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Flowslides in Stockpiled Coal

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SUMMARY Occasional deep-seated flowslides in coking coal stockpiles at the North Queensland port of Hay Point are described. The flowslides result from particularly loose placement of the light, cohesionless material, and saturation of the lower levels of the stockpile due to rainfall infiltration and initial moisture at placement. Consolidated undrained triaxial testing has been used to define the density/stress conditions at which liquefaction occurs. The flowslide mechanism, field verification and preventative measures are briefly discussed.

1 INTRODUCTION

Coking coal from Central Queensland Coal Associates (CQCA) mines at Goonyella, Peak Downs, Saraji and Norwich Park is shipped from the north Queensland port of Hay Point. Annual throughput is about 18 million tonnes. Coal is placed in open stockpiles up to 14 metres high by rail mounted stackers for later reclamation and conveying to the ship loader.

The coal is a particularly light, loosely placed cohesionless earth material with particle sizes ranging from silt and fine sand to coarse gravel. Substantial degradation of the stockpile slopes occurs after rain during the annual wet season. This usually takes the form of erosion gulleys and shallow slumping of a wetter surface layer. On rarer occasions, deep seated instability has occurred with up to 10 000 tonnes of coal moving up to 60 metres laterally in a period of 10 to 15 seconds (see Figure 1).

The rapid movement, flat final slope and almost complete breakup of the mass observed in these slides are also characteristic of flowslides noted in many instances overseas (see Casagrande, 1971). Flowslides have usually been attributed to liquefaction of saturated, cohesionless soils looser than critical density, where shearing is accompanied by generation of substantial excess pore water pressures with a resultant marked loss of strength (eg. Bishop, 1973).

Since literature documenting Australian experience is very limited and the topic is particularly relevant to the mineral industry, this paper first describes the observed field conditions and instability in the Hay Point coal stockpiles. Laboratory investigations to date at James Cook University of North Queensland have concentrated on conditions required for liquefaction in a saturated layer of coal. Some early aspects of this work are reported here, including consolidated undrained triaxial testing. However, it will be noted that the usual CU tests do not fully represent field conditions, and are at best illustrative of the field processes.

2 OBSERVED FLOWSLIDES

Flowslides in the Hay Point stockpiles were first observed during the severe 1973-74 wet season. Seven major slides occurred, generally after cummulative rainfall exceeding 150 mm during the preceeding two or three days (Trollope and Wallace, 1975). Typical geometries of these and subsequent slides are shown in Figure 1. Extensive breakup of the failed mass occurs, and at times flows of a coal/water slurry have broken out of the drier overlying coal.

Few detailed descriptions of these flowslides are available, but salient features of five major slides during 1976-77 are given in Table I. Heavy rain was an obvious factor in the 1977 slides, but it is interesting to note that little if any rain was directly associated with the two slides in August 1976. In such cases however, even light rain falling on the open wagons during the 200 km train journey from mine to port can substantially increase the moisture content at placement, and the operators did

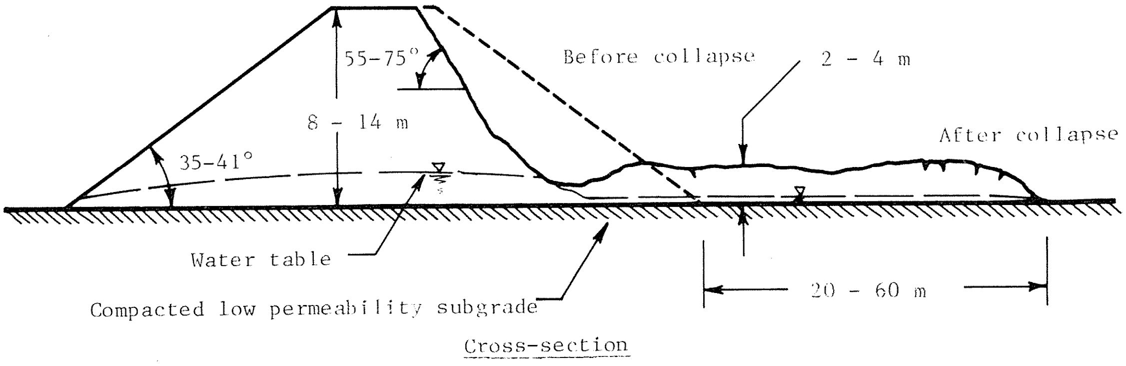

Figure 1 Typical flowslide in Hay Point coal stockpiles

TABLE I

SOME MAJOR FLOWSLIDES, HAY POINT COAL STOCKPILES, 1976-77

Date	Stockpile	Coal type	Stockpile height (m)	Lateral movement (m)	Length of failure (m)	Cumulative rainfall (mm)	Dry density	Other comments
2.8.76	2 South	Saraji	9	18	120	<12	v.loose	Slurry flows prominent
9.8.76	1 South	Saraji	9	20	140	nil	v.loose $(0.84t.m^{-3})$	Collapse during stacking
3.2.77	6 South	Peak Downs	10-12	50-60	150	272 (v.heavy)	v.loose	Collapse during stacking. Large amounts of saturated coal in flow.
9.3.77	1 North	Goonyella	10-11	~30	200	>250	?	Simultaneous failures
9.3.77	1 South	Saraji	10-11	~30	200	>250	?	

in fact observe the coal placed just prior to the first slide to be wetter than usual.

From investigation of at least two slides (post-failure) and several piles used in compaction trials there is known to be a base layer of saturated coal up to several metres thick. This is confirmed by general observations of seepage. Such evidence infers that failure is preceded by saturation and pore pressure development in the bottom layers of coal. This may result from rainfall infiltration and/or downward migration of moisture present in the coal at placement (Trollope and Wallace, 1975; Eckersley, 1977).

3 STOCKPILE CONDITIONS

Coking coal for export is a highly uniform earth material composed of angular particles ranging from silt to gravel sizes. The range of particle size distributions typical of the four CQCA mines is shown in Figure 2. Variations among the four products are primarily in size distribution, particle density and metallurgical properties. Moisture contents ex the mine preparation plants are 9 to 12% by weight. At the time of placement in the port stockpiles, however, this value may increase to about 16% as a result of rain accumulating in the open rail wagons. Specific gravity of the particles is low - 1.33 to 1.38 compared with 2.6 to 2.8 for typical soil minerals.

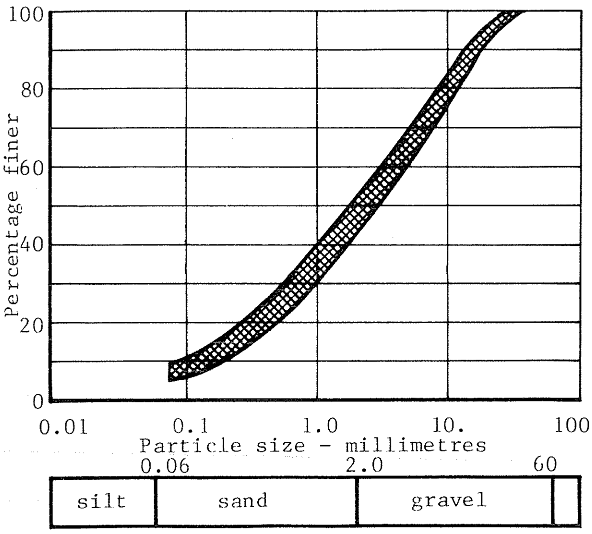

Figure 2 Typical particle size distributions - CQCA mines

The coal is relatively loosely placed with little compaction except that resulting from impact and burial in the stockpile. When dropped directly onto the base from maximum stacker heights, average dry densities of 0.97 t.m^{-3} may be attained (Eckersley, 1977), although 0.88 t.m.$^{-3}$ is more typical for minimal impact (Trollope and Wallace, 1975). At times however it is necessary to extend stockpiles beyond the reach of stacker booms by dozing a series of windrows over the edge of the existing crest. Such coal then runs down the face under its own weight, forming a particularly loose deposit. This method was used for placement of material involved in the two August 1976 slides listed in Table I, and average dry density for the second of these was 0.84 t.m.$^{-3}$. The stable face adjacent to the stacker embankment gave densities around 0.89 t.m.$^{-3}$. In general, density varies significantly from point to point. Stockpiles at the mines normally receive more systematic compaction from dozers spreading the coal and are subject to less extreme moisture conditions, and so are significantly less prone to deep-seated failure.

4 LABORATORY GEOTECHNICAL TESTING

From basic stability considerations and the field records it is evident that behaviour of the saturated coal at the stockpile base is crucial to the development of instability. As a first approximation, consolidated undrained triaxial tests may be used to explore the response of saturated coal at varying dry densities and define conditions under which liquefaction might occur. Coal from Peak Downs and Norwich Park mines has been tested over several years. Recent measurements of undrained shear strength and resaturated permeability of Norwich Park coal are reported here.

4.1 Shear Strength

Standard consolidated undrained triaxial tests were carried out on 200 mm x 100 mm diameter specimens, covering the range of dry densities (0.85 - 1.05 t.m.$^{-3}$) and confining pressures (25 - 120 kPa) relevant to current stockpiles. Particular features of the procedure were:

(a) saturation using back pressures to a value of Skempton's parameter B $\geq$ 0.95,

(b) precise determination of initial specimen volume by measurement of the mass (and hence, volume) of water required to fill the calibrated triaxial cell, and

(c) use of a differential pressure transducer to accurately measure effective stress during liquefaction.

The few particles larger than 19 mm were omitted from the test specimens.

Deviator stresses and excess pore water pressures for four tests consolidated to an effective confining pressure of 50 kPa are shown in Figure 3. For low dry densities (higher void ratios), deviator stresses reached a peak after less than 4 mm axial deformation (2% strain). Further shear was accompanied by increasing pore pressure (decreasing σ_3') and decreasing deviator stress towards some ultimate condition. For the densest specimen (NP-3) pore pressure initially increased, but then decreased after 2 mm deformation (1% strain). Deviator stresses increased sharply until the test was terminated at 8 mm.

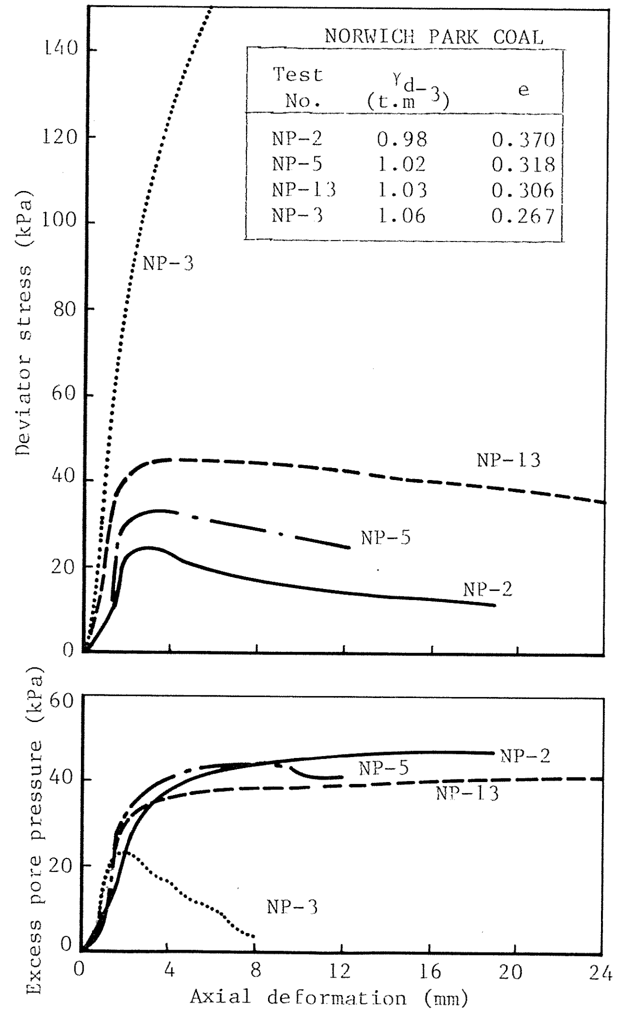

Figure 3 Saturated CU triaxial tests - 50 kPa effective consolidation pressure

Results for the same four triaxial tests are shown as effective stress paths in Figure 4. At large displacements the stress paths approach a strength envelope corresponding to an effective friction angle of 41°. Tests at effective consolidation pressures 25 and 115 kPa gave similar results. The ultimate effective friction angle varies for different coal types depending on particle shape and size distribution. However, ϕ' at peak deviator stress and ϕ values based on total stresses are strongly dependant on stress path and do not necessarily reflect field conditions.

Castro (1969) classified the general form of the deviator stress/pore pressure response of saturated cohesionless soils as

(1) liquefaction, where deviator stress decreases substantially following the peak, and effective confining pressures are reduced to a small proportion of the initial value (eg. test NP-2),

(2) limited liquefaction, where loss of strength is less dramatic (eg. test NP-13) and may be arrested following further shear, and

(3) dilation, where tendency of the specimen to dilate results in pore pressure reductions (eg. test NP-3) with strength eventually of the same order as that from fully drained tests.

On this basis, results for the series have been compiled in Figure 5 as void ratio vs. log of effective confining pressure at the end of consolidation. Line AA represents the transition from liquefaction or limited liquefaction to dilative behaviour, and

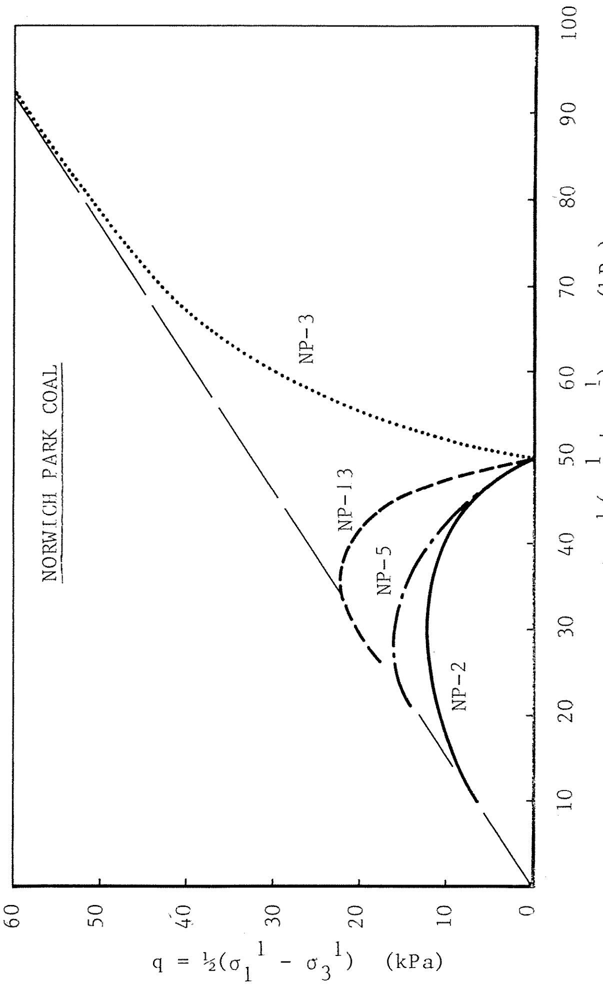

Figure 4 Effective stress paths - CU tests at 50 kPa effective consolidation pressure

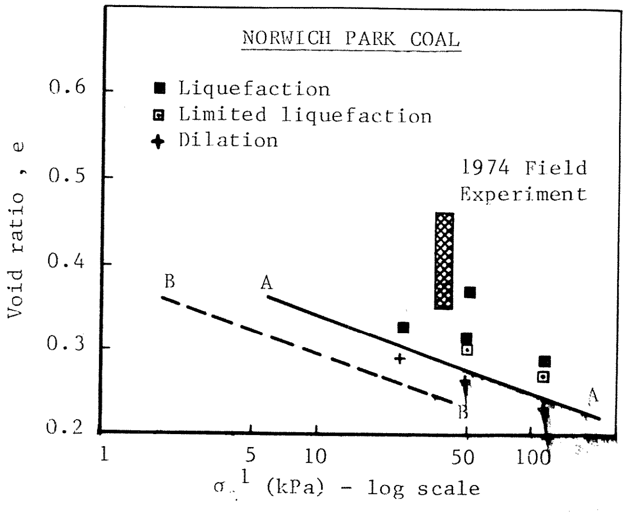

Figure 5 Void ratio - effective confining pressure state diagram

the void ratio required to prevent liquefaction therefore decreases (i.e. dry density increases) with increasing effective consolidation pressure.

Line BB in Figure 5 indicates the ultimate condition for shearing non-dilative specimens at constant void ratio, pore pressure and deviator stress (i.e. the steady state line of Castro and Poulos, 1977). Location of BB has been influenced to a degree by non-uniform bulging of the triaxial specimens (frictionless ends were not available for this series), but results indicated a final steady state independant of initial density and dependant only on σ_3'. For samples consolidated at constant σ_3', the loss of strength during undrained shear is greater for lower dry densities (i.e. greater distance above AA in Figure 5).

It must be noted that the standard CU triaxial tests do not follow realistic field stress paths and that strain control restricts any dynamic component of generated pore water pressures. As such, this procedure is useful only as a first approximation to reality. Considering the relatively few and imprecise determinations of field dry density, and complications due to entrapped air and partial drainage, it was judged appropriate to use existing standard procedures at this early stage. However, the general trend of the results is in agreement with more sophisticated stress controlled tests on sand by Castro (1969) and Lindenberg and Koning (1981). Castro (1969) showed that anisotropically consolidated specimens mobilized peak strengths at lower strains and suffered greater strength reductions than isotropically consolidated cases, but both gave the same e - log σ_3' relationship at steady state conditions (i.e. line BB in Figure 5).

4.2 Resaturated Permeability

Permeability is recognised as one of the most variable parameters encountered in soil engineering. Several series of laboratory tests with specimens 10 to 15 cm in diameter have shown that "saturated" permeability of the product coal may vary by an order of magnitude with even minor alterations to test procedures. Trollope and Wallace (1975) reported that after infiltration to simulate the field wetting process, about 5% air voids frequently remained. They therefore referred to the resaturated condition where remaining air cannot be dislodged without high back pressures or prolonged time periods. Permeability tests have been performed in this resaturated condition, whereas the author preferred to eliminate this further variable for the triaxial tests.

Ten to thirtyfold variations in resaturated permeability have been found to result from combined effects of varying amounts of entrapped air and formation of higher density layers during volume reductions upon resaturation. However, from tests believed to be most representative of the field condition, Peak Downs and Norwich Park coals have the following approximate resaturated permeabilities.

loose (γ_d = 0.9 t.m.$^{-3}$) - k~0.01 cm.sec^{-1}
dense (γ_d = 1.05 t.m.$^{-3}$) - k~0.002 cm.sec^{-1}

5 FLOWSLIDE MECHANISM

The overall mechanism for the deep-seated failures is understood to be as follows. Following placement and/or heavy rainfall, moisture moves approximately vertically down through the stockpile until impeded by the low permeability subgrade. Saturation of the bottom layers of coal results, with height of the water table formed being highly dependant on initial moisture condition and dry density following resaturation. Discharge of the accumulated water through the stockpile toe and lowering of the water table takes several days due to the low head gradient horizontally (Eckersley, 1977).

If shear stresses and static pore water pressures are sufficiently high, shear strength may be exceeded and failure initiated along the stockpile base under virtually drained conditions. The low specific gravity of the coal requires only low water table height (2 to 3 metres) to provoke limiting equilibrium. The situation may be further aggravated by adverse stress redistributions towards the outer part of the base due to volume reductions accompanying resaturation in the main body of the stockpile.

However, it is the consequences of initiation of failure that are crucial to the development of flowslides. For densely packed coal, shearing is accompanied by a tendency for dilation of the mass, pore pressures are reduced, and movement is quickly arrested.

However, for loose, saturated coal (with a void ratio some distance above the liquefaction line AA in Figure 5), shearing is accompanied by a strong tendency for further reductions in the volume of voids. If the slide velocity resulting from drained failure is sufficiently fast and permeability of the coal sufficiently low, excess pore pressures are generated during displacements. A substantial loss of strength occurs along the base and the sliding mass accelerates. The low apparent cohesion of the unsaturated coal above the saturated layer is insufficient to prevent full development of the failure mechanism, and the mass breaks up with drier coal carried along on top of the saturated material, finally deccelerating when sufficient drainage has occurred and a balance is again reached between shear stresses and strength. A complete analysis of permeability conditions and rate of water table increase required for liquefaction to be sustained is yet to be performed, but simple calculations using one-dimensional consolidation theory (Wallace, 1978) showed that the time for pore pressure dissipation in a 0.3 to 1 metre thick layer is similar to the 10 to 15 second duration of observed flowslides.

Validity of the overall mechanism has been confirmed in a limited way by a field experiment. During 1974 a 6 metre high stockpile constructed from loosely placed Peak Downs coal (average dry density 0.88 t.m.$^{-3}$) was brought to failure by infiltration from sprinklers and a series of shallow wells in the crest (Trollope and Wallace, 1975; Trollope, 1975). Complete collapse of the stockpile resulted with flowslides in two directions. Initiation of instability is predicted by analysis based on full arching stresses with conditions measured just prior to failure (Trollope and Wallace, 1975; Trollope, 1975). The consequences of failure initiation may be predicted by plotting effective stresses and void ratios on the state diagram. Vertical effective stress beneath the 6 metre height just prior to failure and the estimated range of void ratios are shown in Figure 5. They clearly plot above AA, indicating that liquefaction would be expected to result given suitable permeability conditions.

6 PREVENTATIVE MEASURES

Given the operating constraints in most large stockpiling operations, the use of retaining walls is neither economic nor practical. Covering the entire stockpile area to avoid rainfall infiltration would be similarly expensive, and only a partial solution. Preventative measures are thus restricted to systematic compaction and various forms of subsurface drainage.

Drainage would be employed with the obvious aim of reducing the height of water tables resulting from rainfall and internal drainage. However formation of low permeability zones, as a result of volume reductions accompanying resaturation and to a lesser degree outwashing of fine coal particles, may render drainage systems almost ineffective. To avoid this, the stockpile should be systematically compacted to a dry density of about 0.95 $t.m.^{-3}$ (for coal types handled at Hay Point), and drains protected by easily replaceable filters.

Systematic compaction of the stockpile from base level up to a dry density of 1 to 1.05 $t.m.^{-3}$ would eliminate virtually all possibility of flowsliding for current stockpile heights with coal types handled at Hay Point. Field compaction trials during 1976-77 showed that densities in this range could be obtained with little effort in lifts 1 to 2.5 metres thick. However, the benefits of compaction have to be balanced against costs of slower reclamation.

In general, the impact of flowslides on the Hay Point operation is minor due to their relatively infrequent occurrence. Major instability has also tended to occur most often on the side of the stockpiles remote from the stacker reclaimer embankments. Danger to staff is minimized by restricting access to this area following heavy rain or placement of very wet coal.

7 CONCLUSIONS

Substantial degradation of the slopes of coking coal stockpiles can occur following heavy rain. On rarer occasions, instability in the Hay Point stockpiles has taken the form of deep seated flowslides. Flowsliding occurs under conditions of particularly loose placement, and water table development above the base due to rainfall infiltration and/or internal drainage of particularly wet coal. The coal types exported through Hay Point are characterised by a low specific gravity and strongly contractant behaviour when in a loose condition. Consolidated undrained triaxial testing of Norwich Park coal has given responses ranging from liquefaction to dilation depending on initial dry density (or void ratio) and effective consolidation pressure. Preventative measures include systematic compaction to a dry density of about 1.05 $t.m.^{-3}$. Subsurface drainage must be accompanied by at least partial compaction to be effective.

8 ACKNOWLEDGEMENTS

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