Combined Seepage and Slope Stability Analysis of Rapid Drawdown Scenarios for Levee Design

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ABSTRACT

The strength of levees can be affected during fluctuations in the water table. It is also possible for the climate to have an influence on the position of the water table in an earth levee. Traditional methods have resulted in approximate methods for dealing with the transient fluctuations of the water table in a levee. These approximations are generally accepted in engineering practice but the question can be rightfully raised as to how these approximations compare to a rigorous transient combined seepage and slope stability analysis. Software technology has significantly changed in recent years and is now at the point where it is much easier to perform transient seepage analyses. There are new questions that can be asked. Does an effective stress analysis diverge significantly from the 3-stage Duncan (1990) analysis? If so, under what conditions?

This paper compares the Duncan (1990) three-stage methodology for analyzing rapid drawdown scenarios to a combined transient seepage and slope stability analysis. Traditional limit equilibrium methods will be utilized in the slope stability analysis and the accommodation of saturated and unsaturated pore-water pressures will be considered. Analyses of a number of typical cross-sections will be considered in order to determine the potential influence of geometry. The intent of the paper is to illustrate scenarios under which the Duncan (loc. cit.) methodology produces similar results to the results of a more rigorous analysis.

INTRODUCTION

The rapid draw-down scenario is one of the most severe loading conditions which can afflict a levee. Rapid draw-down consists of a relatively high water table which has remained against an earth levee for a period of time such that pseudo steady-state conditions are created in the levee. The high water table would be consistent with high water levels during a flooding season. Often such floodwaters can disappear within a relatively short period of time thus creating a rapid draw-down scenario on the levees. In such scenarios, the pore-water pressures present in the levee during the flooding do not have enough time to dissipate. This is particularly true for clay-type materials where the hydraulic conductivity of the material is relatively low. A situation is therefore created in which heightened pore-water pressures on the up-stream side of a levee can trigger either deep or shallow failures.

Such rapid draw-down scenarios can be analyzed by either a i) total stress or ii) an effective stress analysis. Traditionally, the total stress analysis has been utilized as it is easier to implement in practice. However, the fundamentals of the interplay between effective stresses and pore-water pressures are not represented in a total stress analysis. Therefore, the limitation associated with a total stress analysis is related to the fundamental behavior of soil as failure conditions are approached. The total stress analysis may lead to a more conservative design which may result in considerably higher construction costs. This paper explores a comparison between the total stress and effective stress methodologies for typical material types. The potential differences between the two methodologies for deep and shallow slides are examined and the opportunity to optimize designs using an effective stress analysis is examined.

BACKGROUND

The USACE (2003) slope stability engineering design manual divides earth embankments and levees into two categories:

1. Free draining soils
2. Low permeability soils

In the case of free draining soils the design procedure that is recommended is an effective stress analysis where the initial and final pore-water pressure levels are determined from a steady-state analysis where the initial and final conditions of the water table are determined using two separate steady-state seepage analysis.

For low permeability soils, the design manual recommends a three-stage approach which uses a combination of effective strength results and consolidated-undrained (total) strength results to estimate a worst-case scenario that represents a conservative design. The three-stage approach represents a methodology based partly on a total stress analysis as a limiting condition.

The three-stage procedure has evolved from first version called the Lowe and Karafiath (1959) method and later to the USACE (1970) method. Duncan et al. (1990) reviewed both of these methods and suggested an alternative three-stage analysis procedure.

The Duncan et al (1990) total stress approach provides an easy methodology for the analysis of rapid draw-down conditions in an earth dam or levee structure. However, it is subject to the following limitations:

1. The time over which rapid drawdown occurs is not accounted for in the procedure,
2. The method assumes that a consolidated-undrained laboratory test represents the limiting condition along the entire critical slip surface. A single value of undrained shear strength is not appropriate along the entire slip surface (Kerkes, et al., 2003),
3. The determination of an appropriate value for the undrained shear strength value for the analysis can be complicated (Kerkes, et al., 2003),
4. The location of the critical slip surface is assumed to be deep and to not change location during the rapid drawdown sequence.

Given that the Duncan et al. (1990) total stress approach is applied to the engineering design of earth levees it would seem important to more clearly understand the performance of the empirical total stress methodology under differing material conditions. It is worthy of note that the Duncan et al. (loc. cit.) approach was conceived and designed in a time when a geotechnical engineers did not have access to software tools required in order to perform a transient saturated/unsaturated seepage analysis.

METHODOLOGY

The methodology used for the present analysis is to perform a series of analysis which perform a rapid draw-down analysis using both the Duncan et al. (1990) 3-stage approach and an effective stress approach. In order to first prove the correctness of the implementation of the Duncan et al. (1990) method a few benchmarks are first presented. The comparison will then proceed to compare the more complex examples originally presented by Duncan. So the general steps are as follows:

1. Benchmark the Duncan method,
2. Pilarcitos comparison,
3. Walter Bouldin comparison.

It should be noted that there are a significant number of input variables which can influence the outcome of the analysis. Some of the variables include:

- Slip surface location (deep / shallow)
- Stress state approach (effective stress / total stress)
- Saturated / unsaturated shear strength conditions
- Variance in seepage or stress - deformation material properties
- Variance in the slope angle
- Variance in material heterogeneity
- Variations in slope stability calculation methodology (i.e., Spencer, Morgenstern-Price, GLE, etc.)

For the sake of simplicity, the present analysis will focus on: i) comparison between effective and total stress approaches, and ii) variances in material properties.

The SVSLOPE® / SVFLUX™ software (SoilVision Systems Ltd., 2010) are used for the analyses of both the 3-stage methodology and the effective stress combined seepage / slope stability analysis. The effective stress analysis methodology involves two primary steps. First the rapid drawdown scenario is solved in a seepage model using appropriate draw-down boundary conditions. The pore-water pressures are started from steady-state conditions with the reservoir at the maximum elevation. Pore-water conditions are saved at regular intervals. The pore-water pressures are then input into a slope stability analysis and the factor of safety is computed at each saved time-step. The pore-water pressures as well as the external load resulting from the reservoir at its current level are considered in the analysis.

Unsaturated soil conditions are present above the water table in a levee analysis but will not be considered in this comparison. Unsaturated shear strength properties will have the effect of raising the calculated factors of safety.

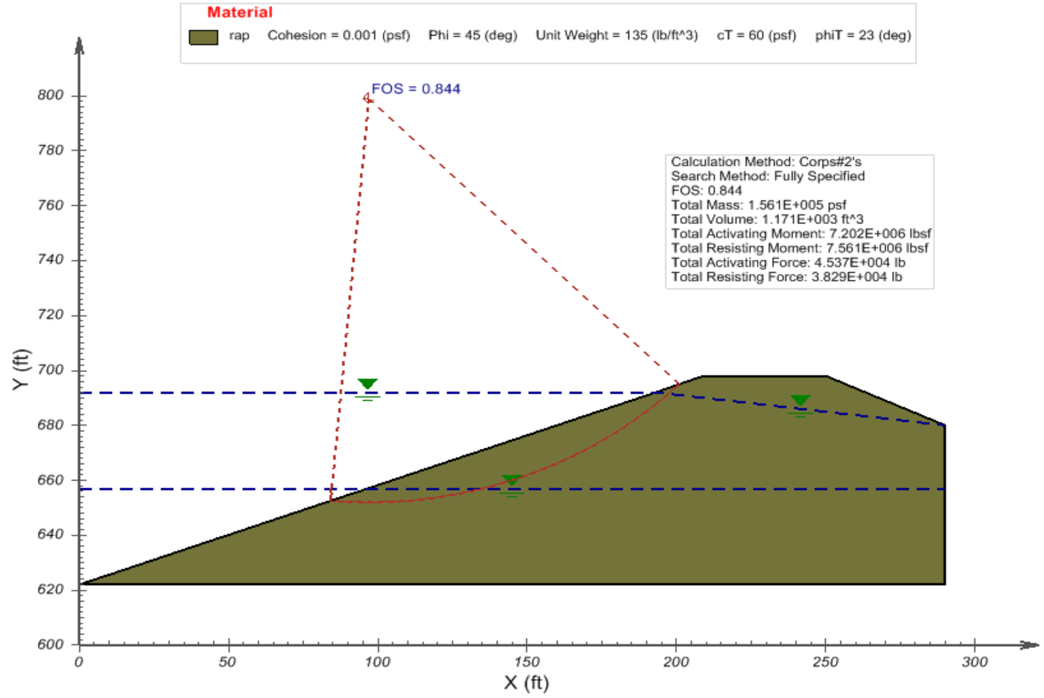
It should be noted that in the reasonable operation of an earth structure there may be fluctuations in the water table and arguably the groundwater table may not truly be at steady-state conditions. It is assumed for the course of this paper that steady-state conditions are present at the start of the analysis.

It is noted that the Duncan 3-stage approach attempts to accommodate the potential influence of consolidated-undrained behavior in the soil. The present analysis does not consider fully coupled unsaturated consolidation behavior in the effective stress analysis during rapid draw-down. The current study focuses on the changing of pore-water pressures in the levee in an uncoupled fashion. While it is recognized that fully coupled analysis may lead to small changes in stress-state (as opposed to an uncoupled analysis), it is the feeling of the authors that the coupling influence is a secondary influence and not likely as influential as the changing of pore-water pressures in an uncoupled way. It should also be noted that the present analysis is focused on limit-state failure conditions and does not consider deformations.

PILARCITOS DAM BENCHMARK

Two examples from the original Duncan et al. (1990) paper are presented for the sake of comparisons in this paper.

The Pilarcitos Dam is a homogeneous rolled earth-fill embankment. The slope failure occurred after the water level was lowered from elevation of 692 to elevation of 657 between Oct. 07 and Nov. 19, 1969.



```
Calculation Method: Corps#2's
Search Method: Fully Specified
FOS: 0.844
Total Mass: 1.561E+005 psf
Total Volume: 1.171E+003 ft^3
Total Activating Moment: 7.202E+006 lbsf
Total Resisting Moment: 7.561E+006 lbsf
Total Activating Force: 4.537E+004 lb
Total Resisting Force: 3.829E+004 lb
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Figure 1 Location of the critical slip surface for the Pilarcitos Dam (Army Corps method #2)

The comparison of the values calculated by the software to values published by Duncan is reasonable. The slip surface in the original paper is specified so any difference must be accounted for in the calculations. Further comparisons with other commercial software packages resulted in differences between 1-3% for methods such as Bishop and Spencer which is reasonable for this type of comparison.

Table 1 Comparison of software FOS calculations with Duncan et al. (1990) for Pilarcitos dam

	Corps #2	**Lowe-Karafiath**
Duncan et al. (1990)	0.82	1.05
SVSLOPE	0.844	0.967
Difference	2.9%	-7.9%

WALTER BOULDIN BENCHMARK

Walter Bouldin Dam is a rolled earthfill embankment. The dam is about 60 feet high, sitting on 80 feet of clayey sand and gravel. Overlying the gravel are a layer of cretaceous clay, a zone of micaceous silt, and a clayey silty sand layer that covers the slope.

During a rapid drawdown of 32 feet in 5.5 hours the Walter Bouldin Dam failed on February 10, 1975.

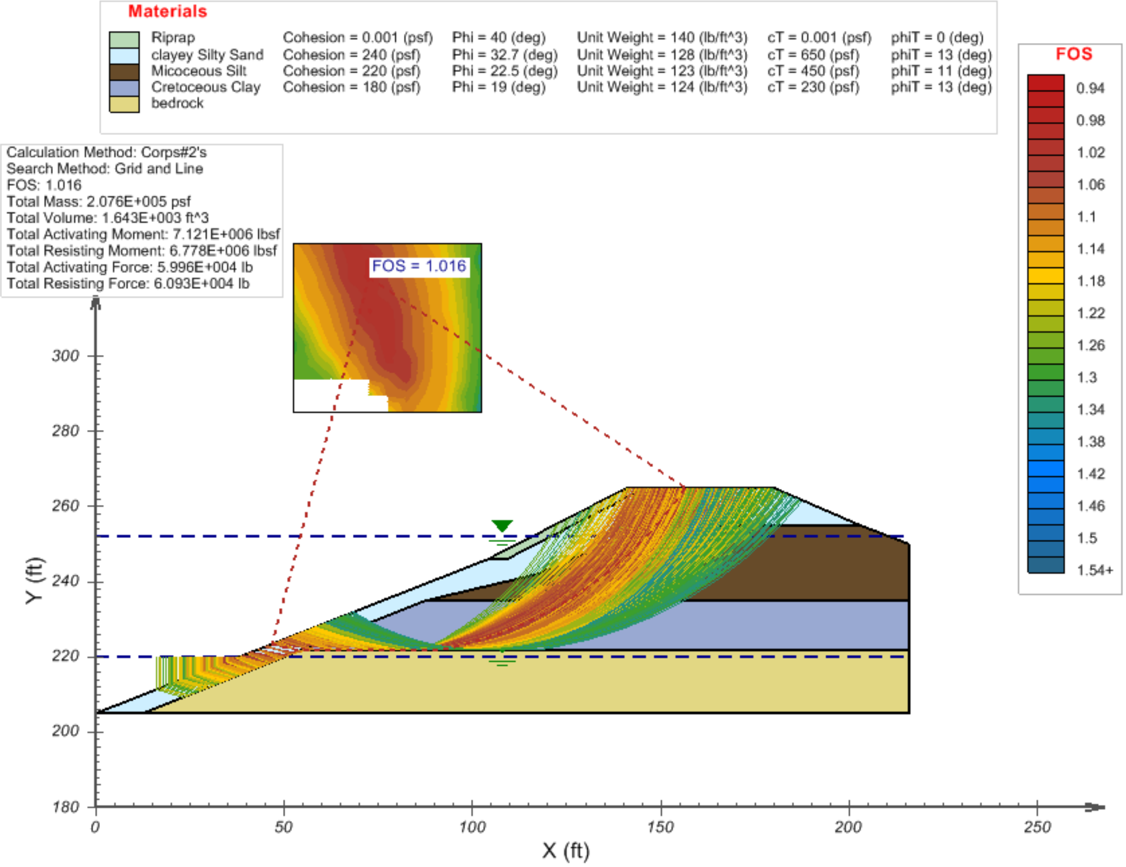

Figure 2 Results of Corps of Engineers #2 method in the software

The results of the benchmark yield differences between +9.2% to -5.0% for the Corps of Engineers #2 method and the Lowe-Karafiath method (Table 2). Further comparisons between SVSLOPE and other commercial software packages (for the 3-stage method) resulted in differences of less than 2.3% for the Bishop and Spencer methods. These differences can be considered reasonable and confirm the validity of the implementation of the 3-Stage Duncan methodology.

Table 2 Comparison of calculated FOS values to Duncan et al. (1990)

	Corps #2	**Lowe-Karafiath**
Duncan et al. (1990)	0.93	1.09
SVSLOPE	1.016	1.036
Difference	9.2%	-5.0%

PILARCITOS DAM EFFECTIVE STRESS ANALYSIS

In this section the Pilarcitos benchmark which was originally analyzed with the Duncan three-stage procedure will be re-analyzed using an effective stress approach. This comparison must be considered approximate at best since performing an effective stress analysis requires hydraulic properties of the dam. No hydraulic properties are available in the original publication. Therefore hydraulic properties will be assumed based on averages for a silty sandy material in the SoilVision database. In this particular example the water was drawn down from an elevation of 692 to an elevation of 657 at a rate of 1.7 feet per day. The dewatering process will then be run first in the seepage finite element model. The upstream boundary condition was represented as a Head Data Review boundary condition in SVFlux. Then the slope stability will be analyzed based on the pore water pressures developed at specific time steps.

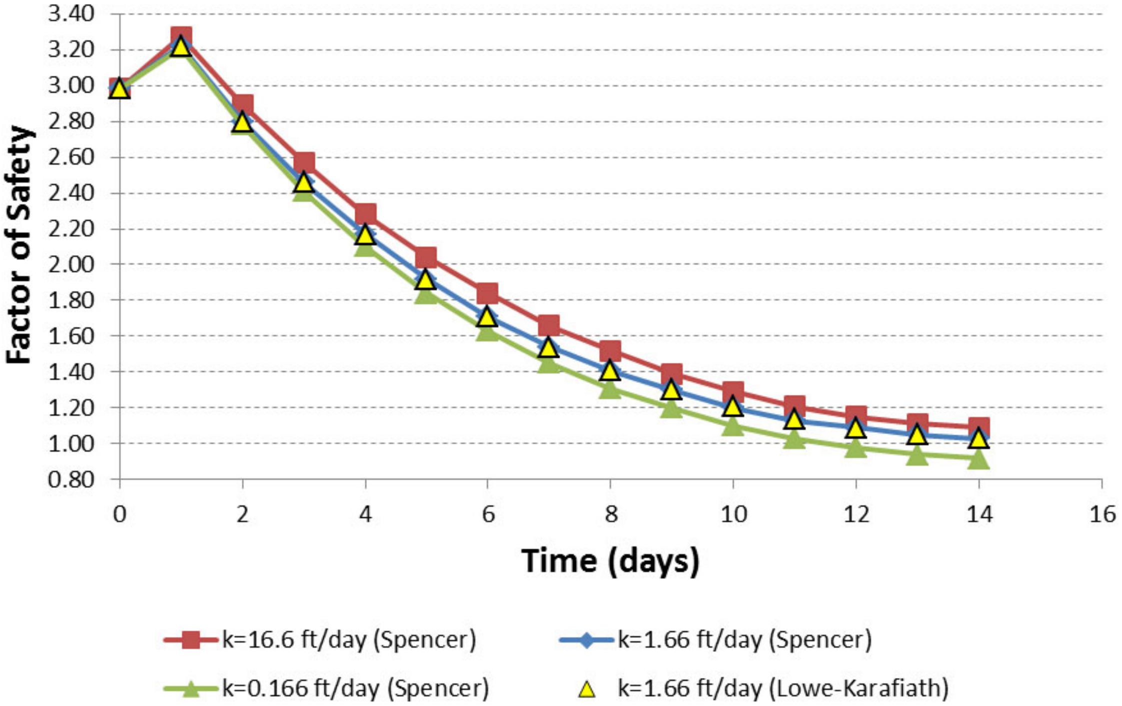

Figure 3 Plot of Factor of Safety vs. time for the Pilarcitos example (Spencer method)

It can be seen from Figure 3 that there is reasonable agreement between the final computed factor of safety from the effective stress method (FOS:Lowe-Karafiath=1.033) and the 3-stage approach (FOS: Lowe-Karafiath=1.05) shown in Table 1. It is also interesting to note that the results are relatively insensitive to the saturated hydraulic conductivity. The extent to which the methods agree will require further investigation.

WALTER BOULDIN EFFECTIVE STRESS ANALYSIS

The Walter Bouldin benchmark (Figure 4) is re-analyzed using an effective stress analysis in this section. This particular example was selected because of the complex geometry presented in the analysis. It must be noted that hydraulic properties are not available for this example and must be assumed. Therefore the following hydraulic properties are assumed for each region in the numerical model. Unsaturated soil properties were not considered in this model at this time.

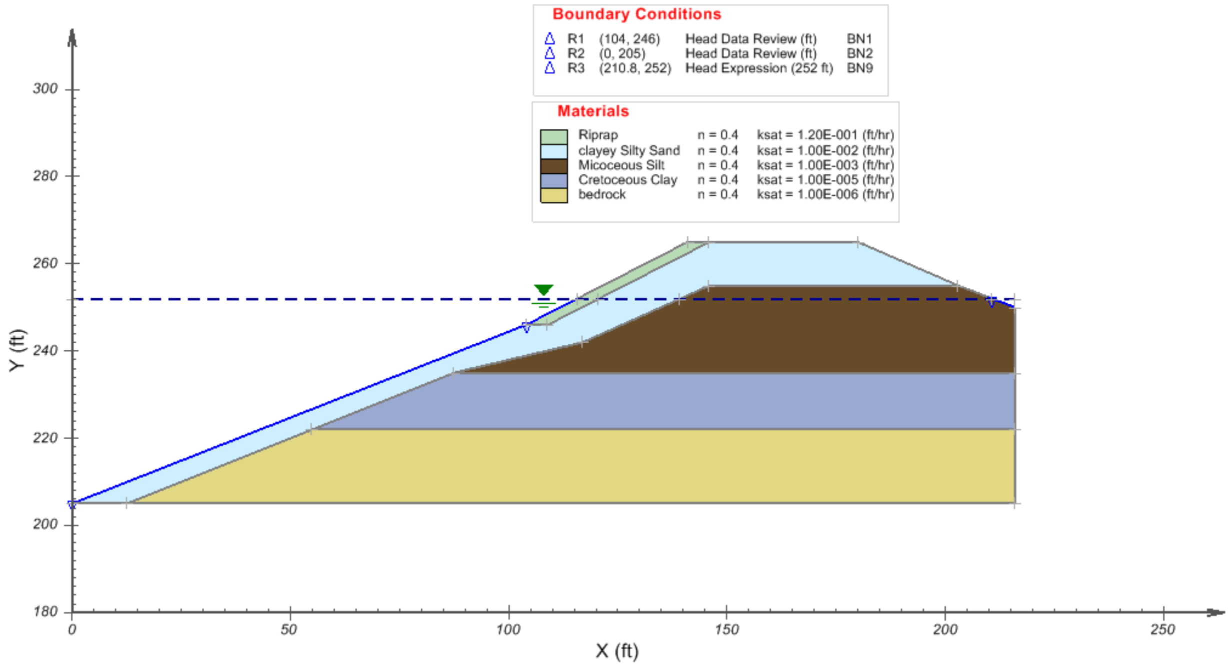

Figure 4 Regions and hydraulic properties used for the effective stress analysis

The model is then first analyzed as a seepage finite element analysis in which the effects of rapid drawdown on the pore water pressures can be quantified. The pore water pressures at each selected time step were then transferred to the stability program which calculated the change in the factor of safety influenced by the changes in pore water pressures. This resulted in the factor of safety versus time plot shown in Figure 5.

It can be seen in Figure 5 that the factor of safety rapidly falls below 1.0 with the original selected hydraulic conductivities (after approx. 2 hrs). Upon further examination of the model it was found that this was because of the high pore-water pressures which are retained in the earth structure after the lowering of the reservoir level. Therefore the hydraulic conductivity of the Clayey Silty Sand material and then later the Cretaceous Clay material were each raised by one order of magnitude. The influence of raising the hydraulic conductivity of the Clayey Silty Sand layer is less significant than the influence of the Cretaceous Clay layer hydraulic conductivity increase. This is because allowing the Cretaceous Clay layer to drain greatly reduces the retained pore-water pressures in the earth dam. Therefore the stability of the earth dam under rapid draw-down is increased.

The Walter Bouldin benchmark highlights the subtleties which may be present in a multi-layer system. If there are multiple layers in an earth dam then the impact of rapid draw-down can vary significantly based on the hydraulic conductivity of the individual layers. A coupled effective stress analysis can provide added insight into the performance of such an earth structure.

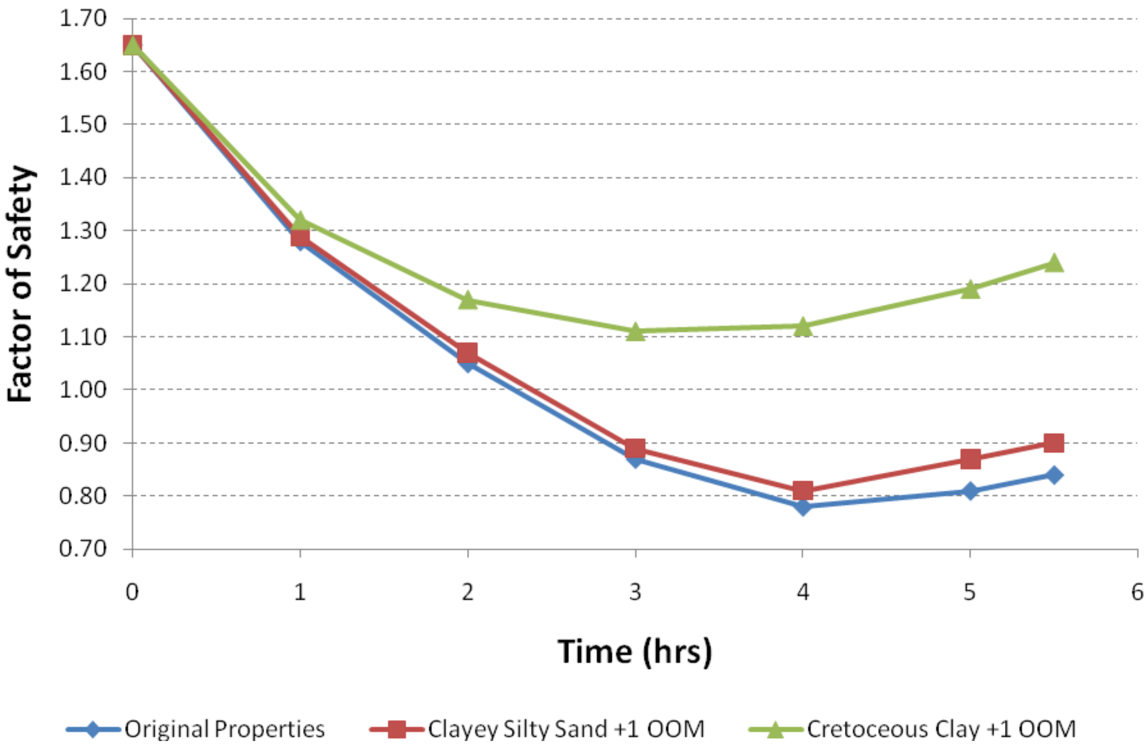

Figure 5 Variance in FOS for various region hydraulic conductivities

CONCLUSION

The analyses presented in this paper show that there are differences between a total stress and an effective stress analysis. The primary difference is related to consideration of transient pore-water pressures in the slope stability analysis. A secondary influence is the effect of geometry on the flow regime in an earth dam or levee. With the advent of more advanced software there is opportunity to more closely simulate the processes governing a rapid draw-down analysis.

The following points are worth noting:

- The implementation of the rapid drawdown presented by Duncan et al. (1990) has been benchmarked and the differences are reasonable.
- The time over which rapid draw-down occurs can be simulated in the saturated/unsaturated effective stress transient seepage analyses.
- In the case of a multi-region earth dam (such as Walter Bouldin) an effective stress analysis can allow detailed insight into the mechanism of failure.

As a general note the total stress Duncan et al. (1990) 3-stage analysis seems to be conservative. There is an opportunity to more closely simulate soil behavior with respect to time and thereby optimize the design of levees with the result that there is a saving in costs by utilizing an effective stress analysis.

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