Physical and numerical modeling of internal erosion in earth hydraulic structures

Key words: suffusion; dikes; physical model; FEM; mixture theory; filtration; energy-based approach

Context

France has a significant inventory of hydraulic structures, including nearly 9.000 kilometers of flood protection dikes, 8.000 kilometers of navigation canal dikes and 1.000 kilometers of hydroelectric canals. The number of small embankment dams is in tens of thousands, while the count of large dams is around 600. An important aspect of this French asset is its age: for example, the majority of dikes are over a century old. The maintenance of this extensive and ancient heritage requires costly upkeep. Moreover, national-scale (Fry et al., 2015) and global-scale (Foster et al., 2000) statistical studies show that only 5% of failures experienced by embankment dikes are due to slope instability, a process well accounted for by risk management tools for such structures. However, 95% of these failures are generated by overtopping and internal erosion phenomena, which are not adequately modeled. This observation highlights the need for scientific progress on soil internal erosion. Risk management concerning internal erosion is particularly challenging because instability can occur even in the absence of submersion of the structure, and it can occur through four distinct mechanisms: backward erosion, piping erosion, suffusion and contact erosion. Especially in the case of suffusion, its development involves coupling between hydrodynamic solicitation and the hydromechanical behavior of soils. This coupling explains the complexity of characterizing the soil susceptibility towards internal erosion and its consequences on mechanical behavior. It is also worth noting that the consequences of climate change on continental hydrology will lead to increased solicitations on these structures, necessitating enhanced surveillance and maintenance.

Approach

Research conducted at the GeM Institute on suffusion has already led to: (i) the development of experimental devices for characterizing the susceptibility to internal soil erosion (Rochim et al., 2017; Marot et al., 2020; Marot et al., 2024), (ii) the development of an interpretation method (Marot et al., 2016), (iii) the identification of predominant parameters and intrinsic quantities (Kodieh et al., 2020; Gelet et Marot, 2022), and finally (iv) the numerical modeling of suffusion (Gelet et al., 2021). The continuation of this work requires the production of experimental results dedicated to the validation of the numerical model, considering different spatial and temporal scales. With this objective in mind, three physical models of different sizes are considered in the long term and in collaboration with various scientific partners: (a) at a small-scale (base length: 1 m, height: 0.45 m and width: 0.15 m), (b) at the intermediate scale (base length around 5.5m, height around 1m and width around 1m), and (c) at the large scale (base length around 30 m, height around 3.5 m and width around 6 m). The confrontation of the obtained results will allow us to study the possible scale effect and to extrapolate these results to the scale of real structures.

The present study will focus on the small-scale physical model, which will be meticulously instrumented to allow for a comparison between experimental and numerical results. We aim, in particular, to measure the effluent flow rate, the erosion rate of eroded particles, the interstitial pressures at different points in the dike, and the three-dimensional deformation of the slope and the crest (photogrammetry, Li et al., 2022 & 2023a; Gelet et al., 2021; Horikoshi et Takahashi, 2015). Postsuffusion density and granulometric measurements will also be conducted to assess the new spatial distribution of fines induced by erosion (Li et al., 2023b).

The experimental tests required for characterizing the soils with respect to suffusion will be realized by using the already developed experimental setups. In light of our recent findings (Oli et al., 2024), it seems that the mechanical state has little influence on the kinetics of suffusion. Nevertheless, the influence of the flow direction, with respect to gravity, appears to be less negligible (Marot et al., 2020). Recall that in a structure as well as in a physical model, the flow is predominantly horizontal or sub-horizontal. Thus, a comparative study on the effect of the flow direction on erosion parameters will complement this experimental part.

The hydromechanical model currently used to simulate suffusion is based on the mixture theory and a constitutive law based on the energy approach (Gelet et al., 2021). This constitutive law has qualitatively represented, on a representative elementary volume (REV), the evolution of the eroded mass rate for different soils (Gelet and Marot, 2022) and different hydraulic loading paths (Kodieh et al., 2021). However, the model needs to be improved by accounting for the possible filtration of the eroded grains between two REVs. This enhancement requires the introduction of filtration rules in the continuation of the work initiated by Locke et al. (2001) and Reboul et al. (2010).

Expected outcomes

The expected outcomes of the project are:

- A study of the effect of flow direction on suffusion parameters
- The development of an instrumented physical model of dike and the realization of several experimental tests
- The implementation of inter-element filtration rules in the existing finite element code
- The numerical simulations of the experimental tests

Required skills

- Skills in experimental geomechanics are required
- Skills in the physical, mechanical and hydraulic characterization of soils are highly recommended
- Skills in FORTRAN or C++ coding are recommended

Complementary information & contacts

This PhD will be located on the Heinlex campus in Saint-Nazaire.
A Curriculum Vitae, a motivation letter and the transcript of records (M1, M2) must be sent, in order to be considered for candidature, by e-mail to:

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