intention of modelling rather flatter slopes and making assessments in terms of effective stress. A much larger container has been developed in which models with pre-installed reinforcement can be subjected to a single sustained acceleration in the centrifuge. These will then be brought to failure by varying the ground water table from below the slope surface and by simulating precipitation from above. In this way it is intended to model field situations such as the site at Godstone referred to in Section 2 above. It is expected

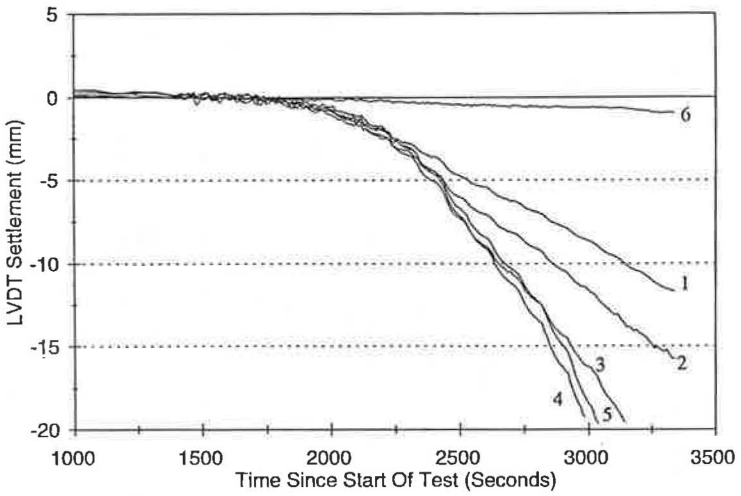


Figure 3 - Time History of Settlement (Model3)

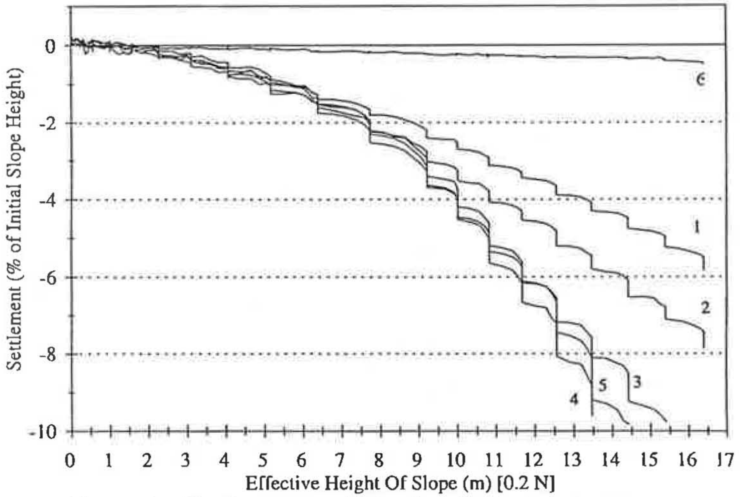


Figure 4 - Settlements v Effective Slope Height (Model 3)

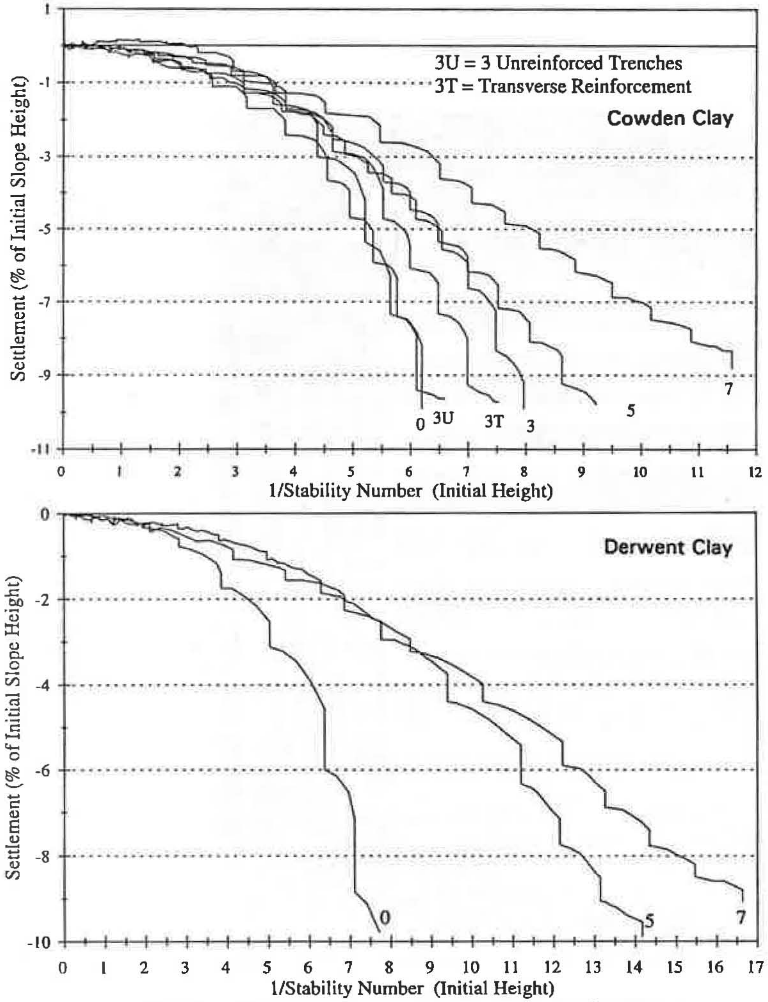
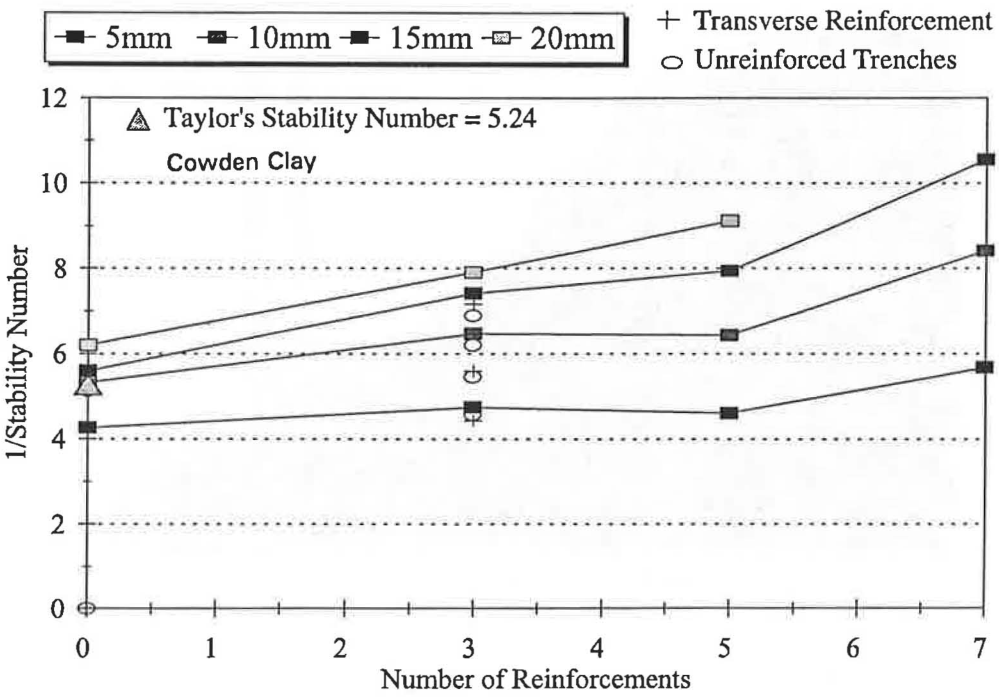


Figure 5 - Comparison of the Settlements Between Models with Varying Reinforcement at One Position



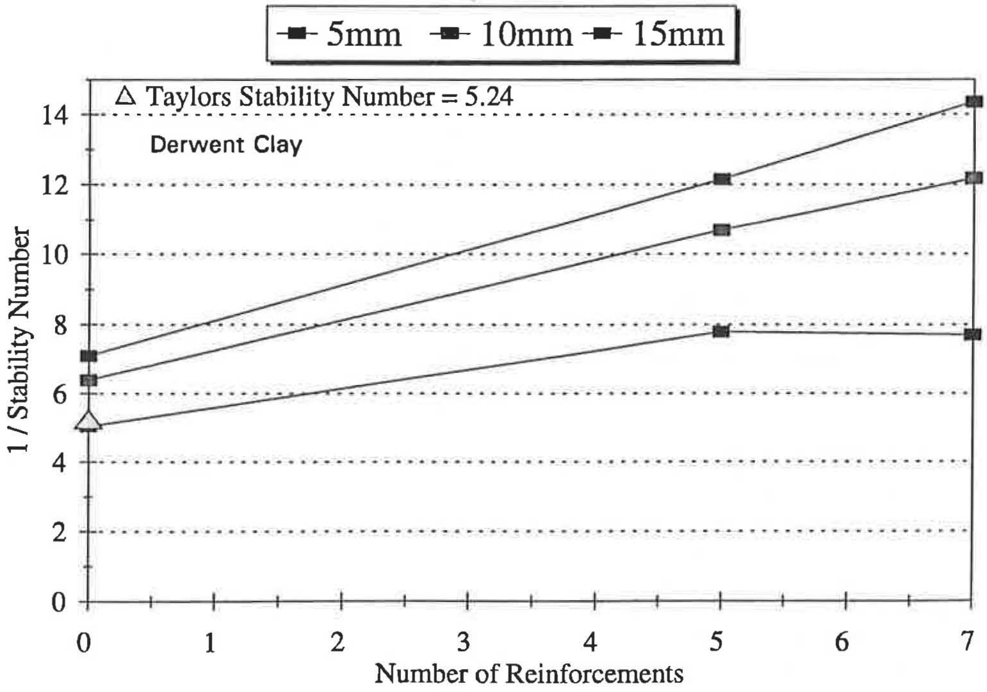


Figure 6 - A Comparison of 1/Stability Number at Identical Limiting Displacements

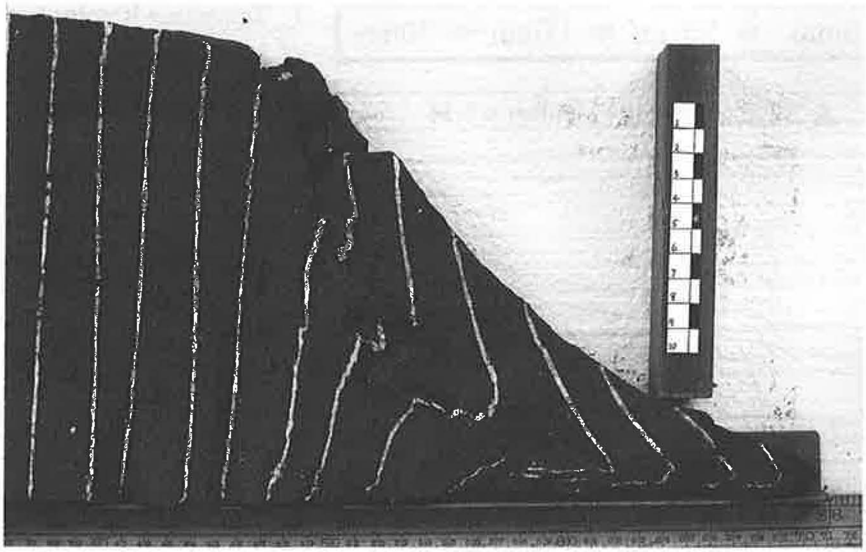


Figure 7 - Section through model 7

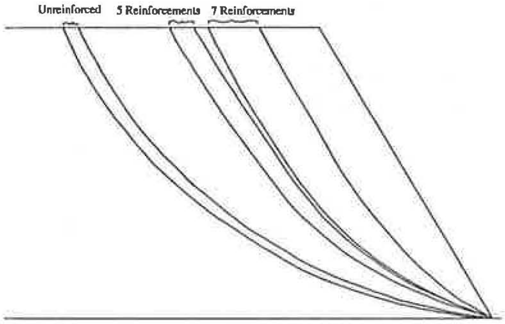


Figure 8 - Rupture planes, Derwent models

that this work will continue until late 1997.

7. COSTS

The field projects completed so far have been characterised more by their differences than by their similarities. It is not possible to make rigorous cost comparisons with conventional techniques - however savings of the order of 10-25% would appear to be feasible based on project experience to date. The speed and reduced impact on existing vegetation of the technique offers the possibility of further cost and environmental advantages over other methods for improving the stability of existing natural and formed slopes.

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