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A Case History of Liquefaction Flow Failures In Mountainous Mine Waste Dumps

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ABSTRACT

Over the past 25 years there have been a large number of flowslides in Rocky Mountain coal mine waste dumps located in British Columbia, Canada. The flowslides occurred rapidly and displayed surprisingly long distance of runout up to 2 km. Detailed field, laboratory studies, and analyses indicate that static collapse of saturated or nearly saturated sandy gravel layers within the dumps are responsible for the initial failure and ensuing flow failures. In addition to field and laboratory studies, finite element analyses were carried out on three case histories. The analysis results indicated that the flow like liquefaction failures of these waste dumps can be triggered by gradually raising of perched water tables contained within thin layers of poorly draining waste material in these slopes. This paper reviews the site condition and failure pattern observed in the mountainous mine waste dumps and investigates the mechanism of static liquefaction failure by finite element methods.

KEYWORDS

Liquefaction, Flow failure, Steady state, Collapse surface, Sandy gravel, Waste dumps, Stress redistribution, Finite elements.

INTRODUCTION

Mine waste dump stability has been a continuing concern for Western Canadian Rocky Mountain coal mine operators. A large number of flowslides in these mountainous mine waste dumps have been observed in the past 25 years. A documented data(Golder Associates, 1992) shows 42 major flowslides in British Columbia coal mine waste dumps and an industry survey on 31 active sites in this area(Piteau Associates, 1991) reveals 18 instabilities out of 81 individual dumps.

The flowslides in the Rocky Mountain mine waste dumps exhibit rapid flow like movement of large amount of materials and long distance of runouts. The waste dumps are constructed as end-dumped fills with repose angles about 38° and heights between 100 and 400 meters. Safety factor calculations, normally carried out for each dump, show that the dumps are stable. There is a general lack of understanding on the sudden flow like failure of the dumps under static conditions.

A joint effort between Federal Government, University and industrial was carried out from 1992 to 1995 to investigate the site, climatic, material and dumping conditions at the Rocky Mountain coal mine waste dumping sites and to study the instability and failure mechanics of these dumping slopes. This study includes site investigation, laboratory tests and numerical modeling. The main objective of the work is to examine the role of liquefaction mechanics under static conditions and possible mitigative strategies that could be practically implemented to minimize the risk of the flowslides (Dawson et al., 1992). This paper presents part of the results and numerical modeling in this research. The results of numerical modeling verified that static liquefaction could be responsible for the waste dump flowslides, illustrated a manner in which large scale shear stress redistribution are occurred during collapse.

FIELD STUDIES ON FLOWSLIDES IN ROCKY MOUNTAIN COAL MINES

Field studies were carried out at three minesites, i.e. the Quintette Marmot 1660 dump site, the Fording South Spoil dump site and the Greenhills Cougar 7 dump site. The three events spanned a broad range of dump heights (100 to 400m), failure volumes (0.2 to 3 million m^3), and runout distances (700 to 2200 m). Two of the failures which took place during the fall months and the one failure that occurred in the spring revealed the presence of finer grained sandy gravel materials. The finer materials were seen to be mostly associated with the basal portions of the runouts. Where the underlying foundation materials were exposed, clean contacts with the overlying waste rock were observed. Observations of dumping practices revealed the typical segregation of the dumping could be periodically interrupted by a sandy gravel layer capable of retaining significant moisture and forming a local or perched water table. In-situ density testing revealed that these materials exhibited permeabilities similar to the granular materials that have been known to liquefy. All three case histories showed evidence for sufficient water availability prior to failure.

BACK ANALYSIS ON FLOWSLIDES IN MOUNTAINOUS MINE WASTE DUMPS

Back analyses on the three flowslides were carried out by an incremental finite element method and the liquefaction model developed at the University of Alberta. This paper introduces the back analysis and the liquefaction model through numerical modeling on the Greenhills Cougar 7 flowslide.

A Strain Softening Liquefaction Model

The critical state boundary surface theory was developed by Roscoe et al.(1958). In this theory, a critical state line has been defined in p'-q-e three dimensional space. The critical state line relates the soil strength and yielding behavior to the soil structure directly. This is a necessary feature for a soil experiencing complicated stress paths or histories, such as over-consolidation, loading in variable drainage conditions and loading under both dynamic and static conditions. It is more importance for highly mobile soils, such as the loose sands under undrained conditions in which the soil strength and yielding behavior may change rapidly depending on the current soil structures.

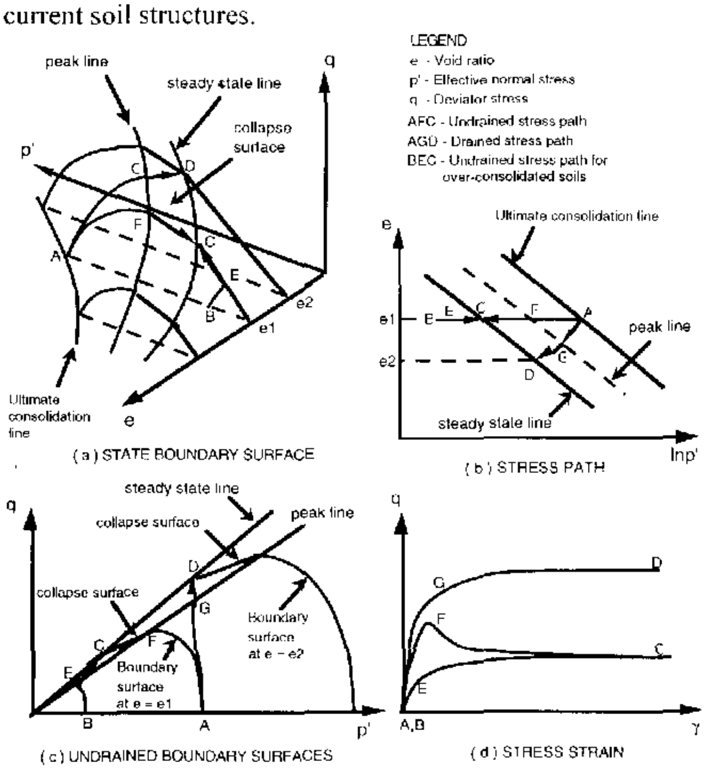

Fig. 1 State Boundary Surface For Loose Sands

Soil grain structure collapse in which the soil strength reduces rapidly from a peak value to a residual under undrained conditions or sudden volume change occurs under drained conditions have been observed in laboratory tests(Sladen et al., 1985, Skopek et al., 1994). The residual strength of loose sands under undrained conditions has been defined as a steady state by Castro et al.(1975). Figure 1 shows schematically a boundary surface introduced by Gu et.al (1992, 1994) for loose sands to incorporate the concept of steady state and collapse surface into the framework of critical state boundary surface theory. As shown in Figure 1(c), each undrained boundary surface is respective to a constant void ratio e and depends on the soil structure directly rather than on the normal stress. A strain softening liquefaction model has been developed and implemented into a finite element program based on the undrained boundary surfaces (Gu et al., 1993, 1994).

The Greenhills Cougar 7 Flowslide

The Cougar 7 dump at the Greenhill's Mine located near Elkford, British Columbia was constructed in the winter of 1991 between February and May. The dump was inactive and remained stable for 13 months until a large flowslide occurred in the morning about 07:00 am of May 11, 1992. Approximately 200,000 cubic meters of failure debris slid off the 100m high waste dump, traveled across an access roadway, and flowed down slope for a total runout distance of 700m. The cross sections and runout profile for the slide are shown in Figure 2. The site conditions prior to and immediately following the failure event were investigated by Golder Associates(1992) and the BC Ministry of Energy, Mines and Petroleum Resources(1993). Cracks were noticed on the dump face in the previous night. Seepage zones were also noticed. By a judgment of the short time in which a service truck couldn't escape from the hazard area, the failure occurred very rapidly and the debris attained considerable velocity.

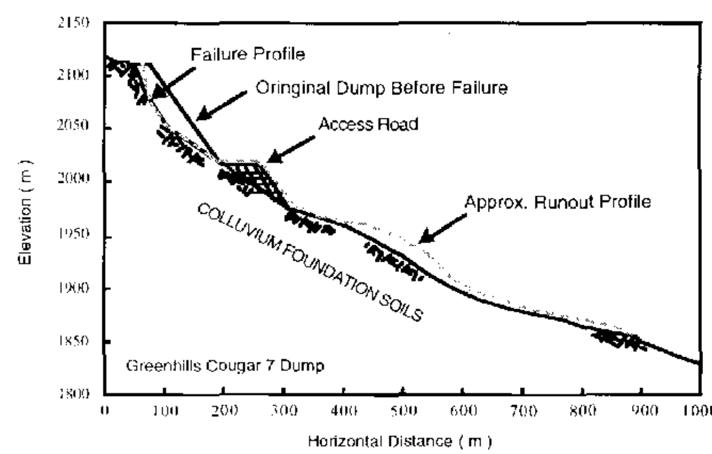

Fig. 2 Flow Failure of Greenhills Cougar 7 Dump

The site investigation(Dawson et al., 1992) revealed that the dump was developed in the headwater area of Cataract Creek. Water was observed flowing through the runout debris below the original dump toe during the investigation. The runout zone of the Cougar 7 dump consisted predominately of sandy gravel materials. The dozer cut revealed a wet sandy gravel layer at the foundation contact. Layers of fines were observed near the dump crest and in the failure debris. It is clear that the dump was riding on a fine saturated layer before the failure.

Strain Softening of Sandy Gravel In The Laboratory

Undrained triaxial tests were conducted on lab prepared sandy gravel samples in 10.2cm diameter cells. The samples were prepared by removing oversize particles(-20mm) from the field sampled materials. Results for a typical strain softening undrained test are shown in Figure 3. The peak strength is reached at an axial strain of about 2%. The steady state strength of about 80 kPa is achieved at the axial strain of about 20%. The results from all test samples indicate that the steady state points mostly lie close to a straight line defined by a slope of 1.5 on the p'-q plane which is equivalent to an effective friction angle of 38°. The peak strength relationship shows a straight line with a slope of about 1.1 which is equivalent to an effective friction angle of 20°. At average stresses of 50 to 300 kPa brittle behavior is well defined, the stress paths in this range show a collapse surface with a slope of about 0.5 on the p'-q plane.

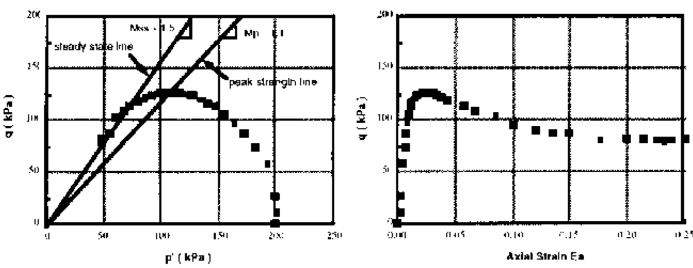

Fig. 3 Strain Softening of Sandy Gravel In An Undrained Triaxial Test

Initial Driving Shear Stress

The initial stresses in the dump slope were calculated by incremental steps to simulate the construction of the dump in layers parallel to the face. The hyperbolic model (Duncan and Chang, 1970) was used to model the soil behavior during the construction.

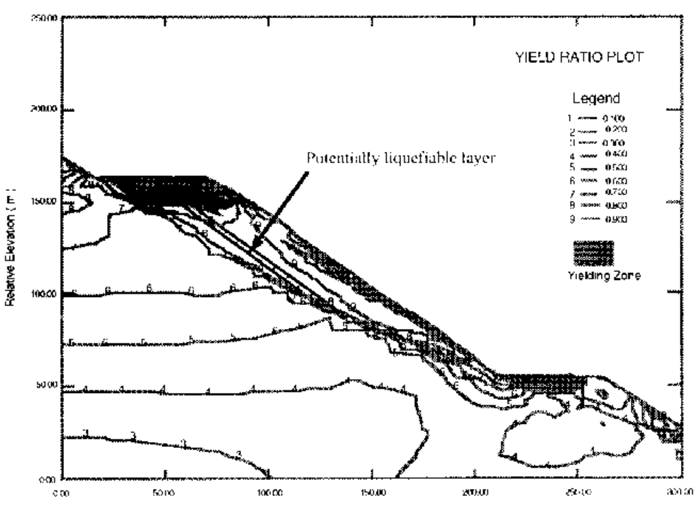

Fig. 4 Initial Yielding Ratio In Greenhills Cougar 7 Dump

Figure 4 shows the initial yield ratio in the Greenhills Cougar 7 dump. The results indicated a stable slope with a yielding zone near the crest. The displacements are small and appear to be controlled. But the initial stresses for a potentially liquefiable layer in the dump are found sitting in a critical state that is very close to the peak line. Any small increase in pore water pressure could bring these materials to collapse.

Back Analysis of The Greenhills Cougar 7 Flowslide

The potentially liquefiable layer in Greenhills Cougar 7 dump was assumed to be located about 15m behind the dump face based on the site investigation. As pore pressures are built up in the liquefiable layer as a result of rising water table in this layer, collapse occurs. Figure 5 shows the failure pattern of the dumping slope initiated by stress re-distribution in the slope. The yield zone in the dump that has expanded from the crest to toe and the pattern of displacements well indicate the post failure profile.

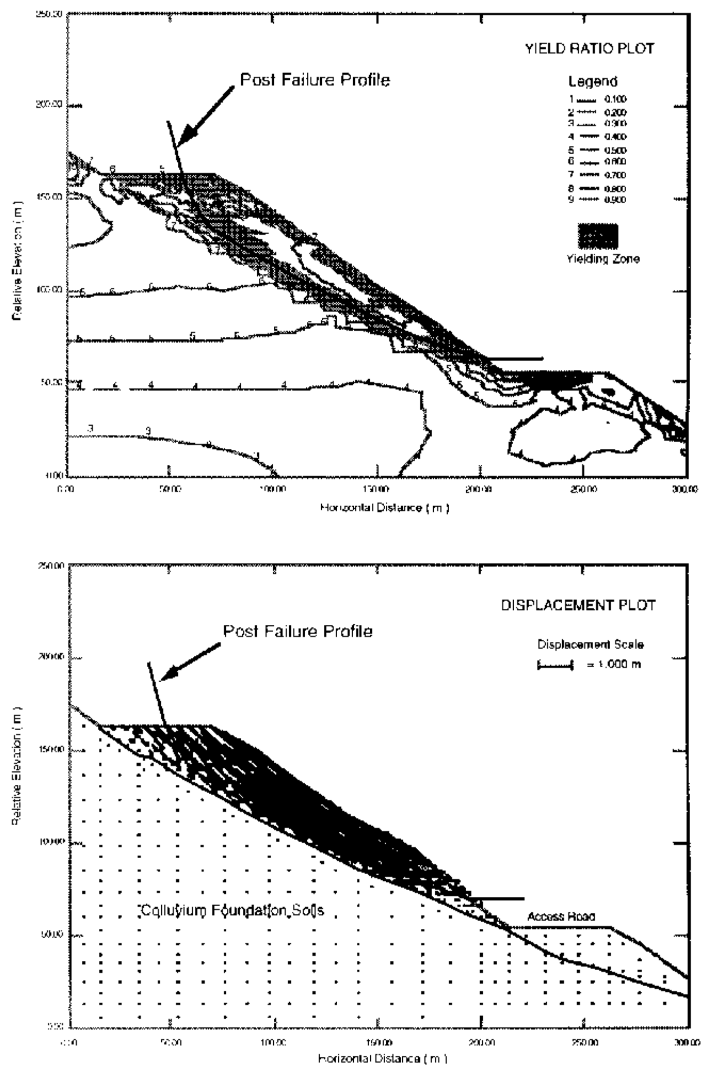

Fig.5 Yielding and Collapse In Greenhills Cougar 7 Dump

CONCLUSIONS

This paper presents part of the results obtained in a study on flowslides in Rocky Mountain coal mine waste dumps under static and drained conditions. The framework of the study is founded on the concepts of steady state and progressive failure soil mechanics. Numerical modeling on the Greenhills Cougar 7 flowslide demonstrated a manner in which overall collapse or progressive failure occurs. A local failure of brittle materials may occur initially by increase of pore water pressure that bring these materials to an unstable state. A local failure of the material need not always result in flow sliding in a slope. If the unbalanced stress generated by local material failure can be re-balanced by surrounding non collapsing materials, only limited deformation may develop. Otherwise, local material failure may initiate large scale shear stress redistribution and result in sudden flowslides in the slope.

The effects of initial driving shear stress, the pore water pressure and the soil mobility on liquefaction instability have been recognized by some earlier studies(Seed et al. 1975, Finn 1981, Morgenstern 1992). This paper provides a vivid example to predict liquefaction failure and consider these effects by finite element methods. An enhanced understanding of the instability mechanics leading to waste dump flowslides has been obtained by numerical modeling and field studies on these case histories that allows for mitigative measures to be developed with greater confidence.

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