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SLOPE STABILITY ANALYSIS USING NUMERICAL SIMULATION-BASED FINE-ELEMENT METHOD AND LIMITED EQUILIBRIUM METHODOLOGY

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ABSTRACT: Slope failure probability can be calculated using simple numerical approaches, as described in the article. Modeling complex-geometric slopes using numerical methodologies based on the Finite Element Approach and the Limit Equilibrium Method yields results in a fairly clear and fast manner. Rapid water loss at the upstream slope caused the San Luis Dam to collapse after 14 years of operation. The investigation of this dam made use of numerical techniques. The principal reason the slope gave way, according to Stark and Duncan (1992), was because the shear strength of the clay decreased from its peak to its residual strength, leading to the development of extra cycle stresses. Rocscience Slide-6.0 and Rocscience Phase-2 were among the expert programs used to conduct the numerical simulations. Software features like drawdown allow for the incorporation of cyclic loading effects. Using the residual shear strength characteristics of clay obtained from Stark and Duncan (1992) and examining the slope stability in two separate cases—the full reservoir capacity scenario and the rapid drawdown case—the factor of safety was estimated. In a fast drawdown scenario, the results indicate that the factor of safety is one in the event that the upstream slope collapses. Due to their simplicity and speed in solving complicated geotechnical problems, numerical methods are an essential tool for failure prevention during the design process.

Keywords: Slope Stability Analysis; San Luis Dam; Numerical Analysis; Dam Failure; Limit equilibrium Method; FEM; Rapid drawdown.

1. INTRODUCTION

Several significant alterations have been made to the computational aspects of slope stability analysis as a consequence of the development of software and the increasing prevalence of the usage of computers. The completion of complex and extensive research is now easier and takes less time than it did in the past. It is possible that we will be able to guarantee an exact answer by employing the concepts of equilibrium and force physics, provided that the quantities that are input are entered correctly. You will be able to get the most out of the software, avoid making mistakes that could lead to bad design, and have a good understanding of soil mechanics and ideas related to soil strength if you go through the process of becoming an expert user. The finite-element approach and limit equilibrium techniques have seen recent advancements that have made it possible to conduct realistic deformation evaluations on slopes, embankments, and open excavations. Utilizing the soil constitutive model that is most appropriate and having a decent representation of the soil's stress-strain behavior are two things that should be done in order to produce numerical simulation results that are similar to the behavior of the soil mass in its natural environment [1].

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Two numerical simulation techniques that can be used to quickly and reliably test stability on artificial as well as naturally occurring slopes are the shear strength reduction (SSR) and the finite element method (FEM). Both of these techniques are referred to as "shear strength reduction." In comparison to restricted equilibrium, finite element analysis has the advantage of not making any assumptions about the location or geometry of the critical failure surface [2]. This is one of the advantages of finite element analysis. The material qualities and boundary conditions of the model can be altered in order to get the desired outcome, which allows for the simulation of a variety of ground situations. It is necessary for the designer to be aware of these relevant details before beginning the process of planning and designing. The difficulty in acquiring these cutting-edge techniques with respect to In the past, the implementation of stability analysis was a far more time-consuming and difficult process in and of itself.

For the purpose of slope analysis, numerical methodologies are described, with a particular emphasis placed on the San Luis Dam case study. Approximately 170 kilometers to the southeast of San Francisco is where you will find the San Luis dam, which is situated in the central valley of California. A significant upstream slip occurred as a consequence of the reservoir going through a drawdown of 180 feet in a span of 120 days, which occurred after the dam had been working for fourteen years. The component that was not functioning properly reached a height of two hundred feet. The diagram in Figure 1 illustrates the cross section of the dam. In Table 1, the material qualities of each and every material that was used in the construction of the dam are given. A additional classification of the minerals is depicted in Figure 1, which includes the zones. Figure 1 depicts the situation of the upstream soil slope after it has collapsed, and the dotted line represents this condition. Due to the highly ingrained Slide started somewhere upstream of the Dam and extended all the way down below the foundation baseline [3]. After conducting their investigation, Stark and Duncan (1992) came to the conclusion that the breakdown was caused by a significant decrease in power from the peak to the residual value. Only softened shear strength was used in stability calculations, which resulted in safety factors that were more than one. This was due to the fact that residual strength was not present during the whole design and construction process of the dam.

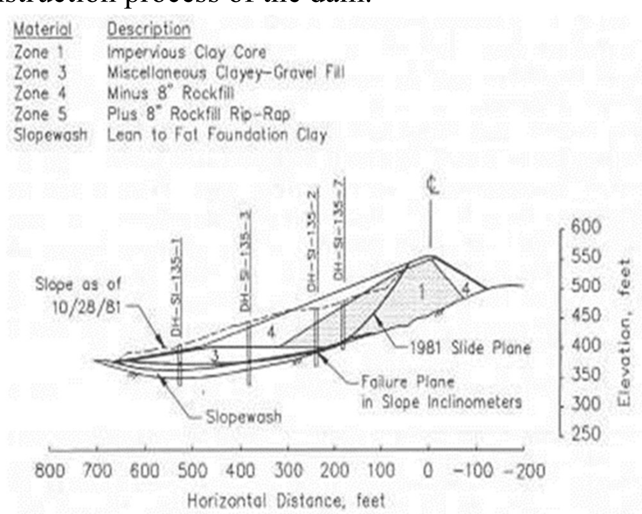


Figure 1: San Luis dam cross-section (Stark and Duncan 1992).

Problem Statement

Specifically, the San Luis Dam in San Francisco served as the case study that was deployed in order to demonstrate the application of numerical methodologies. Due to the quick drainage at the dam, the upstream slope began to deteriorate after it had been in service for fourteen years. According to Stark and Duncan (1992), the most likely cause of failure was the weakening of stiff clay to its residual value, which was a concept that was largely unknown at the time. Additionally, the influence of cyclic stress that was caused by the rapid drying of the water was also a contributing factor. It is possible for us to demonstrate how slopes react under a variety of different combinations of circumstances and derive conclusions that are applicable to real-world scenarios if we precisely model and analyze these factors using numerical software.

2. RELATED WORRK

NUMERICAL MODELING AND ANALYSIS

Slope Geometry and Material Properties

An illustration of a cross section of the dam is shown in Figure 1. This section is used to generate the geometry of the model. When stated in degrees, slope angles of 18 degrees upstream and 23 degrees downstream are considered to be significant. The material properties that were published by Stark and Duncan (1992) served as the foundation for this work. The material border option of the software was utilized in order to accomplish the separation of separate material zones. In order to simulate the behavior of soil under stress and strain, the Mohr-Coulomb failure criterion was utilized. In accordance with Stark and Duncan (1992), before to the collection of block samples, the location was subjected to a consolidation and direct shear test. The specimens were examined in both dry and wet circumstances during the testing process. However, it was discovered that soaking did not have any effect on the compressibility of the soil. There was no discernible change in the shear strength parameters of the material after immersion [3]. Figure 2 illustrates the outcomes of the test.

Figure 2: Direct Shear Test upstream slope shear strength (Stark and Duncan 1992).

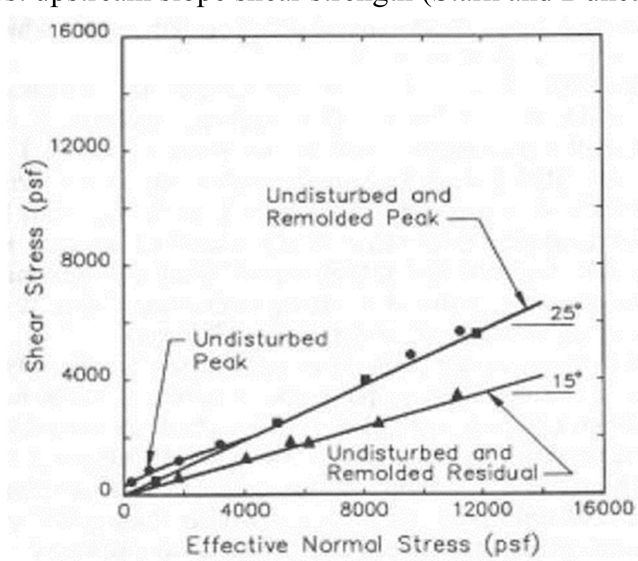


Table 1 contains a summary of the material qualities that were utilized in the analysis. You can find this summary by clicking here. For the purpose of this investigation, the parameters of shear strength that are derived from residual strength are utilized. With the use of this data, a factor of safety calculation was carried out for the upstream slope. This calculation took into consideration both the full capacity of the reservoir as well as the drawdown situation.

Table 1: The characteristics of shear strength that are utilized in numerical analysis

Material	Peak Strength		Residual Strength	
	c' (psf)	Φ' (degree)	c' (psf)	Φ' (degree)
Slope wash upstream	0	25	0	15
Zone 1	220	25	0	20
Zone 3	110	25	0	15
Zone 4 and 5	0	40	---	---

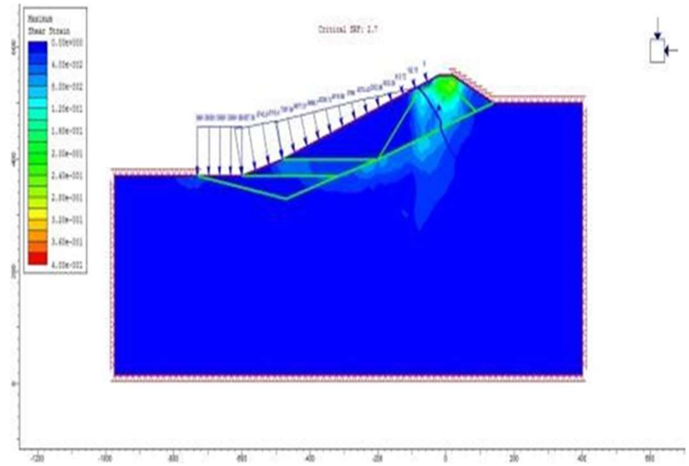
3. RESULTS

ROCSCIENCE PHASE2 STABILITY ANALYSIS

For the purpose of modeling and analysis that was carried out on Rocscience Phase2, the material characteristics that are detailed in Table 1 were applied. The Rocscience Phase2 program is a highly efficient two-dimensional elasto-plastic finite element stress analysis program that may be utilized for surface excavations as well as underground excavations in a variety of rock and soil types. There are a wide range of engineering projects that could potentially benefit from the utilization of this program. Some examples of these projects include support design, finite element slope stability, groundwater seepage, and probabilistic analysis. Among the most significant characteristics of this program is the capability to do a finite element slope stability study by employing the shear strength reduction approach [4]. This is one of the most crucial capabilities. In this experiment, ordinary strain conditions were utilized, and the maximum number of iterations that could be carried out was 500. The utilization of a triangular graded mesh with three nodes was chosen as the method of choice, and there were sixty nodes on the perimeter of the exterior area. The level of the reservoir is kept at 530 feet, according to the maintenance. It was decided to specify a fixed end boundary condition in order to facilitate the modeling of the downstream slope of the dam. It was determined that the failure was caused by the cyclic loading that took place as a consequence of the rapid decline; hence, the two examples that are presented below were analyzed. The results of the analysis that was carried out on each of the cases are visually shown in Figures 4 and 5.

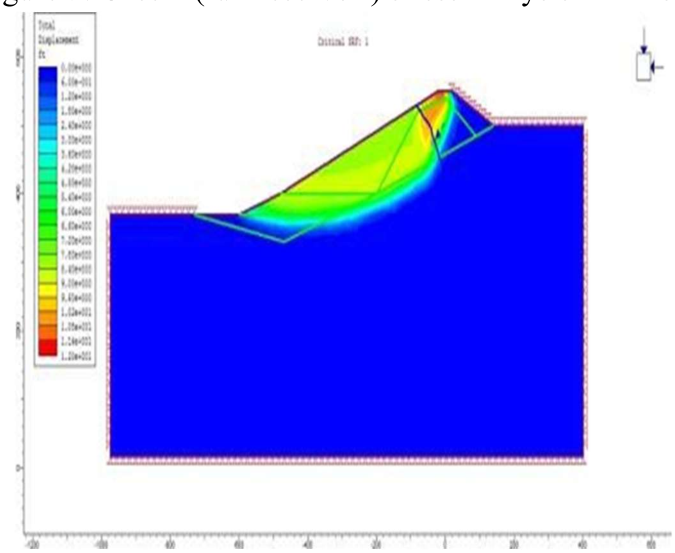
Case 1: Reservoir at its maximum capacity

Case 2: With a head drop of 180 feet, the rapid drawdown



Case 1

Figure 3: Case 1 (full reservoir) stress analysis in Phase 2



Case 2

Figure 4: Evaluation of Phase 2 stress in Case 2 (Rapid Drawdown)

ROCSCIENCE SLIDE-6.0 STABILITY ANALYSIS

In order to determine the safety factor and compare the results with those obtained from finite element modeling (FEM), Rocscience Slide-6.0 was subjected to a stability analysis that utilized the limit equilibrium approach. Seepage and slope stability are just two of the many geotechnical engineering issues that must be taken into account. The limit equilibrium technique has long-term effects on both of these conditions. Through the utilization of the fully plastic Mohr-Coulomb criterion, this technique provides a description of the stress-strain behavior of the soil. Within the framework of this numerical static analysis methodology, equations [5, 6] are utilized in order to retain mass equilibrium.

Figure 1 illustrates the results of producing a looping slip surface and making adjustments to the slope restrictions in order to guarantee that the required slip surface will traverse through the spots that have been specified. We were able to determine the minimum safety criterion for the slip surface that was most pertinent by utilizing the auto-refine slope search functionality. Within the context of cyclical loading scenarios, this approach can be utilized to represent situations in which the pore water pressures are not given adequate time to attain and maintain a condition of equilibrium.

In Rocscience Slide-6.0, the only scenario that is taken into consideration is the rapid decline scenario. It is possible for the upstream slope to become less stable when water is quickly taken from the reservoir. This is the reason why this occurs. Figure 5 illustrates the results of the investigation to display.

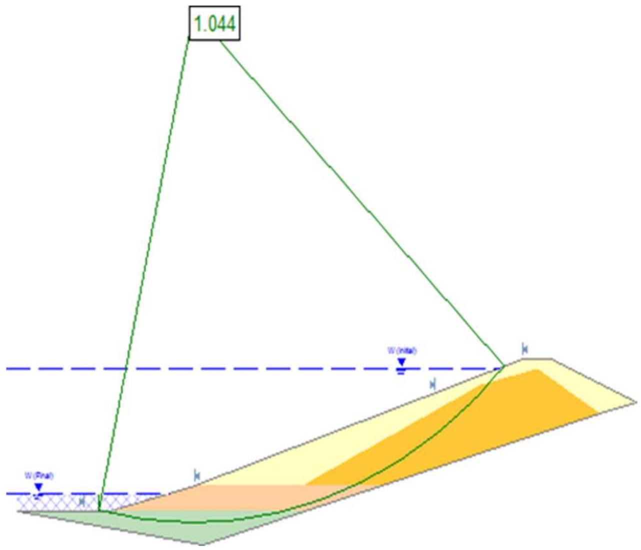


Figure 5: Drawdown case stability analysis for Rocscience Slide-6.0

DISCUSSION ON RESULTS

This section of the report contains the results of the stability analysis that was carried out using the finite element method (FEM) and the limit equilibrium methodology. It was necessary to do the analysis in order to disclose the findings later on. As a result of the fact that the critical strength reduction factor for scenario 1, which is the point at which the reservoir is operating at its maximum capacity, is 2.7, one could reach the conclusion that the slope is stable. At this moment, the reservoir is operating at its full capacity, which is the utmost volume it can contain. On the other hand, the critical strength drop factor is equal to one in scenario 2, which is usually referred to as the drawdown situation. This is the case since scenario 2 is a drawdown condition. Consequently, this implies that there is a chance of slope failure occurring, which is precisely what has transpired in the event that actually took place. To put it another way, the drawdown case is a scenario that is analogous to the actual situation that people find themselves in every day. The findings from Rocscience Slide-6.0 are in agreement with the FEM study, and it has been demonstrated that the factor of safety is equal to one for the scenario that includes rapid drawdown. This is identical to what was discussed earlier. An additional piece of evidence demonstrating that the two pieces of study are comparable is provided by these findings. Because it represents the critical slip surface, Figure 3-5 depicts both of the analyses that were carried out. This is because the critical slip surface is depicted in Figure 3-5.

4. CONCLUSION

Through the work that is provided here, it is demonstrated how easy numerical approaches can be applied to forecast the behavior of slopes under a wide variety of loading conditions. As a result of the fact that these methods have the potential to serve as a very essential guideline throughout the early stages of design, failure can be controlled. For the purpose of demonstrating the efficacy of the finite element technique and the limit equilibrium method in stability analysis of slopes, a case study of the San Luis dam was utilized. The dam had been in operation for fourteen years until it collapsed due to an instance of fast drawdown. The application of a case study was the means by which this objective was attained. The material's strength was rather strong while it was in its dry form; but, as it transitioned from its peak to its totally softened state, its strength steadily decreased until it eventually reached its residual value and slope disintegrated. This occurred as the material migrated from its peak to its fully softened state. It was necessary for the software simulation to incorporate both a full capacity reservoir and a drawdown case in order to provide an accurate representation of the loading circumstances. Both of these hypothetical situations were acted out.

Based on the findings of the inquiry, it was determined that the factor of safety in Rocscience Phase2 and Rocscience Slide-6.0 is comparable to one hundred percent for the rapid drawdown case that indicates failure. As a result of the inquiry, this was the conclusion that was reached. Because of this, the application of numerical approaches is not only easy, but it also provides a very precise estimation of the strength characteristics of dams, excavation support systems, and other structures that are comparable.After conducting an exhaustive investigation, it was discovered that the effect of cyclic loading in stiff clays, which is caused by the repeated wetting and drying of stiff clays, may be accurately represented by making use of the sophisticated features that are available in software. This was discovered after the extensive investigation was carried out. A careful consideration was followed by another serious consideration, which ultimately led to the formation of this conclusion. Moreover, in situations such as these, it is recommended to conduct laboratory tests on the clays in order to determine whether or not cyclic loading would result in continuous deformation and loss of strength. This is done in order to determine whether or not the clays will be able to withstand the loading. Additionally, it is recommended to substitute the altered shear strength parameters in numerical simulation in order to obtain results that are more analogous to the actual behavior of materials on site. This enables the simulation to produce findings that are more accurate. Because of this, the findings that were acquired are certain to be more accurate. Therefore, in order to prevent the failure of the soil mass, the loading condition on clays can be altered depending on the findings of the program, or a portion of the loads can be reduced. Both of these options are available. These two choices are both up to consideration.

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