INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

STABILITY OF CRACKED EARTH DAMS ON COLLAPSIBLE DEBRIS FANS

STABILITE DES BARRAGES SUR TERRAINS A EFFONDREMENTS FACILES

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SYNOPSIS: Static stability techniques are reported for existing cracked debris fan earth dams in the western United States founded on collapsible soils. The limitations of classical slope stability methods are discussed and the use of the finite element codes ABAQUS and MADAM illustrated on 3 case histories. The MADAM code has been developed to model the response of earth structures founded on moisture induced debris fan collapsible soils and contains a customized constitutive soil model SAMS, Stability Analysis of Metastable Soils. Techniques for modeling collapse of the debris fan foundation by horizontal and vertical moisture propagation, together with a sinkhole model are shown. Insitu characterization of soil behavior and collapse potential is made by the prebored pressuremeter, with recommendations given for a field specialty testing procedure. Suggestions are made, based on preliminary MADAM analysis, of the optimum dam rehabilitation technique by geogrid reinforced "cloaking" of the side slopes.

INTRODUCTION

The Soil Conservation Service, USDA, in the arid western states of the U.S. has responsibility for the monitoring, analyses and possible rehabilitation of over 40 cracked debris earth dams. These dams typically have no permanent impoundment, are 6-12m high and in excess of 600 m long, were constructed from native debris fan soils over the past 30 years to trap sediment debris carried from the mountains in flash, high intensity, flood. Their construction displays minimum zoning, low compaction effort and little, to no, performance monitoring since completion. Their foundations comprise the original debris fan deposits, without treatment prior to construction. These structures display moderate to severe distress features, principally longitudinal cracks with some sinkhole evidence and basin settlement. Moisture induced collapse from the occasional shallow impoundment, and moisture shadow effects, have been identified as the cause of cracking. In these arid climates, summer day time temperatures in the low humidity air reach 120 degrees F. The dam structure has continued to be depleted of moisture and now is in a stiff brittle condition unable to tolerate differential movement. Longitudinal cracks of the order 100 mm to 150 mm wide and 6m to 20m long, are evident 4m deep, spaced 2m to 3m apart up the dam slopes.

Geotechnical stability analysis and the design of remedial measures is complicated by a number of factors including: 3 dimensional effects around a sinkhole, less than complete saturation of foundations soils, and the coarse grained nature of soils, with cracking on the embankment. Indeed the U.S. Commission on Large Dams reported (Millett and Dodd, 1990), that the topic of static foundation analysis, design and remedial treatment was among the highest priorities for improved techniques, especially treatment to protect from natural hazards.

In general, the foundations for the dams are comprised of Silty-Sandy-Gravel mixtures ranging from SM to GP-GM with sufficient fines present (approx. 15%) to provide collapse potential. Collapse is evident from moist sinkholes of up to 6m diameter with surface depressions in excess of 0.45m. The dam cracking displays a dynamic life of repeated opening, closing, and seasonal movement. Encroaching human activity and housing development has reinforced the need for thorough stability evaluations to be undertaken.

Only very limited success at best can be claimed for limit equilibrium based factors of safety and have previously been discussed (Smith, et. al., 1991). Limit equilibrium approaches give little insight into the likely critical stability concerns, due to the absence of any kinematic model in these methods. Failure is likely from excess foundation settlements, the magnitude of these movements, the ductility of the dam and its toleration for differential settlements (which may induce further damage) govern the problem, and therefore dictate remedial measures. It remains a high priority to ensure the undesirable situation of transverse cracking is avoided. Stability of a badly fractured embankment under a full impoundment, with the 50 year recurrence period flood, represents the worst case scenario. To date, cracked dams in the field have undergone repair by trenching and the inclusion of broadly graded filters.

It is appropriate to use more advanced numerical methods, i.e. the finite element method, to model: the stress chronology within the dam, study cracking conditions, the merits of a range of remedial techniques, and finally produce recommendations for treatment of proposed new dam foundations. Numerical simulation, which include construction and all the post construction property modifications from moisture changes, preclude the use of many constitutive models and commercial codes. As a way of gaining preliminary insight into the dynamics of moisture effects the code ABAQUS (Hibbet et. al. 1990) was used with a temperature (moisture) dependent Von Mises plasticity model. To complete a more thorough analysis the code MADAM (Meta-stable Analysis of DAMs) was composed which includes a customized collapse moisture dependent constitutive model. The use of these codes is demonstrated on three case study dams, Fredonia in Arizona, and Greenslake and Ferron in Utah.

"ABAQUS", "SAMS" AND "MADAM"

ABAQUS is a general purpose FEM program with extensive element types and several constitutive models suitable to soil analysis including elastic, elastic-plastic (Von-Mises) and extended Drucker Prager. For study of the damaged dams the nonlinear Von-Mises model was used and the temperature dependency feature invoked to give soil collapse. Numerically the flow of moisture and heat through a porous media are governing by the La Place equation. To model soil collapse the elastic modulus and yield stress were reduced linearly with an increase in temperature. Arbitrarily 1 degree was assigned to pre-collapse conditions and 5 degree to post-collapse conditions. Calibration of the decay in modulus and yield stress was made from results of field measured prebored pressuremeter test results in both pre- and post-collapse conditions from the procedure given later.

This "moisture" dependent model was qualitatively verified in a small rectangular box mesh of 3.0 m wide 1.5 m deep. Following gravity turn-on as body force a distributed load of 30 kPa was applied followed by the 4 degree temperature elevation. The initial elastic settlement increased by 4 orders of magnitude upon "collapse" and gave settlements of equal orders of magnitude to those observed in the field. Results from ABAQUS using this technique on a generic dam profile are in the following section.

SAMS is a customized finite element constitutive model for use with moisture induced collapsing soils. The formulation of the model is an adaptation of the Single Surface Model (SSM) developed by Lade and Kim (1988) and Lade

(1989) to derive the constitutive relationships of granular materials for implementation into finite element programs. The SSM describes the constitutive behavior of granular, cohesive, and cemented soils. It consists of a single yield surface and is based on concepts of elasticity and plasticity theories. The plastic behavior consists of a failure criterion, and non-associated flow rule, a yield criterion that describes surfaces of equal plastic work, and a work hardening/softening law. In addition to the features found in the Single Surface Model, SAMS accounts for the variation in soil properties with a change in state (moisture content) that is typical of collapsible soil deposits. The variation in properties with moisture content is assumed to be linear at this time, with the option of creating a non-linear relationship as more data becomes available. SAMS adjusts the constitutive parameters between limiting states of dry (natural) and wet (near saturation) soil moisture states. The algorithm necessitates high quality laboratory, or insitu, tests for the soil to be available in both states to provide constitutive input. Figure 1 illustrates the relative decreases in failure stress state from dry to wet, and Figure 2 the relative increase in plastic work which occurs, in a laboratory diatomite sample.

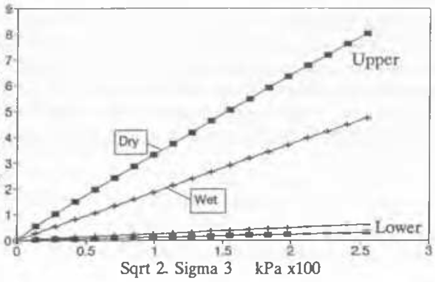

Figure 1. Failure Surfaces for Dry and Wet Diatomite on the Triaxial Plane

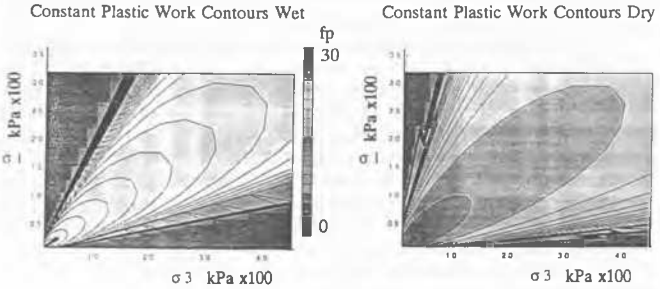

Figure 2. Plastic Work Contours in Wet and Dry Diatomite

MADAM is a special application of the finite element method to the mechanics of metastable soils, via the moisture state dependency, and the SAMS constitutive model. The general constitutive and numerical techniques applied are well developed and understood in various specialty areas of engineering, and are tailored and combined here to provide the desired modelling capability in a soil mechanics application. The framework for MADAM was derived from a moderately developed finite element computer code called 'Soil Analysis Code' (SAC), (Hermann and Mish, 1983), for soil consolidation analysis.

The current version of MADAM includes linear elastic, pressure dependent elastic, and the SAMS non-linear elastoplastic moisture state dependent, soil models. The SSM is included as a subset of the SAMS model. The soil models also include effective stress analysis capabilities, but this has not been tested with the SSM in MADAM, as it was not identified as a priority during program development. The inclusion of pore fluid pressure evaluation also, at this time, excludes the metastable analysis.

MADAM includes an algorithm to simulate fill placement for the construction for embankments and cutoff facilities. The algorithm uses a relative activation time for the element which is to be added to the overall system during construction. There is no limit on the number of elements which can be activated using the construction simulation. The current moisture propagation features in MADAM are user defined via the load-time history specifications at the nodes. This method utilizes the degree of freedom assigned to the pore fluid pressure to specify and track the level of saturation at a particular node. Propagation is simulated by varying the saturation level at the node, or group of nodes, with time over the desired node configuration. This node configuration then defines the assumed wetting front. A full description of SAMS and its implementation into MADAM cannot be given here but is available (Slyh & Smith 1992).

The ABAQUS generic work reported in the following section was completed on a SUN SPARC Station 1, operating in the UNIX environment. MADAM has been composed to execute within the DOS operating system on 386/486 machines. A pre-processing data generating program (MADIN) has been written in FORTRAN 77 to compose debris dam FEM meshes with 525 nodes and 432 elements to fixed mesh proportions. Output variables are plotted and contoured by the graphical interpreter package TECHPLOT.

For both ABAQUS and MADAM the tracking of confining pressure (Sigma 3) and peak shear (Tau max) has been employed as the basis for interpretation of the onset of cracking and consequential damage. The formation of damage kinematics from settlement has also been monitored to correlate to field observations at Fredonia, Greenslake and Ferron sites.

"ABAQUS" RESULTS

The ABAQUS code was used with the generic plain strain mesh of 224 elements (8 node temperature dependent quads) and 745 nodes. This early investigation was designed to validate the FEM as both qualitative and quantitatively able to simulate a moisture induced collapse phenomenon. The technical literature contains no other known attempts to use numerical approaches for this category of problem; present state of practice calls only for pseudo-consolidation methods by a double consolidometer tests (Houston et al 1988). Three principal foundation collapse mechanisms were modeled: localized sinkhole activity, moisture propagation upstream to downstream, and localized upward moisture propagation. A summary of results and conclusions are given below.

Localized surface depressions pond available water and produce frequently observed sinkholes, typically 5m to 7m in diameter. This model employed a temperature source at the upstream dam slope toe following construction simulation. Use of elastic and Von Mises models gave basin surface displacements of 0.27m and 0.62 m and tensile stresses on the downstream slope of 110 kPa and 196 kPa respectively. Extended Drucker Prager failed to converge since the change in properties placed the stress state outside the contracting failure surface violating equilibrium. Tensile stresses on the downstream slope were less, and highly concentrated at the slope toe.

Modeling of subsurface moisture flow moving transverse from the basin downstream beneath (and into) the dam was made by shifting the temperatures some one element at a time over 20 steps. Results clearly demonstrated the dynamic nature of the tensile wave which moves up the side slopes from upstream to downstream, as shown in Figure 3, with the Von Mises model. Tension commences with the "moisture" front still over 1 dam height in distance upstream of the slope toe. The tension wave passing over the dam has effected both slopes with up to 230 kPa tension, when the elevated moisture front is beneath the crest. Beyond this stage tension reduces and stresses return to a more normal state with the moisture under the downstream slope toe. At this point the dam is expected to be cracked on both slopes with deeper cracks on the lower 2/3 of the slope. A "roll over" of the dam has taken place under the 12 cm in the foundation collapse. This crack migration is observed in the field over a period of months to years, with crack widths opening and closing under repeated moisture "waves".

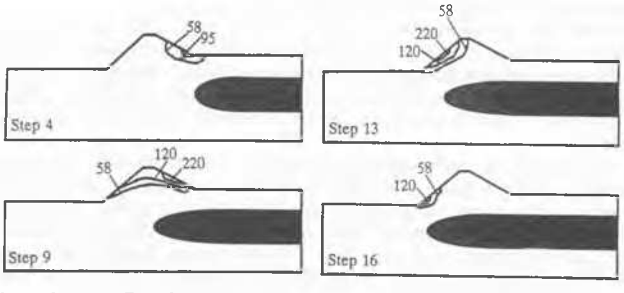

Figure 3. Dam Tension (kPa) Wave "Roll Over" in the Elevated Moisture Position Shown

For localized upward moisture the temperature source commenced at the base of the mesh and moved vertically one element at a time beneath the upstream slope toe in 7 steps. At the 3rd step significant tension is developed concurrently on both slopes at a depth to dam crest height ratio of 2.2. These two zones soon coalesce placing the entire dam in tension with stress climbing to over 240 kPa on the slopes. This mechanism suggests cracking may reach through to the foundation.

"ABAQUS" Summary

Many observed field features can be reproduced by ABAQUS. Strong confirmation is given that transverse, upstream to downstream repeated moisture passages will continue to produce soil collapse and a dynamic crack pattern in the field. Of all the mechanisms the most critical is a full collapse of a column of soil beneath a slope. Magnitudes of settlement and predicted crack depths (from tension zones) match the observed field dam behavior. Given the limitations of plane strain analysis, only longitudinal cracks can be postulated, clearly 3D sinkhole activity modifies this pattern. Numerical experiments with higher dam Ko from compaction reduced the levels of tensile stress marginally but were deemed insufficient to modify any of the overall conclusions.

CASE STUDY SITES

Three debris dam sites with a history of moisture collapse damage were selected for MADAM trial implementation; Fredonia, Greenslake and Ferron.

General Topography and Geology of Sites

Fredonia dam is over 3 km long and reaches 8 m in crest height. Side slopes are 3:1 upstream and 2:1 downstream. The dam shows no zoning, built entirely of compacted upstream borrow sandy silts, which are quite gypsiferous. Triassic Maenkopi formation shales, claystone and siltstone with gypsum underline basin soils below 16m. A cutoff trench is present with 1:1 side slopes to a maximum of 6m primarily in an attempt to remove collapsible soils. The dam shows severe distress over a central length of 45m with longitudinal cracks up to 4m deep. Double consolidometer samples give between 5% to 15% collapse strain. The depth of collapsible basin soils from pressuremeter testing is of the order 11m (5 layers of elements in the MADAM generic mesh).

Greenslake Dam, located in Cedar City, Southern Utah, is again comprised of compacted basin fill material. This area is well documented for its moisture induced collapse settlements (Rollins and Williams, 1991). The structure is zoned, 5.5m high and 0.6 km long with a 1.5m deep central cutoff zone. Foundation soils consist of stratified sands, silts and gravels with cobbles, on a sloping 5% basin. Field samples indicate relative compaction of 79% to 95% in the dam shell. Following an impoundment in 1967 for 3 months basin collapse reached 1.6m and cracking of the nearby dam slope was reported up to 6m deep. A total of 400 m^3 of soil slurry grout was pumped in these cracks. Pressuremeter tests indicate collapsible basin soils to 4.6m deep *and significant collapse potential within the compacted dam core and cut-off trench.*

Ferron Dam in central Utah is 0.4 km long, 6.7m high and has side slopes 3:1 upstream and 2.5:1 downstream. A 3m deep cutoff is present at the upstream toe. Steep siltstone hills flank the 5.5 sq. km basin, with the resulting basin silts fine grained and homogenous to a depth of 11m. Egg shaped basin sinkholes 0.45m deep and 6m x 10m on plan are seen. The dam is zoned with a compacted silt core and rockfill slopes (which deny field crack observation). Collapsible basin soils are found to a 5.0 depth.

Figure 4 schematically illustrates to scale the 3 dams and the relative depth of collapse soils beneath the structure modelled in MADAM.

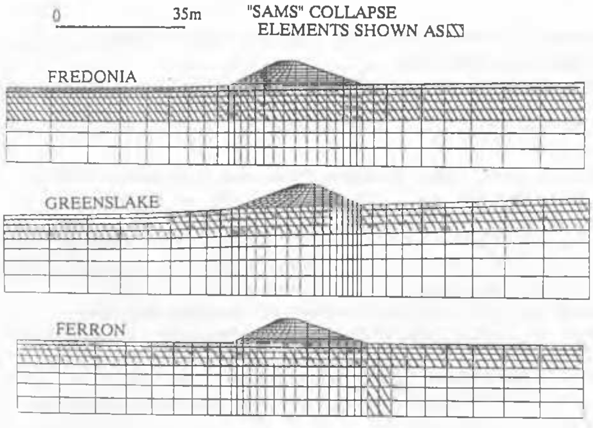

Figure 4. "MADAM" Meshes Showing Collapse Elements for Study Sites

Field Pressuremeter Tests

Due to the heterogenous and often coarse nature of the fan soils the prebored pressuremeter (PMT), TEXAM (Roctest 1986) unit was employed with a long NX probe of 1850 cc initial capacity. Five day PMT investigations were conducted at each site during March and April of 1991. Some modifications to ASTM standard 4719-87 were designed to capture soil behavior pre-, during- and post- collapse. Field experience at 5 debris fan sites from a total of 45 tests have now been completed. The present recommendation for these tests is to conduct stress controlled (strain controlled is acceptable) expansion in boreholes formed by air as the circulation fluid. Testing is conducted in dry holes and wet tests conducted by placing the probe dry and flooding by pouring 20-30 liters of water down the hollow supporting drill string. Test expansion commences after a 30 minute wait time. Figure 5 gives a typical PMT response for the dry and wet tests in the Fredonia basin, 3m deep. Some wet test expansions do suggest a collapse trigger pressure is measured in the early expansion phase.

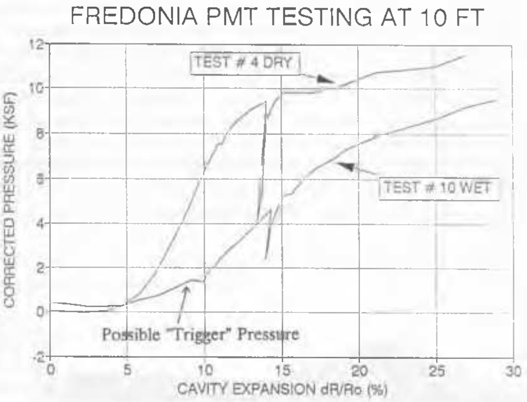

Figure 5. Prebored Pressuremeter Tests Dry and Wet Curves in Basin

FREDONIA "MADAM" POST MORTEM

Dam construction and upstream to downstream moisture propagation, to full saturation, was completed in 18 steps. The first 6 steps consisted of the construction sequence. Figure 6 illustrates horizontal stresses after steps 9 and 11 with the tensile wave influencing all of the upstream slope and the majority of the downstream slope. Interestingly tensile stresses do not propagate into the collapsible foundation material. Relief for the dam to a more "comfortable" state does not show until the moisture front reaches below the crest. The conclusion of the analysis shows slight residual tension in the lower 1/3 of the upstream slope. Total basin settlement were 30 cm. outside of the dam footprint and 38 cm. at the dam crest. Levels of tensile stress do exceed the ABAQUS projection by 50%-80%.

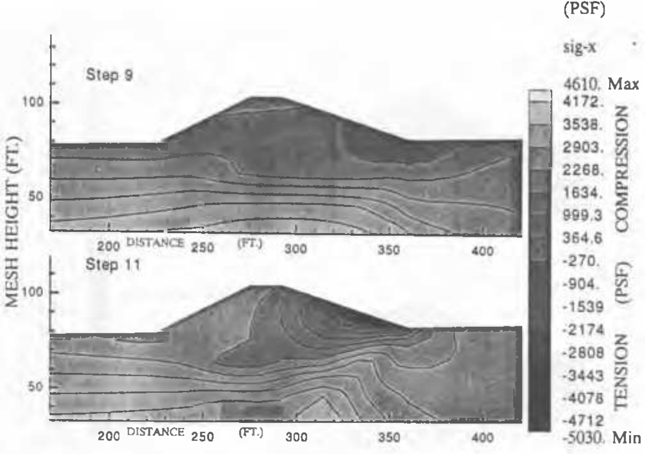

Figure 6. Horizontal Stress Contours for the Transverse Moisture Model at Fredonia

The uniform upward propagation of moisture across the full dam width shows differential settlement, and some damage (when ABAQUS did not) and is to be expected. This differential movement arises from the accuracy of MADAM modelling employing field PMT derived constitutive parameters (Slyh and Smith, 1992).

With no sinkhole field evidence, MADAM modelling indicates the transverse moisture propagation model is the likely culprit damaging the Fredonia structure. MADAM estimates of longitudinal crack positions, depths (from tension zones) and settlement match well the reported distress at the dam.

GREENSLAKE "MADAM" POST MORTEM

No field PMT data is available to produce realistic zoning in the model to match the field. Therefore the Greenslake MADAM analysis was on a homogenous dam with cutoff. The top 4 foundation element rows and the cutoff were made SAMS constitutive collapse models, the bottom 4 were SAMS non-collapsible. Three primary moisture models were made: transverse propagation, sinkhole, and vertical propagation.

A total of 5 steps accomplished construction and the following 12 steps horizontal moisture propagation. The reduced stress state from arching in the cutoff is quickly removed as the moisture front approaches the dam. With a collapsible cutoff the initiation and growth of tension in the upstream slope appears later than the Fredonia dam. These zones begin their propagation more fully with the moisture front at the slope toe. Compressive stresses also recover quicker in the upstream slope due to the reduced core stiffness producing, paradoxically, more ductility than in a less stiff dam. This feature continues throughout this model, Figure 7, and no complete tension envelope on both slopes ever appears. Tension zones propagate very little from the sinkhole, basin tension cracks are to be expected. The upstream slope only shows distress.

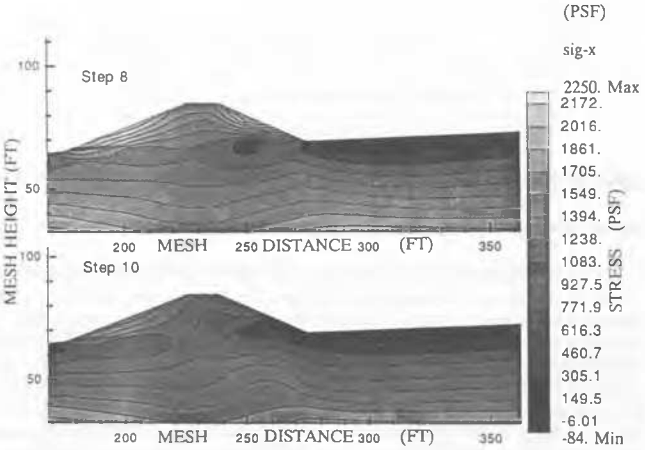

Figure 7. Horizontal Stress Contours for the Transverse Model at Greenslake

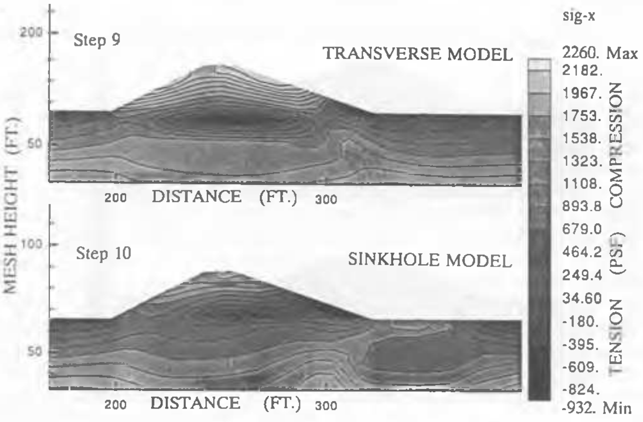

Figure 8. Horizontal Stress Contours at Ferron Dam (PSF)

FERRON "MADAM" POST MORTEM

The chief variation present in the FEM model is cutoff placement beneath the toe, the top 4 foundations element rows are made collapsible and the cutoff is treated as stable. Construction stresses show no bridging effects and higher compressive stresses when compared to either Fredonia or Greenslake. Significantly less tension shows up on the upstream face in the transverse moisture model due to the improved support and higher structural stiffness due to the reinforcing effect of the upstream cutoff. Maximum tensile stresses show up within the core below the upstream slope as displacement indicates the dam spreading laterally into the collapsing foundation.

The observed "egg shaped" sinkhole suggest distinct subsurface linear features which are difficult to model in 2D plane strain with a 6m wide and 7.5m deep sinkhole model. When fully developed 2/3 of the upstream face is expected to show damage, Figure 8. The levels of tension reached in this model, Figure 8, show Ferron to be most vulnerable to sinkhole activity. This agrees well with observed field behavior.

REHABILITATIONS OPTIONS

Limit equilibrium mechanisms are inadequate to determine the serviceability deflection limits for damage to an earth debris dam. The design of repair and rehabilitation measures are also beyond the scope of these methods.

The use of MADAM permits exploration of some options to repair and rehabilitate these structures, Smith et al. (1991). The range of maximum desirable dry to wet property changes which prevent distress showing in the model, can be reported. The options being considered and studied at present included: recompaction, injection of sodium silicate to the foundation (Rollins, 1992), crack dressing and geogrids. Preliminary MADAM analysis suggests a "cloaking" technique by side slope addition would be effective. The existing slope surface is benched and successive lifts of stable compacted fill with "wrap around" geogrid placed as cells. This Geogrid Cloaking technique would produce a ductile coat able to tolerate large differential movement prior to damage, and rehabilitation could be completed long term without removing the structure from service.

CONCLUSIONS

1. Static stability of these dams is not directly the important issue. They are well able in a dry, stiff, brittle state to stand competent as individual highly fractured "blocks". Piping erosion from a significant impoundment following a flash flood is most likely to breech the structure given MADAM prediction of the existence of transverse cracks.
2. Based on analysis of Greenslake, Fredonia and Ferron dams the MADAM code is well able to capture transverse, vertical and localized moisture movement in the foundation.
3. The use of a specially developed FEM constitutive model, SAMS, in the code MADAM is able to predict the critical moisture and foundation collapse scenario.
4. By application of MADAM to the 3 case study sites the damage and settlement patterns predicted correlate well to field observed dam distress.
5. Use of the *chronologic* modeling of moisture movements is important to accurately study the onset of damage.

REFERENCES

Hermann, L. & Mish (1983). User Manual for SAC. University of California Davis, September 1983.

Hibbet, Karlsan & Sorrenson (1990). ABAQUS User Manual, Rhode Island.

Houston, S.L., Houston, W.N. & Spodola, D.J. (1988). Prediction of Field Collapse of Soils Due to Wetting" *Journ. Geo. Eng. Div.*, ASCE, Vol. 114, No. 1, pp. 40-58.

Lade, P.V. (1989). Single Hardening Model with Application to NC'Clay. *Jour. of Geo. Eng. Div.*, ASCE, Vol. 116, No. 3, 1989, pp. 394-415.

Lade, P.V. & Kim, M.K. (1988). Single Hardening Constitutive Model for Frictional Materials. *Computers and Geotechnics*, Vol. 6, 1988, pp. 31-47.

Millett, R.A. & Dodd, J.S. (1990). Survey on State of Dam Foundation Engineering. *Proc. 10th Annual USCOLD Lecture Series*, New Orleans.

Roctest, Inc. (1986). TEXAM User Manual, Plattsburg, New York.

Rollins, K. (1992). Stabilization of DED Foundations by Sodium Silicate, *Portland State University*, Research Report GE-SCS-05-92.

Rollins, K. and Williams (1991). Collapsible Soil Hazard Mapping for Cedar City, Utah. *Proc. 27th Symposium on Eng. Geology and Soils*, Logan, Utah, April 1991.

Slyh, R. & Smith T. (1992). MADAM: Theoretical Development and Constitutive Model. Vol. 1, *Portland State University*, Report GE-SCS-10-91.

Smith, T.D., Slyh, R., Deal, C. & Uhacz, K. (1991). The Design of Debris Fan Repair Techniques Employing Numerical Methods. *Proc. 27th Symposium on Eng. Geology and Soils*, Logan, Utah, April 1991.