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Towards a reliability-based monitoring system for uplift under concrete buttress dams

J. Dyberg Thonée, M. Zamzami, J. Spross
KTH Royal Institute of Technology, Stockholm, Sweden
jdy@kth.se
0009-0000-7988-2939, 0009-0003-9547-6529, 0000-0001-5372-7519

M. Westberg Wilde
KTH Royal Institute of Technology, Stockholm, Sweden&AFRY, Solna, Sweden
0000-0003-2584-1183

F. Johansson
KTH Royal Institute of Technology, Stockholm, Sweden
0000-0002-8152-6092

Abstract

Uplift is one of the major forces acting on concrete dams and is inherently difficult to predict. In dam safety guidelines, uplift is typically evaluated deterministically, assuming simplified pressure distributions along the concrete–rock interface. For buttress dams, the concrete–rock contact area is smaller than that of gravity dams, but in the presence of persistent fracture planes in the rock foundation, the effective area over which uplift can act can be substantially larger. Due to the low self-weight of buttress dams, this poses a significant safety concern, as sliding stability has been shown to be sensitive to variations in uplift.To address these safety concerns, pore pressure monitoring with alarm thresholds and predefined countermeasures has been proposed in dam safety guidelines. However, there is limited guidance on how such alarm thresholds should be defined or implemented in practice.In this paper, we introduce a reliability-based framework in which alarm thresholds are derived from target probabilities of failure. The methodology is demonstrated for a concrete buttress monolith with characteristics similar to those of an existing dam in northern Sweden, where the probability of sliding failure is evaluated with uplift pressure represented by a random variable. The proposed framework enables the upper tail of the pore pressure distribution to be truncated at the alarm threshold, allowing stability requirements to be satisfied in re-evaluations of existing dams without structural measures while maintaining the required level of safety. Practical considerations when defining alarm thresholds are discussed, including how exceedance of an alarm threshold may reflect long-term changes in hydraulic behaviour caused by deterioration processes in the rock foundation and how to provide sufficient lead time for pre-defined countermeasures.

Keywords

Uplift pressure, Alarm thresholds, Monitoring, Probability of failure, Dam safety.

1 Introduction

Concrete buttress dams are commonly used for hydropower purposes as a material-efficient alternative to gravity dams. The reduced self-weight due to their slender design is compensated by mobilisation of vertical hydrostatic load through the inclined upstream front plate and by the limited concrete–rock interface beneath the buttress. However, in the presence of sub-horizontal fracture planes, uplift pressure may act along a larger fracture interface and increase the resulting load (Goodman et al. 1983). Such fracture planes are relatively common in Nordic rock masses due to stress relief associated with post-glacial rebound and are, during dam safety evaluations of existing structures, sometimes identified in the rock foundation under monoliths where they were previously unknown. Uplift pressure is also inherently variable and depends strongly on local geological conditions (Hanna et al. 1993; Hu and Ma 2016). Therefore, the description of uplift pressure is subject to uncertainties arising from spatial variability beneath the monolith, fluctuations in reservoir water level, potential clogging of the drainage system, and possible degradation of the grout curtain (Ruggeri 2004). Consequently, uplift pressure is expected to vary spatially and over time, and as the exact nature of this variation is uncertain, it may be represented as a random variable in stability analyses. Despite this, existing design guidelines for stability evaluations do not explicitly address uplift pressure along fracture planes beneath buttress dams, nor do they account for the variability of uplift pressure (e.g. FERC 2016a; Swedenergy 2020).

Monitoring of uplift pressure with piezometric measurements can support dam safety assessments by providing continuous information on hydraulic conditions in the foundation. For a monitoring system to be effective, the monitored parameters must be representative of the processes governing stability, and alarm thresholds must be linked to structural performance limits and predefined countermeasures (ICOLD 2000). Existing guidelines emphasises the need for alarm thresholds (e.g. FERC 2016b) but provides limited guidance on how these should be defined. For an existing structure, lead time must be carefully estimated, to not create an overly conservative or excessively sensitive system (Pate-Cornell and Benito-Claudio 1987). This requires identifying the processes influencing the monitored behaviour and evaluating plausible scenarios and their lead times for countermeasures (Dunnicliff 1993).

Piezometric measurements from operating buttress dams in northern Sweden have shown that uplift pressures beneath some monoliths equipped with drilled drainage holes can be significantly lower than those assumed in current design guidelines. In this study, it is demonstrated how dam stability evaluations can be improved using a reliability-based framework in which uplift pressure is represented by a random variable. By defining alarm thresholds for pore pressure, less conservative uplift pressure assumptions can be used compared to those suggested in deterministic design guidelines, while still ensuring an adequate level of safety. The proposed methodology is demonstrated through an example evaluating the probability of sliding failure for a single buttress monolith. Practical aspects related to defining pore pressure alarm thresholds are also discussed, including processes that may lead to increased uplift pressure over time.

2 Methodology

2.1 Evaluated scenarios

Two scenarios were considered to illustrate how a measurement-based evaluation of uplift, combined with a monitoring system with alarm thresholds, can improve the evaluated safety of a monolith in a buttress dam. In both scenarios, the probability of sliding failure was evaluated using probabilistic calculations, where the friction coefficient of the rock joint (δ_{F}), and the unit weights of rock (γ_{r}) and concrete (γ_{c}), were treated as random variables. Although ice load (I) is likely associated with considerable variability (Westberg Wilde and Johansson 2016), it is for simplicity assumed constant in this analysis, and the associated uncertainty is therefore not included within the scope of the study. In Scenario A, uplift was assumed deterministic in accordance with the Swedish dam safety guidelines RIDAS (Swedenergy 2020). In Scenario B, the pore pressure at the measurement point (u) was treated as a random variable and controlled through a monitoring system in which the alarm threshold was defined to meet the target probability of failure. The methodology is illustrated through a calculation example for a buttress monolith based on an existing dam equipped with drainage and previously strengthened with pre-stressed anchor cables (Fig. 1). The sub-horizontal fracture acting as a potential

sliding plane was assumed based on observed geological conditions at the site, where similar fractures have been identified.

2.2 Limit state function and input data

The sliding plane was assumed to have an inclination of 10° from the horizontal (α) as illustrated in Fig. 1.The uplift force (U) was assumed to act along the fracture constituting the potential sliding plane under the dam. The hydrostatic load (H) was defined by the water pressure resulting from the head difference (h_{RWL}) between the reservoir water level (RWL) and the sliding plane. The ice load (I) was assumed to act at the RWL. All these forces (U, H and I) were assumed to act along the full width of the monolith (w_{fp}). The force from the pre-stressed anchor cables (T) was calculated considering an installation inclination (θ) of 50° relative to the sliding plane. The total vertical force from self-weight (W_{tot}) was calculated as the sum of the weights of the concrete monolith, the rock mass above the sliding plane, and the vertical force from the water acting on the front plate.

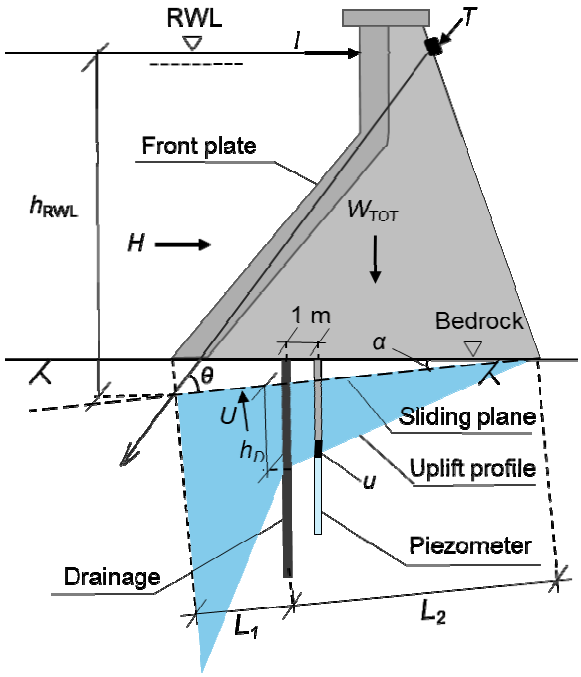


Fig.1 Cross-section of the buttress monolith and the forces acting on the potential sub-horizontal sliding plane in the rock foundation. Arrows indicate considered forces.

The limit state function for sliding failure along a sliding plane can then be derived from the Mohr-Coulomb failure theory and expressed as the shearing forces acting along the sliding plane:

$$G = [W_{\mathrm{tot}} \cos\alpha + T \sin\theta + (H + I) \sin\alpha - U]\delta_{\mathrm{F}} - [(H + I) \cos\alpha - (W_{\mathrm{tot}} \sin\alpha + T \cos\theta)]. \quad (1)$$

For Scenario A, U was calculated with uplift defined by h_{RWL} at the dam heel and decreasing linearly toward the dam toe, with the pressure at the drainage location reduced by 50% according to the Swedish dam safety guidelines, RIDAS (Swedenergy 2020). For Scenario B, U was calculated as a function of u given by

$$U = [L_1 h_{\mathrm{D}} + L_1(h_{\mathrm{RWL}} - h_{\mathrm{D}})/2 + L_2 h_{\mathrm{D}}/2\,] w_{\mathrm{fp}} \gamma_w, \quad (2)$$

where h_{D} is the pressure head at the drainage location, scaled from the measured u at the piezometer location distanced 1 m from the drainage via

$$h_{\mathrm{D}} = u/\gamma_w \times L_2/(L_2 - 1), \quad (3)$$

With γ_w denoting the unit weight of water, and L_1 and L_2 the distances indicated in Fig. 1. The coefficient of variation (COV) for u was assumed to reflect both spatial variability beneath the monolith and temporal variations in uplift pressure, guided by indications of pore pressure variability in fractured rock foundations as reported by Pereira et al. (2021) and by the COV proposed for the total uplift force U by Westberg Wilde and Johansson (2016). The parameters in Eqs. 1-3 are defined in Table 1.

Table 1. Input data.

Description	Symbol	Distribution	Value
Distance from dam heelto drainage	L_1	Constant	6 m
Distance from drainage to dam toe	L_2	Constant	26 m
Distance from RWL to sliding plane	h_{RWL}	Constant	38 m
Monolith width	w_{fp}	Constant	8 m
Ice load	I	Constant	1600 kN
Tension force in anchor cables	T	Constant	3000 kN
Volume of concrete	V_{c}	Constant	1450 m^3
Volume of rock	V_{r}	Constant	700 m^3
Volume of water above front plate	V_{w}	Constant	2650 m^3
Measured pore pressure	u	Normal	μ = 51 kPa COV = 20%
Friction coefficient of rock joint[1]	δ_{F}	Normal	μ = tan(42º) COV = 7%
Unit weight of concrete[2]	γ_{c}	Lognormal	μ = 24 kN/ m^3 COV = 3%
Unit weight of rock[3]	γ_{r}	Lognormal	μ = 26.5 kN/ m^3 COV = 2 %

[1] (Johansson et al. 2010, Ríos-Bayona et al. 2021).
[2] (JCSS 2001)
[3] Mean value and standard deviation from investigations at Forsmark (SKB 2005) presented by Westberg Wilde & Johansson (2016).

2.3 Reliability analysis

In reliability calculations the probability of violating a limit state, G, is defined as $p_{\mathrm{f}} = P(G \leq 0)$. A safety requirement is set as $p_{\mathrm{f}} \leq p_{\mathrm{T}}$, where p_{T} is the target failure probability. The level of safety is commonly expressed by the reliability index β, where $\beta = -\Phi^{-1}(p_{\mathrm{f}})$ and Φ is the standard normal distribution function. The calculated β is then compared with a target value β_{T}. For a large-consequence dam, β_{T} = 5.2 (Westberg Wilde and Johansson 2016). If the target is not met, one possibility is to implement alarm thresholds on a monitored random variable (Spross and Johansson 2017), such as the pore pressure (u). The alarm threshold value required to satisfy p_{T} is found by considering the threshold as a truncation of u, and solving the following equation for u_{alarm}:

$$P(G \leq 0 | u \leq u_{\mathrm{alarm}}) = p_{\mathrm{T}}. \tag{4}$$

For the investigated scenarios, the probability of sliding failure was calculated using Monte Carlo simulation (5 billion simulations performed in MATLAB), with a relative error of approximately 9% at the 95% confidence level, which was considered acceptable while maintaining a reasonable computation time.

3 Results

The results from the two scenarios illustrate the importance of how uplift is evaluated in the stability analysis. For Scenario A, where U was evaluated in accordance with the guidelines, the uplift pressure at the piezometer location was calculated to 148 kPa (deterministic value), resulting in a reliability index of $\beta = 3.4$, which does not satisfy the requirement β_{T} = 5.2. However, for Scenario B, where U was evaluated as a function of the measured u following Eq. 2 (μ=51 kPa, COV= 20%), it was found that the target reliability could be satisfied by introducing an alarm threshold at 70 kPa (Eq. 4). Thus, the different outcomes of the two scenarios demonstrate how the safety requirements for this monolith can be met using a monitoring system, where uplift is evaluated from piezometric measurements and controlled through alarm thresholds, rather than by performing structural measures.

4 Discussion

4.1 Monitoring system as an alternative to structural measures

Comparison of Scenarios A and B highlights the sensitivity of sliding reliability to the assumed uplift representation. In Scenario B, the uplift force is expressed as a function of pore pressure at the piezometer location, where pore pressure is modelled as a random variable and the upper tail of its

distribution is truncated at the alarm threshold. Although no structural modifications are made to the dam, sufficient safety can still be ensured as long as the continuously monitored pore pressure does not exceed the alarm threshold. This monitoring-based approach better reflects the actual hydraulic conditions beneath the dam and can potentially reduce unnecessary conservatism. However, at the same time, it increases sensitivity to deviations from the assumed behaviour. As noted by Spross et. al. (2014), an issue with using piezometric measurements in stability evaluations lies in ensuring that exceptional uplift loads are controlled, as measurements primarily reflect normal operating conditions and may therefore not capture such behaviour. In the proposed monitoring framework, this limitation is addressed through continuous pore pressure monitoring combined with defined alarm thresholds, where exceedance triggers predefined countermeasures.

4.2 Uncertainty considerations when defining alarm thresholds

The main advantage of measurement-based uplift evaluation is the reduction of epistemic uncertainty through site-specific observations. However, it is important to recognise which sources of uncertainty are represented in the assumed variability. A major uncertainty that should be reflected in the uplift variability is model uncertainty arising from the derivation of uplift based on measurements from a single piezometer, together with the assumption of linearity along the uplift profile. Another important component is the inherent variability, both spatially and over time. In addition, as dams operate for many decades in natural environments where conditions cannot be fully controlled, temporal variability arising from long-term deterioration processes must also be considered in the evaluation of uplift variability, and thus in the design of the monitoring system.

In practice, operational alarm thresholds should allow sufficient lead time to identify the cause of increased pore pressure and implement appropriate countermeasures. Establishing such limits therefore requires identifying processes that may increase uplift over longer time periods and estimating the rate at which they may develop. For dams equipped with drainage, a probable cause of increased uplift pressure over time is clogging of drains. As drainage significantly reduces uplift, clogging of drains may lead to a gradual increase in uplift pressure (Ruggeri 2004). The conditions for clogging are highly site dependent (da Silva 2015), and reported rates vary substantially. Swedish case studies indicate gradual deterioration corresponding to approximately 10% clogging over 30 years (Johansson et al. 2017), although more rapid clogging of up to 50% within 10 years has been documented (Farinha et al. 2005). For dams equipped with grout curtains, another possible cause of increased uplift is degradation of the grout curtain (Ruggeri 2004). This process might be driven by chemical leaching, with calcium leaching widely recognised as a durability concern (Yu and Zhang 2017). As the grout deteriorates, the seepage in existing fractures beneath the dam may increase, leading to increased uplift pressure (Yue et al. 2022). Although chemical degradation of grout curtains has not been widely studied for Swedish dams, long-term increases in uplift of approximately 40–50% have been reported as the anti-seepage function of grout curtains deteriorates (Zhang et al. 2021; Yue et al. 2022). However, both the magnitude and timescale are strongly site dependent.

Both clogging of drainage systems and degradation of grout curtains are typically slow processes, which enables the use of alarm thresholds while still allowing sufficient time to analyse the situation and implement countermeasures. Such measures, including cleaning or re-drilling drainage holes and re-grouting the grout curtain, can be operationally demanding and may also cause unexpected changes in the foundation conditions, as observed by Spross et al. (2016) during re-grouting which caused washout of fractures. However, alarm thresholds should not be applied if achieving the target reliability requires them to be set excessively low, as this would imply a high probability of interventions becoming unavoidable.

5 Conclusions

In this paper, a methodology is outlined for monitoring the stability of existing dams through piezometric measurements of pore pressure with alarm thresholds defined within a reliability-based framework. The approach demonstrates how piezometric measurements can be used to represent uplift pressure in stability evaluations when combined with a monitoring system with defined alarm thresholds. Such an approach may allow existing monoliths to fulfil safety requirements without structural measures, provided a monitoring system capable of detecting changes in uplift behaviour and alarm thresholds that allow sufficient lead time for predefined countermeasures. Further research is needed to better understand uplift variability, including identifying and quantifying the different components of uncertainty associated with uplift pressure and with how uplift pressure is modelled.

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References

da Silva, J. F. (2015) Clogging of drains and its influence on the stability of concrete dams. Proceedings of the ARMA US Rock Mechanics/Geomechanics Symposium:ARMA-2015-140.

Dunnicliff, J.(1993). Geotechnical instrumentation for monitoring field performance: John Wiley & Sons.

Farinha, F., E. Portela, C. Domingues, and L. Sousa (2005) Knowledge-based systems in civil engineering: Three case studies. Advances in engineering software 36 (11-12):729-39.

FERC (Federal Energy Regulatory Commission) (2016a) Engineering Guidelines for the Evaluation of Hydropower Projects: Chapter III Gravity Dams, Washington, DC

FERC (Federal Energy Regulatory Commission) (2016b) Risk-informed decision making (RIDM)-risk guidelines for dam safety (Interim Guidance).

Goodman, R. E., B. Amadei, and N. Sitar (1983) Uplift pressure in crack below dam. Journal of energy engineering 109 (4):207-21.

Hanna, A. W. , H. D. Plewes, R. Wong, and W. C. Seyers (1993) Investigations of high uplift pressures beneath a concrete dam. Canadian Geotechnical Journal 30 (6):974-90.

Hu, J., and F. Ma (2016) Comprehensive investigation method for sudden increases of uplift pressures beneath gravity dams: Case study. Journal of Performance of Constructed Facilities 30 (5):04016023.

ICOLD (International Commission on Large Dams) (2000) Automated dam monitoring systems: Guidelines and cae histories, Bulletin 118 Paris, France

Johansson, F., A. Krounis, and M. Westberg Wilde (2017) Igensättning av dränage under betongdammar– Orsaker, övervakning och åtgärder: Energiforskrapport 2017: 369.

Pate-Cornell, M. E., and C. P. Benito-Claudio (1987) Warning systems: Response models and optimization. Uncertainty in risk assessment, risk management, and decision making:457-68.

Pereira, R., A. L. Batista, L. C. Neves, and J. M. Casaca (2021) A priori uplift pressure model for concrete dam foundations based on piezometric monitoring data. Structure and Infrastructure Engineering 17 (11):1523-34.

Ruggeri, G. (2004) Working Group on Uplift Pressures under Concrete Dams, Final Report. ICOLD (International Commission on Large Dams), Italy

Spross, J., and F. Johansson (2017) When is the observational method in geotechnical engineering favourable? Structural safety 66:17-26.

Spross, J., F. Johansson, and S. Larsson (2014) On the use of pore pressure measurements in safety reassessments of concrete dams founded on rock. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 8 (2):117-28.

Spross, J., F. Johansson, L. K. T. Uotinen, and J. Y. Rafi (2016) Using observational method to manage safety aspects of remedial grouting of concrete dam foundations. Geotechnical and Geological Engineering 34 (5):1613-30.

Swedenergy (2020) Betongdammar [Concrete dams]. Energiföretagens riktlinjer för dammsäkerhet (RIDAS) [Swedish Hydropower Companies' Guidlines for Dam Safety]. Swedenergy, Stockholm

Westberg Wilde, M., and F. Johansson (2016) Probabilistic model code for concrete dams. Energiforsk AB, Stockholm, Sweden

Yu, Y., and Y. X. Zhang (2017) Coupling of chemical kinetics and thermodynamics for simulations of leaching of cement paste in ammonium nitrate solution. Cement and Concrete Research 95:95-107.

Yue, J., Z. Shen, L. Xu, and K. Zhang (2022) Numerical analysis the calcium leaching effect in concrete and concrete-rock interface on concrete gravity dam anti-sliding stability. Case studies in construction materials 17:e01158.

Zhang, K., L. Xu, L. Qiu, J. Tan, C. Yang, and K. Zhang (2021) Numerical analysis of concrete gravity dam seepage characteristics evolution considering the calcium leaching effect. Advances in Civil Engineering 2021 (1):9042863.