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# Approach to Estimate the Probability That Internal Erosion Will Initiate a Breach through an Embankment Applied to Levees with an Important Linear and Heterogeneous Facies

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**Abstract:**Internal erosion in embankments and their foundations is one of the maincause of levee failures. Unfortunately, this potential failure mode cannot be easily analyzed using numerical equations or models and the associated risk is difficult to quantify. This issue was studied within the hazard studies of the Drac river levees system in Grenoble city in France, maintained by the SYMBHI (Syndicat Mixte des Bassins Hydrauliques de l'Isère) and EDF (Electricité de France) as part of the new French "levees" regulation of 2015. To evaluate the probability of failure of the levees systemdue to internal erosion mechanisms, a probabilistic model is developed based on an empirical approach combining a back-analysis of levees behaviour duringthe impoundment of part of the levees system and the probability assessment proposed by Vick (2002). This approach allows the definition of a hydraulic gradient used in the assessment of the probability of failure. The need for such method was motivated by the important levee linear to be studied (about 36 km) and the heterogeneous facies of the levees system due to the successive construction stages and the heterogeneities of the foundation materials. Indeed, this heterogeneity makes the deterministic approach illusory. The defined approach is applied to the whole embankment system in order to identify, for a given flooding scenario, critical profiles where the risk of internal erosion could be significant. A detailed analysis of the secritical profiles is then carried out in order to refine the probability of failure due to internal erosion.

Keywords: internal erosion; levee; failure; risk; probability; embankment.

## 1 Introduction and context of the study

The Drac river levees system, maintained by the SYMBHI (Syndicat Mixte des Bassins Hydrauliques de l'Isère) and EDF (Electricité de France), iscomposed of about 36 kilometers of embankments (Figure 1), a large part of which is located in the city of Grenoble (France). The protected area by the levees system covers an area of 53 km², where 580 000 people live.

**Figure1.**Embankment along the Drac River

The levees along both the Drac and Isère rivers are historical embankments that have been built in many successive phases since the Middle Age, mainly using locally available alluvial materials. The embankments have progressively evolved with the urban development of the city of Grenoble and today present a great variety of profiles and composition.

In collaboration with SYMBHI (the levees system manager) and ISL (project management assistant), ARTELIA carried out ahazard study for this levees system, in accordance with the French levees regulation updated in2015 and later on in 2019.The purpose of the hazard study is to present and justify the expected performance of the levees system in all circumstances, based on a risk analysis that relies on the collection, management and analyses of all relevant information and data.One of the steps in the development of hazard studies is to carry out a functional analysis of the performance of the levees system with respect to its various failure modes. This analysis must allow, for the different failure scenarios considered, to establish the probability of failure according to the flood level.

Four main mechanisms can potentially lead to an embankment failure and water entering in the flood protected area: external erosion, overflow, internal erosion and sliding. For the hazard study, the probability of water entering the flooded protected area is determined for each mechanism to assess the levees safety flood level and hazard flood level. The safety level and hazard level are defined by the French regulation as follows: the levee safety flood level and the hazard flood level are associated to a probability of failure of 5 % and 50% respectively for all the mechanism identified on a selected embankment section.Safety and hazard levels determined by the hazard study give the associated return flood periods.Among the four failure modes considered, internal erosion is a key failure mechanism.

The present technical paper describes the methodology specifically developed for this project to evaluate the probability of failure due to internal erosion mechanisms.

## 2 Geotechnical context

Available geotechnical data were analyzed along the whole length of the project, in order to describe the general context of the different families of horizons encountered in and below the embankments. Alluvial materials from the river bed, composed of sand, gravels and locally silty deposits were encountered in various proportions within the embankments and their foundation, sometimes interlayered. As expected, the geotechnical context of the Drac river levees was proven to be particularly complex due to the significant length of the levees system (about 36 kms), resulting in highly variable ground conditions but also in various embankment types and geometries.

## 3 Internal erosion hazard

The type of internal erosion mechanism (backward erosion piping, contact erosion, suffusion or concentrated leak erosion) that can develop is primarily depending on the soil profile and flood duration.In order to accurately characterize the internal erosion mechanisms that can develop, data such as the grain size distribution, the permeability or the resistance to erosion (as characterized by a Hole Erosion Tests) of both the foundation and the embankment fill are necessary.

In the case of the Drac river levees, the flood duration (around a day) is insufficient for the development of suffusion or contact erosion. Based on the type of materials, the embankment geometry and observed disorders (transversal and longitudinal pipes, tree vegetation, burrow, etc.), the most probable failure modes are backward erosion and concentrated leak erosion. However, given the highly variable ground conditions, the process of identifying the most likely mode of erosion-led failure is very difficult.Even with a significant number of investigation points to better characterize the ground conditions, there is still the risk of missing critical zones from an internal erosion point of view.

This was the basis for developing a specific empirical methodology to assess the probability of occurrence of a given internal erosion mechanism. The proposed methodology is therefore an expert approach which combines the back-analysis of the levees behaviour during the impoundment of a part of the levees system and the probability assessment proposed by Vick (2002).

## 4 Proposed methodology

The proposed methodology is an expertapproach to assess the probability of failure of a given internal erosion mechanism for any embankment's profile along the Drac levees system. The site specific proposed methodology includes the following steps:

a/ back-analysis of the embankments behavior during a documented event to identify critical zones and calculate the associated hydraulic gradient

b/ relate the probability of failure to the site specific hydraulic gradient value using the observational approach proposed by Vick 2002

c/ calibrate a normal distribution function for the probability of failure due to internal erosion

### 4.1 Case history: St Egrève dam impoundment impact on levees behavior

The Saint Egrève dam is part of the Drac levees system. During the staged impoundment of the Saint Egrève dam in 1990 / 1991, a 5 km long section of the levees system, located directly upstream of the dam, became a permanent water loaded structure.During the staged impoundment, the water loaded embankments were regularly monitored and disorders (were observed) were well documented. The main observations were as follows:

- Numerous leakages ;
- Progressive clogging of the leakages by the fines in suspension in the river.

In the end, despite the impoundment duration (up to several months compared to flood events lasting about a day), and despite the leakages observed, no breachrelated to internal erosion was observed.

Based on these observations, two critical profiles were selectedto evaluate typical hydraulic gradient values below which internal erosion mechanisms do not develop. These zones were subject to leakages for several months without structural damage. The calculated mean hydraulic gradient is 0.18 ± 0.02 (ranging from 0.16 to 0.20).

### 4.2 Estimation of the probability of failuredue to internal erosion of the Drac levees system

The estimationof the probability of failure is based on the empirical approach suggested by Vick (2002)and presented in Table 1. The Vick's approach is adapted fromthe United States Bureau of Reclamation (USBR).

**Table 1.**SuggestedVick's probability (2002)

| Verbal description | Probability suggested by Vick (2002) |
|---|---|
| The known physical conditions and/or processes, which can be described and qualified with full confidence, justify the non-occurrence of the phenomenon | 0.01 |
| Some confidence in the probability of non-occurrence but the reverse possibility cannot be ruled out | 0.10 |
| No reason to believe that one outcome is more or less likely than the other | 0.5 |
| Some confidence in the probability of occurrence but the reverse possibility cannot be ruled out | 0.9 |

During the impoundment of the St-Egrève dam, the embankments were water loaded with a hydraulic gradient "i" estimated in the order of 0.18 ± 0.02 (between 0.16 and 0.20).Using Vick's terminology, for a hydraulic gradient i of 0.18, one can have "some confidence in the probability of non-occurrence [of an internal erosion breach] but the reverse possibility cannot be ruled out". Vick suggests that this case (gradient of 0.18) should have a ten percent probability.

We note that internal erosion is a phenomenon with a strong threshold effect. Therefore we consider that a ten percent increase in the maximum gradient calculated during the impoundment(i.e a hydraulic gradient of 0.20) leads to an increase of one probability class (i.e. failure probability of fifty percent corresponding to a hydraulic gradient of 0.22). A normal probability distribution is then proposed to match the two previous conditions with the following parameters: expectation of 0.22 and standard deviation of 0.031. The distribution function is presented in Figure 2.

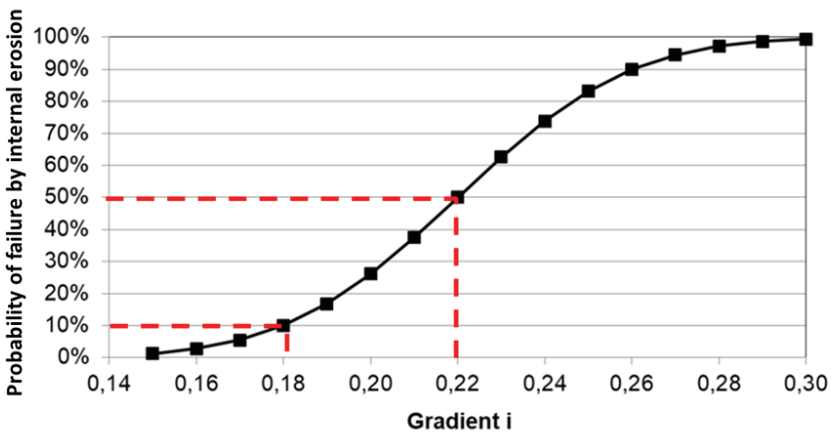


**Figure2.**Normal distribution function of the probability of failure due to internal erosion as a function of thehydraulic gradient.

The Table 2 shows the tabulated values.

**Table2.**Normal distribution functionof the probability of failure due to internal erosion.

| Gradient | 0,15 | 0,16 | 0,17 | **0,18** | 0,19 | 0,20 | 0,21 | **0,22** | 0,23 | 0,24 | 0,25 | 0,26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Probability | 1% | 3% | 5% | **10%** | 17% | 26% | 37% | **50%** | 63% | 74% | 83% | 90% |

Therefore, the approach shows that the 5% limit defined in French regulation is reached for a hydraulic gradient of 0.17 and the 50 % limit defined in French regulation is reached for a hydraulic gradient of 0.22.

## 5 Application to the Drac levees system

The "global" geometric hydraulic gradients were calculated for the representative profiles of the entire levee system for different flood events (return period of fifty years: Q50, a hundred years: Q100 and two hundred years: Q200).Figure 3 illustrates the method for the calculation of the hydraulic gradient“i”.

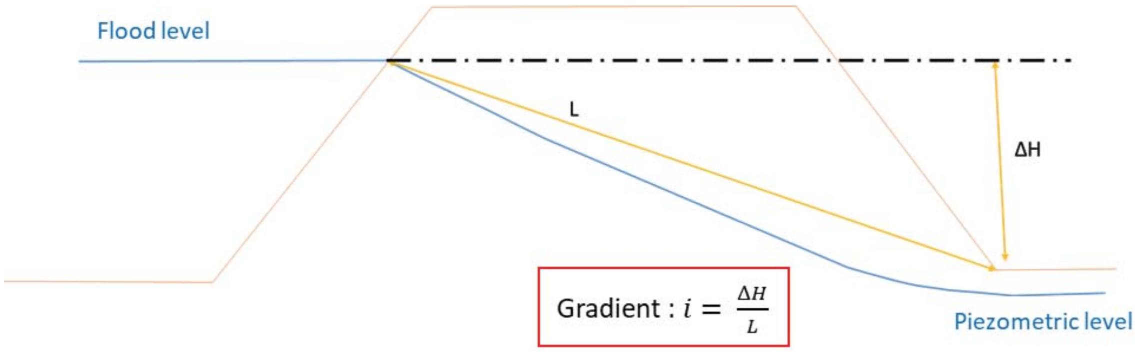


**Figure 3.** Geometric hydraulic gradient calculation method.

Thus, using the site specific distribution function presented in Figure 2, all the critical embankment profiles, for which the risk of internal erosion could be significant, i.e. the profiles for which the hydraulic gradient is higher than 0.17 (or profiles with a probability of failure greater than 5% as defined in the French regulation) were identified for the three different flood events. A detailed analysis of the risk of internal erosion was then undertakenfor each of the critical profiles that were identified, taking into account the context of the embankment, i.e. the presence of favorable or unfavorable elements which could respectively lead to lower or increase the probability of failure, such as:

- the presence of masonry riprap;
- the presence of vegetation,
- the presence of disorders identified during technical inspections of the levees (burrows, etc.),
- the presence of buried structures and/or pipe networks within the embankment or its foundation.

The final estimation of the probability of failure due to internal erosion is adjusted as follows:

- re-calculatingthe hydraulic gradient by adjustingthe length of the flow paths when a riprap layer or a stone facing in good conditionis present (see Figure 4);
- degrading the probability of failure by a flat rate of thirty percent when unfavorable contextual elements have been observed on the dikes (tree stumps, burrows, etc.).

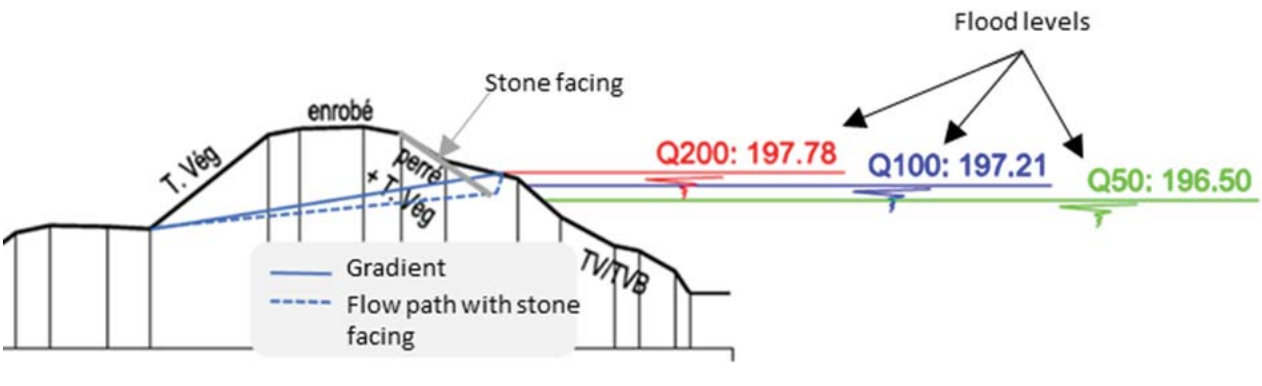


**Figure4.** Illustration of how the presence of riprap or stone facing is taken into account in the calculation of the geometric hydraulic gradient.

The results of the risk analysis allowed us to determine for the different profiles and flood events:

● Flood events for which the probability of failure due to internal erosion is equal to or less than 5% (below the safety level).

● Flood events for which the probability of failure due to internal erosion is between 5 % and 50 % (above the safety level but below the hazard level).

● Flood events for which the probability of failure by internal erosion is higher than 50% (higher than the hazard level).

The probabilities of failure obtained for the internal erosion are then combined with all the others failure modes such as overtopping, external erosion and slope stability failure, that can occurs in the embankment system.The safety flood level corresponding to a breach probability of 5% and the danger flood level corresponding to a breach probability of 50% are thus defined.

## 6 Conclusions

The analysis of the internal erosion risk is particularly challenging for a large linear of levees, with variable profiles and very heterogeneous composition. Given the significant uncertainties, the application of conventional criteria (such as Lane, Seillmeijer, etc.) did not prove to be suitable for the project with the risk of missing critical zones from an internal erosion point of view.

For the Drac levees systems, the most probable modes of failure due to internal erosion,considering the flood event duration, the nature of materials and the dyke geometry, are backward erosion and concentrated leak erosion.

To evaluate the probability of failure due to internal erosion, the proposed“expert”approach consistsfirstly in studying the behavior of the embankments upstream the St Egrève’s dam during dam impoundment to evaluate the critical hydraulic gradient from which some leakage were observed without failure. Then, it was proposed to use the method proposed by Vick (2002) to associate a probability of failure to the hydraulic gradients issued from the St Egrève’s dam impoundment back-analysis.

The method allowed to identify all the profiles that are potentially critical with regard to the risk of internal erosion.The detailed risk assessment was then concentrated on the identified critical profiles only. Without this first screening, such a detailed risk assessment would not have been conceivable given the length of the levees system.

However, the method must be applied with caution, bearing in mind the following limits of its application:

● It is a method allowing to highlight critical sectors, but a refined and expert analysis of these sectors must be systematically applied to the sectors identified in order to refine the probabilities of rupture given by the gradient curve;

● This gradient approach method was developed for this embankment system. Indeed, the presence of a well-documented rex of permanent water loading of a part of the dyke system, has made it possible to calibrate a rupture probability curve as a function of the gradient. The generalization of this calibration to other containment sectors is therefore not valid;

Finally, the proposed method,developed in collaboration with SYMBHI and ISL,remains fundamentally based on an "expert assessment". The method allows to associate, from observations of the actual behavior of the embankments, a probability of failure due to internal erosion, which is usually difficult to quantify.

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