

# Physical Modelling of Sequential Slope Failure

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**SUMMARY** A precis of the design considerations and testing results associated with the physical model study of the kinematics of a slope failure is given. The case investigated was a simple granular slope underlain by a thin weak cohesive stratum.

## 1 INTRODUCTION

The majority of analyses and numerical models associated with the investigation of slope stability are based on the concept that soil, or rock, behaves as a continuum. Although this approach is satisfactory for some soils, it has been shown that the response of granular materials may be more aptly described by discontinuum mechanics (e.g. Trollope, 1968). Because of the nature of granular materials, the stability analyses used for the design of slopes may not be relevant due to the invalidation of the assumptions inherent in the analyses. Furthermore, the importance of the slip mechanism and the physical constraints promoting its formation are generally disregarded in the slope stability calculations.

The study reported here was concerned with the definition of the kinematics of failure for a granular slope underlain by a thin weak stratum. Although the range of application for the results is relatively small, the situation is found in many surface mining operations. The development of a physical model for the study revealed several design characteristics and means for the interpretation of results which should be considered in all plane strain modelling.

## 2 FIELD EXAMPLES

The mechanism which resulted from the failure of a granular slope underlain by a weak layer was primarily of the two-wedge type. Figure 1 shows the general form of a failed slope, which is more distinct in cases where the transition between the slope and the weak layer is well defined; and the layer is thin in comparison with the height of the slope. Mining waste dumps have provided many excellent examples of the two-wedge mechanism with some being reported by Blight (1969) and Boyd *et al.* (1978), and it may be demonstrated that a two-wedge mechanism may have been present in the initial stages of the Aberfan disaster (vide Bishop *et al.* 1969). The formation of the two-wedge mechanism has been observed in embankments and natural slopes; however, the clearly defined nature of the landslips associated with mining waste dumps led to the concentration of research in that particular area.

With reference to Figure 1, some of the important features of the two-wedge slip in field cases are:

- i) a relatively thin weak base layer;
- ii) uniform movement along the base slip plane;

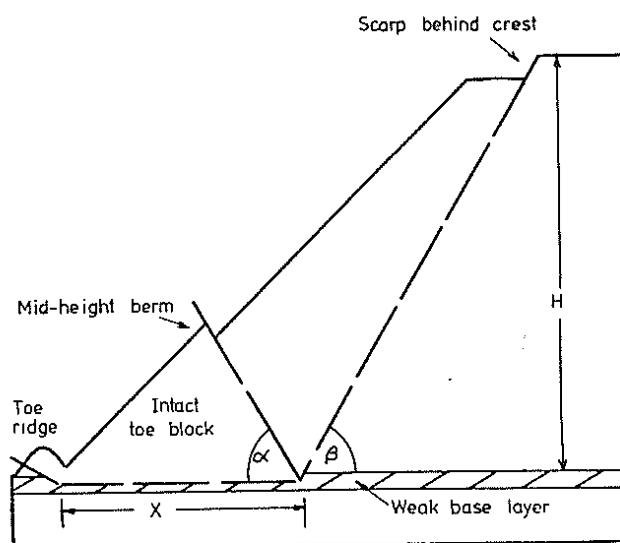


Figure 1 General slope failure profile

- iii) intact condition of the toe block, and sometimes a rill of foundation material pushed up by the toe block;
- iv) the appearance of a mid-height berm or a gentle S-shape of the slope face; and
- v) formation of a slip scarp just behind the crest of the slope.

Thus, a successful physical model of the field situation would reflect the characteristics of the slope both before and after a slump. Many mining dump failures were of considerable lateral extent and could be properly considered as plane strain phenomena.

## 3 PHYSICAL MODEL FORMULATION

### 3.1 Purpose of Model

The research was based on the events which led to the formation of a two-wedge failure mechanism, rather than the response of a particular prototype. Therefore, the use of similitude was not critical, although some broad characteristics (outlined above) needed to be included in the response of the model. James (1971) discussed three classes of physical model from which the second class was chosen for this study. This approach required the

detailed measurement and analysis of a small scale model as if it were a prototype, after which the analysis established to be most suitable for the situation was applied to a full scale prototype and the responses compared.

Because of the important role played by the two-wedge mechanism in the failure of the slope, the definition of the kinematics of that mechanism was the chief factor in the choice of model and subsequent design of the experimental apparatus. The use of a physical model in preference to a numerical model stemmed from the extreme difficulty in reproducing real material response and large scale movements; however, two models, one a block jointed finite element program (cf. Burman, 1971) and the other a dynamic relaxation program (cf. Cundall, 1971), were used for a qualitative comparison with field and physical model responses.

### 3.2 Details of Model

The model was at laboratory scale (in the order of 1 m long) and consisted of two dissimilar materials. The granular slope was constructed of a well graded, cohesionless, dry silica sand in a loose state with the face of the slope at the sand's angle of repose. This slope rested on a horizontal uniform layer of bentonite slurry, mixed to a moisture content of 900%. The dimensions of a typical model slope were:

Base length	1100 mm
Width	745 mm
Height	400 mm
Angle of repose	34°
Sand density	1500 ± 20 kg m <sup>-3</sup>
Bentonite thickness	5 - 30 mm.

Further information on material characteristics is given in a later section.

### 3.3 The Modelling Apparatus

It is not feasible to construct apparatus which does not have any effect on the materials used; however, there are certain design characteristics which may be incorporated in the design of the apparatus which will significantly reduce any adverse response. Deflections within the apparatus were limited to less than 1% of those expected to induce an "active" state in the sand under maximum loads (cf. Arthur and Roscoe, 1965); and the width to height ratio was 1.9, which would promote plane strain conditions (cf. Bransby and Smith, 1975). The effect of sidewall friction was minimised by the use of plate glass thoroughly cleaned with acetone before each test.

The bentonite was not strong enough to support the full thrust of the slope; therefore, a mechanical device along the sand-bentonite interface supported the slope and was retracted for the initiation of failure. This device tended to hasten the first few millimetres of movement, but an experiment which did not employ the base strengthening device showed that it did not affect the sequence of development or the characteristics of the failure mechanism. Figure 2 shows a schematic diagram of the strengthening device which was fixed beneath the floor of the sample enclosure.

## 4 MATERIAL CHARACTERISTICS

### 4.1 Modes of Testing

The description of the stress-deformation characteristics of loose sand is dependent on the

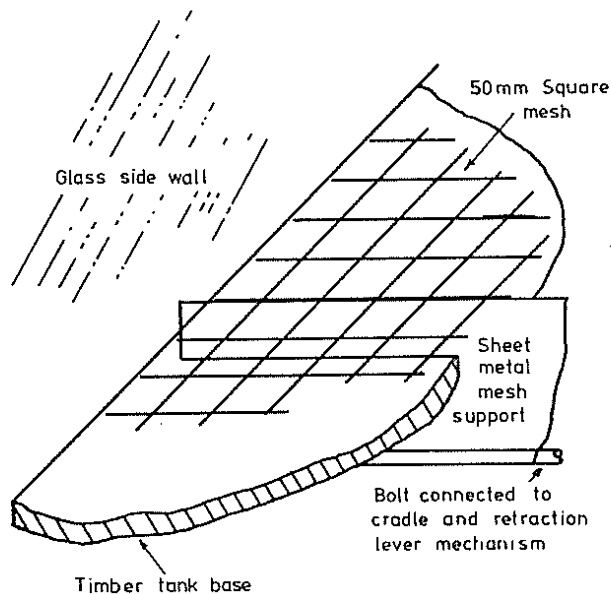


Figure 2 Strengthening device

type of test used. Thus, it was necessary to use plane strain tests at low confining pressures (less than 10 kPa) to record the response of sand as it might be observed in the model. Although the difference in strength (internal friction angle) between plane strain and triaxial tests on loose sand is very small, the deformational response in the test is significantly different, with the plane strain sample showing a much faster rise to peak strength and an increase in volume under axial compression (cf. Lee, 1970). Because of the possibility of some error in the data from the plane strain tests, a series of direct shear tests was carried out and the results were found to agree with the former tests. The bentonite was used in a state beyond its liquid limit (~600%) and behaved as a non-Newtonian fluid. The bentonite had a yield stress and was thixotropic; however, limited testing facilities permitted only an order of magnitude estimate of the yield stress to be made.

### 4.2 Interpretation of Tests Results

The sand's stress-deformation response in plane strain was compared with several continuum and particulate theories such as the Mohr-Coulomb criterion, Rowe's stress-dilatancy theory (Rowe, 1962), Parkin's particulate model (Parkin, 1965), and the Granta Gravel critical state model (Schofield and Wroth, 1968); however, none of these approaches proved satisfactory. The author found that the Freudenthal (extended von Mises) failure criterion fitted the observed stress response, but there were insufficient reliable test results available to extend this part of the research.

The study of the kinematics of failure led to the derivation of a deformational failure criterion which corresponded well with the octahedral stress characteristics measured during the plane strain tests. Figure 3 shows a generalised representation of this criterion which is summarised as:

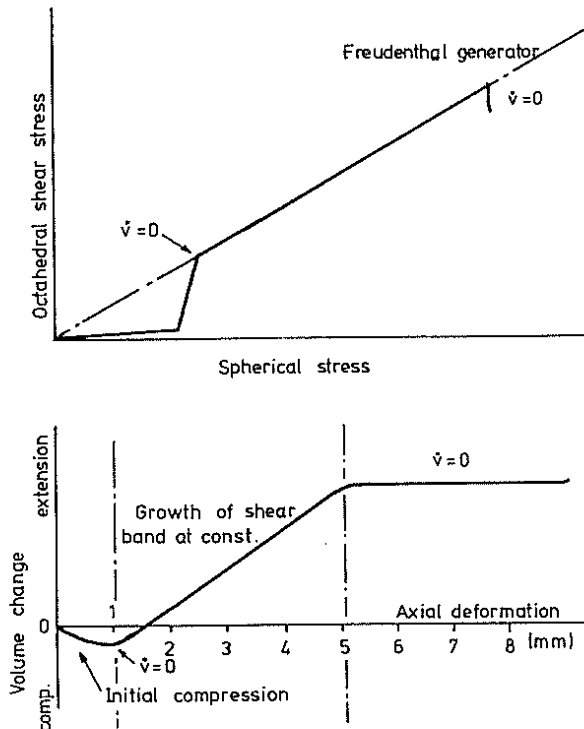


Figure 3 Deformational failure criterion

- i) initial compression up to 1 mm movement;
- ii) onset of failure when the rate of volume change becomes zero, followed by growth of the shear zone at constant dilatancy up to an axial deformation of 5 mm;
- iii) cessation of growth of the shear zone with further slip taking place within the zone at practically zero dilation.

An estimation of the strength of the sand was made using a Mohr-Coulomb diagram in which the failure was defined along the observed slip plane rather than along the angle of maximum obliquity, and yielded  $35^\circ$  and  $33^\circ$  for peak and residual values respectively.

An extrusion rheometer was used to estimate the yield strength of the bentonite slurry and a value of .7 kPa was measured; however, the reliability of the value was low and should only be considered as an order of magnitude indicator. There was no measurement of the increase of the yield strength due to thixotropy, but the elapsed time between the placement of bentonite and the initiation of failure was kept at approximately 1½ hours in each of the experiments.

## 5 MODELLING RESULTS

### 5.1 Testing Programme

The major variable in the model was the thickness of the base layer, indicated in Section 3.2. A total of thirteen tests were carried out with at least two tests at each base thickness to ensure the repeatability of the results. Eight of the tests were recorded with a 16 mm Bolex movie camera and the resulting films were examined in detail for

the qualitative description of the failure sequence. The remaining tests were recorded using a 35 mm single lens reflex camera with frames taken at varying time intervals and one of these sets was used for a quantitative examination of the model response. The measurements were made through a digitised Zeiss Stecometer with the data being punched onto paper tape and typed for a hard copy.

### 5.2 Sequence of Failure

Both qualitative and quantitative evidence was examined for the determination of the sequence of formation of the two-wedge failure mechanism. Figure 4 shows an idealised form of this sequence in four parts:

- i) the simultaneous development of two slip planes - one through the weak layer and the second through the granular slope cutting the free surface just behind the crest; between the two planes is a broad shear zone dividing the front of the slope into toe and crest regions;
- ii) movement of the two regions along their respective slip planes with the distortion in the shear zone tilting the lower half of the crest region away from the toe;
- iii) formation of a third slip plane within the shear zone between the first two planes with no further shear distortion in that zone; and
- iv) movement along the three slip planes with negligible volume change within the toe and crest regions.

The method of data collection and recording did not allow any further distinction in the initial stages of the failure sequence; however, it is the author's opinion that the first two slip planes form concurrently.

By observation of coloured sand lines in the model, the displacement at which the slip plane through the slope was first recognised was measured. The average of six values was  $9 \pm 2\frac{1}{2}$  mm and the predicted displacement was 6.2 mm, using the author's deformational failure criterion (vide Section 4.2). An alternative prediction for the formation of the slip plane based on a failure strain gave the necessary displacement as 25 mm, which was more than twice the observed value.

### 5.3 Deformation of the Weak Layer

The characteristics of the slip planes in the granular slope were the main feature of the modelling results; however, the deformation patterns in the bentonite gave information which supported the definition of the sequence of failure. The slip plane through the bentonite formed close to the bottom of the layer with an abrupt termination at the point of intersection of the three slip planes which formed the mechanism. The weak layer beneath the immediate toe of the slope buckled in compression during the formation of the mechanism and did not push out a "passive" wedge, as might be expected. The horizontal displacement of the weak layer above the slip plane was constant along its length.

### 5.4 Characteristics of Mechanism

The characteristics of the slip mechanism in plane strain were not directly obtained from the photographs at the side wall due to the frictional

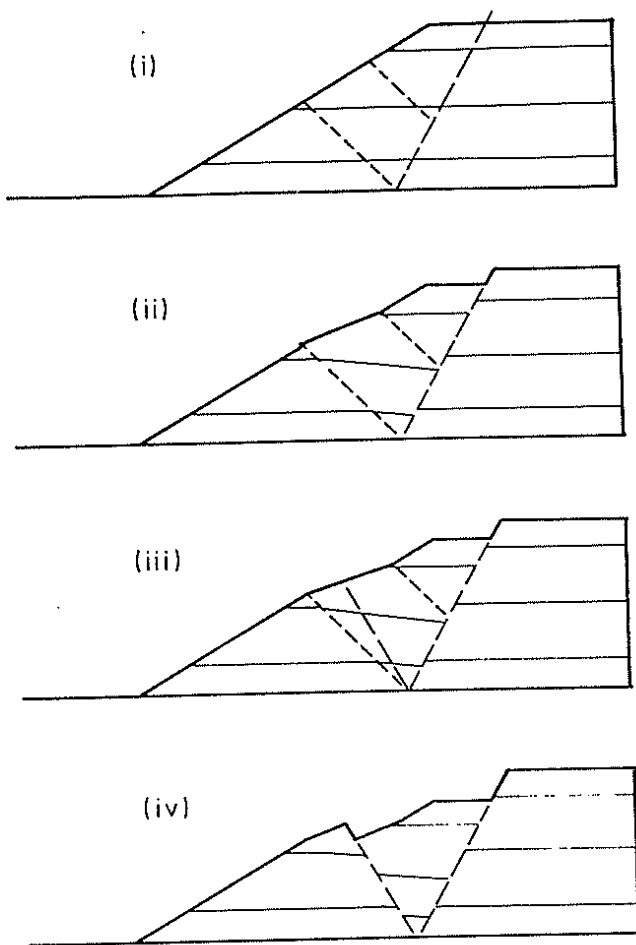


Figure 4 Failure sequence

effects; however, after corrections were applied, the values for the parameters defined in Figure 1 were:

$$\begin{aligned}\alpha &= 75^\circ \pm 10^\circ \\ \beta &= 56^\circ \pm 5^\circ \\ \frac{x}{H} &= 1.15 \pm .1\end{aligned}$$

Variation of the thickness of the weak layer (5-30 mm) did not alter the sequence of formation or the characteristics of the mechanism. The total displacement of the toe region varied non-linearly with the thickness of the layer and the relationship was:

$$s = 40 (t^1 - 2) \quad (1);$$

where  $s$  = total displacement (mm),  
 $t^1 = \log_2 t$ ,  
 $t$  = layer thickness (mm).

## 6 FURTHER USE OF RESULTS

The next stage in the modelling process was to attempt to describe the observed results by a stability analysis or a numerical model. The scope of this paper does not allow further discussion on this matter, which may be pursued in Dunbavan (1979).

The basis of this modelling arrangement may produce more meaningful quantitative results with the use of large format cameras and different exposure techniques. It may be possible to place instruments within the model; however, great care would be required to ensure that the presence of the instruments did not influence the sequence of development of the mechanism.

## 7 CONCLUSIONS

The use of an idealised small scale physical model showed that a two-wedge mechanism, which had some similarity with field situations, developed in a discrete sequence of events. There was no evidence to support the relevance of progressive failure (by stress distribution) to the formation of the mechanism. Large scale movement of the toe region was dependent on the formation of the third slip plane; however, the visual recognition of a slip plane is related to the deformational response of the particular material in the slope. The deformation required to form particular slip planes does not alter the concept of the kinematics of failure being a discrete sequence of events.

The development and investigation of the model revealed that frictional edge effects may not be discounted; however, careful attention to the relationship between the displacements at the centre and the side walls of the model allowed these effects to be corrected. The response of the model was interpreted with the knowledge of the stress-deformation characteristic of the material, which had been established in plane strain tests at stress levels similar to those in the model. A review of some literature on plane strain and triaxial testing of loose sand showed that the stress-deformation response used in conjunction with a small scale model requires attention in the use of relevant constraints.

## 8 ACKNOWLEDGEMENT

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