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Assessment of rapid drawdown of a cofferdam and main dam using a coupled transient seepage-stability model that considers the reservoir level increase, steady-state level duration, and drawdown using actual hydrographic data for a given river

Charlie Harrison, Jaime Villaamil & Keith Ainsley
Knight Piésold, Vancouver, BC, Canada
Rick Berg
Ledcor, Vancouver, BC, Canada

ABSTRACT

Rapid drawdown of water impounded by an earthfill dam structure can have detrimental effects to the stability and permeability of the dam core. The assessment of rapid drawdown typically involves assessing an instantaneous drawdown case with excess porewater pressures in the low hydraulic conductivity clay core of a dam estimated using B-bar, or other ratio. The use of the instantaneous drawdown case can be traced back to the early development of the limit equilibrium method of slices and its use for the design of earth embankment dams when designers relied solely on slide rules for completing calculations. With the advent of the finite element method and micro-processors, computing ability now far surpasses any of the tools available to dam designers prior to the turn the 21st Century. Engineers now have tools and methods to estimate the actual flood frequency and duration for a given river and develop input parameters for a transient seepage analyses. Coupled to research in the area of unsaturated soil mechanics in the last 20 years or so, engineers can now assess the change in porewater pressure within a dam for a given flood scenario, with the flood routing controlled either by a diversion system (cofferdam), a spillway, and in some cases a low level outlet (permanent dam). The authors present the methodology for determining the duration – rise, steady-state, and drawdown – for a flood event that is used in a transient seepage analysis that is coupled to a stability assessment. The results provide a temporal assessment of the change in stability of a dam over the full duration of a flood. Sensitivity analyses are provide to highlight some of the constraints of the proposed methodology. An example is provided for a conceptual level dam on an actual river in Alberta, Canada, considering both the cofferdam and permanent dam.

Resume

L'évaluation de l'abaissement rapide consiste généralement à évaluer un cas d'abaissement instantané avec des pressions excessives d'eau interstitielle dans le noyau d'argile à faible conductivité hydraulique d'un barrage estimé à l'aide de la barre B ou d'un autre rapport. L'utilisation du cas de tirage instantané peut être reliée au développement précoce de la méthode des coupes à l'équilibre limite et à son utilisation pour la conception de barrages en remblai en terre, lorsque les concepteurs s'appuyaient uniquement sur des règles de calcul pour effectuer les calculs. Avec l'avènement de la méthode des éléments finis et des microprocesseurs, la capacité informatique dépasse de loin tous les outils disponibles pour les concepteurs de barrages avant le tournant du XXIe siècle. Les ingénieurs disposent désormais d'outils et de méthodes pour estimer la fréquence et la durée réelles des inondations dans une rivière donnée et pour définir les paramètres d'entrée nécessaires à l'analyse transitoire des infiltrations. Couplés à la recherche dans le domaine de la mécanique des sols non saturés au cours des vingt dernières années, les ingénieurs peuvent maintenant évaluer l'évolution de la pression des eaux interstitielles dans un barrage pour un scénario d'inondation donné, le tracé de l'inondation étant contrôlé soit par un système de dérivation (cofferdam), déversoir et, dans certains cas, une décharge de bas niveau (barrage permanent). Les auteurs présentent la méthodologie permettant de déterminer la durée - augmentation, état stationnaire et diminution - d'un événement d'inondation utilisé dans une analyse d'infiltration transitoire couplée à une évaluation de la stabilité. Les résultats fournissent une évaluation temporelle du changement de stabilité d'un barrage sur toute la durée d'une inondation. Les analyses de sensibilité mettent en évidence certaines des contraintes de la méthodologie proposée. Un exemple est fourni pour un barrage à niveau conceptuel sur une rivière en Alberta, Canada, considérant à la fois le batardeau et le barrage permanent.

1 INTRODUCTION

Rapid drawdown of water impounded by an earthfill dam structure can have detrimental effects to the stability and permeability of the dam core. The assessment of rapid drawdown typically involves assessing an instantaneous drawdown case with excess porewater pressures in the low hydraulic conductivity clay core of a dam estimated using B-bar, or other ratio. The use of the instantaneous drawdown case can be traced back to the early development of the limit equilibrium method of slices and its use for the design of earth embankment dams when designers relied solely on slide rules for completing calculations.

Engineers have the tools and methods to estimate the actual flood frequency and duration for a given river and develop input parameters for a transient seepage analysis. Coupled to research in the area of unsaturated soil mechanics in the last 20 years or so, engineers can now assess the change in porewater pressure within a dam for a given flood scenario, with the flood routing controlled either by a diversion system (cofferdam), a spillway, and in some cases a low level outlet (permanent dam).

The authors present the methodology for determining the duration – rise, steady-state, and drawdown – for a flood event that is used in a transient seepage analysis that is coupled to a stability assessment. The results provide a temporal assessment of the change in stability of an embankment dam over the full duration of a flood. Sensitivity analyses are provided to highlight some of the constraints of the proposed methodology. An example is provided for a conceptual level dam on an actual river in Alberta, Canada, considering both the cofferdam and permanent main dam.

2 INSTANTANEOUS RAPID DRAWDOWN

Instantaneous rapid drawdown was developed to assess this particular condition when engineers still relied on slide rules to complete limit equilibrium analyses of dam structural stability. Care was taken to draw an accurate flownet to ascertain the porewater pressures in the clay core at the maximum operating level of the reservoir. Stability of selected sliding surfaces were undertaken under the maximum porewater pressures with the reservoir level at its maximum level. Further stability calculations were then completed using the same porewater pressure conditions (i.e. no dissipation of pressure) or if considered, a $\bar{B}$ ratio less than 1, but never zero. An assessment of this nature never considers the actual rate of drawdown, regardless of the cause of the drawdown.

The continued use of the instantaneous rapid drawdown seems dubious since dam engineers now have access to tools much more sophisticated than a slide rule. Furthermore, consideration must be given to several facets of the reasoning behind carrying out a rapid drawdown assessment that engineers equipped with slide rules could not account for in their calculations.

Firstly, the cause of the maximum reservoir water level is going to control the rise and fall of the reservoir level. For instance, a 1 in 200-year flood event will not deposit the full volume of water in the reservoir at once but result in a gradual rise in water level. The water level will have a steady-state condition of some duration, depending on the length of the storm event responsible for the flooding.

Secondly, the dissipation of the storm will result in a gradual drop in the reservoir due to a decrease in precipitation. And finally, in combination with the storm event, and its frequency of precipitation, the feature that controls the lowest possible reservoir level will also have an impact on the rate of the reservoir water level change. For example, a spillway will be designed to pass a given flood event, and its invert will also equate to the lowest permissible reservoir level. The authors recognize that flow through a powerhouse or a low-level outlet could also lower the reservoir water level, but the rate of drawdown would be considerably less than that of a spillway.

3 PROPOSED METHODOLOGY

3.1 Overview

The authors have developed an alternate methodology for assessing the structural stability of a cofferdam and main dam under drawdown conditions. The methodology not only considers the maximum possible porewater pressures in a clay core dam, but also the porewater pressures at time increments along the complete duration of the reservoir water level rise and fall.

The methodology utilizes a coupled seepage-stability model (Geoslope 2018) that can provide the incremental porewater pressures during a modeled reservoir event so that the structural stability can be assessed for each porewater pressure condition.

3.2 Flood Routing Model

A simple reservoir flood-routing model was developed using the software HEC-HMS. The model was used to predict the temporal and spatial variations in a flood hydrograph as it moves through the reservoir of interest. The process basically consists on accounting for the volumes of inflow, reservoir storage and outflows from the reservoir outlets at each time-step throughout the duration of the flood. The three key inputs required in this model, which are briefly described in the following sections, are as follows:

- An inflow flood hydrograph, describing the passing of the flood,
- The depth vs. capacity relationship of the reservoir, and
- The performance characteristics and number of outlets associated with the operation of the facility

The key result obtained from the flood routing model are the outflow hydrograph from the reservoir outlets, as well as the reservoir elevation for each time-step of the simulation. These results will be used to inform the transient seepage-stability model described in the sections below.

3.3 Transient Model

A transient seepage model is used to determine the porewater pressures at given time increments during the reservoir event under consideration. As with any finite element program, careful consideration must be given to the meshing of the model, and the timestep increments that will provide a solution that converges during every timestep.

Transient seepage models require more complex input parameters than just the saturated hydraulic conductivity and vertical to horizontal ratio for a given soil. A transient model also needs to consider the compressibility of the clay core to determine the amount of water per unit volume that will be released due to the change in head with time

3.4 Hydrologic Transient Boundary Function

A hydrologic transient boundary function is provided by the flood routing model described above. The function provides the actual reservoir water level over time, as shown in Figure 2. The non-linear shape of the rise and fall of the reservoir over time indicates that a flood event is complex in nature. It should also be noted that 1) the approximate third order polynomial increase in the reservoir level does not provide a lot of time for the clay core to become saturated even when considering the steady-state portion of the function, and 2) the approximate sixth order polynomial decrease in the reservoir water level provides a significant amount of time relative to the incremental drop in water level for porewater pressures in the clay core to dissipate.

3.5 Soil Properties

3.5.1 Index and Shear Strength Properties

The index and shear strength properties listed in Table 1 are required for the proposed analyses. The hydraulic properties listed are the saturated properties on the soil. These are the base properties considered when a soil is considered to be fully saturated, an underlying assumption in classical soil mechanics. Given the transient nature of the proposed analyses, soil properties other than the saturated case need to be considered, as the soil will be unsaturated above the phreatic surface

3.5.2 Hydraulic Functions

Hydraulic functions that provide the incremental change in water content and hydraulic conductivity due to changes in matric suction are required to determine the unsaturated soil properties for the proposed assessment methodology. The properties required to develop the hydraulic functions are listed in Table 2.

Table 1. Index and Shear Strength Parameters for Materials Used in the Structural Stability Model

Unit	Unit Weight	Effective Cohesion	Effective Friction	Pore Pressure Coefficient
	kN/m^3	kPa	°	B-bar
Glacial Till Core	20	0	32	0.4
Rockfill	21	0	38	N/A

Table 2. Saturated and Unsaturated Hydraulic Parameters Used in the Seepage Model

Unit	β[1]	w_{sat}[2]	w_{res}[3]	ψ_{min}[4]	ψ_{max}[5]	k_{sat}[6]	$\frac{k_x}{k_y}$[7]	α[8]
	kPa^{-1}	ratio	ratio	kPa	kPa	m/s		°
Glacial Till Core	1E^{-5}	0.3	0.1	0.01	1,000	1E^{-7}	1	0
Rockfill	0	0.2	0.1	0.1	200	1E^{-3}	1	0

[1] Compressibility of the soil. Rockfill assumed to be controlled by point-to-point particle contact, where particles are considered to be incompressible and not susceptible to particle crushing.

[2] Saturated water content

[3] Residual water content at the maximum matric suction

[4] Minimum matric suction

[5] Maximum matric suction

[6] Saturated hydraulic conductivity

[7] Ratio of the horizontal to vertical hydraulic conductivity

[8] α is the rotation angle for the horizontal hydraulic conductivity

Close form solutions are available to determine the hydraulic functions based on grain size distribution curves (Chapuis 2016). However, software for assessing transient seepage problems typically provide built-in tools for determining the functions (i.e. Geoslope 2018). In the example described below, the example soils provided in the software used (Geoslope 2018) were utilized to provide an example that is reproducible. The input parameters considered in the example below are provided in Table 2.

4 EXAMPLE

4.1 Conceptual Project Description

The hypothetical project consists in the development of a 1,000 MW hydropower plant in the province of Alberta, Canada. Two temporary 25-m high earth-fill cofferdams will be constructed to safely divert the river flows around the work site during construction of the plant. The upstream cofferdam will divert the flows into diversion tunnels, and a cofferdam downstream of the plant site will be built to ensure backwater in the channel does not enter the work site. This diversion scheme will allow for the construction of the main project facilities on the main river channel, which include: 1) main earth-fill embankment, 2) concrete spillway, 3) intake, 4) powerhouse, and 5) penstocks. Once all the main project facilities have been commissioned, the cofferdams will be removed, and the filling of the reservoir will commence.

The main embankment will extend from the concrete spillway and powerhouse complex to tie in with the natural terrain on each abutment. The embankment will be comprised of zoned earth-fill with an impervious core. Upstream and downstream faces of the embankment may require rip-rap protection in order to prevent erosion. A typical section of the earth-fill embankment is shown on Figure 1.

4.2 Flood Routing Model Setup and Results

The following sections describe the inputs to the flood routing model and presents the key results that will inform the seepage-stability model.

4.2.1 Inflow Flood Hydrograph

Historical streamflow data from a Water Survey of Canada (WSC) hydrometric station located 95 km upstream from the site of interest and having a period of record of 60 years were used for this study. After screening the data, it was found that the annual maximum daily mean flows are on average 4% lower than annual peak instantaneous flows, thus confirming that a daily discretization of the inflow hydrograph would capture the flashiness of the flood events. Streamflow data from the WSC station were used to generate a unit flood hydrograph. Furthermore, flood quantiles for various return periods were estimated by fitting the annual maximum flows to a Gumbel distribution. The resulting flood quantiles were upscaled to the site of interest based on drainage area and were then used to generate inflow flood hydrographs based on the developed unit hydrograph.

4.2.2 Reservoir Capacity

A Digital Elevation Model (DEM) was downloaded for the site of interest from the Alberta Government website to evaluate the capacity of the available reservoir, based on various embankment elevations. The DEM was used to generate the depth vs. capacity relationship of the reservoir based on the chosen embankment, using a one meter depth interval spacing.

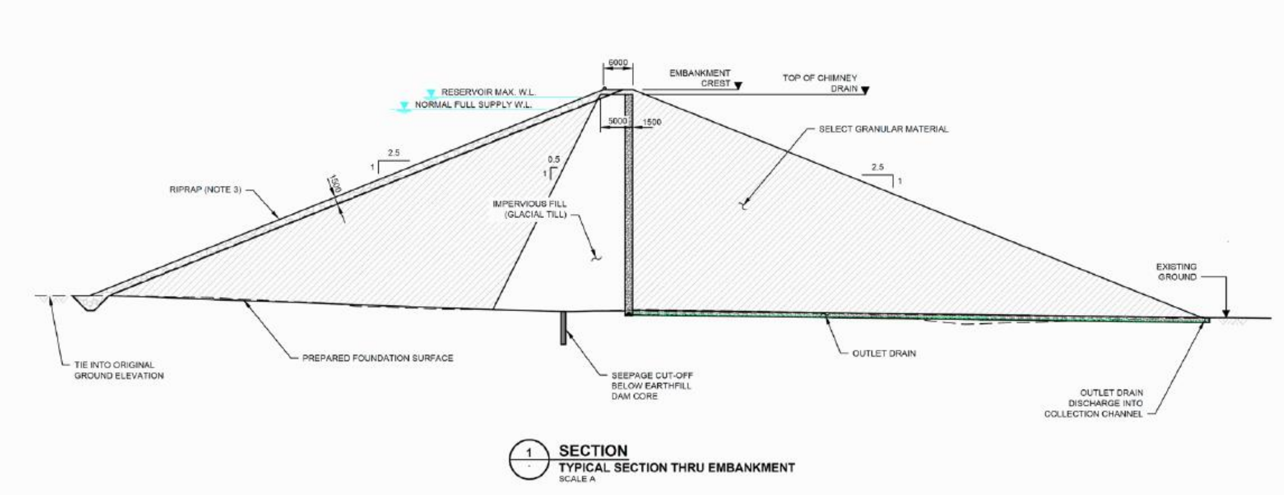

Figure 1: Earth-fill Embankment Typical Section

4.2.3 Reservoir Outlets

4.2.3.1 Cofferdams and Diversion Tunnels

Two temporary earth-fill cofferdams will be constructed to divert flows during construction of the main project facilities. The cofferdams will be 25 m high and approximately 750 m in length. Four concrete-lined tunnels, each 17 meters in diameter and 3 km long, will be constructed through bedrock and will be used to convey the flows away from the construction activities. The discharge characteristics of the tunnels are primarily driven by the depth of water in the reservoir behind the upstream cofferdam. The tunnels have been designed to convey the 50-year flood event, estimated as 16,500 m3/s, while allowing for 1 meter of freeboard.

4.2.3.2 Main Embankment Spillways

Two concrete ogee spillways will be constructed adjacent to the earth-fill main embankment; an operational spillway, used to control the release of flows during normal operation of the power plant, and an emergency spillway, designed to provide additional capacity during extreme flood events. The spillways have been designed to convey the Probable Maximum Flood (PMF), estimated as 32,000 m^3/s, while allowing for one meter of freeboard. The flood-routing model assumes that the drawdown of the reservoir water level after the flood event will be limited by the spillway invert elevation.

4.2.4 Flood Routing Model Results

Flood routing model results were generated for the following two scenarios:

- Cofferdam: An inflow flood hydrograph corresponding to a return period of 20 years is diverted from the construction works by means of the diversion tunnels. The model evaluates the reservoir water level change with respect to the cofferdam elevation during the passing of the flood.
- Main Embankment: An inflow flood hydrograph corresponding to a return period of 200 years passes through the main embankment spillways once the power plant has been commissioned. The model evaluates the reservoir water level change with respect to the spillway inverts and main embankment crest elevations during the controlled release of the flood flows.

Figure 2 shows the inflow flood hydrograph as well as the corresponding outflow hydrograph resulting from the reservoir-routing model for the cofferdam scenario. Figure 3 shows the reservoir elevation for each time-step of the simulation with respect to the cofferdam crest elevation. Furthermore, Figure 4 shows the inflow flood hydrograph as well as the corresponding outflow hydrograph resulting from the reservoir-routing model for the main embankment scenario. Figure 5 shows the reservoir elevation for each time-step of the simulation with respect to the spillway inverts and main embankment crest elevations. The reservoir elevation time-series shown in the figures below are used to inform the seepage-stability model discussed in the following sections.

4.3 Seepage Model Setup

The geometry of the seepage and stability models are provided on Figure 6, with Case 2g illustarted. The dimensions of the embankment and clay core are shown on Figure 6. The meshing for the transient seepage model is quadra-triangular in shape with a width of 1.0 m. A drainage blanket that is 22 m long and 1.0 m high at the downstream toe of the embankment is modelled as a Total Head boundary condition with a head of 276 m.

No filter zones were considered in the model as the hydraulic properties of fine and coarse filters were considered to be similar enough to the embankment shell rockfill such that the filters could be ignored and modeled as part of the shell rockfill. Depending on the gradational characteristics of the filter zones and the rockfill in relation to the clay core, the filters may have to be considered in other cases.

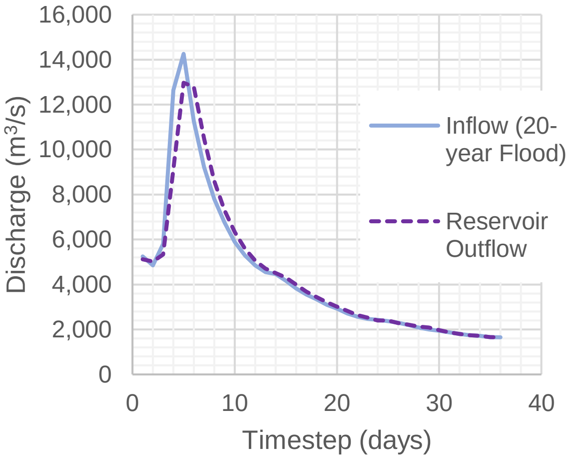

Figure 2: Flood Routing Results for the Cofferdam Scenario

The boundary condition on the upstream face of the embankment was set as a head boundary condition function equivalent to the function shown on Figure 3. The function will model the rise and fall of the reservoir under flood conditions described above.

The transient model was set up to match the overall time considered by the head boundary condition. A total of 144 timesteps were used on a exponential scale, with an initial increment size of 21,600 sec (Geoslope 2018). Model results were saved for every time step.

4.4 Structural Stability Model Setup

The structural stability model utilizes the limit equilibrium method and the Morgenstern-Price’s method of slices to estimate the factor of safety for a given slip surface (Geoslope 2018). The factor of safety is defined by the resistance to sliding divided by the load driving the

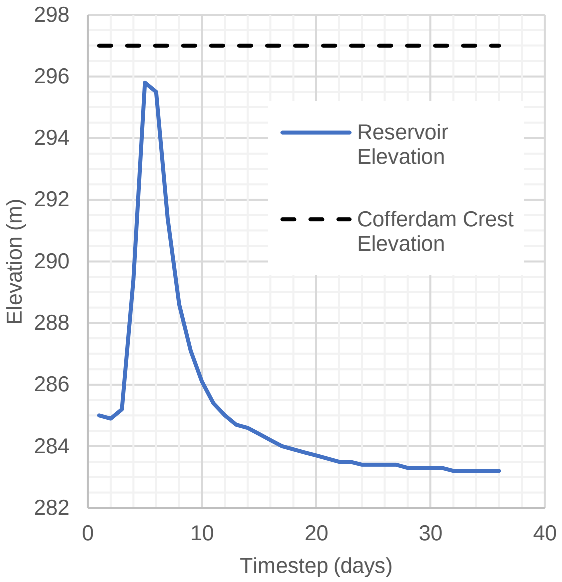

Figure 3: Resulting Reservoir Elevation for the Cofferdam Scenario

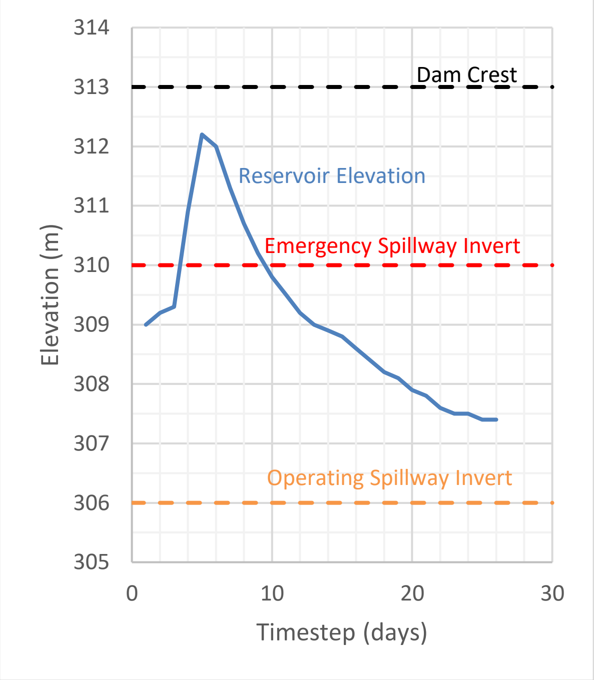

Figure 5: Resulting Reservoir Elevation for the Main Embankment Scenario

movement. A factor of safety of unity is typically assumed to be the onset of movement along the sliding surface.

The entry and exit method for defining the slip surfaces was utilized. This allows the user to set where the head scarp of the failure will develop and where the failure surface will breakout at the toe of the slope. The entry and exit points for the surfaces are defined either as a point or range. Where a range is considered, then the number of entry and exit points along each range is defined (Geoslope 2018).

4.5 Results

An instantaneous rapid drawdown assessment (Geoslope 2018) was run for the base case embankment layout and soil parameters (Case 1) for comparison purposes. The minimum factor of safety for this scenario was 1.2. When compared to the results of the transient rapid drawdown assessment, the instantaneous rapid drawdown assessment is overly conservative and not representative of the actual embankment stability. Furthermore, a minimum factor of safety of 1.2 is below the recommended factor of safety of 1.3 for rapid drawdown in the Canadian Dam Association's dam safety guidelines (CDA 2013). The transient rapid drawdown assessment provides a minimum factor of safety well above the recommended factor of safety of 1.3 (CDA 2013). This provides the ability for a dam designer to optimize the layout of the embankment by increasing the slopes of the clay core and decreasing the width of the rockfill, assuming that the rapid drawdown case is the governs the design of the embankment.

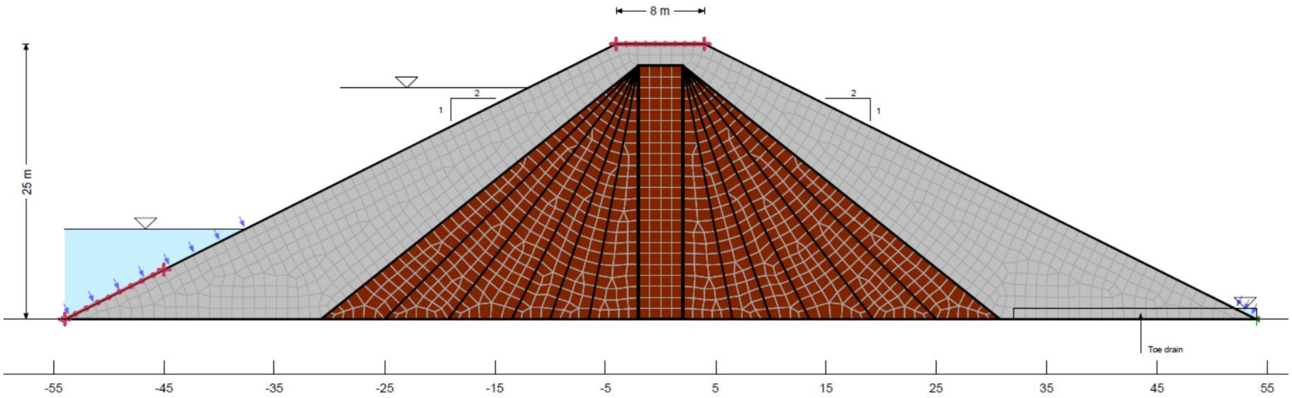

Figure 6. Model layout for seepage and stability analyses

Table 3. Summary of Cases Considered during the Sensitivity Analyses

Case	Slope of Core	Factor of Safety	
		Min	Max
2a [1]	Vertical	n/a	n/a
2b	0.2H:1V	1.4949	1.5530
2c	0.35H:1V	1.4953	1.5506
2d	0.5H:1V	1.4957	1.5502
2e	0.75H:1V	1.4964	1.5513
2f	0.1H:1V	1.4945	1.5515
2g	1.25H:1V	1.4433	1.5492

[1] seepage model did not converge

The results of the transient rapid drawdown assessment are illustrated on Figure 6, with the time step presented on the horizontal axis and the factor of safety presented on the vertical axis. The vertical case is presented on Figure 6 and is indicated as Case 2a in Table 3. Case 2a did not converge and is only shown for illustrative purposes.

A sensitivity assessment of the angle of the slopes of the clay core was carried out to determine if there were limits to the proposed transient rapid drawdown methodology. The range of slope angles, indicates as cases 2b to 2g, and their corresponding minimum and maximum factors of safety, are presented in Table 3 and on Figure 6, with boxes indicating the zones detailed by Figures 7 and 8. The sensitivity analyses indicate that over the range of clay core slopes considered, there is only a 3.4% and 0.24% difference, as indicated by the plots on Figures 7 and 8, respectively, and the data in Table 3.

5 DISCUSSION

5.1 Impacts on Construction

When comparing the results of the instantaneous rapid drawdown with those of the transient rapid drawdown, there is the potential to reduce the overall volume of clay core material. This is advantageous as for many projects the availability of glacial till that meets the project requirements could be limited. Although the model considering vertical clay core slopes did not converge, the likelihood of ever considering the use of vertical is very low due to issues of constructability. However, since every slope angle of clay core converged, and the relative difference between the results for each is negligible and all would be considered as having a factor of safety of 1.5 when reporting to one significant figure, there is still room to optimize the design of the clay core based on its index properties, hydraulic conductivity, compressibility, and other attributes.

Ultimately, consideration needs to be given to specifying the clay core material by more than just its gradational limits. Even when considering the instantaneous drawdown method, the excess porewater pressure is the governing factor when assessing the structural stability of a dam. Ultimately, the dissipation of the excess porewater pressures will be controlled by the compressibility of the soil and its hydraulic conductivity. Typically, only the gradational limits are used to verify a clay core meets the project requirements prior to its use, and then only in-situ density testing is used to verify the placed clay core material will meet the performance criteria set for the dam. Unless analyses support the target density by correlating the target density to the acceptable hydraulic conductivity and compressibility, both of which are intrinsic soil properties that are affected by the density of the soil, then there is now reasonable sense of reliability regarding the target density. The proposed rapid drawdown method provides a basis for justifying the assessment of the density in relation to hydraulic conductivity and compressibility in order to further optimize the design of the clay core and reduce overall project costs.

Consideration also needs to be given to optimizing the size the diversion structure used to convey water around the construction area. The normal pool level, and rate of drawdown, will be controlled by the diversion structure conveying water around the construction area. The larger the diversion structure, the lower the normal operating water level and the faster the rate of drawdown.

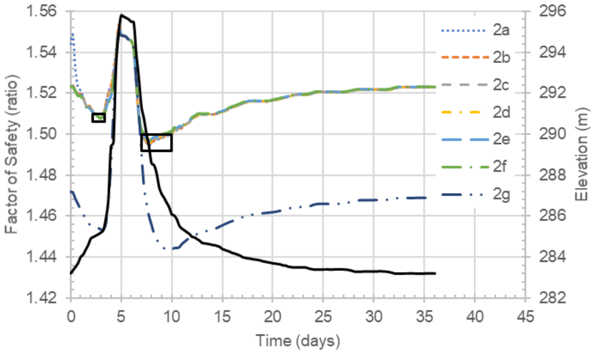

Figure 6. Results of Transient Rapid Drawdown Analyses

An iterative process will be required to find the most cost-effective arrangement for the cofferdam and diversion layout, as one or the other could govern the design of the diversion scheme. However, by providing a more detailed assessment of the cofferdam, a designer could also provide significant savings to a project by limiting the size of the cofferdam and diversion structure, especially if tunnels are proposed to convey water around the construction area.

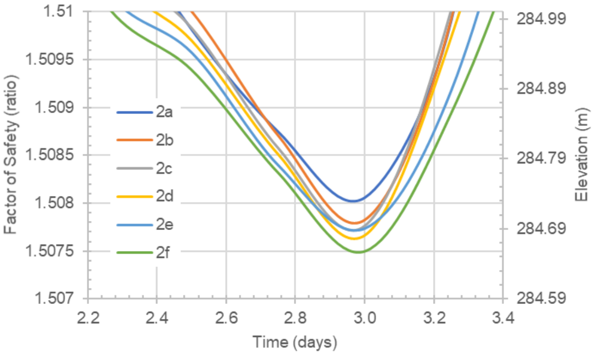

Figure 7. Minimum Factors of Safety during the increase in water level

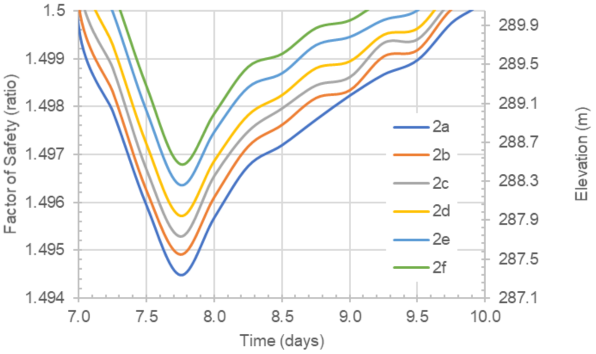

Figure 8. Minimum Factors of Safety during drawdown

5.2 Cofferdam

Cofferdams are temporary embankment dams that are used to divert water courses for the purpose of providing dry working spaces in ‘dry’ conditions (i.e. areas typically submerged but may still require dewatering due to seepage). Cofferdams are typically designed to relatively low flood return periods, on the range of 1 in 20 years to 1 in 50 years, depending on the level of risk the owner and/or contractor wish to take on. Depending on the length of time a cofferdam is left in place, it could be subjected to numerous water level fluctuations between its normal operating level and maximum flood level (with or without freeboard considerations for wind run up). However, the water level is likely never to expose the toe of the cofferdam, as there will likely always be a flow of water through the diversion structure. Due to head losses along the diversion structure, the water level will be elevated above the toe and always providing a minimum amount of buttressing of the upstream face of the dam. Essentially this leads to the finding that a conservative case of taking the drawdown level to or below the toe of the embankment is not justified.

5.3 Main Embankment

Main embankment dams with the purpose of water supply or generation of hydropower will also have water level controls that will ultimately control the minimum depth of the reservoir. All water retention dams requiring some level of head to drive the flow of water either to water treatment facilities or to produce power. Typically, the spillway for an embankment dam will control the minimum water level in the reservoir, unless the am has a low-level outlet for sluicing sediment. This results in a fairly minimal range over which the water level will fluctuate during operations – normal or during flood events. Again, this negates the need for conservative rapid drawdown assessments that consider the maximum flood water level and a water level at the toe of the dam. If the water level is actually going to change from a flood level down to the toe of the dam over the course of minutes or hours and not weeks, as was considered above, then the dam has more than likely undergone a breach and upstream failure of the dam is a mute point. At this point, the concern is going to be the runout of the dam breach, not minor dam upstream slope failures.

By limiting the range of water drawdown, the design can then further optimize the design of the dam and reduce the overall cost assuming the rapid drawdown case governs the design. And if the instantaneous rapid drawdown case did govern the design, implementation of the proposed transient method may lead to another case governing the design. Regardless of the outcome of using the proposed method, capital costs can potentially be reduced, which will be seen as an incentive to the owner or client to pay for the additional work required when carrying out transient seepage analyses.

5.4 Limitations

The current assessment assumes that the filters have the same hydraulic conductivity as the rockfill shells. This not explicitly true and is likely only applicable to preliminary design. The difficulty is assessing the actual saturated and unsaturated properties of the filter or filters would require materials to be available. Filter materials may not actually be available until construction is well underway and design assumptions cannot be validated until that time.

The current model also ignores the foundation of the cofferdam. The authors are aware that the presence of a horizontal, low conductivity material that becomes unsaturated during the assessment will lead to non-convergence of the model. Consideration must be given to any surface exposure of horizontal, low conductivity material must be assessed. However, future work is required to determine the model parameters required to result in a fully converged model.

5.5 Future Work

Consideration should be given to coupling the above proposed transient rapid drawdown methodology with a stress-strain assessment to have a more realistic representation of the compressibility of the clay core. A water retaining embankment dam will undergo many fluctuations of the reservoir water level over its serviceable life. It should be expected that the compressibility of a clay core will change over time. Multiple changes in water content of a clay core is equivalent to reaching a steady-state stress condition at the end of the loading period during an oedometer test.

Under these conditions it would be necessary to run the assessment multiple times, taking into account the incremental change in the compressibility of the clay core. One would expect that after a given number of cycles, N_i, of rising and lowering the water level, the results of the transient rapid drawdown assessment would equalize over the range of N_{i+1} to N_{i+x}.

6 CONCLUSION

The proposed transient rapid drawdown assessment presented here offers a potential alternative to the traditional instantaneous rapid drawdown assessment. The proposed method is not considered conservative and only relies on more recent developments in geotechnical engineering, such as unsaturated soil mechanics and numerical modelling.

The benefit of transitioning to the proposed method provides the opportunity to optimize the design of embankment dams, temporary or permanent. Unlike the instantaneous method, which provides overly conservative results, the proposed method offers a method that can be used to decrease the capital costs associated with the construction of embankment dams.

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