New French Guidelines for Structural Safety of Embankment Dams in a Semi-probabilistic Format

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Abstract

Both in France and in most countries, hydraulic works (dams and levees) have remained excluded from semi-probabilistic methods and regulations and their design was, until recently, of a deterministic nature, without formal rules. In this context, the French Committee on Large Dams – FRCOLD - initiated, with a panel of experts from the French engineering industry and related government agencies, a research project to define a semi-probabilistic limit-state method for the design of embankment hydraulic works.

This paper accounts for the work done over two years, presents the more important provisions emerging from this project and describes the benefits of a limit-state approach. It is arranged according to the Eurocode format: design situations and associated load combinations, geological and geotechnical model, internal hydraulic model, limit states and corresponding conditions.

Introduction

Until now, there was no truly standard method in France for justifying the stability of embankment dams. French engineers made use of internationally recognised publications like those issued by the US Bureau of Reclamation [11], the US Army Corps of Engineers [10] or the French Committee on Large Dams [6]. Safety in these guidelines is taken into account in a deterministic manner.

The gradual involvement of Eurocodes in construction computation did not significantly help develop the principles of hydraulic work design. Indeed, although in theory nothing stands in the way of using Eurocodes for construction computation, Eurocode 0 (EN 1990) provides that, for the design of special construction works (nuclear installations, dams, etc.), other provisions than those in EN 1990 to 1999 might be necessary. Consequently, Eurocodes are not integrated computation rules for hydraulic works, and the project designer will have to seek professional guidelines for their design. In practice, it is noted that, today, none of the French engineering consulting agencies uses Eurocodes for dam design.

In this context, FRCOLD decided to draw up its own guidelines on the stability analysis of embankment dams and levees, with a clearly operational focus. This task was undertaken in 2007 and achieved beginning of 2010 by a working group from FRCOLD representing the very best of French engineering skills and national bodies involved in hydraulics engineering (see acknowledgment). This work had a double objective: to harmonise French practice and adopt a limit-state analytical format. The outcome is a set of French guidelines for the structural analysis of embankment dams and dikes [3].

Embankment Hydraulic Works in Relation to Eurocodes

General Rules for Design per Eurocodes

Although Eurocode 0 (EN 1990) tends to exclude dams from its scope, Eurocode 7 [4] indicates that the provisions in this section apply to small dams and infrastructure embankments. "Small dam" is not defined in Eurocode 7; however, so as to lay down a commonly accepted definition, the International Commission on Large Dams considers a dam as "large" when it is more than 15 m high above its foundation.

The design procedure provided by Eurocodes includes the following steps:

- Defining design situations;
- Defining limit-states to be taken into account;
- Assessing values for loads and defining load combinations;
- Assessing values for soil properties;
- Designing limit-states based on limit-state conditions.

Such steps are also included in deterministic practices pertaining to embankment hydraulic work design although they are not necessarily properly standardized in the computation notes and practices are relatively heterogeneous.

Eurocodes bring in the concept of characteristic value, which does not usually appear in deterministic computation notes for dams: the G_k characteristic value of a G load (respectively, R_k for R strength) is a cautious measurement of load intensity (of strength intensity, respectively). In Eurocodes, such cautiousness in measuring the parameters is taken into account by a 95% fractile (or 5%, depending on the positive or adverse nature) of the considered load or strength probability distribution. Using statistical methods may only be performed when data come from sufficiently homogenous identified populations or when enough feedback is available. To this end, the spatial variability of parameters on the volume of soil ruling the limit-state, the test data scattering and the statistical uncertainty related to the number of tests should all be taken into account.

In a number of fields, including hydraulic works, it is only seldom possible and relevant to resort to statistics. Cautious measurement therefore should rely on an expert assessment produced from available test results or from guideline values found in the literature. The characteristic value is then a cautious and proficient assessment of the material load or strength causing limit-states to appear.

Semi-Probabilistic Limit-State Method for Embankment Dams and Levees Developed by FRCOLD

In a conventional manner, the project team reviewed design situations, loads and values representative thereof, strengths, limit-states and limit-state conditions.

Design Situations

The Eurocode 0 advises to classify the design situations within three categories as follows: permanent, transient, accidental. On the same basis but using a slightly different terminology and formally considering how important flood-related specific situations are, we suggest the following classification for design situations:

- Normal operating situation: Normal Water Level for dams;
- Transient or unusual situations: end of construction, rapid emptying and operational basis earthquake (OBE) situations;
- Accidental situations, including: maximum credible earthquake (MCE), accidental situations related to external hazards (impact from fast gravity hazard, avalanche, etc.).

A specific category of design situation was introduced to meet the specific requirements of embankment hydraulic work design: flood situations. Those include:

- Unusual flood situation: specific to dams for flood control and to flood protection dikes. It relates to protection goals for challenges assigned to the relevant work. It typically has a 10 to 100 years return period;
- Exceptional flood situation: pertains to all types of dams and relates to floods that increase the reservoir level up to the Maximum Headwater Level (MHL). This situation return period is in the range of 100 to 1,000 years for small levees and dams and goes up to 10,000 years for large embankment dams;
- Extreme flood situation: pertains to all dams and dikes and relates to reaching a level above which the work might suffer from major damages that may quickly lead to break. We suggest that the related return period should be an order of magnitude over the exceptional flood situation.

The last category of design situations correspond to failures of elements or components directly involved in the safety of the dam such as: failure of one or more valves of a spillway, failure of an overflow spillway by partial or complete obstruction due to ice jams; disruption of the drainage system (including if a drain pump), failure of a conduit, failure of waterproofing (core, upstream face, contact between the gallery and the upstream face perimeter or diaphragm wall) etc. These failures can lead to water levels potentially worse than the previous situations. The determination of rare or accidental situations related to failures of the security features derives from the risk analysis study, which is in the French regulation mandatory for dams of classes A and B and dikes of classes A, B and C. The risk analysis studies will be used to estimate the probabilities of failure of the security features (means of drainage, flood evacuation devices, etc.) combined with the water level in the reservoir. It evaluates overall probability of occurrence attached to a scenario combining the simultaneous failure of a component and a water level. Depending on the likelihood of the situation examined, it may be considered as rare situation (probability greater than 10^{-3} to 10^{-4} per year) or as accidental (probability less than 10^{-4} per year).

Load Representative Values

Typically, loads have been classified within three categories:

- Permanent loads which are the embankment dead load, the ancillary works and equipment weight;
- Variable loads: action of water, snow, wind, road capacity;
- Seismic accidental load defined according to the design earthquake and that may be backed up with a specific assessment of the action of water.

Computation intensities for permanent loads are obtained from their characteristic value; those for variable loads of water are directly assessed in the design situation (pursuant to AN 4.1. provision in the French national appendix to Eurocode 7); finally, computation intensities for accidental loads are agreed from a unique rated value.

Strength Properties

The procedure we recommend for formalizing geotechnical data includes the following three steps.

1. The geological model for foundation intends to provide information on the foundation level, its bearing capacity, its sealing, and to assess the stability of the abutments, the risks of differential settlements and erosion of the foundation.
2. Then, the geometrical model draws up a streamlined representation of the work and foundation geometry. Most frequently, such representation consists in wisely selecting cross sections of the work.

3. The geotechnical model for foundation and embankment which comes to determining the characteristic values of geotechnical parameters. It defines a representation framework for foundation and work strength properties so as to assess as accurately as possible the behavior and security thereof in relation to the different limit-states. Creating a geotechnical model requires the following:

- To identify the failure mechanisms and their related limit-states and to combine with suitable behavior laws and limit-state models;

- To identify materials contained in the embankment and the foundations;

- To best assess, using characteristic values, the properties of materials contained in the embankment or the foundations involved in rheological laws and limit-state conditions.

Limit-States

In a conventional manner, the developed semi-probabilistic method differentiates the SLS (Serviceability Limit-States) and the ULS (Ultimate Limit-States).

SLS are associated with the serviceability of the dam and availability thereof during its working life. The main structural elements of the dam, ensuring its availability, are defined according to the following practicalities: sealing, filtration, discharge, security monitoring and environmental protection.

ULS are associated with losses of static balances or failure modes of embankment hydraulic works, summarized below in table 1:

TABLE 1: MAIN ULTIMATE LIMIT STATES

Scale	Type	ULS
Intergranular and hydrostatic forces at global scale	Shear	Overall stability - Sliding
		Seismic stability without pressure rise
		Lack of bearing capacity - punching
	Soil heave	Hydraulic uplift
Hydrodynamic forces at global scale	Static or dynamic liquefaction	Boiling
		Liquefaction
Hydrodynamic forces at local scale	Erosion	Internal erosion
		Erosion by overflowing
		Scouring

The FRCOLD guidelines for embankment dams and levees provide detailed recommendations for the following ULS:

- Overall stability – Sliding;
- Lack of bearing capacity – punching;
- Hydraulic uplift;
- Scouring.

ULS related to seismic situations will be treated in a specific document, to be issued end of year 2010. And ULS related to erosion will be treated in another document to be issued end of year 2011.

Overall stability (Sliding) Limit-State

Physical Models for Sliding Limit-State

Such limit-state may be approached through various physical models based on slices computations implementing relatively advanced assumptions. The models mainly used in standard engineering practices are the following: Fellenius, Bishop, Janbu, Morgenstern-Price. Many authors discussed these subjects, including [1] who provides an update on the various methods and [12] who goes through the Morgenstern-Price algorithm.

The slices computation methods consist in cutting the slope along an assumed sliding surface (Figure 1). The resulting shape is then cut into slices. The slice balance is studied following various inter-slice force assumptions. Lastly, some of these methods attempt to control force balance (Janbu), others abide by the balance of moments (Fellenius, Bishop), and the most comprehensive methods control both types of balances (Morgenstern-Price).

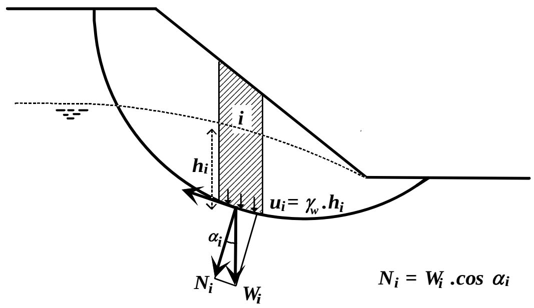

Figure 1: Physical Model for Sliding Limit-State (slices methods)

Selecting a Set of Partial Factors

The selection of partial factors was based on approach 3 of the Eurocode 7 and inflected by hydraulic work design practice which brings up security criteria differentiation depending on the design situation [10], [9]. Such partial factors are applied to characteristic values specific to material strength properties.

The limit state condition is written as an inequality which compares, first the ratio of resisting forces (or their moment) on driving forces (or their moment) of other hand the coefficient model. The mathematical expression of the limit state condition depends on the model adopted; it involves the characteristic values of strength properties weighted by their partial factor and representative values of actions corresponding to the reviewed design situation. For example, with Fellenius method (which is not the most recommended method) and an effective stress calculation, the limit state condition is written as in Equation (1):

$$\frac{\sum_i \left[\frac{c'}{\gamma_{mc'}} \cdot \frac{b}{\cos\alpha_i} + \left(\frac{W_i}{\gamma_{mw}} \cos\alpha_i - u_i \frac{b}{\cos\alpha_i} \right) \frac{\tan\varphi'}{\gamma_{m\tan\varphi'}} \right]}{\sum_i W_i \sin\alpha_i} > \gamma_d \quad (1)$$

Calibration of model factor

One major step in our work was to find a solution to the model factor calibration issue. We used the conventional approach and the calibration principle consisted in searching for the best equivalence between the semi-probabilistic method security levels and those arising from deterministic practices [7]. Therefore, the γ_d model factors calibration was performed in reference to control standard practices so as to remain as close as possible to current sizing. The agreed set of partial factors was based on the approach 3 of Eurocode 7, and inflected by hydraulic work design practice. Computations were performed for several test works. The final selection of suggested model factors included the required consensus to be reached within the industry and specific to each standardization process.

The set of partial and model factors agreed for the FRCOLD semi-probabilistic method is outlined in Table 2.

TABLE 2: SET OF PARTIAL AND MODEL FACTORS FOR OVERALL STABILITY LIMIT-STATE

Design situations	Partial factor applied to cohesion ($\gamma_{c'}$) and to the tangent of angle of friction ($\gamma_{\tan\varphi'}$)	Partial factor applied to unit weight (γ_γ) and to soil strength ($\gamma_{R;e}$)	Model factor γ_d
Normal operating	1.25	1	1.2
Transient or unusual	1.1	1	1.2
Exceptional flood (MHL)	1.1	1	1.2
Extreme flood	1	1	1.1
Accidental	1	1	1.1

The above rules are modulated in some cases:

- It is sometimes useful or necessary to conduct a more comprehensive model, for example by finite element method, as an alternative or in complement to the model for calculating the equilibrium limit. The finite element calculations can provide a vision of deformations and local safety factors. The stability criteria may remain similar to those for the limit equilibrium calculations: the calculations can be performed with the characteristic values of the criterion of plasticity and stiffness module, bearing the same partial factors applied to the soils properties and presented in Table 2.
- For the situation at the end of construction, in addition to calculating effective stresses, it is possible to conduct a calculation in terms of total stresses.
- For dams with plastic clay materials, special precautions must be taken and a specific section is devoted to those cases.

Uplift Limit-State

The hydraulic uplift limit state at the downstream toe must be considered when the dam or the dike has been built on a foundation with a geological stratification consisting in a low permeability soil layer overlying a more permeable layer of soil. This can lead to water pressure under this layer of soil that could destabilize it.
The stability criterion is expressed by comparing weight of the layer of low permeability soil and water pressure under this layer.

This is controlled by adequate drainage, which is drilling for example in the impermeable layer downstream toe (relief wells). This is the solution for dams.
Where this is not possible, the limit state condition is established by considering:

- Water pressure acting under the soil layer, u;
- The total stress given by the weight of the soil layer, σ_v.

Cohesion is neglected.

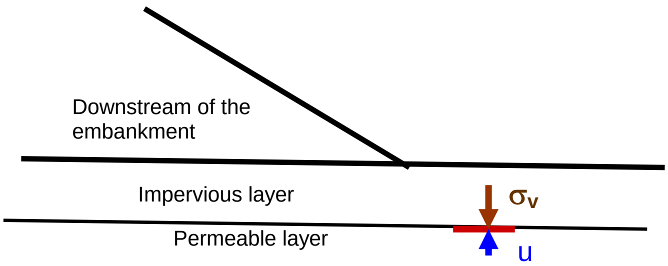

Figure 2: Physical Model for Uplift Limit-State

The limit state condition is as follows (Equation 2), with the set of partial and model factors of table 3:

$$\gamma_u \, u > \gamma_m \, \sigma_v \qquad (2)$$

TABLE 3: SET OF PARTIAL FACTORS FOT UPLIFT LIMIT-STATE

Design situations	Partial factor (γ_m) applied to weight of soil	Partial factor (γ_u) applied to water pressure
Normal operating	0.9	1.2
Transient or unusual	0.9	1.2
Exceptional flood (MHL)	0.9	1.2
Extreme flood	1	1.1
Accidental	1	1.1

Bearing Capacity of the Foundation

The concept of bearing capacity of the foundation refers to a criterion of shear failure of the foundation for punching failures. These are failures of the foundation soil characterized by the fact that the embankment collapsed while undergoing traction. The failure of the foundation is general since the entire width of the embankment is concerned. The failure pattern of the foundation soil is similar to that which occurs under a shallow foundation and can therefore be studied as such.

The worst case is generally the end of construction (short term situation). The stability check should therefore assume the embankment being built instantly, without dissipation of pore pressures in the foundation. Only new dams or projects of heightening of ancient dams are concerned.

The vertical stress q under an embankment of height H and weight density γ can be approximated by:

$$q = \gamma H \qquad (3)$$

Mandel & Salençon have proposed a solution in which the limit pressure on a soil with a cohesion c_u can be written:

$$q_{max} = c_u N_c \qquad (4)$$

with Nc: coefficient function of B/D, where B is the average width of the embankment at half height and D the thickness of compressible foundation. Nc is determined from charts but can be approximated by 4 + 0.5 B/D.

The limit-state condition can be expressed by Equation 5, with the set of partial factors of table 4. The value of 1.4 for γ_m is the value recommended for c_u in Eurocode 7 and the value of 1.2 for model factor is consistent with the value adopted for overall stability limit-state in case of transient situations.

$$q_{max}/ \gamma_m > \gamma_d q \qquad (5)$$

TABLE 4: SET OF PARTIAL FACTORS FOT BEARING CAPACITY OF FOUNDATION

Design situations	Partial factor (γ_m) applied to undrained cohesion	Model factor γ_d
Transient or unusual	1.4	1.2

Conclusion

This paper accounts for the work done as part of an FRCOLD project intended to develop a semi-probabilistic method for designing embankment hydraulic work stability. The resulting outputs, to be released in 2010 with the support of the FRCOLD, are of various kinds.

Developing a semi-probabilistic method requires accurately and formally structured designs, which accounts for a scientific challenge in itself. The implemented procedure successively discussed: loads, strengths, design situations and load combinations, limit-states and conditions thereof. The Eurocode format proved well-fitted to these works after a number of adjustments. On that account, a specific category of design situations – flood situations – was put forward. Moreover, we suggest that variable actions of water should be directly assessed in the studied design situation. Finally, there are mostly not enough available data to enable any statistical appraisal of characteristic values for strength properties, which is therefore performed through an expert assessment considering simple statistical computations, identification tests, literature data and feedback on similar materials.

One major step in this work was to find a solution to the model factor calibration issue. We used the conventional approach and the calibration principle consisted in searching for the best equivalence between the semi-probabilistic method security levels and those arising from deterministic practices. Therefore, the γ_d model factors calibration was performed in reference to control standard practices so as to remain as close as possible to current sizings. The agreed set of partial factors was based on the approach 3 of Eurocode 7, and inflected by hydraulic work design practice. Computations were performed for several test works. The final selection of suggested model factors included the required consensus to be reached within the industry and specific to each standardization process.

The suggested application allows us to bring interesting findings into general use, which we observed on the various applications carried out during calibration work. The first application pertains to comparing the deterministic practice with the FRCOLD semi-probabilistic method. It shows similar security levels between both methods, which makes sense considering the FRCOLD semi-probabilistic method calibration against the deterministic practice.

The second application relates to comparing the Eurocode 7 with the FRCOLD semi-probabilistic method. It appears that the approach 2 of Eurocode 7 may not be used directly for embankment hydraulic works considering the significant discrepancies in security levels against building industry practices. This conclusion may also be extended to designing normal water level situations through the approach 3 of Eurocode 7.

Ongoing work

As pointed out previously, ultimate limit states related to seismic situations will be treated in a specific document, to be issued end of year 2010, with a consistent methodology. And ULS related to erosion will be treated in another document to be issued end of year 2011, as a deliverable of a national research project on internal erosion (ERINOH project).

All those documents will form, in a near future, a global and complete framework for justification of dams and dykes of any types in the French context, and also with possible applications in other countries.

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