Fluid reservoir slope instability due to drawdown affect

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ABSTRACT
Fluid reservoirs such as raw water reservoirs and wastewater lagoons are often constructed using relatively impervious natural materials such as highly plastic clays. These soils can gradually achieve near total saturation during operation of the reservoir and remain saturated for an extended time period after fluid levels have been drawn down. In some cases, the drawdown rate is rapid in comparison to the dissipation rate of excess pore water pressures causing slope failures of the interior slopes. Although most failures are not catastrophic, they can significantly increase maintenance costs.

This paper describes the results of a numerical analysis used to evaluate a drawdown effect on four selected models which were developed based on several case history events in Alberta (Canada). The purpose of this analysis is to develop a technique suitable for a quick evaluation of the drawdown effect on reservoir slopes and determine an appropriate drawdown rate that allows for reservoir maintenance.

The technique is based on numerical analysis to create a stress-strain distribution within the reservoir berm prior to a drawdown event, to determine a flow net within the berm prior to and after the drawdown event and to determine the minimal factor of safety on the reservoir berm slope after the drawdown event. The influence of soil properties, slope inclination and drawdown rates on slope stability are discussed in the context of providing acceptable drawdown rates and slope geometry for the considered cases.

RESUME
Les réservoirs tels que ceux qui sont utilisés pour stocker l'eau, et les lagons qui sont utilisés pour les eaux usées, sont souvent construits avec des matériaux relativement imperméables, comme par exemple les argiles très plastiques. Ces argiles peuvent graduellement atteindre une saturation presque totale pendant l'opération du réservoir et restent saturées pendant une longue période après l'abaissement du niveau de l'eau dans le réservoir. Dans certains cas, le taux d'abaissement du niveau est rapide en comparison avec le taux de dissipation des excès de pression dans les pores. Cet abaissement rapide provoque la faillite des pentes intérieures. Bien que la majorité des faillites ne soient pas catastrosphiques, elles peuvent augmenter le prix de l'entretien de façon significative.

Cet article décrit le résultat d'un analyse numérique utilisée pour évaluer l'effet de l'abaissement du niveau de l'eau dans le cas de quatre modèles qui furent développés et qui sont basés sur plusieurs cas historiques en Alberta (Canada). Le but de cette analyse est de développer une technique valable pour effectuer une évaluation rapide de l'effet de l'abaissement du niveau d'eau dans un réservoir sur la stabilité des pentes internes du réservoir et de déterminer le taux d'abaissement optimum du niveau d'eau qui permette l'entretien du réservoir.

La technique est basée sur une analyse numérique qui permet de créer une distribution des contraintes et des tensions à l'intérieur des levées du réservoir avant un évenement d'abaissement du niveau de l'eau. La technique permet aussi de déterminer le réseau des équipotentielles à l'intérieur des levées avant et après les évènements d'abaissement du niveau de l'eau. Cela permet aussi de déterminer le facteur de sécurite minimum sur les pentes des levées après l'abaissement du niveau de l'eau. L'influence des propriétés des sols, de l'inclinaison des pentes, des taux d'abaissement du niveau d'eau et de la géométrie des pentes sur la stabilité des pentes sont discutés dans le contexte d'un taux d'abaissement du niveau d'eau et d'une géométrie des pentes pour les cas considérés.

1.0 INTRODUCTION

The stability of earth structures or natural slopes under rapid drawdown conditions has been considered by many authors, as a sufficient number of such cases were recorded showing that it is important, if not critical. Morgenstern listed 16 cases in which rapid drawdown triggered landslides on the upstream face of earth dams (Morgenstern 1963). Various landslide events due to water-level changes are outlined in chapter 4 of the section Landslide triggering mechanism (Landslide Investigation 1996).

Rapid drawdown may impose very severe loading on slopes and is frequently the design condition that controls an earth structure slope angle.

Generally, the stability during rapid drawdown event has been analyzed using effective or total stress methods.

Effective stress methods were developed by Morgenstern (Morgenstern 1963) and Wright and Duncan (Wright et al. 1987)

Total stress methods were developed by Duncan, Wright and Wong (Duncan et al.1990), Corps of Engineers (Corps of Engineers 1970) and Lowe and Karafiath (Lowe and Karafiath 1960).

The technique described in the paper uses an effective stress approach to determine the stress-strain distribution prior to drawdown, then determine the pore-pressure distribution prior to and after the drawdown event, and finally to search for a critical slip surface after the drawdown event.

The soil properties, slope geometry and drawdown conditions for numerical models were selected on the basis of several drawdown events recently recorded in Alberta. Three slope angles, two soil types and four drawdown rates were used as main variables in the analysis.

The purpose of the analysis was to evaluate the slope stability after a drawdown event in the context of providing acceptable drawdown rates and slope geometry for given soil properties and fluid levels in reservoirs.

A slope stability analysis using effective soil parameters and a fully saturated soil conditions after a drawdown event was performed on the same numerical models to compare the obtained values of factor of safety with the values obtained using this technique.

The factor of safety values for effective soil parameters and fully saturated soil conditions after a drawdown event obtained using this technique were also compared to the results obtained using Morgenstern's approach (Morgenstern1963) on the same numerical models.

2.0 DRAW-DOWN MECHANISM

Prior to the lowering a water table along an earth slope, the pore-pressure distribution in the slope is governed by the equilibrium conditions for the flow of water through porous media. When the water level outside the slope drops, the stabilizing influence of the water pressure on the slope is lost. If the water level subsides so rapidly that the pore pressures within the slope do not have time to change in equilibrium with the drop in external water level, the slope becomes less stable.

Therefore, one of the major factors for slope stability conditions is the capability of the soil to relieve the pore pressure during a rapid drawdown. This ability depends on the permeability of the slope soils. Less permeable soils will require a longer time to establish equilibrium between pore pressures within the slope and external fluid level than a more permeable soil.

Quantification of an appropriate time to allow equilibrium conditions to develop depends of many parameters and is rather complex due to difficulties in determining when the slope is under total or effective stresses. In addition, an unsteady flow conditions within the slope until the new equilibrium is established makes this evaluation more complicated.

A typical response of slope to rapid drawdown is presented on Figure 1.

3.0 EXISTING METHODS FOR RAPID DRAWDOWN ANALYSIS

Stability during rapid drawdown has been analyzed in two basically different ways: by using either effective stress or total stress methods. Both methods treat free draining materials in the same way. Their strengths are analyzed in terms of effective stresses assuming that the pore pressures within them are hydrostatic.

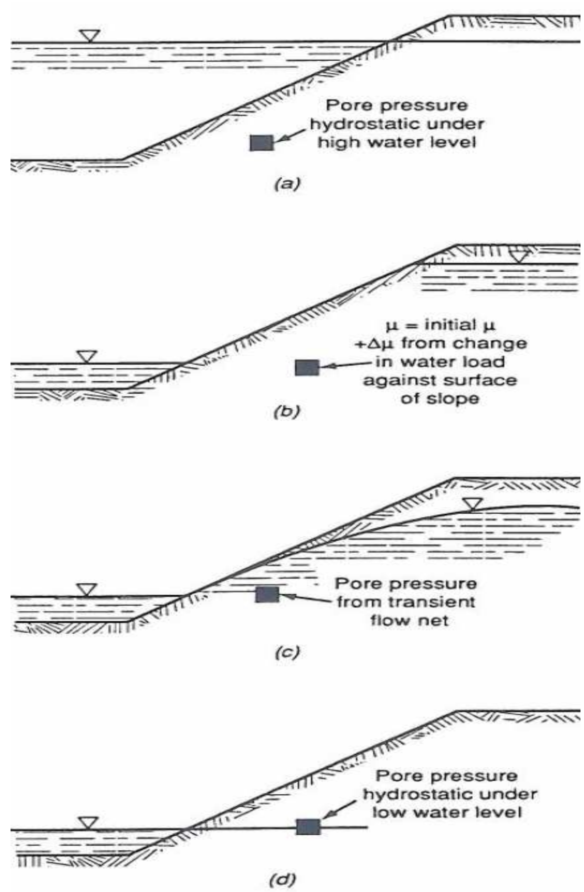

Figure 1 (Landslide Investigation 1996).
a) Initial equilibrium condition,
b) After drawdown but before consolidation adjustment,
c) After consolidation and
d) Final equilibrium condition (Lambe and Whitman 1969)

3.1 Effective Stress Methods

The advantage of effective stress methods is that it is relatively easy to evaluate shear strength parameters by means of isotropically consolidated undrained (IC-U) triaxial tests with pore pressure measurements. The disadvantage of effective stress methods is that it is difficult to estimate with accuracy the pore pressures that will exist within non-free draining materials during drawdown.

In most cases effective stress analyses of stability during a rapid drawdown event have used assumptions regarding pore pressures that were suggested by Morgenstern (Morgenstern 1963). Morgenstern estimated pore pressures during drawdown by assuming that the pore pressure parameter ($\bar{B}$) is equal to unity.

Wright and Duncan (Wright, et al. 1987) used procedures for estimating pore pressures during drawdown by using Skempton's pore pressure parameters A and B.

Some other authors considered the non-steady flow conditions following drawdown by using theoretical methods, but they have not considered the behavior of the soil with regard to dilatancy, which means the control of pore pressure during drawdown was not applied.

3.2 Total Stress Methods

Many problems associated with estimating pore pressures for effective stress analysis can be avoided by using undrained total stress methods.

Total stress methods assume that the undrained shear strength of the soil is related to the consolidation pressures in the slope prior to drawdown.

Corps of Engineers Method, (Corps of Engineering 1970) Lowe and Karafiath's Method (Lowe and Karafiath 1960) and Duncan Wright Method (Duncan, et al.1990) consider undrained total stress conditions for rapid drawdown analysis.

The Corps of Engineers method defines conditions before drawdown to determine consolidation pressures along the slip surface. Based on these values it is determined which effective or total stresses should be used. The criterion is to use the stress whichever gives lower strength on the slip surface base. A disadvantage of this approach is that the use of total stress can not be justified as the circles used to develop the total stress envelope combine the effective stress during consolidation with deviator stress at failure, and do not represent a state of stress in the soil at any given time.

The Lowe and Karafiath Method uses a two-stage analysis procedure. In this method the undrained shear strengths are related to consolidation pressures. A strength envelope is plotted such that the horizontal axis is the effective stress on the failure plane during consolidation and the vertical axis is the shear stress on the failure plane at failure. The principal stresses ratio during consolidation Kc can vary from unity (for consolidation under isotropic stresses) to Kf the value at failure. The testing required however to establish these strength envelopes is very difficult and requires considerable time as the stresses must be increased slowly to avoid the possibility of the sample to fail during consolidation.

A method developed by Duncan, Wright and Wong (Duncan, et al. 1990) combines the Corps of Engineers and Lowe and Karafiath's methods. Duncan, Wright and Wong estimated that anisotropic consolidated undrained strengths (AC-U) can be determined by a linear interpolation from isotropic consolidated undrained test (IC-U). The method consists of a determination for each soil in the cross section as to whether drainage will occur during drawdown. The strength envelopes required for the analysis, both drained and undrained strengths for material that drain during drawdown, and for materials that are undrained during drawdown are then determined. A slope stability analysis with input of such data and with a selected slip surface is then performed, and the factor of safety after drawdown is obtained. A disadvantage to this approach however, is considered to be the lengthy computer calculations necessary to search for critical slip surface,.

4.0 THE PROPOSED TECHNIQUE

The technique used in this paper explores the possibility of developing a fairly quick and accurate method to predict the behaviour of a reservoir slope under drawdown conditions. While the conclusions based on the analysis are specific to the cases considered, the technique may have future applications for a range of soil types, slope geometries and drawdown conditions. The technique consists of the following three steps:

1. Numerical modeling using effective stresses and fluid levels along the slope to obtain stress-strain distribution prior to the drawdown event;

2. Seepage analysis to obtain pore pressure distribution and position of the phreatic surface prior to and after a drawdown event for different draw-down rates; and

3. Slope stability analysis to determine the critical slip surface after the drawdown event for selected draw-down rates.

Two sites, where a drawdown event has been experienced were used to calibrate the numerical models. At the considered sites, uniform, low-permeability but poorly compacted clays and silts triggered slope instabilities after rapid drawdown. The soil properties, slope geometry for each facility and the reported drawdown rates were used to establish numerical models for the analysis. A brief description of each site is as follows:

VALLEYVIEW - A wastewater lagoon cell in Valleyview Alberta, was constructed in 1993 with the floor elevation at 675 m and the top of the berm elevation at 680 m. The interior berm slope was built at 3H:1V. The berm was comprised of high plastic stiff silty clay overlying a stiff to very stiff and medium plastic clay till. The typical operating water level was at 679.5 m. The reservoir level was lowered by 3.5 m, to a level 1.0 m above the floor during a period of about four days with a drawdown rate of approximately 0.9 m per day. The lagoon slope subsequently experienced sloughing and instabilities along almost its entire length.

EDSON - The Town of Edson's sewage lagoon experienced similar instabilities after a rapid drawdown of about 1.0 m over a day period. The berm geometry and the berm fill properties were similar to those at the Valleyview Lagoon.

4.1 Numerical Models

The effective stress soil properties of the clay fill and the native clay till used in the analysis are presented in Table 1.

Table 1: Effective Stress Soil Properties

Soil	γ kN/m3	Phi deg	c kPa	E MPa	μ %	k cm/sec
Clay Fill	18	18	2	40	0.4	3.1E-6
Clay Till	19	25	5	90	0.4	1.4 E-5

A range of draw-down rates were selected as follows: 3.5m in one day, (3.5m/day) over two days (1.75m/day), over 15 days (0.23m/day) and over 31 days (0.12m/day).

Model 1 was established with soil properties from Table 1 with a slope angle of 3H:1V and selected draw-down rates.

Model No. 1 is presented in Figure 2.

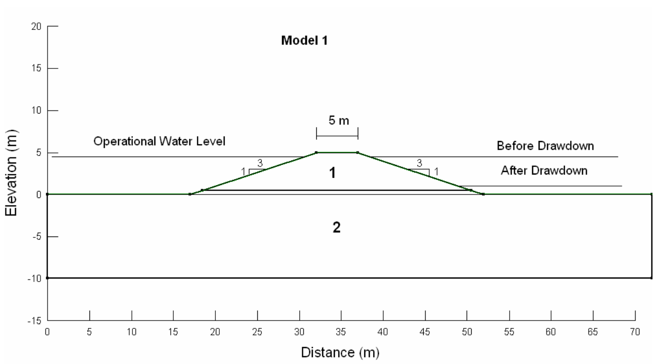

Figure 2. Model No.1; Slope 3H:1V

Model No. 2 was established with the same soil properties and draw-down rates as for Model 1 but with a slope angle at 5H:1V. Model No.2 is presented on Figure 3.

Model No 3 was developed using the same slope geometry and draw-down rates as for Model 1, however, the clay fill soil parameters were changed to reflect the impact of better fill quality on the slope stability under the same draw-down rates.

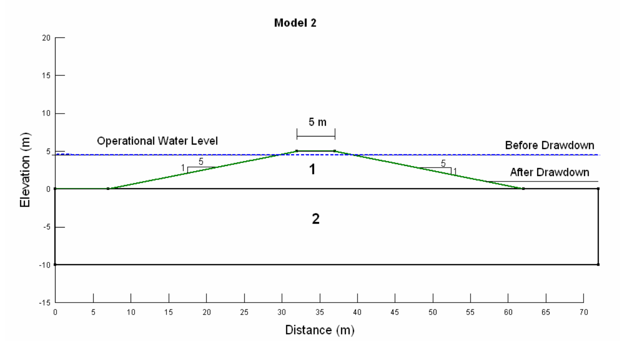

Figure 3 Model No.2; Slope 5H:1V

The following effective soil properties were used for Model 3.

Table 2: Effective Soil Properties for Model No.3

Soil	γ kN/m3	Phi deg	c kPa	E MPa	μ %	k cm/sec
Clay Fill	19	25	2	70	0.4	1E-6
Clay Till	19	25	5	90	0.4	1.4 E-5

A numerical analysis on Model No. 4 with the same soil properties fluid levels and draw-down rates as for Models 1 and 2, but with a slope at 2H:1V was also performed to determine the influence of the slope angle on the stability.

The model geometry is presented on Figure 4.

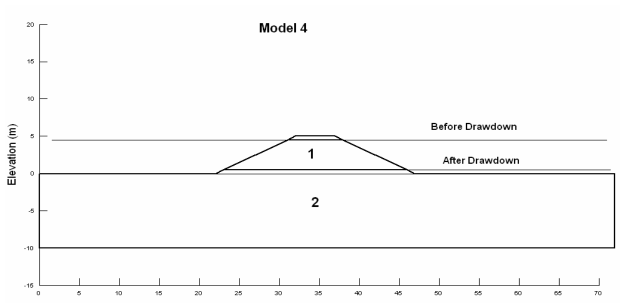

Figure 4: Model 4, Slope at 2H:1V

4.2 Numerical Analysis Results

The numerical analysis provides the critical factor of safety values versus draw-down rates for given soil conditions and pore pressure distribution simulated in Models 1to 4.

A factor of safety equal to unity was used to determine the draw-down rates at the marginally stable slope conditions. The factor of safety value of 1.3 was used to determine the draw-down rate required to keep the slope at conditions that can be considered stable after the draw-down event.

Figure 5 shows the factor of safety values versus draw-down rate for all four numerical models.

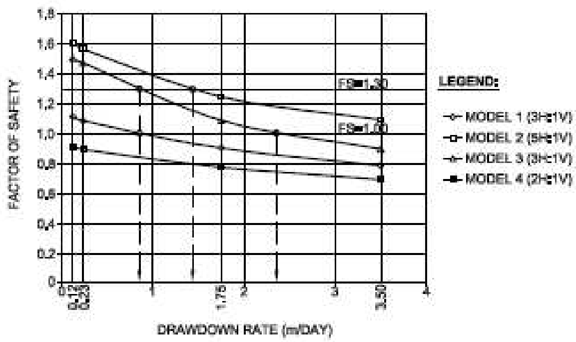

Figure 5 - Factor of Safety versus draw-down rate

As seen in Figure 5, factor of safety values range from 0.68 for a slope at 2H:1V and a drawdown rate of 3.5m/day to 1.61 for a slope at 5H:1V and a drawdown rate of 0.012 m/day with the same soil properties,.

Model No. 1 with a drawdown rate of 0.85m/day, which corresponds to the Valleyview Lagoon and Edson Lagoon draw-down rates, shows a marginally stable slope which would be expected under these conditions. Model 1 indicates that even with a drawdown rate of 0.12 m/day or less the factor of safety of 1.3 can not be achieved.

The results from Model No. 2 with 5H:1V slopes indicates that a drawdown rate of 1.45 m/day is required to maintain a minimum factor of safety of 1.3. This model indicates that factor of safety for a drawdown rate of 3.5 m/day is still above the unity (FS=1.1) which can be acceptable value for a short term slope stability.

The results from Model No. 3 with 3H:1V slopes but with better fill properties indicates that a drawdown rate of 0.85 m/day is required to maintain a minimum factor of safety of 1.3. This model indicates that such slope will be marginally stable at a fairly high drawdown rate of 2.35 m/day.

The results from Model No. 4 with 2H:1V slopes indicate that factors of safety below unity can be expected regardless which drawdown rate I applied, which means such steep slope and soil properties would not be stable.

Figure 6 shows that slopes at 4H:1V or flatter with a drawdown rate of 0.23 m/day or lower with corresponding soil parameters are achieving the desired factor of safety of 1.3.

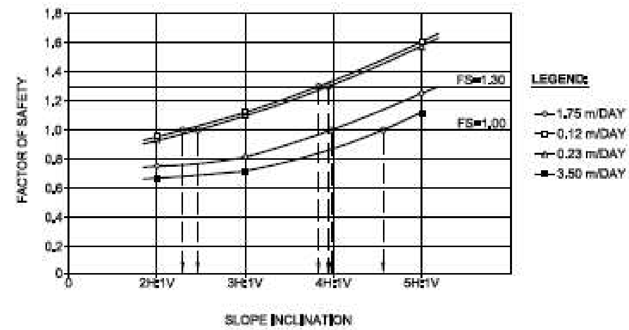

Figure 6: Factor of Safety versus Slope Inclination

With drawdown rates between 0.12 m/day and 0.23 m/day the slopes between at 2.3H:1V and 2.5H:1V would be marginally stable. However, with drawdown rates of 1.75 m/day or higher the considered slopes wouldn't be stable.

4.3 Fully Saturated Soil Conditions

Analyses were performed on the Model 1 (Slope 3H:1V) Model 2 (Slope 5H:1V) and Model 4 (Slope 2H:1V) with the same soil properties using fully saturated soil conditions after the drawdown event which can be considered the worst possible drawdown scenario. These values were compared to the values obtained using Morgenstern's approach (Morgenstern 1963). The factor of safety values is presented on Figure 7.

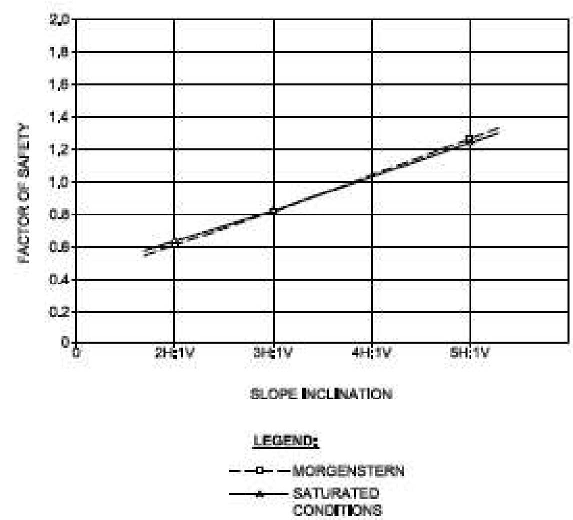

Figure 7: A comparison of factor of safety values for saturated soil conditions and based on Morgenstern's approach

The good agreement between these two analytical approaches is logical as the same assumptions relative to pore pressure parameter B are used for Morgenstern's stability charts for earth slopes during rapid drawdown and for fully saturated soil conditions after the drawdown event analyzed using this technique.

5.0 CONLUSIONS

1. Rapid drawdown effect on slope stability depends of many factors such as soil properties (particularly the soil permeability), slope geometry, drawdown rates, etc. It is obvious that the degree of the slope stability during a drawdown event is directly related to the soil capability to release pore pressures as soon as possible following the decrease in fluid level along the slope.

2. The rate of the decrease in reservoir fluid levels has a significant impact on slope behavior during a drawdown event. This parameter is usually manageable in man-made earth structures and therefore, it is desirable to control the decrease in fluid level wherever possible.

3. Modeling of a rapid draw-down effect on slope stability is a complex task, because the stress conditions in the slope are usually somewhere between total and effective stress stages, and the relation between them varies by the progress of drawdown event. Also, a real pore pressure distribution until equilibrium is established is not simple to model.

4. Existing methods for rapid drawdown analysis require extensive laboratory testing to be able to obtain reliable input parameters, and lengthy computer programs to run analysis. The proposed technique is based on effective soil parameters only and a commonly used commercial numerical analysis can be used.

5. Modeling used in this paper can reflect a rapid drawdown event or setup with a controlled drawdown rate along the slope to determine the time needed for subsequent pore pressure dissipation following the decrease in external fluid levels to achieve stable slope conditions.

6. Factors of safety values obtained on saturated soil conditions using the technique and obtained using Morgenstern method for a rapid drawdown rate evaluation show good agreement. This could be expected as the same assumption for pore pressure parameters were used in both approaches.

7. Generally, the proposed technique provides fairly reasonable values of factor of safety for the considered cases. However, the performed analysis for this paper covers a narrow range with respect to slope properties and needs further refining and additional analysis to provide a range of factor of safety for a wider range of soil properties, slope geometry and drawdown rates.

6.0 REFERENCES

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