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INVESTIGATION OF SLOPE MOVEMENTS IN A COASTAL SAND DUNE IN SOUTH-EAST QUEENSLAND

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Summary This paper presents the results of monitoring and investigation of slope movements which occurred in a coastal sand dune in South East Queensland, at a time of elevated groundwater levels. The magnitude and pattern of displacement suggest that a Factor of Safety of very close to 1 developed as a result of the rise in groundwater levels. Subsurface investigations identified the presence of a layer of former swamp deposits (sandy clay and clayey sand) beneath the dune, which has been interpreted as the layer in which shear displacement was concentrated. Finite element and limit equilibrium analyses using a Mohr-Coulomb constitutive model yield consistent results, and indicate that an angle of friction of 11° is required for a Factor of Safety of 1 for a failure mechanism which passes through the former swamp deposits. Such a low friction angle is inconsistent with limited laboratory testing on the material. Further work is being undertaken to better understand the mechanisms which led to the development of large scale movements, in order to better predict the potential future development of such movements.

1 INTRODUCTION

Results of monitoring and analyses carried out in relation to slope movements which occurred in a coastal sand dune in South East Queensland are presented in this paper. The sand dune is a relatively young dune, which extends over older swamp deposits. The crest of the dune is approximately 80 m above the toe, and the slope of the dune is 23° on average with steeper sections of up to 40° in places. A contour plan for the dune is illustrated in Figure 1, and a cross-section through the dune is illustrated in Figure 2. In late 1998, a downward displacement of 3.3 m developed near the crest over a period of approximately 17 days. The downward displacement at the crest was accompanied by the development of a 2.7 m scarp mid-way down the dune, and an upwards movement of 4.3 m at the toe of the dune, indicating horizontal movement of a lower wedge of sand and downward movement of an upper wedge.

2 DESCRIPTION OF DUNE MOVEMENTS

The slope movements developed at a time when dredging associated with a sand mining operation was being carried out at a distance of 400m behind the toe of the dune, in a dredge pond with a water level at 35m above the toe. The location and level of the dredge pond were within the normal operational guidelines for the mine.

For several days preceding the first observed formation of cracks in the slope, loud rumbling noises were heard emanating from the dune. Such behaviour has been previously observed to precede large slope movements in similar terrain in the area. Four days after the first rumbling sounds were heard, a crack was observed in the ground along the crest of the north-west dune, and crude measurements of slope movement were instituted at that time (measurement using a tape measure between two stakes). More detailed monitoring using surveying equipment was established shortly thereafter, and measurements of the vertical displacement at the crest were made every fifteen minutes initially.

The cumulative displacement measured at the crest is illustrated in Figure 3. More than 1 m of vertical movement developed at the crest over the first 48 hours of movement. A total movement of approximately 3.3 m developed over a period of approximately 17 days, after which time the movement slowed to less than 0.5 mm/hour. The slope has remained stable since that time. Detailed information regarding the rates of displacement in the first seven days of movement are illustrated in Figure 4, with information on tidal water levels close to the toe of the dune. It can be seen that the rate of movement is closely tied to tidal fluctuations, and that peaks rates of movement occur approximately 1.5 hours after tide peaks. The mechanism of tidal influence is yet to be considered in detail.

In addition to the movement at the crest, a mid-slope scarp developed (which was first observed the day after the first observation of the upper crack). At the completion of monitoring, a relative displacement of 2.7m had developed at the mid-slope scarp. The location of the upper and mid-slope scarps and the recorded movement for these features are illustrated in Figures 1 and 2 (the cross-section illustrated in Figure 2 is for the section on which the largest slope

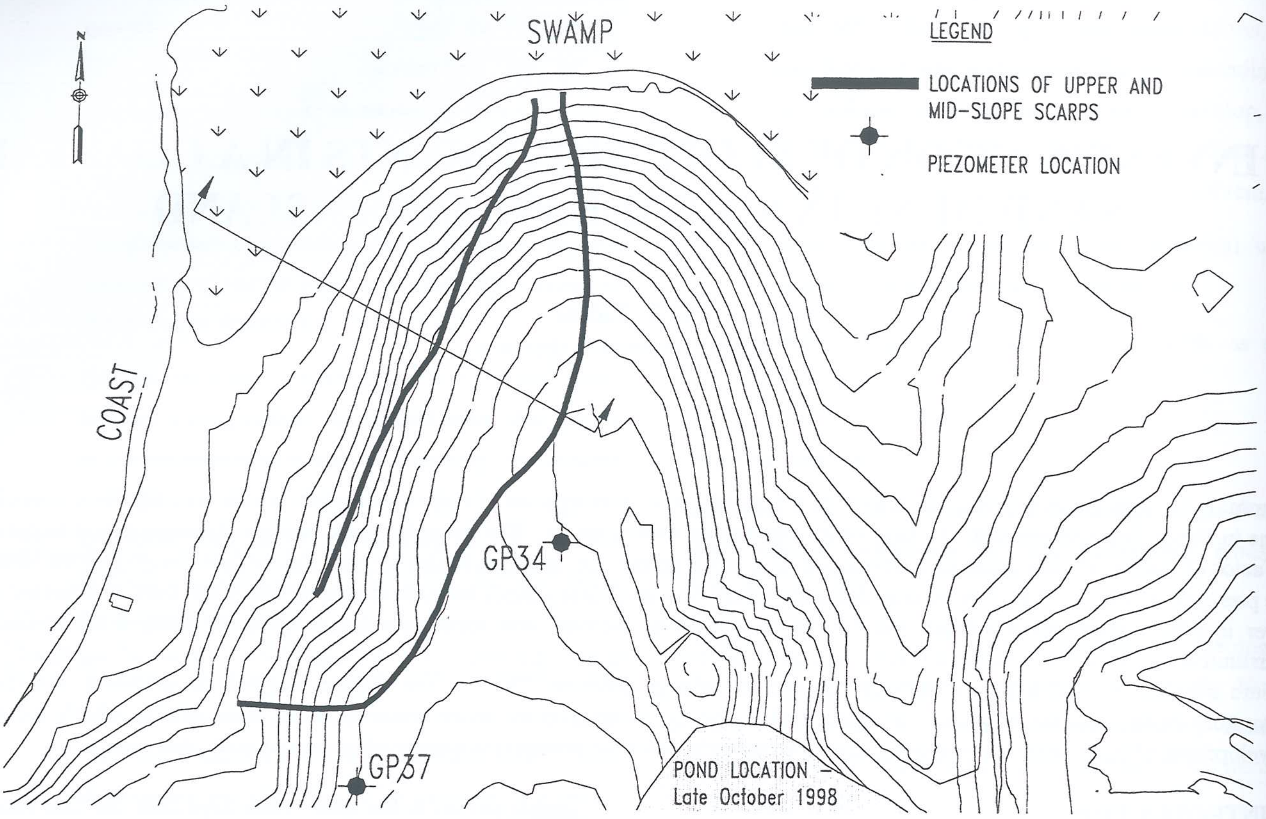

Figure 1 Plan of sand dune

movements were measured). Apart from some leaning trees near the toe, there was no readily apparent evidence of mounding in this area. However, significant displacements developed in this area, as indicated by surveying carried out prior to and following the movements (refer to Figure 2).

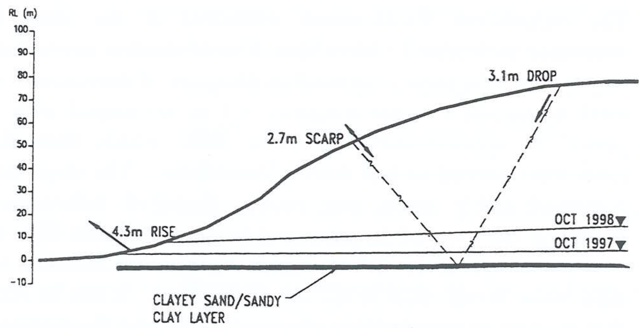

Figure 2 Cross-section through dune indicating measured displacements

3 GROUNDWATER CONDITIONS

The water table within the dune rose over a period of approximately 8 months preceding the slope movements, in response to seepage from the mine dredge pond. The pond moved towards the dune from the east, and on 30 October 1998 was located as shown in Figure 1.

The results of water level monitoring at two piezometers in the vicinity of the dune are illustrated in Figure 5. The locations of these piezometers are shown in Figure 1. It can be seen that the water table at the rear of the dune was at an elevation of approximately 7 m AHD in the period prior to direct influence from the dredge pond, and that peak levels in excess of 18 m AHD were recorded on 6 November 1998. Water levels dropped relatively rapidly following 6 November, as the dredge pond was moved away from the area of slope movements. The results also indicate that similar groundwater levels were present along the length of dune where movements were observed.

4 SUBSURFACE INVESTIGATIONS AND LABORATORY TESTING

Drilling and cone penetrometer testing was carried out at a number of locations along the toe of the dune, and at three locations near the crest of the dune, to assess the nature of materials beneath the dune, and to assess the extent of the suspected swamp deposits beneath the dune. As indicated in Figure 1, swamp deposits were present around the base of the dune to the north and west, and the shape of the dune indicated that it had been blown out over pre-existing swamp deposits.

Drilling and cone testing results identified the presence of a layer of variably sandy clay/clayey sand beneath the dune, with a variable percentage of organic material (refer to Figure 2). Some samples of this material were essentially peat. The layer extended along the majority of the toe of the dune, and was present in the boreholes drilled from the crest of the dune. Samples of clayey material from beneath the crest of the dune were very stiff to hard (as would be expected for clay normally consolidated beneath an 80 m high dune), and samples from beneath the toe were generally firm. It appears that the layer of sandy clay/clayey sand was deposited in a lake, over a previously deposited, relatively deep layer of weathered sand. The investigation did not identify the presence of any other layers on which movements could have potentially developed, and it has been assumed that shear displacement was concentrated in this layer.

Shear box testing on a sample of clayey sand from this layer yielded an angle of friction of 27°. Additional laboratory testing on further samples recently obtained is currently underway.

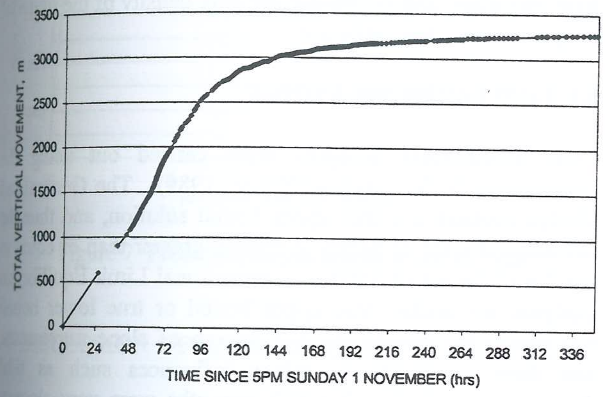

Figure 3 Cumulative displacement measured at crest

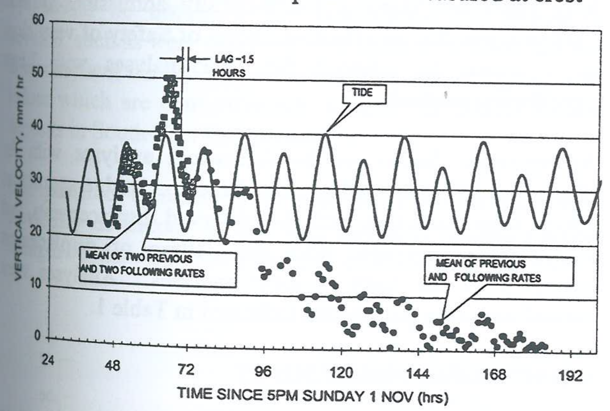

Figure 4 Rates of displacement at crest

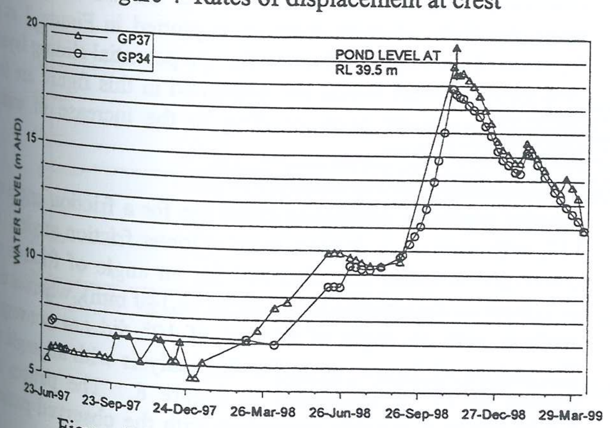

Figure 5 Measured groundwater levels at crest of dune

BACK-ANALYSIS OF MOVEMENTS

5.1 General

Back-analyses to assess the conditions which led to the development of the slope movements described above have been undertaken using two approaches:

- non-linear stress-strain analysis using the finite element technique
- Limit Equilibrium methods

Finite element analyses have the advantage that they do not make a priori assumptions regarding stress distributions or locations of limiting soil stresses, and stresses and displacements are therefore determined by considerations of equilibrium, strain compatibility, and soil strength. Limit equilibrium methods, which are widely available and are relatively easy to use were also used for back-analysis, since such methods would ideally be used in any analysis of future potential problems of a similar nature.

Prior to commencement of the back-analyses, it was necessary to consider the choice between drained and undrained analyses. Loading of the slope took place over a period of approximately 8 months as the water table in the dune rose and increased the weight of sand above the potential sliding layer. In addition to the increase in total stress due to increased bulk density (possibly with consequent pore pressure increases depending on the rate of loading), pore pressure increases develop as a result of equilibration with the raised water table. In the extreme case of rapid increase in water level, the pore pressure increase in the lower permeability potential sliding layer would initially depend on total stress changes and the A and B pore pressure parameters. For typical values of A and B, the pore pressure changes which would accompany such an undrained loading would be less than the pore pressure changes which would develop as a result of equilibration with the raised position of the water table. Thus, in this case, drained conditions should be more critical than undrained conditions. Analyses for this study have therefore been carried out as drained analyses, with pore pressures that correspond directly to the rising level of the water table in the sand dune. It is possible that the dune movements developed prior to the full equilibration of pore pressures, in which case the actual soil strengths would be somewhat less than indicated by the back analysis.

5.2 Finite Element Modelling

In the finite element modelling carried out for this study, soil behaviour was described using an elastic, perfectly plastic constitutive law, with a limiting shear strength condition defined in terms of the Mohr-Coulomb failure criterion.

The finite element mesh used for analyses is illustrated in Figure 6. The lateral boundaries of the model were specified as zero horizontal displacement boundaries, and the basal boundary was specified as a zero displacement boundary. The lateral boundaries were chosen to lie outside the limits of observed slope movements. The formulation of the finite element model is for plane strain conditions, and therefore

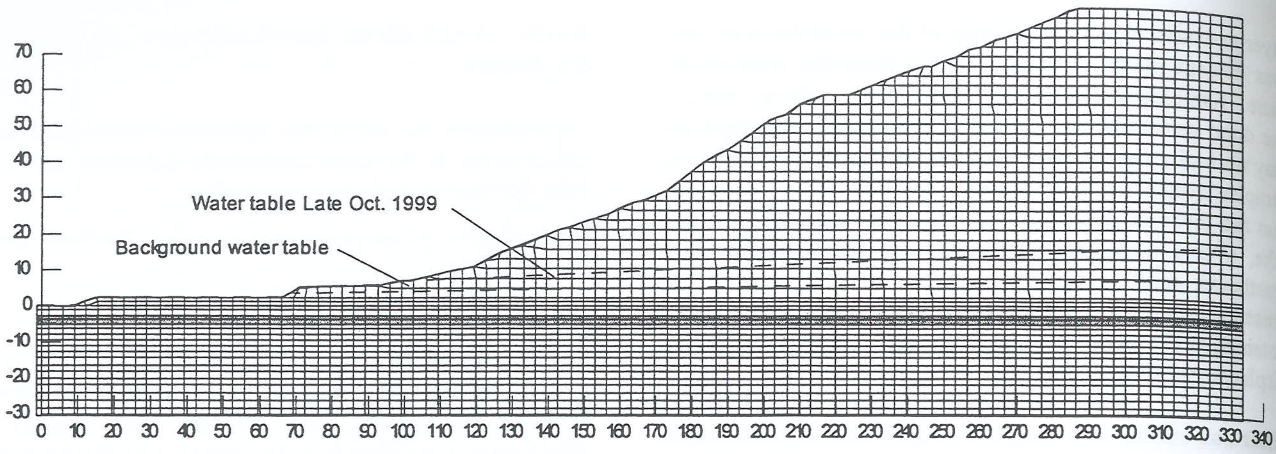

Figure 6 Finite Element Mesh

represents a slope which is infinitely long and of uniform cross section in the direction perpendicular to the section which was analysed. The cross-sectional geometry adopted for the model is that of the cross section on which maximal slope movements occurred. The implications of the assumption of plane strain conditions are discussed further in the following.

Properties adopted for the various slope materials are summarised in Table 1. Properties for the dune sand were based on previous testing. Variable strengths were adopted for the material in the clayey sand/sandy clay layer, in order to determine the angle of friction for which large slope movements were initiated in the model.

Table 1– Material Properties Adopted in the Finite Element Model

Material	Strength Properties	Density
Dune sand	$\phi' = 32°$	γ =19 kN/m3 below water table γ =16 kN/m3 above water table
Sliding layer	ϕ' = variable	γ =18 kN/m3
Underlying sand	$\phi' = 35°$	γ =19 kN/m3

Analyses were carried out for two water table elevations, as illustrated in Figure 1. The two water table conditions are based on the water table profiles for steady state conditions prior to the water table rise, and for the conditions at the end of October following a water table rise over the previous 8 months. At this stage, no attempt has been made to consider the effects of tidal fluctuations.

The stress history of the slope was imitated by commencing modelling with an approximately horizontal ground surface, and then sequentially adding layers of material to the model to simulate accretion of the dune over a period of time. Stress conditions in the slope were calculated in this manner for the case of steady state water table conditions, and changes from this condition were then calculated by increasing the water table elevation, and increasing the bulk density of the material in the zone of water table rise.

5.1 Limit Equilibrium Analyses

Limit Equilibrium analyses were carried out using the Generalised Wedge Method (Giam, 1989). The Generalised Wedge Method is a true upper bound solution, and thus the calculated Factor of Safety is strictly greater than or equal to the "true" Factor of Safety. Conventional Limit Equilibrium analyses are neither true upper bound or true lower bound analyses. The magnitude and pattern of slope movements, and their sensitivity to minor influences such as tidal fluctuations, indicates that soil strengths were very close to fully mobilised along a kinematically admissible surface. This suggests that an effective Factor of Safety of very close to 1 should be adopted for back-analyses with Limit Equilibrium methods.

As discussed further in the following, analyses with the Generalised Wedge Method were based on wedge geometries which were consistent with the observed displacements, and which were consistent with the pattern of displacement indicated by the finite element analyses. Analyses were carried our using parameters indicated in Table 1.

6 BACK ANALYSIS RESULTS

Horizontal displacement, calculated at the toe of the dune using the finite element method, is plotted in Figure 7 as a function of the angle of friction for the potential sliding layer. The displacements which are illustrated in this figure are for the load increment corresponding to the increase in water table.

Limited plasticity developed at the toe for a friction angle of 15°, with increasing displacement at lower friction angles. A converged solution was obtained for an angle of friction of 11° (with displacements of the order of 140 mm), whereas the analysis with an angle of friction of 10° did not converge. The pattern of displacement for the analysis with an angle of friction of 11° is illustrated in Figure 8. The pattern of displacement is roughly consistent with the observed pattern of displacement. However observations of the displacement at the upper scarp suggest displacement developed on a plane at a much steeper angle than that indicated by the finite element analysis. Similarly, the finite element analysis indicates the likely formation of a mid-slope scarp at a lower elevation and on a steeper plane than that observed.

Analysis using the Generalised Wedge Method was carried out using the wedge geometries indicated in Figure 8, and a friction angle of 11°. The calculated Factor of Safety for this case was 0.98.

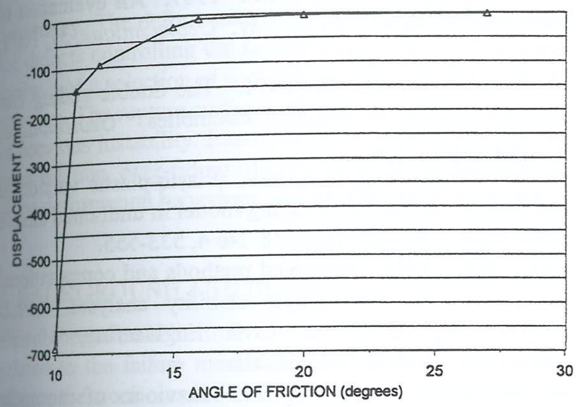

Figure 7 Predicted displacement at toe of dune

7 DISCUSSION OF BACK ANALYSIS RESULTS

The back analysis results indicate that an angle of friction of 11° would be necessary for large slope movements to develop, such as were observed. An angle of friction this low is inconsistent with the results of laboratory testing, and with values which are conventionally adopted for similar swamp deposits in South-East Queensland.

One possible explanation is that large movements have previously developed at this site, and have caused residual strength to develop along the pre-existing slip surface. It should be noted, however, that laboratory testing carried out to date has not indicated that residual shear strength is substantially less than peak shear strength for the sandy clay/clayey sand layer beneath the dune.

The mechanisms for the development of a pre-existing slip surface are not evident. For a previous slip to have caused residual strength to develop on a discrete failure surface, it would be necessary for it to have developed after consolidation of the pre-existing swamp deposits beneath the dune (since failure on a discrete plane would not generally develop in a soft clay). A possible trigger for previous movements could be an earthquake.

It is worth noting that even for friction angles as high as 27°, the finite element analyses indicated the full development of plasticity in the clayey sand/sandy clayey layer, in almost the entire length from beneath the crest to the toe. Full development of plasticity was predicted in limited areas for the conditions preceding the water table rise, and the area of plasticity extended towards the toe as a consequence of the water table rise.

Although the full development of plasticity was predicted locally by the finite element analyses, large-scale displacements did not develop in the model since the local conjugate failure directions were not aligned horizontally. Relationships between local shearing on conjugate planes and overall shear displacements have been discussed extensively in the literature (for example, de Josselin de Jong (1971, 1988), Airey and Wood (1987), and Wroth (1987)). It has been postulated that, for example, displacements in a shear box test develop on vertical surfaces, and that overall horizontal displacements are made up of a combination of shearing on vertical surfaces and rigid body rotations (de Josselin de Jong, 1971). The references cited above indicate that shearing which develops as a result of such a mechanism provides less resistance than would be indicated by the angle of friction and the stress normal to the overall direction of shear displacement.

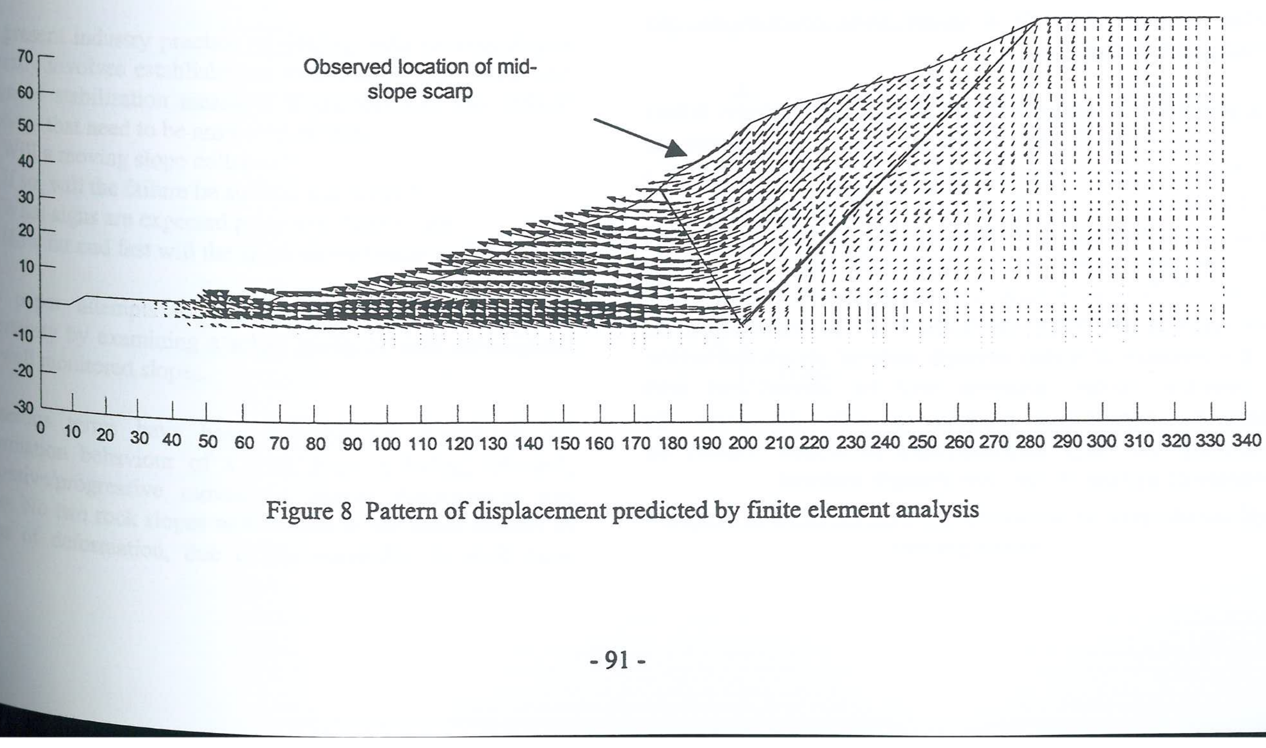

Figure 8 Pattern of displacement predicted by finite element analysis

It appears possible that displacement at the toe may have been initiated by such a mechanism, leading to progressive development of movement through the remainder of the layer already at limiting conditions. The observed rumbling from the dune for a period of several days prior to the development of movement at the crest indicates a progressive development of movement commencing at the toe. Further analysis using alternative constitutive models (for example the constitutive models developed by de Josselin de Jong (1971, 1988)) may provide additional insight into the conditions which led to movement.

8 CONCLUSIONS

Large displacements which have developed in a coastal sand dune overlying former swamp deposits have been analysed using finite element and limit equilibrium techniques, in an attempt to understand the factors which led to the development of movement. Understanding the mechanisms which led to the movement is important, since future mine paths will pass within a similar distance of coastal dunes which are similarly located over former swamps.

The analyses yielded consistent results which indicate that for a Factor of Safety of 1 to develop as a result of an observed water table rise, an angle of friction of 11° is required for a layer of organic sandy clay and clayey sand which was encountered beneath the dune. The failure mechanism predicted by the analyses is similar to that observed in the field.

Laboratory testing on a sample of clayey sand collected from the likely sliding layer beneath the dune has indicated an angle of friction of 27°, which is consistent with values typically adopted for swamp deposits in the area. Mechanisms for the development of a plane of weakness with a friction angle of 11° are speculative only, but might include the prior development of plane with residual shear strength due to large scale movements caused by an earthquake. Geomorphological evidence of previous large scale movements would be difficult to discern, and evidence for the presence of a plane of weakness with very low angle of friction may be difficult to obtain from conventional site investigation techniques.

It is possible that analyses based on a Mohr-Coulomb failure criteria has led to under-prediction of the friction angle for the former swamp deposits beneath the dune, since such a model requires one of the conjugate failure directions to align horizontally for failure to develop. However, it is not clear that this requirement would necessarily hold in a system where soil plasticity is fully developed on inclined planes, but movement is essentially constrained to the horizontal plane by the presence of higher strength material above and below. If possible, further analyses will be carried out with alternative constitutive models, in order to assess the possibility that large displacements developed without the presence of a plane of very low strength material.

Further analyses will also be carried out in relation to similar large scale movements, which have previously developed at the mine in the batters of the dredge pond. Analysis of similar movements will hopefully assist in the assessment of whether such movements require the presence of very low shear strength materials.

9 REFERENCES

1. Airey, D.W. and Wood, D.M.. 1987. An evaluation of direct simple shear tests on clay. *Geotechnique*, 37, No 1, 25-35.
2. de Josselin de Jong, G. 1971. The double sliding free rotating model for granular assemblies. *Geotechnique*, 21, No 2, 155-163.
3. de Josselin de Jong, G. 1988. Elasto-plastic version of the double sliding free rotating model in undrained simple shear tests. *Geotechnique*, 38, No 4, 533-555.
4. Giam, S.K. 1989. Improved methods and computational approaches to geotechnical stability analyses. Ph.D Thesis, Department of Civil Engineering, Monash University, Melbourne, Australia.
5. Wroth, C.P. 1987. The behaviour of normally consolidated clay as observed in direct shear tests. *Geotechnique*, 37, No 1, 37-43.