Remedial measures planned to prevent surficial failures

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ABSTRACT
Surficial slope failures are occurring frequently on finite slopes. Predominant cause of such failures is antecedent rainfall following a period of drought. Desiccation cracks formed during drying facilitate infiltration of rainfall. This phenomenon results in a reduction of matric suction. The consequent reduction of soil shear strength results in skin slides. Typical skin slides in one of the earthen dam are presented and the effect of rainfall is discussed. Details of various laboratory studies performed on a combination of admixtures are discussed. It is concluded that a combination of lime and fibers helps mitigate swell and shrinkage properties of soil.

RÉSUMÉ
Les échecs superficiels de pente arrivent fréquemment sur les pentes finies. La cause prédominante de tels échecs est hauteur des précipitations antécédente que la suivant une période de sécheresse. La dessiccation craque formé pendant le séchage facilite l'infiltration de hauteur des précipitations. Ce phénomène a pour résultat une réduction de succion de matric. La réduction consécutive de force de cisailles de sol a pour résultat les chutes de peau. Les chutes typiques de peau dans un des barrage en terre sont présentées et l'effet de hauteur des précipitations est discuté. Les détails de diverses études de laboratoire exécutées sur une combinaison de mélanges sont discutés. Il est conclu qu'une combinaison d'aides de chaux et fibres adoucit propriétés joli et de recul de sol.

1 INTRODUCTION

Several rolled earth fill embankment dams in the United States and other parts of the world are constructed of clayey soils with medium to high plasticity. A major concern for the maintenance engineers is the occurrence of surficial failures also called skin slides. Surficial failures of fill slopes are quite common during or after prolonged rainfall (Day, 1993). Surficial failures on slopes typically extend to a depth of about 1.2m (4ft) (Evans, 1972). In many cases, the failure surface is parallel to the slope face (Infinite slope failure).

Figure 1 indicates the schematic of typical surficial failure. During summer or periods of drought, desiccation cracks are induced by evaporation of water and the consequent shrinkage of the soil (Omidi et al, 1996). Clay soils tend to shrink during drying due to development of substantial matric suction in the pore structure of fine grained soils. The depth of desiccation cracks were reported in the literature increasing from a few centimetres to over 10m (33 feet) (Nahlawi and Kodikara, 2006). When it rains, water infiltrates into the soil through the desiccation cracks. As the wetting front increases, the permeability parallel to slope increases and thus the seepage occurs parallel to the slope (Day, 1996). Infiltration increases pore water pressure which leads to reduction of shear strength triggering failure (Rahardjo et al, 1994, Cho et al, 2002). Apart from rain fall intensity, other factors such as rainfall characteristics, antecedent precipitation, soil characteristics, topography also contribute to the failure of any slope (Churches and Miles, 1987).

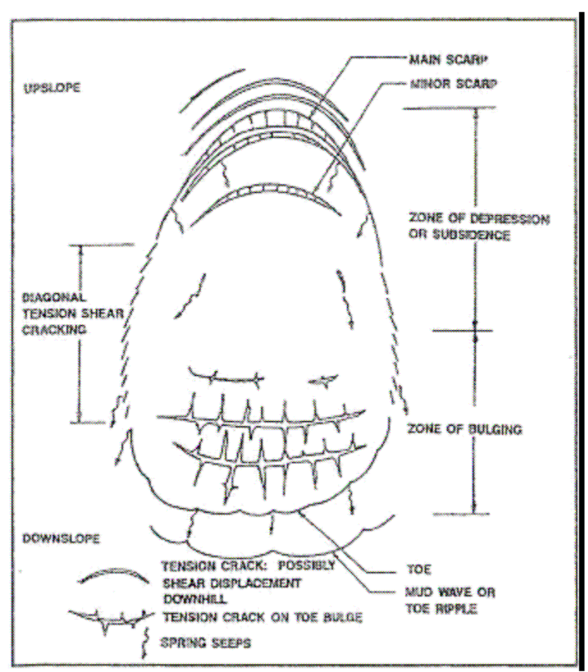


Figure 1. Plan view of typical surficial slope failure (Source: Abramson et al, 2002)

2 FAILURE MECHANISM

Surficial failures can be sudden and unexpected. Sometimes they may be preceded with cracks or other signs of imminent failures (Day, 1996). A slope exhibits higher strength during dry season as the soil is in unsaturated state with negative pore water pressure and matric suction. This can also result in overestimation of factor of safety. Many unsaturated slopes fail during heavy rains following reduction in matric suction and increase in pore water pressures. (Lim et al, 2006). Soil-water characteristic curve which relates volumetric water content of the soil with matric suction determines the failure mechanism. The phenomenon is effected by the flux boundary conditions viz., rainfall infiltration, evaporation and evapo-transpiration at the interface of soil and atmosphere (Rahardjo et al, 2007). The problem is aggravated as the weight of moist soil acts as surcharge. The resisting factors are the drained cohesion and internal friction. The turfing and vegetation on the slopes too contributes to safety. Reduction of soil moisture due to transpiration helps in gaining strength. It has been studied that plant roots enhances shear strength of soil as reinforcement (Waldron, 1977; Day, 1993). Studies of natural and synthetic fiber reinforcement in sand proved increase in shear strength due to reinforcing effect (Gray and Ohashi, 1983, Day, 1996). The fact that the cause of failure can be other than rainfall can not be ignored and all failures need to be investigated properly.

3 HISTORY OF GRAPEVINE DAM

Grapevine Dam is located 30 Km northwest of Dallas in the state of Texas, USA. The dam was constructed between January 1948 and June 1952. The length of dam is about 3.76 Km and the dam has a maximum height of 39m.

3.1 Geology of Dam Site

The dam is underlain by the upper cretaceous age Woodbine formation and by quaternary age alluvial and terrace deposits.

3.2 Climate of North Central Texas

The dam is located in North Central Texas and the climate is humid subtropical with hot summers. There is a wide range of temperature variation in either extreme. Precipitation also varies from less than 500 mm to more than 1000 mm.

3.3 Properties of Dam Soil

Seven borrow areas adjacent to the dam site were selected as earth fill source for the construction of dam. The dam consists of low to high plasticity silty sandy clays (CL to CH) and silty clayey sands (SC). The liquid limit is in the range of 24 to 56% and the plasticity indices range from 11 to 37%. Proctor compaction tests on the borrow soils indicate an optimum moisture content of 7.5% to 18.5% and maximum dry density of 17.5 to 20.8 kN/cum. The soil has strength parameters of 5 to 40 kPa cohesion and 17^{o} to 35^{o} of angle of internal friction as obtained from direct shear tests

The dam is underlain by the upper cretaceous age Woodbine formation and by quaternary age alluvial and terrace deposits. Prior to testing, soil contaminant levels and electrical resistivity at the site were measured and recorded to provide data for comparison. During the pilot test, power consumption, temperature distribution, water flow budget, MPE (multiphase extraction) and SVE (soil vapour extraction) operations, and contaminant levels were monitored daily.

4 SURFICIAL FAILURES AT GRAPEVINE DAM

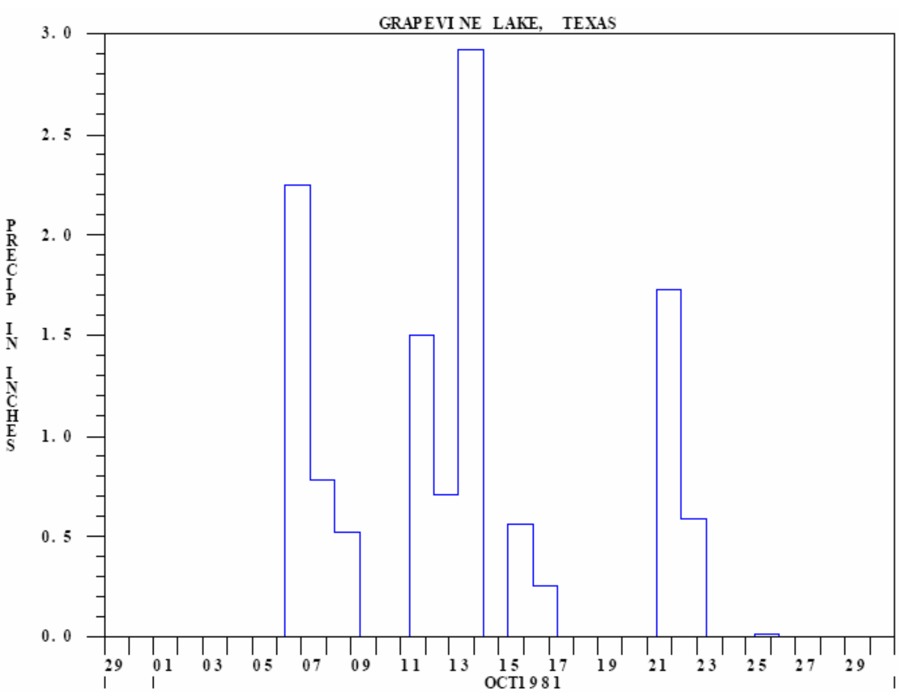
A typical skin slide occurred at Grapevine Dam in Texas State of USA is shown in Figure 2. Various other failures recorded at the same dam is listed in Table 1.

Table 1. Historical surficial slope failures at Grapevine Dam

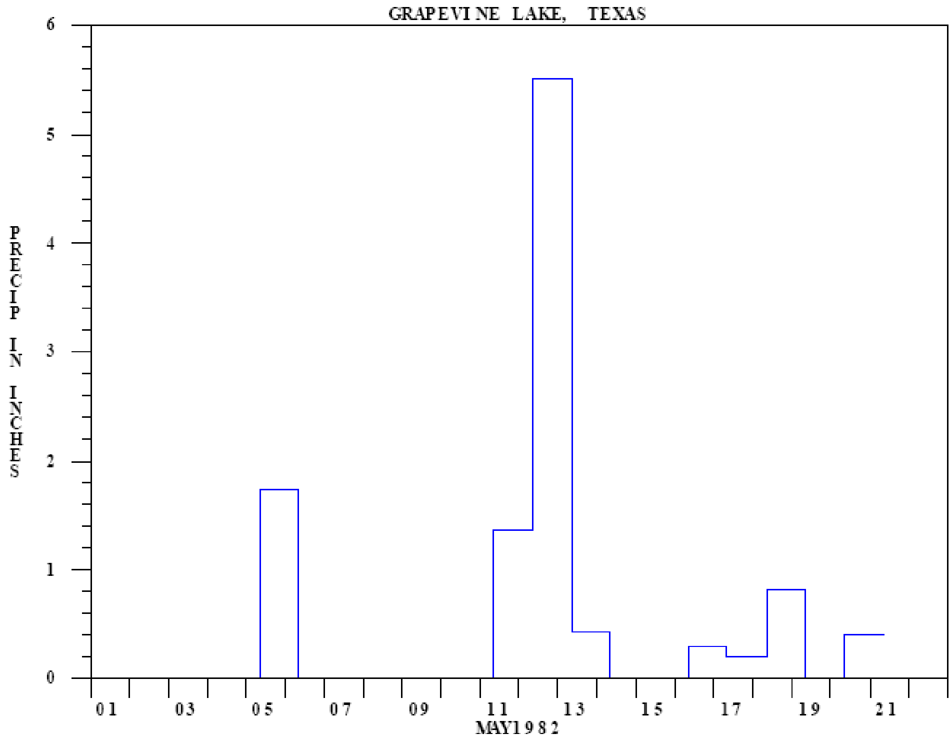
Date of slide	Slide Width × Length (mxm)	Rainfall observations during the month (and preceding month where necessary)
26 Feb 1965	30×12	157 mm- Feb
05 Jun 1970	36×14	16 mm - June, 92 mm-May
09 Feb 1973	25×5	49 mm-Feb, 83 mm-Jan
23 Apr 1973	23×11	154 mm-Apr,
03 Apr 1974	60×21	64 mm-Apr, 58 mm-Mar
10 Apr 1974	15×11	64 mm-Apr, 58 mm-Mar
--Jun 1976	18×21	36 mm-June, 153 mm-May
-- Jun 1976	27×21	36 mm-June, 153 mm-May
17 Jan 1977	46×20	61 mm-Jan
17 Jan 1977	15×15	61mm-Jan
07 Feb 1977	43×15	43 mm-Feb
-- Jun 1977	46×15	17.5 mm-June, 25 mm-May
27 Oct 1981	16×21	360 mm-Oct
27 Oct 1981	16×18	360 mm-Oct
10 Jan 1982	46×21	59 mm-Jan,4 mm-Dec81
19 May 1982	71×18	347 mm-May
19 May 1982	32×18	347 mm-May
09 July 1982	34×21	69 mm-July, 109 mm-July
13 Mar 1989	30×--	95 mm-Mar, 94 mm-Feb
04 Nov 2004	46×23	127 mm-Nov, 145 mm-Oct

As per the available records the depth of the surficial failure is varying from 0.3 to 2 m. There were occasions that on the same day more than one failure were noticed at different locations. Majority of the failures occurred nearer to the crest on the slopes. It can be seen from table 1 that antecedent rainfall is the primary reason to trigger most of the surficial failures. Analysis of typical failures presented below gives further insight. .

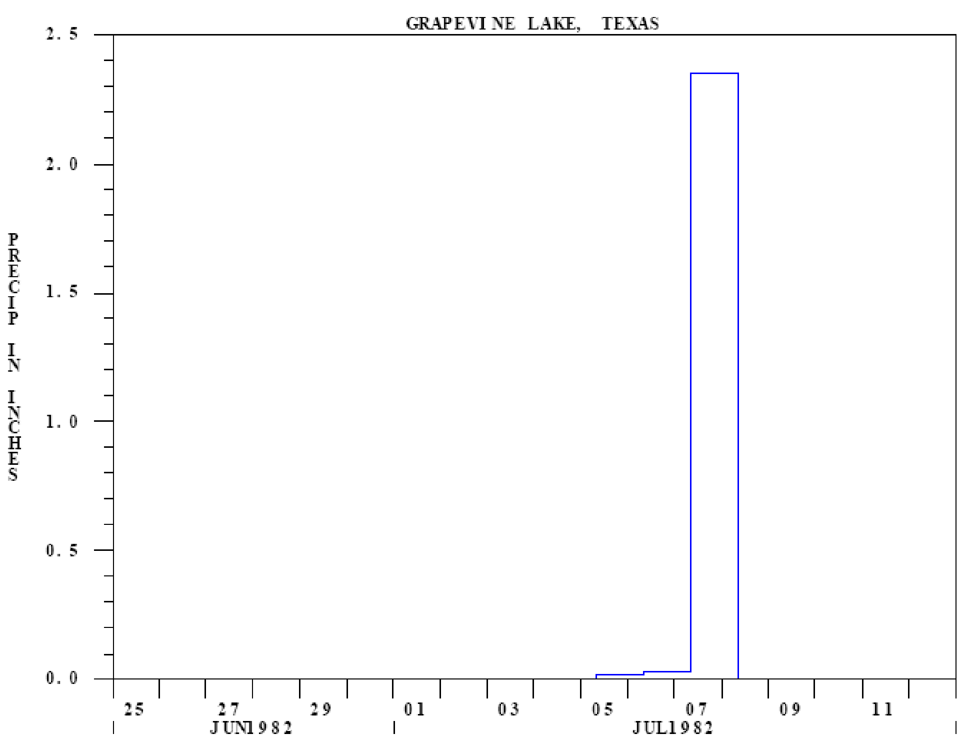
Figure 2. A Surficial slope failure at Grapevine Dam, Texas, USA



(a)



(b)



(c)

Figure 3. Precipitation graphs showing daily rainfall a) October 1981, b) May 1982 c) July 1982 (Source: USACE)

Figures 3 (a) to (c) gives the details of daily rainfall for few typical failure cases cited in Table 1.

Figure 3(a) revealed that during the month of October 1981, there was rain for about 10 days and the highest intensity of rainfall occurred on October 14th. It can be construed that the infiltration of rain water and extension of the wet front resulted in a reduction of matric suction and shear strength triggering the slope failure observed on October 27th. It can be seen from Figure 3 (b) that there was rain on May 19th, 1982 when the skin slide occurred. This slope failure was preceded by a high intensity rain fall of 140 mm during the week prior as well as intermittent rainfall during the preceding weeks. It can be construed from Figure 3(c) that the failure on July 9th, 1982 was triggered with a rainfall intensity of 40 mm just prior to 2 days. However it was observed that for the failure occurred on March 13th, 1989 there was very scanty rainfall prior to the failure which underlines the caution to be observed while investigating the cause of failures.

5 REMEDIAL MEASURES

Various types of remedial measures have been used to repair failed sections of embankments. Rammed aggregate pier soil reinforcing elements were used to stabilise two slope failures along the shoulder of two US Highway 71, Louisiana and US Highway 167, Arkansas (Parra et al, 2007). The performance of the section after repairs was said to be satisfactory.

The skin slides at Grapevine Dam were repaired using a variety of techniques with varied success. In most cases, initially the loose soil from the skin slide location was removed and after doing proper benching, the bank was repaired with same soil or using borrow pit soil. Subsequently, lime was mixed with soil and the mixed soil was properly filled and compacted as per specifications. The repair costs of the slides are running into millions of dollars.

Considering the potential impact to public safety, and the cost to repair new and recurrent slope failures, improvements to the state-of-the-art are required to develop innovative and cost-effective embankment repair measures and techniques. Relevant aspects of research carried out jointly by USACE and UTA are summarised below. The research findings are also expected to be useful for maintaining highway embankments and to mitigate crest cracking which is a serious maintenance problem at several earthen dams.

6 LABORATORY STUDIES

It is very vital to control the shrink swell behaviour of the embankment soil in order to prevent surficial failures. Based on the literature and results of previous research, it was proposed to use a combination of lime, polypropylene fibers and compost (organic) in different dosages to achieve the objective. Table 2 shows the notation used and the different type of admixtures used for the laboratory study.

Table 2. Soil Specimen Notation System for Grapevine Dam

Treatment type	Notation
Dam control soil	GV-CTRL
Soil with 0.15% polypropylene fibers	GV-F0.15
Soil with 0.30% polypropylene fibers	GV-F0.30
Soil with 0.40% polypropylene fibers	GV-F0.40
Soil with 4% hydrated lime	GV-L4
Soil with 8% hydrated lime	GV-L8
Soil with 0.15% polypropylene fibers and 4% lime	GV-F0.15-L4
Soil with 0.15% polypropylene fibers and 8% lime	GV-F0.15-L8
Soil with 0.30% polypropylene fibers and 4% lime	GV-F0.30-L4
Soil with 0.30% polypropylene fibers and 8% lime	GV-F0.30-L8
Soil with 20% Compost (Organic)	GV-020

7 DISCUSSION OF RESULTS

Various tests including grain size distribution, atterberg limits, standard proctor compaction, direct shear, volumetric shrinkage, and one dimensional free swell test are conducted. Volumetric swell and shrinkage test results are depicted below at OMC.

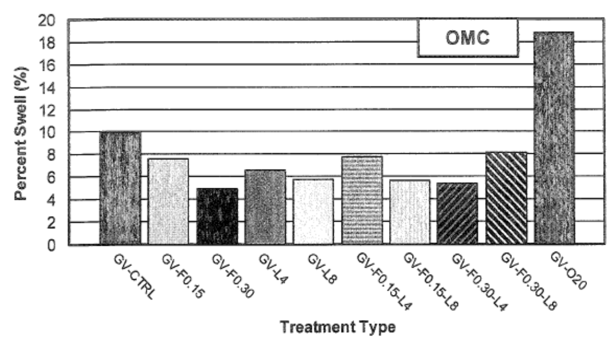


Figure 4. Vertical free swell results

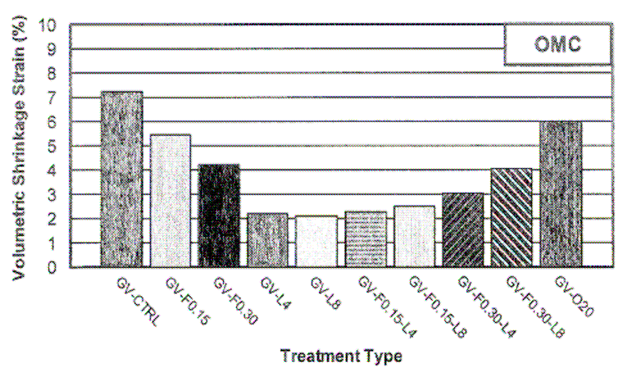


Figure 5. Volumetric shrinkage strain results

Figures 4 and 5 indicate that swell and strain were controlled when the soil is treated with fiber and lime. Compost-treated soil exhibits high swell and shrinkage with respect to other treatments. However, the inclusion of compost helps preserve soil moisture which mitigates the formation of desiccation cracks.

8 CONCLUSIONS

Surficial slope failures are a common occurrence for earthen dams and embankments. These slope failures can be triggered by infiltration of rain into the soil slope due to formation of desiccation cracks. The research was focussed on reducing formation of desiccation cracks and minimising swell and shrink characteristics of soil by adding admixtures. Laboratory studies are found to be very promising to mitigate formation of desiccation cracks and subsequent surficial slope failures by mixing soil with lime, compost and fibers. Based on the laboratory study of admixtures, further study is also being conducted to monitor the field performance by construction test sections using a combination of lime, lime and fibers and compost.

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