Soil slope stability of hydropower reservoirs - from geological site investigation to design of mitigation measures

La stabilité des talus de réservoirs hydroélectriques - de l'investigation géologique du site à la conception de mesures d'atténuation

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ABSTRACT: Many reservoir slopes are affected by different types of instabilities during the first impoundment, due to reservoir level fluctuations and due to earthquakes. These potential failure processes are caused by complex hydro-mechanically coupled processes, which in most cases cannot be fully assessed during the design stage due to a limited knowledge of the soil behaviour and properties. Thus, for the site selection and the design of power storage plants, especially for the risk assessment and mitigation of potentially unstable soil slopes, a systematic methodology for the selection of the appropriate stability measures is presented. Based on case studies from both engineering projects and literature, a methodological approach and a decision matrix for the design of appropriate mitigation measures depending on the failure mode and size of the potentially instable slope are proposed.

RÉSUMÉ : Un grand nombre de talus à proximité des réservoirs sont affectés par différents types d'instabilités en raison des fluctuations des niveaux de réservoir et en raison de tremblements de terre. Ces procès potentiels de défaillance sont causés par des transformations complexes hydromécaniques, qui dans la plupart des cas, ne peuvent être entièrement évalués au cours de la phase de conception en raison d'une connaissance limitée sur le comportement et des propriétés des sols. Ainsi, pour la sélection des sites et la conception des installations de stockage d'énergie, il est essentiel de tenir compte des expériences antérieures et d'appliquer ces connaissances à la conception de nouvelles installations pour créer une stratégie d'évaluation des risques et d'atténuation. Ici une méthode pour la sélection des mesures de la stabilité appropriées en fonction du mode de défaillance est fournie. Basé sur des études de projets et de la littérature une méthodologie systématique et une matrice de décision pour la conception de mesures d'atténuation appropriées en fonction du mode de défaillance et la taille de la pente potentiellement instables sont proposées.

KEYWORDS: soil slope stabilization, mitigation measures, decision matrix

1 INTRODUCTION AND FRAMEWORK

1.1 *Reservoir slope instabilities (causes, triggers)*

Concerning site selection studies for a water storage reservoir, particular focus has to be placed on the assessment of terrain stability, especially in the dam area but also along the reservoir slopes.

In general, failures are related to changes of stability parameters of natural slopes or artificial cuts. Related to reservoirs, the disturbance may be caused by water level changes (due to first impoundment and/or recurring water level fluctuations during operation) which may cause catastrophic (uncontrollable) slope failures of all sizes. According to Riemer 1995, the causes and triggers of soil displacements include, e.g.

- change of consistency due to saturation (fine soils)
- change of effective stresses (pore pressure)
- groundwater flow (steady and transient flow)
- external erosion, e.g. caused by waves
- internal erosion (suffosion, subrosion)

At the design stage of a reservoir, these processes have to be considered in order to assess the slope stability. Commonly, slope failures are only treated when they affect the serviceability (storage volume loss, operational restrictions, land use along shoreline, water quality) or failure of a reservoir and its surroundings.

1.2 *Slope stability assessment and risk management*

Extensive literature reviews of landslides and reservoirs as well as detailed case studies have been carried out by many authors (e.g. in Riemer 1995). In particular deep-seated rock slides have been monitored and investigated intensively, and monitoring results have been reported over the last decades (Leobacher and Liegler 1998, Tentschert 1998, Jäckli 1996, Watson et al. 2006, Barla et al. 2010).

Moreover, process based investigation methods and monitoring measures have been developed (Keusen 1998, Zangerl et al. 1999, Leobacher and Blauhut 2010).

The issue of slope stability, in particular for dam safety, during rapid drawdown and earthquake loading and has been studied widely (e.g. ICOLD 1980, Casagrande 1937, Sherard 1963, Alonso and Pinyol 2009). Besides the stability assessment,(e.g. according to Casagrande 1937), it is expected that engineers are able to make a statement not only on stability but also on the consequences of potential mass movements.
Following the stability assessment, a risk management plan may be produced. Whereas several research projects on landslide risk management have been undertaken (e.g. ICG 2009 and 2011), only few data concerning slope stability in the vicinity of water reservoirs are publically available..

Here, an overview of a systematic approach to assess the slope stability before and after reservoir impoundment with particular consideration of earthquake and rapid drawdown conditions and a proposal for a customized toolbox for slope stabilization in cohesive and granular soils are provided.

2 SLOPE STABILITY ASSESSMENT

A possible flowchart for the slope stability assessment is provided in Figure 1. The individual steps are described in the subchapters below.

2.1 *Site selection*

The site selection process for hydropower reservoirs is driven by the need to optimise decision criteria which are initially mainly of an economic nature,.

In the best case, several sites are shortlisted based on economic factors followed by comparisons of options and more detailed feasibility studies including detailed geological and geotechnical investigations and designs.

2.2 *Geological and hydrogeological model*

A geological and hydrogeological model may be developed using the following investigation techniques (selection):

- geological site mapping, incl. structural geological surveys;
- remote sensing and terrain analyses (e.g. optical images, LiDAR, DEMs);
- hydrogeological field surveys (mapping of springs, surface flow systems incl. discharge measurements, recharge and infiltration characteristics);
- groundwater measurements, tests and monitoring (spring parameters e.g. EC, T and discharge, stage-discharge stream gauges, groundwater elevation gauges, piezometers/hydraulic heads, tracer tests, hydrochemical and isotopic analyses, etc.);
- core drillings with in-situ measurements and tests (e.g. core SPTs, geophysical borehole logs, geotechnical and hydraulic tests, e.g. packer tests, water pressure tests, dilatometer tests) and (un)disturbed rock/soil sampling;
- geophysical surveys (surface and borehole seismics);
- slope monitoring (geodetic surveys, inclinometer measurements and others).

Based on these data, a comprehensive rock mass model may be established, which in turn constitutes the basis for the subsequent steps (see Figure 1).

2.3 *Geotechnical model and assessment of actual slope stability*

Based on the geological model (incl. results from lab and field tests), characteristic soil parameters and a geotechnical model are defined. "Characteristic" soil properties may be i) obtained from field and lab tests and/or ii) back calculated from the geological model, (taking into account the soil strata and slope inclinations). In the latter case an assumption on earthquake loads which have already been acting on the slope has to be made and included in the back analyses. When using back calculations it is assumed that the slope is in limit equilibrium. Ideally both approaches should be combined.

These calculations yield values for the assessment of the actual slope stability. However, these assessments are commonly based on geological and geotechnical models of limited accuracy due to a limited number of available results from laboratory and field tests. Therefore, the "real" soil parameters are to be verified at the latest at the stage of the first impoundment of a reservoir.

2.4 *Assessment of slope stability under changed boundary conditions*

The boundary conditions of reservoir slopes may change drastically due to impoundment and rapid drawdown

Therefore the back calculated geotechnical slope model (see above) has to be adapted to these changed boundary conditions and the slope stability has to be reassessed. From this analysis four different scenarios may be obtained (see Figure 1):

In the best case, the slope stability is not affected by the new boundary conditions at all. This is the case when the failure plane is located entirely above the shoreline.

The remaining three cases may be assessed according to i) the size and shape of the potential landslide mass and ii) the acceptance of the consequences of a failure.

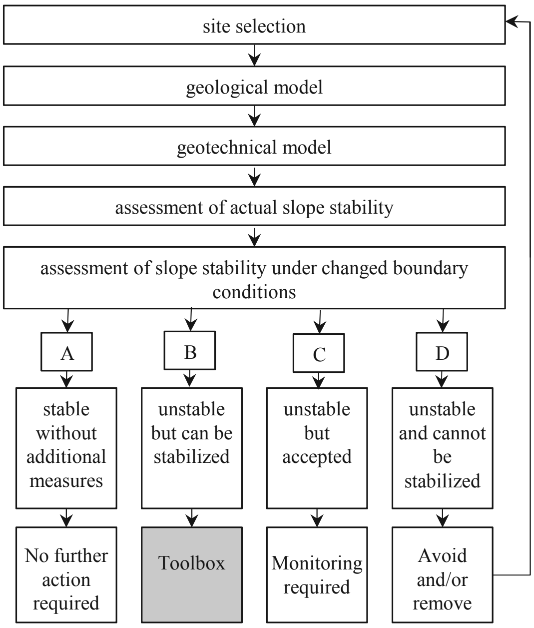

Figure 1: Flow chart for the assessment of slope stability (explanations , see text).

The decision whether a potential slope failure is acceptable depends on various criteria: If the slope stability deteriorates, proof has to be provided that the safety of the dam and its surroundings are not affected. This means that the size and the velocity of potential landslides do not cause critical tsunamis overtopping the dam.

For this proof and the risk assessment, the slope deformation behaviour has to be evaluated according to the types shown in Figure 2. While deformation types 1 and 2 are commonly unproblematic and type 3 requires a sound risk assessment, the stick-slip behaviour of type 4 landslides is much more difficult to predict. Such deformation behaviour requires intensive monitoring and a fundamental knowledge of the soil properties (Barla et al. 2010, Leobacher and Liegler 1998, Zangerl et al. 1999).

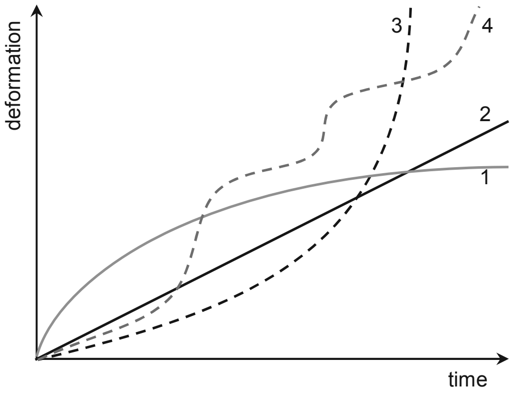

Figure 2: slope kinematics (temporal deformation types): (1) decreasing slope velocity; (2) constant velocity; (3) accelerating and failing slope; (4) episodic accelerated slope (after Keusen 1998)

Planning any mitigation measures depends on the geometry and depth of landslides. Concerning this, the classification of landslide thickness (according to BAFU 2009 and ICG 2011) is shown in Table 1.

Table 1: Landslide categories as a function of the depth of movement (acc. to BAFU, 2009 and ICG 2011).

Category	Depth of movement [m]	
	BAFU 2009	ICG 2011

Superficial	0 -2	< 0.5
Shallow		0.5 - 3
Medium	2 - 10	3 - 8
Deep	> 10	8 - 15
Very deep	> 30	> 15

Depending on the findings from the above mentioned work packages (Ch. 2.1. to 2.4) four possible slope scenarios and respective measures may be differentiated (Figure 1):

- A) stable without additional measures, no further action is required.
- B) unstable due to changed boundary conditions and cannot be stabilized with feasible measures. However, the slope instability may be avoided by flattening the slope by massive earth works.
- C) unstable due to changed boundary conditions but the consequences of the instability do not affect the serviceability of the reservoir and are therefore acceptable and do not affect the serviceability of the facility.
- D) potentially unstable due to changed boundary conditions but can be stabilized with additional stabilization measures: for this case a toolbox is presented in Table 2; depending on the geometry, of the potential slide and its failure mode, the required measures may be chosen.

3 MITIGATION MEASURES

3.1 *Superficial and shallow landslide mitigation measures*

Shallow landslide (i.e. < 3m thick, see table 1) mitigation measures aim to prevent surface erosion and to improve the drainage capacity of the uppermost meters. Appropriate measures comprise, e.g.:

- drainage trenches, to reduce the length of drainage path and hence erosion; they may be lined with geotextiles and combined with drainage tubes;

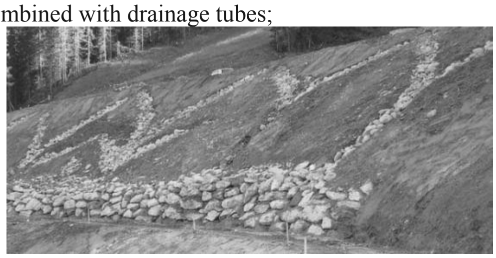

Figure 3: reservoir slope featuring drainage trenches above the storage level.

- wave protection, to prevent soil from external erosion

Figure 4: Wave protection measure (stone wall) in an impounded reservoir.

- cultivated crib walls;
- geomembranes, along with soil nailing, gabion mattresses and/or blocks as surface erosion protection, especially for fine-grained soils; nails are used primarily to stabilize the geotextile and secondarily to stabilize the soil itself;
- geomembranes, along with flat gabions, as erosion protection measure.

Protection in the vicinity of road cuts above the shoreline comprises gabion walls and soil nailing, used as artificially steepened natural slope measure.

3.2 *Medium to deep seated landslide mitigation measures*

By installing a defined grid of geotextile wrapped stone columns, the shear strength of the soil may increase and the length of the drainage path in the soil can be shortened. Both effects increase the slope stability. Also, by means of local soil substitution with material of higher shear strength and permeability, the stability and erosion protection are improved.

Supporting embankments may be used to prevent erosion and to stabilize deep seated potential slip circles. Such embankments have already been successfully applied to stabilize unstable slopes of operating hydropower facilities.

If subaquatic soil instabilities (i.e. below the reservoir water level) are accepted, which may acceptable if they do not influence the serviceability of the reservoir, but the shore above water level has to be protected, a pile wall at the height of the maximum water level may be installed as a protection measure.

3.3 *Very deep seated landslide mitigation measures*

Very deep seated (i.e. > 15 m thick, see table 1) landslides generally require cost-extensive mitigation and monitoring measures such as drainage drillings and adits (Bonzanigo et al. 2007, Zangerl et al. 2010).

4 COMBINATIONS OF MEASURES

In order to find feasible and appropriate combinations of mitigation measures, Table 2 presents a matrix of scenarios (scenarios 1 to 7).

- Scenario 1 represents possible combinations of protection measures below storage level to prevent superficial mass movements and erosion.
- Scenarios 2 to 7 combine mitigation measures against potential superficial instability with medium to deep seated mass movements. Whereas in scenario 2 flattening of the upper part of the slope reduces the driving force of a potential instability, in scenario 3, the increase of the safety level is obtained by increasing the resisting force at the toe of the slope. Note that for scenario 3 the safety against surface erosion is given when using accordingly graded fill material. In contrast, when combining measures as shown in scenario 4, measures for both failure mechanisms have to be designed individually. This may also be the case for scenario 5.
- The most drastic measure is hence the soil replacement depicted as scenario 6, whereas in scenario 7 the goal is that the safety of the slope above the impoundment level remains, without taking into consideration the stability below the measure.

Table 2: Matrix of combinations. +: appropriate measure/combination. ` inappropriate measure/combination.

1	2	3	4	5	6	7	**Scenario**	
+	ˈ	ˈ	ˈ	ˈ	ˈ	ˈ	drainage trench	**superficial instability**
+	ˈ	ˈ	ˈ	ˈ	ˈ	ˈ	wave protection	
+	+	ˈ	+	+	ˈ	ˈ	geomembranes with gabbion mattresses	
+	+	ˈ	+	+	ˈ	ˈ	geomembranes with soil nailing	
+	+	ˈ	+	+	ˈ	ˈ	cultivated protection walls	
ˈ	+	ˈ	ˈ	ˈ	ˈ	ˈ	flatten slope geometry by soil removal	**shallow to medium deep seated instability**
ˈ	ˈ	+	ˈ	+	ˈ	ˈ	flatten slope geometry by support fill	
ˈ	ˈ	ˈ	+	ˈ	ˈ	ˈ	Deep soil nailing	
ˈ	ˈ	ˈ	ˈ	+	ˈ	ˈ	soil improvement (e.g. vibro replacement)	
ˈ	ˈ	ˈ	ˈ	ˈ	+	ˈ	soil replacement	
ˈ	ˈ	ˈ	ˈ	ˈ	ˈ	+	pile wall	

5 RESIDUAL RISK ASSESSMENT

The residual risk from a potential mass movement has to be analysed independently from mitigation measures. This is due to the fact that the mitigation measures are designed for a certain defined load (e.g. design earthquake). However, remaining residual risks may comprise events larger than the design event and resulting slope instabilities. Thus, also the impacts of such instabilities on both the safety of the dam and reservoir (probability and consequences of overtopping) have to be assessed.

For this both empirical approaches (Fritz et al. 2003, Heller 2007) and numerical models (e,g, Grilli and Watts 2005) may be applied.

6 MONITORING MEASURES

Slope stability behaviour can be monitored a) pointwise, b) linear and c) areally and can be measured in-situ and/or by remote sensing methods (see Sect. 8 References). Point data can be obtained through triangulation, levelling, GPS surveys, wire extensometer, joint- or crackmeter, laser distance meter and water level gauge measurements. Line data may be obtained from inclinometer, extensometer and Trivec measurements and/or from fibre optic sensing techniques. The deformation field of a surface of a landslide can be obtained by photogrammetry, terrestrial or satellite based radar interferometry and terrestrial or airborne laser scanning. A variety of these monitoring methods has already been successfully applied to some well-documented reservoir slopes (e.g. Leobacher and Liegler 1998, Tentschert 1998, Watson 2006, Zangerl et al. 2009, 2010).

7 CONCLUSION

Assessment of slope stability of potential reservoir sites requires interdisciplinary knowhow, comprising intensive field investigations and sound determination of soil characteristics. Data thus obtained enable the assessment of slope stability (due to changed boundary conditions) and the design of appropriate mitigation measures.

For the design phase, possible scenarios of mitigation measures are described and presented in a matrix form. These measures serve as a basis during later design phases and during execution when the stabilization measures are allocated to the appropriate slopes in the reservoir according to the corresponding refined geological model and boundary conditions.

The scenarios 1 to 7 (Table 2) may be applied to different slope conditions (Figure 1: A to D), i.e. areas with acceptable slope stability, areas where near-surface stabilization measures are required, and areas with shallow to deep seated mass movements which have to be stabilized.

On the basis of available geological surface and subsurface data (field survey, geophysics, drillings) representative geological slope cross sections are established in order to illustrate, evaluate and assess the current and future slope stability in the individual regions. These geological sections and geotechnical data are used to for stability calculations.

Due to the repeated water level fluctuations, some areas may experience erosion and landslide processes (landslides, flow processes), especially in areas with large granular or cohesive soil layers. Stability studies including all load cases (including earthquakes) have to be carried out. If the safety calculation without stabilization measures returns an insufficient safety factor, measures required to achieve the required level of safety have to be determined. The goal of constructing mitigation measures is that the slopes for the mentioned load combinations (including earthquake load) remain stable.

For the monitoring of slope stability during the construction and operating phase, instrumental measurements of selected slope areas are required. These include both episodic campaigns and permanent measurements, e.g. geodetic surveys, levelling and inclinometer measurements.

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