*Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.*

# Rapid filling-drawdown cycling effects on the seepage and slope stability of PSPs embankment dams

## Efectos de los ciclos rápidos de llenado y descenso sobre la filtración y la estabilidad de taludes de presas de terraplén de centrales reversibles

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ABSTRACT: The application of Pumped Storage Plants (PSPs) worldwide is growing. For many components of PSPs, such as embankment dams, design guidance and recommendations of several international organizations are applied in lieu of criteria specific to PSPs, even though such guidelines are often formulated for irrigation and water supply dams. As such, their application to the design of components within PSPs, which can have operating regimes that involve daily or weekly oscillations in hydraulic head, may result in overly conservative and uneconomical design outcomes. To further promote the adoption of PSPs, analyses can be undertaken to provide a basis for refining the design criteria for PSP embankment dams. This paper presents an analytical comparison of transient and long-term steady state seepage analyses for an earthfill dam with internal drains. The analysis compares the impacts that both cyclical operational reservoir level oscillations and steady reservoir levels have on the phreatic surface, seepage flow within internal drains, and the upstream slope stability for rapid drawdown conditions. The analysis allowed an accurate definition of the internal water level, which can be used to optimize the drainage and the dam geometry.

KEYWORDS: dams, pumped storage plants, transient seepage, rapid drawdown.

## 1. INTRODUCTION

Pumped Storage Power Plants (PSPs) allow the management of intermittent energy sources and their integration is expected to increase in the following years. Central components of PSPs are the lower and upper reservoirs, which regulate water volumes according to the generation requirements (daily, monthly, seasonally, etc.). The reservoirs are used to be constructed as saddle embankment dams, which can cover extensive perimeters, having a significant impact in the CAPEX. Moreover, since the embankments must withstand rapid cyclic loads during pumping and generation; in addition to preventing water seepage, sealing measures like geomembranes, asphaltic lining, or concrete face are commonly employed, further increasing the costs.

The geotechnical design of traditional reservoir dams typically considers steady-state seepage conditions, which results in a fixed phreatic surface that extends throughout the embankment. Conversely, in the context of PSP reservoirs, the rapid variations of the water level are expected to impose a reduced the level of phreatic surface that does not extend throughout the whole dam body. By performing transient seepage analyses for different soils, Sayah et al. (2023) found that the long-term phreatic surface is lower than the one obtained with a steady-state seepage, which also resulted in lower flow towards the drains. While recommending optimizations on the drain design, the authors did not provide recommendations for the upstream slope stability, which is subjected to continuous cycles of rapid drawdown.

This paper complements the seepage analyses performed by Sayah et al. (2023) by including additional unfavorable scenarios in the context of slope stability. Furthermore, the slope stability of the upstream slope is evaluated, where the water level is defined by the results of the transient seepage analyses. Corresponding comparisons are made with a steady-state scenario, which due to the intrinsic simplifications on the flow regime, can induce to conservative designs.

## 2. BACKGROUND OF THE STUDY

Seepage assessment in earthfill dams typically involves two types of analyses: steady-state and transient. These analyses aim to determine gradients, flow, pore pressure, and head loss. Steady-state analyses disregard time variability and maintain constant boundary conditions, while transient analyses consider time-varying conditions, such as reservoir filling. In the case of PSP reservoirs, due to the continuous water level variations, transient analyses can provide more realistic estimations of the long-term phreatic level within the dam, which subsequently results in accurate boundary conditions for the slope stability evaluation.

The purpose of this study is to carry out seepage analyses in a transient regime given by the variation of the daily water levels of PSPs to evaluate the incidence on the phreatic water level in the dam body. Through these analyses, the study also aims to determine the flow directed to the drains and to evaluate the upstream slope stability for a drawdown scenario. The results can be used to suggest suitable criteria for the drains design and for the upstream slopes, as current criteria (ICOLD, USBR, USACE) may be conservative for dams experiencing cyclical variations. In addition, steady-state analyses have been conducted, whose results will provide a baseline for comparisons with the common criteria adopted in dam design.

A standard earth dam configuration of approx. 15 m height with internal drains (see Figure 1) has been adopted. Three different fill materials are considered: sand SP-SM (F1), loamy sand SM (F2 and F3), and sandy silt ML (F4), while its foundation is constituted of sandy silt ML (B1). The upstream and downstream slopes are 3H:1V and 2.5H:1V, respectively.

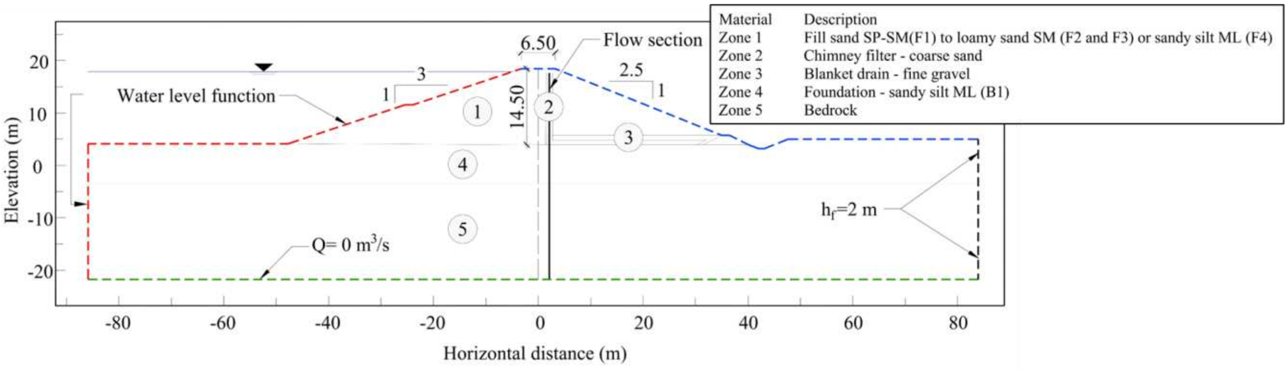

Figure 1. Dam configuration and boundary conditions adopted for the numerical model.

## 3 SEEPAGE ANALYSIS

### 3.1 Boundary conditions and material properties

In PSPs plants, depending on the reservoir capacity, there are four categories of operation: pure pumping with daily storage, pure pumping with weekly storage, pumping associated with seasonal storage, and seasonal pumping (Schleiss, 2005). The first condition is the least likely to embody a steady-state condition, while the last one can eventually induce a steady-state condition depending on the permeability of the materials.

Seepage analyses have been carried out for pure pumping with daily storage with an additional timeframe dedicated for ordinary periods of maintenance. Therefore, the following cases have been analyzed; Case A: daily water level variations on the reservoir water level (Figure 2-a), and Case B: daily water level variations followed by a two-week halt in power production by maintaining the reservoir at its full operating level (Figure 2-b).

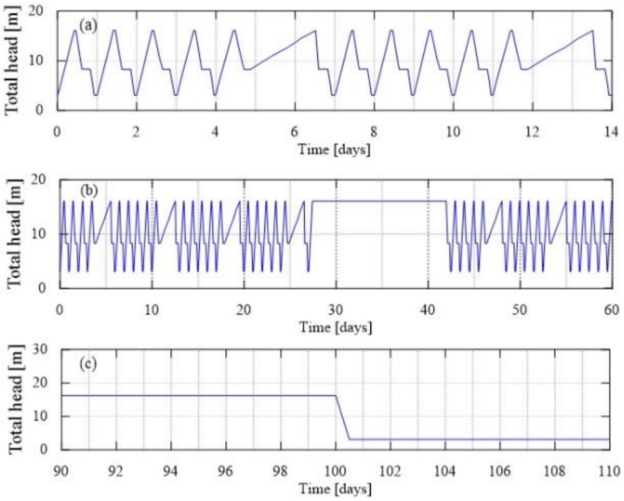

Figure 2. Water level functions considered in the transient-seepage analyses (a) Case A: daily variation scenario. (b) Case B: two weak halt scenarios. (c) Case C: permanent water level followed by rapid drawdown scenario.

In addition, to compare the effects of steady-state conditions for embankment dams, a scenario in which a rapid drawdown occurs after the reservoir is maintained at its full capacity for a significant period is evaluated, so that steady-state conditions are reached. This scenario is defined as Case C and the corresponding water level function is presented in Figure 2-c. In this case, the drawdown time is 0.5 days as in the daily cycles of Case A and B.

Several available software enable seepage and stability analysis. In this research, SLIDE 2 (Rocscience 2024) was used, which is a widely used geotechcnial software and also allows the direct integration of the results of the seepage analysis in a stability analysis. For Case A and B of Figure 2, a minimum period of 120 days with an interval of 0.2 days was established to accurately capture the impact on the dam due to the variations of the reservoir levels. Specific boundary conditions were considered: the cyclic functions of Case A and B of Figure 2 were applied on the upstream slope and the left edge. The bottom boundary condition is modelled as a no-flow boundary via a zero normal infiltration rate. Downstream free flow was allowed, while the expected ground water level of 2 m was set at the right edge. The boundary conditions applied in SLIDE are shown in Figure 1.

For Case C of Figure 2, the same boundary conditions were maintained with the only exception of the upstream slope, where a constant head corresponding to the maximum expected elevation during reservoir operation was imposed until a fixed water level was observed within the dam.

Unsaturated soils have an impact on infiltration and pore pressure propagation in embankments. Their behavior is characterized by the Soil-Water Retention Curve (SWRC) and the hydraulic conductivity function (HCF). The SWRC establishes the relationship between the suction matrix and the volumetric water content, being essential to predict the HCF. The SWRC and HCF were defined by Sayah et al. (2023) from the literature based on the van Genutchen (1980) model. Table 1 and

Figure 3 present the parameters and the SWRC and HFC curves for the fill and foundation materials.

Various materials have been simulated to evaluate the incidence of the permeability on the phreatic level. The backfill materials include sand (F1), silty sand with two different permeabilities (F2 and F3), and sandy silt (F4) with the same permeability as the dam foundation. The foundation is represented by a sandy silt (B1) followed by bedrock imposing a nearly zero seepage boundary condition. Drains are modeled with higher permeabilities, enhancing directed flow to the drains, and allowing rapid convergence of the water table within the dam. Despite it is preferred to adopt less permeable soils for backfill so that a larger head loss can be achieved, employing higher permeabilities is a conservative approach in the context of seepage and drain design.

Table 1. Permeability and anisotropy of the materials of the dam.

| Case | Material type | Horizontal Permeability -Kh [m/s] | Anisotropy relation Kv/Kh [-] |
|---|---|---|---|
| F1 | Sand | 1.0E-04 | 0.1 |
| F2 | Loamy sand | 5.0E-05 | 0.1 |
| F3 | Loamy sand | 1.0E-05 | 0.1 |
| F4 | Sandy silt | 1.0E-06 | 0.1 |
| B1 | Sandy silt | 1.0E-06 | 1 |

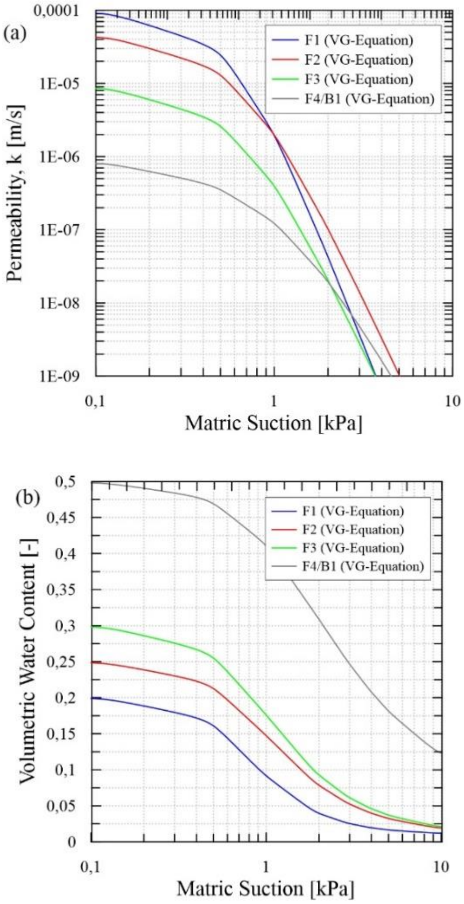

Figure 3. Curves for (a) permeability vs matric suction (HCF) and (b) volumetric water content vs matric suction (SWRC).

### *3.2 Seepage analysis results*

Transient seepage analyses have been performed for the following combinations of Fill-Foundation: F1-B1, F2-B1, F3-B and F4-B1, adopting the SWRC and HCF curves shown in Figure 3 and the water level functions of Figure 2. Figures 4-a through 4-f present the calculated long-term minimum and maximum phreatic water levels within the dam body for Case A and Case B. . The figures also include the corresponding phreatic levels for Case C, where the maximum level represents a steady state condition when the water level stabilizes in the dam and is reached before the sudden drawdown. While the minimum level is the phreatic level after the drawdown.

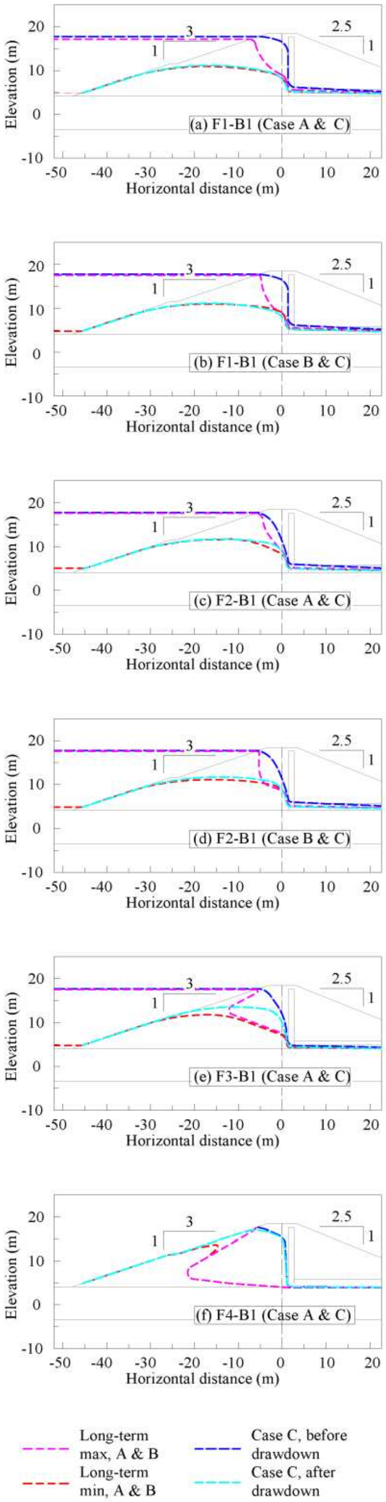

Figure 4. Phreatic level location at various stages of the transient seepage analyses.

As can be observed in Figure 4, for Case A and B (oscillating conditions) the maximum phreatic water level remains at a considerable distance behind the chimney filter, even when the flow in the drains has stabilized. While in Case C (fixed reservoir level), the phreatic water level approaches the chimney filter. In addition, the phreatic level in Case A and B remains below Case C and the major difference occurs with lower permeabilities of the dam fill (analyses F3 and F4).

When evaluating the phreatic levels after the rapid drawdown, a similar difference is observed in Case A and B when comparing to Case C. In Case C, since the initial water level covers a large area of the upstream slope, the resulting water level after the drawdown also remains within a large area, particularly when the permeability is lower (analyses F3 and F4).

Following the transient-seepage analysis, the flow within the drain system has been graphed over the entire duration for the combinations F1-B1, F2-B1 and F3-B1, which is depicted in Figure 5. F4-B1 is not included since the low permeability results in a very low flow transmitted to the drains. This figure also includes the water head functions for the two scenarios depicted in Figure 2. Case A, reflecting daily variation, and Case B, representing scheduled maintenance. It is evident in Figure 5-b that due to the high permeability of the fill in combinations F1-B1 and F2-B1, the water level stabilizes relatively quickly. Conversely, for combination F3-B1, where the fill's permeability is lower, the convergence time is notably extended. Similarly, the drain flow is higher for combinations F1-B1 and F2-B1 compared to F3-B1.

The combinations F1-B1 and F2-B1 were evaluated for the water function defined for Case B , where a constant water level is maintained for two weeks (see Figure 5-c). In this analysis, a similar convergence can be observed shortly after the water level returns to the cyclic fluctuation, being representative of the dam operation (see Figure 5-d).

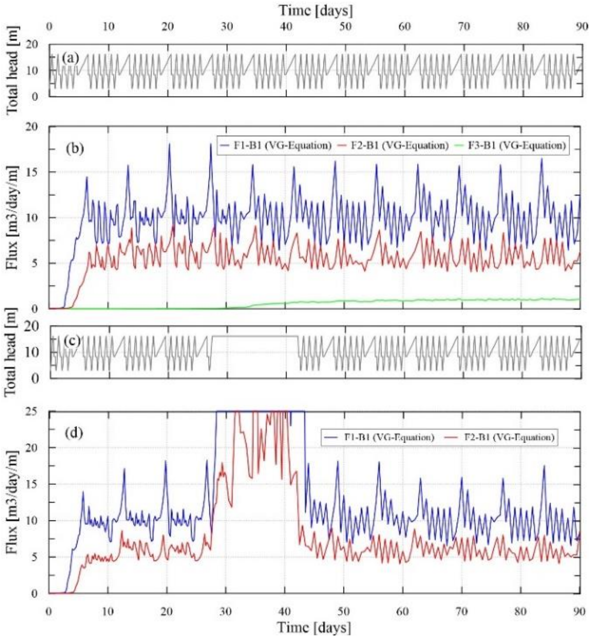

Figure 5. Flow in the horizontal blanket drain vs time for (a) Case A water level function: daily variation scenario and (b) Case B water level function: scenario for a schedule maintenance or unscheduled shutdown.

The average flow for each combination depicted in Figure 5 was computed upon convergence. Additionally, the flow was estimated for the drains system as presented in Table 2 for both water functions, Case A and B. The flow obtained by a steady-state analysis are also listed in Table 2. It should be noted that due to the low permeability of the foundation, the flow in the chimney and the drains are similar and are not differentiated in Table 2.

Table 2. Flow results for the drains system.

| | | | **Drains system** | | |
|---|---|---|---|---|---|
| **Model** | **Fill** | **ks [m/s]** | **$Q_{Case\ A}$ [m³/d/m]** | **$Q_{Case\ B}$ [m³/d/m]** | **$Q_{steady\text{-}state}$ [m³/d/m]** |
| F1-B1 | Sand | 1.00E-04 | 10.2 | 10.3 | 36.1 |
| F2-B1 | Loamy Sand | 5.00E-05 | 5.7 | 6.0 | 18.3 |
| F3-B1 | Loamy Sand | 1.00E-05 | 1.0 | - | 3.4 |
| F4-B1 | Sandy Silt | 1.00E-06 | < 1 | - | < 1 |

### *3.3 Filter and drain design*

The capacity of the drainage elements of a dam is based on the dimensions and permeabilities of the drain materials. Based on Darcy's law, the USACE (2000) recommends the following expressions to estimate the flow capacity for the blanket drain and the chimney.

$$q_{blanket} = \frac{k_1 \times {h_1}^2}{L_1} \tag{1}$$

$$q_{chimney} = \frac{k_2 \times h_2 \times w}{L_2} \tag{2}$$

Where $k_1$ = permeability of the material of the blanket [m/s]; $h_1$ = vertical thickness of the blanket [m]; $L_1$ = length of the blanket [m]; $q_{blanket}$ = discharge capacity per meter of blanket width [m/s/m]; $k_2$ = vertical drainage permeability of the chimney [m/s]; $h_2$ = height of the chimney [m]; $L_2$ = length of the chimney [m]; w = thickness of the chimney drain [m]; $q_{chimney}$ = discharge capacity per meter of chimney width [m/s/m].

Figure 6 presents the factors of safety (FoS = flow capacity / flow of the model) of the chimney and blanket drain, where the drains capacity was calculated by adopting a minimum constructed width of 0.5 m for the chimney and a thickness of 1.5 m for the blanket. Due to the significantly lower flow obtained for the oscillation condition (Case A and Case B), the values of FoS are at least 3 times the ones obtained in the permanent condition (steady state). times the ones obtained in the permanent condition (steady state). It is important to note that in the models with fill material of lower permeability, the FoS in transient situations exceeds FoS>100 due to the high head loss that results in a very low flow transmitted to the drains. These cases are presented in dashed lines for materials F3-B1 and F4-B1.

Given that the standards state that a minimum FoS of 10 must be adopted in the drain design (USACE, 1993), based on the expected flow estimated for oscillation conditions, there is the possibility to adopt a lower FoS. The flow analyses result in a $FoS_{CaseA\text{-}CaseB}/FoS_{Steady\text{-}State}$ ~ 3, what implies that the reference value of 10 can be significantly optimized (up to a third for this specific case). It is worth mentioning, however, that the analyses have been conducted for specific materials and dam geometry, therefore, further research can be developed considering other fill types and operating conditions. In addition, ongoing and future projects shall be properly instrumented to monitor water level variations, in order to confirm or even optimize the findings of this study.

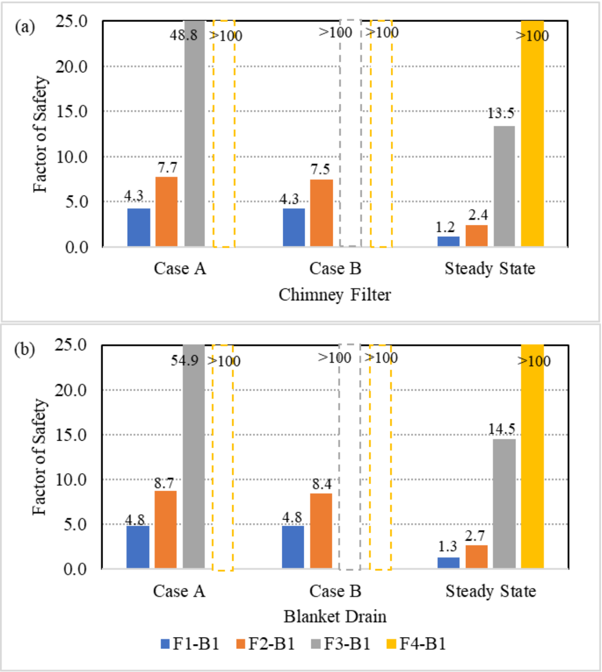

Figure 6. Factor of safety for (a) chimney filter and (b) blanket drain.

## 4. SLOPE STABILITY ANALYSIS

The slope stability of earth-fill dams is usually evaluated for the following conditions: end-of-construction, long-term, rapid drawdown, and earthquake. The corresponding factors of safety (FS) for each condition are shown in Table 3 (USACE, 2000), where it can be observed that higher FS are required for the long-term-stability, while for the other cases, a lower FS is required since they represent temporary or extreme cases. In the case of earthfill dams with frequent water level variation, however, the rapid drawdown scenario represents a usual condition. Therefore, higher FS shall be adopted; for instance, the DWR (2012) recommends a FS ≥1.4 for frequent, large, tidal fluctuations rapid drawdown slope stability.

This study focuses on the evaluation of the slope stability in the upstream slope for a rapid drawdown scenario as explained in the following sections.

Table 3. Slope stability factors of safety (FS) (USACE, 2000).

| Type of slope | Applicable stability conditions and required FS | | |
|---|---|---|---|
| | **End-of - construction** | **Long-term (steady state seepage)** | **Rapid draw-down** |
| New levees | 1.3 | 1.4 | 1.0 to 1.2 |
| Existing levees | - | 1.4 | 1.0 to 1.2 |
| Other dikes and embankments | 1.3 | 1.4 | 1.0 to 1.2 |

### *4.1 Considerations on the rapid drawdown analysis*

Rapid drawdown occurs when the reservoir level outside a slope drops so fast that impermeable soils within the slope do not have sufficient time to drain.

As explained by Duncan & Wright (2005), when the water level drops, the stabilizing effect of the water outside the slope is lost, and higher shear stresses are mobilized for equilibrium. The shear stresses within the slope are resisted by undrained strength in zones of low permeability and by drained strength within zones of higher permeability. This is a severe loading condition that can cause failure of slopes that are stable before drawdown.

Whether a soil zone drains or not can be estimated by calculating the value for the dimensionless time factor, T, given by:

$$T = \frac{c_v t}{D^2} \qquad (3)$$

Where T = dimensionless time factor [-]; $c_v$ = coefficient of consolidation [m$^2$/s]; t = time for drawdown [s]; D = drainage distance [m].

According to Duncan et al. (1990), if the calculated value of T is equal to 3 or more, the dissipation of pore water pressure induced by the drawdown exceeds 98%, and it is reasonable to assume that the material is drained. Table 4 presents the estimation of the T value for the different earthfill materials considered in the dam. It can be observed that for material F1, a value of T=41 is obtained, therefore, drainage is expected at the upstream slope. In cases F2, F3, and F4, the T value is gradually reduced, being all lower than T=3. Therefore, the rapid drawdown slope stability analyses are performed for these cases.

Table 4. Determination of the T factor to define rapid-drawdown conditions.

| Parameter | F1-B1 | F2-B1 | F3-B1 | F4-B1 |
|---|---|---|---|---|
| | **Sand** | **Loamy-Sand** | **Loamy-Sand** | **Clayey silt** |
| Cv [m2/s] | 9.4E-02 | 4.7E-03 | 9.4E-04 | 4.7E-05 |
| t [day] | 0.5 | 0.5 | 0.5 | 0.5 |
| t [s] | 43200 | 43200 | 43200 | 43200 |
| D [m] | 10 | 10 | 10 | 10 |
| T | 41 | 2.0 | 0.4 | 2.0E-02 |

### *4.2 Water level definition*

The water level before and after the drawdown is needed to define the corresponding stresses for equilibrium. Figure 4 depicts the long-term water level within the dam before and after the drawdown. The blue and cyan lines represent Case C of Figure 2, and the red and magenta lines correspond to Case A and B.

It is worth highlighting that for Case A and B, the water level represents the minimum and maximum long-term equilibrium on the water level within the dam obtained after numerous cycles of the water level variation in the reservoir. While in Case C, the upper water level corresponds to the long-term phreatic surface when maintaining the reservoir at its maximum operation level and is the level before the drawdown. Moreover, the level after the drawdown was determined with a transient seepage analysis when considering a reduction of the level of the reservoir in 0.5 days.

### *4.3 Geotechnical parameters*

Duncan et al. (1990) proposed a three-stage analysis procedure for the shear strength definition and slope stability analyses for a rapid drawdown scenario. The first stage consists of evaluating the conditions prior to drawdown, in order to estimate effective stresses along the slip surface. For the second stage, the slope stability after the drawdown is evaluated to estimate preliminary factor of safety. The third-stage computations are performed to check whether effective or total stress would induce the lowest factor of safety.

For free-draining materials, effective stresses are used for all three stages, with different pore water pressures based on water levels and seepage conditions. Conversely, in the case of low-permeability zones, effective stresses are used for the first stage, before drawdown, and total stresses and undrained strengths are used for the second stage, after drawdown. For the third stage, the lower of the drained and undrained strengths is used, whichever is lower, to be conservative.

At the second stage, Duncan et al. (1990) defined the minimum and maximum limits for the undrained shear strength based on the stress ratio ($Kc = \sigma'_{1c}/\sigma'_{3c}$). The relations are represented in the undrained shear strength, $\tau_{ff}$, vs the effective normal stress on the failure plane during consolidation, $\sigma'_{fc}$. The lower bound corresponds to the envelope of an isotropically consolidated-undrained (IC-CU) test, therefore, Kc=1. While the upper limit corresponds to the maximum stress ratio at which the soil can be consolidated before any undrained loading is applied, which can be related to the effective stress envelope or a drained test (Kc=Kf).

While different soils are considered in the seepage analyses, in order to have a direct comparison of the effects of the phreatic level on upstream slope, the same parameters have been adopted for the different fills, F2, F3, and F4. F1 is not considered since the soils are expected to fully drain during the draw-down as explained in 4.1.

Table 5 lists the shear strength parameters of an isotropically consolidated undrained triaxial test and of a drained test. The values can be related to a loose sand with fines or to a low plasticity silt with sand content. To determine the relationship between $\tau_{ff}$ and $\sigma'_{fc}$, the strength enveloped is represented accordingly, as shown in Figure 7. The figure includes the minimum strength envelope for an isotropically-consolidated condition ($K_c$=1.0), and the maximum strength ($K_f$=$K_c$). The corresponding intercepts on the ordinate and the slope angles are also listed in Table 5.

Table 5. Geotechnical parameters.

| Material | | Envelope in terms of τ vs σ' | | Envelope in terms of $\tau_{ff}$ vs $\sigma'_{fc}$ | |
|---|---|---|---|---|---|
| | | **Drained** | **IC-U** | **$K_c = K_f$** | **$K_c = 1.0$** |
| Fill (F1, F2, F3, F4) | c' / $d_{kc=1}$ [kPa] | 5 | 15 | 5 | 17 |
| | ϕ / $\psi_{kc=1}$ [°] | 28 | 14 | 28 | 15.7 |

Where c' = effective cohesion [kPa]; ϕ' = effective friction angle [°]; $d_{kc=1}$ = intercept in the Kc=1 envelope [kPa]; $\psi_{kc=1}$ = slope of the Kc=1 envelope [°].

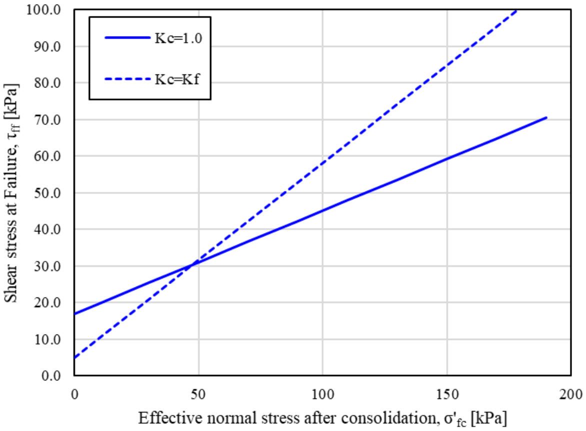

Figure 7. Shear strength envelopes adopted for the rapid drawdown analyses according to Duncan et al. (1990).

### *4.4 Results of the slope stability analysis*

Subsequently, slope stability analyses were performed for the rapid drawdown starting from a fixed reservoir level (Case C of Figure 4) and for the oscillating conditions (Case A of Figure 4). To have a direct comparison on the influence of the permeabilities of the materials and the phreatic level within the dam, three failure surfaces have been defined: General failure surface (S1), upstream slope failure surface (S2), and lower upstream slope failure surface (S3), which are maintained for all the cases analyzed. In addition, the surfaces are not considered to extend through the foundation material (B1). To analyze the effects on the dam itself, these surfaces have been located to cover an extensive area of the upstream slope, as well as the lower zone. Figure 8 and Figure 9 present the failure surfaces for the drawdown analysis in Case A and Case C, respectively, while Table 6 summarizes the corresponding factors of safety. In addition, the relation between the factors of safety of Case A and Case C analyses ($FS_{Case\ A}/FS_{Case\ C}$) are included in Figure 10.

As explained by Duncan et al. (1990), the rapid drawdown stability method considers the stress state before the drawdown. Therefore, the accurate identification of the water surface is fundamental, for the slope stability analysis. In Case C (see Figure 9), the water level before the drawdown does not have significant differences for the various permeabilities considered, while the level after the drawdown results in a sequential decrease for higher permeabilities. This results in higher FS as the permeability increases as shown in Table 6.

In Case A, as shown in Figure 8, the maximum phreatic level within the dam (before the drawdown) does not fully saturate the upstream slope, in difference with Case C, therefore, the initial stress conditions vary. With lower permeability, materials F3 or F4, there is a significant zone of the dam than remains unsaturated, which influence the initial stress and mobilized shear strength in the slice, therefore, a higher FS than in the case of high permeability material (F2) is reached, as can be observed in Table 6.

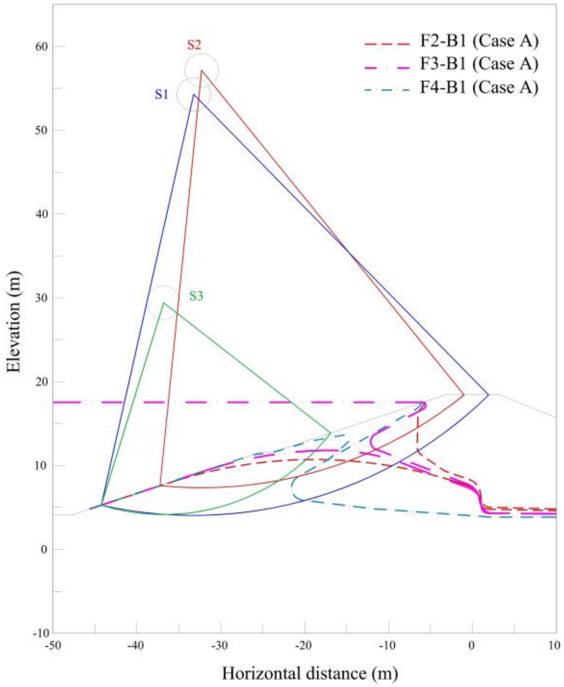

Figure 8. Failure surfaces for the slope stability analysis for a rapid drawdown (Case A).

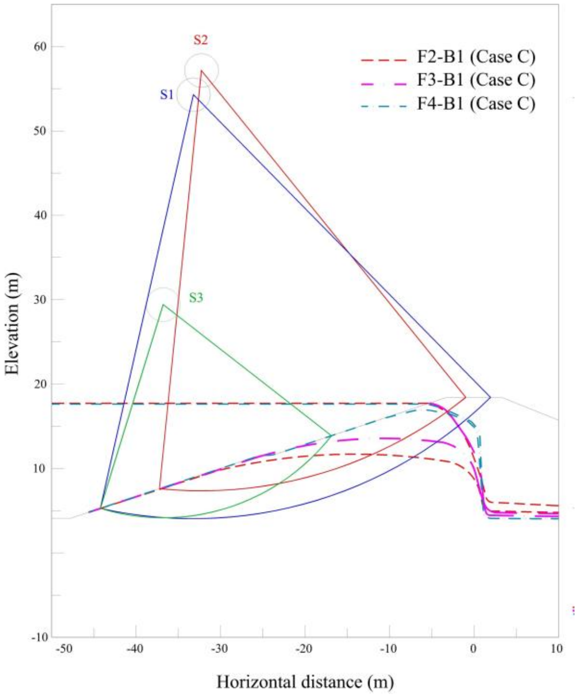

Figure 9. Failure surfaces for the slope stability analysis for a rapid drawdown (Case C).

When comparing the relation of the factors of safety as shown in Figure 10, a pattern in the increase in the relation $FS_{Case\ A}/FS_{Case\ C}$ is observed. With more permeable materials (F2), the water level tends to stabilize faster and there is no major difference between $FS_{Case\ A}$ and $FS_{Case\ C}$. Conversely, when the materials are less permeable, the long-term water level for Case A is significantly lower than in Case C, producing a lower FS for Case C. It is worth highlighting that in the case of the smaller failures surface (S3), since it is located in a zone of the dam that remains fully saturated in both cases, independently of the material permeability, there is no major difference in the result of the FS, as shown in Figure 10.

Table 6. Factors of safety for the rapid drawdown analysis.

| Material | Seepage case | S1 | S2 | S3 |
|---|---|---|---|---|
| F2 - Loamy sand (k=5E-5 m/s) | Case A (oscillating) | 1.46 | 1.27 | 1.45 |
| | Case C (fixed with sudden drawdown) | 1.43 | 1.21 | 1.40 |
| F3 - Loamy sand (k=1E-5 m/s) | Case A (oscillating) | 1.60 | 1.38 | 1.36 |
| | Case C (fixed with sudden drawdown) | 1.41 | 1.20 | 1.31 |
| F4 – Sandy silt (k=1E-6 m/s) | Case A (oscillating) | 1.52 | 1.36 | 1.27 |
| | Case C (fixed with sudden drawdown) | 1.29 | 1.20 | 1.26 |

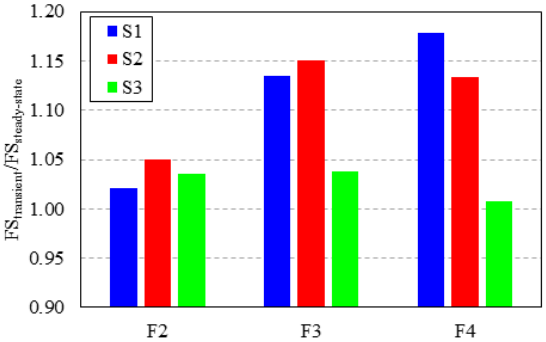

Figure 10. Relation between the factors of safety ($FS_{Case\ A}/FS_{Case\ C}$).

In embankments subjected to continuous variations of the reservoir level, such as those of PSPs, the rapid drawdown constitutes an ordinary condition. Therefore, the standards state that a higher FoS for the upstream slope shall be adopted, i.e. 1.4 instead of 1.2. However, this recommendation is based, on rapid drawdown analyses that start from a steady-state scenario, represented as Case C (USACE, 2003), which does not consider the continuous variations on the reservoir level that is not expected to fully saturate the upstream slope. Therefore, to meet the FS criterion, a less step slope may be recommended, resulting in a conservative design. For the same case, when simulating the daily variations of the reservoir level (Case A), which represents the most plausible scenario, a larger FS can be reached, meeting the stability requirements and guaranteeing the long-term stability of the dam.

A transient-seepage analysis with daily variations, such as Case A, however, requires additional hydraulic parameters and computation time, especially in low-permeability materials. Therefore, in practice, it may not always be possible to perform such analysis. Subsequently, the FoS of 1.4 can be reduced when utilizing a steady-state seepage analysis.

## 5 CONCLUSIONS

Transient seepage analyses were conducted to account for the daily fluctuations in water levels within embankment dams of Pumped Storage Plants (PSPs). This allows to correctly define phreatic water level within the dam body, which subsequently permits a better estimation of the drain flow and the slope stability of the upstream slope. The results were compared with steady-state conditions to determine the influence of rapid water level changes of PSPs on design criteria for the drains and the upstream slope. International standards are typically based on steady-state conditions, although it is acknowledged that such conditions may not be met during the dam's lifespan.

Long-term observations of the phreatic surface in the dam body revealed that during water reservoir oscillations, the maximum phreatic water level when considering daily water level reservoir variations remains behind the chimney filter, while the minimum level results in partial dam saturation. Conversely, when adopting a fixed water level (steady-state condition), the phreatic water level reaches the chimney filter, leading to higher flow.

The results showed that transient seepage analyses with daily variations yielded a significantly lower drain flow, around 3 to 5 times lower, depending on the permeability of the fill, compared to steady-state conditions. Nevertheless, ongoing, and future projects shall implement proper instrumentation to monitor water level variations so that better estimations on the flow on drains can be achieved through numerical models. This could lead to substantial optimizations in drainage design, facilitating the adoption of PSPs in the future.

Regarding the slope stability, the upstream slope was evaluated for a rapid drawdown scenario through a limit equilibrium analysis. Since the transient seepage analysis with daily variations provides a more accurate and less conservative water level and pore water pressure distribution throughout the dam body, the factors of safety resulted in larger values than in the case of fixed reservoir level (steady-state condition) with sudden drawdown. Consequently, possible optimizations of the upstream slope may be achieved when accounting the effects of transient and oscillating seepage for the design of PSP embankment dams.

## 6 ACKNOWLEDGEMENTS

We would like to extend our sincere appreciation to the Steering Committee of Lombardi Engineering and specially to Alberto Vanni, for their invaluable contribution to the revision of this paper. Their expertise and insightful feedback greatly enhanced the clarity and quality of our work.

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