International PhD Thesis: Nantes Université & ShanDong University

Microstructural and erosion behaviour studies of vegetation-treated soils of hydraulic earth structures for power generation systems

Keywords: erosion, overtopping, suffusion, root-soil interaction, x-ray tomography, wetting-drying cycles

Background

Hydraulic earth structures such as dikes and dams are critical infrastructures in modern power generation systems. They contribute to 1416 gigawatts (GW) installed capacity of hydropower, accounting for over 15% of the world's electricity production and 47% of the renewable power generation (IEA, 2024; IHA, 2024). The hydraulic earth structures also provide cooling water for approximately 60% of word's nuclear power plants (WNA, 2021), in addition to ensuring transportation, agricultural irrigation and flood protection. These structures are vital for the global energy transition that balance intermittent sources like wind and solar.

An important issue of world's hydraulic earth structures is aging and related increasing maintenance cost. Many dams have reached or are approaching the lower limit of their expected lifespan, typically 50 years. Statistical studies at both the national (Fry et al., 2015) and global levels (Foster et al., 2000) have shown that approximately 95% of dam failures are attributed to two primary mechanisms: overtopping (depending on the structures, responsible for 20 to 37% of instabilities) and internal erosion (depending on the structure, responsible for 30 to 74% of instabilities); while only 4% are related to sliding. Fell and Fry (2013) distinguished four forms of internal erosion: concentrated leak erosion, backward erosion, contact erosion and suffusion. Among the four dominant mechanisms of internal erosion, suffusion appears as one of the most complex. Indeed, suffusion selectively mobilizes the fine particles of a soil that can be dislodged by the interstitial infiltration flow and transported through the voids formed by the coarser particles. Therefore, the understanding of both overtopping and internal erosion processes appears as a major challenge to optimize the maintenance of earth structures and to guarantee their integrity.

With the current irreversible trend of global warming, these old hydraulic earth structures are expected to suffer from the intensification of hydro-mechanical processes. Indeed, the probable consequences of climate change on the continental hydrology will bring more sever hydraulic loadings on these structures with the necessity of more surveillance and maintenance. Even in the most favourable scenarios, the servicing conditions of global hydraulic earth structure will worsen, exposing the related power generation systems under higher risks. As a consequence, the costs of maintenance and repair are rising, with studies indicating that these costs can be 10 to 30 times higher than those of dam removal (Perera et al., 2021). These observations highlight the urgent need for scientific progress on soil erosion and engineering implementation of effective mitigation strategies to improve the stability and longevity of hydraulic earth structures. Among these strategies, two are worth citing: lime treatment and vegetation coverage. The current study focuses on the later since it benefits from a smaller environmental impact and is also cheaper.

Vegetation, through the development of root networks, can anchor soil particles, enhancing soil cohesion and shear strength, while the above-ground biomass reduces the impact of rainfall, surface runoff and evaporation. To date, the effect of vegetation-treated on the erosion behaviour has been little studied. Lann et al. (2024) showed that the erosion rates are smaller on vegetated slopes than on bare slopes due to the root reinforcement and canopy interception, in agreement with Li et al. (2022) who concluded that the overtopping erosion for vegetated slopes is also lower, protecting the slopes especially in flood-prone areas from destabilising. However, as roots grow, they produce gaps at the soil-root interface and thus increase soil permeability. They can also create macro-pores within the soil, which potentially favour internal erosion processes and particularly suffusion. How these deterioration mechanisms compete with the soil reinforcement and how the hydraulic earth structures behave due to the presence of vegetation remains largely unknown (Vergani et al., 2021; Zhang et al., 2019., Zanetti et al., 2015). In addition, the effectiveness of vegetation depends on plant species, root structure and environmental conditions; so that, tailored approaches for different geographical and climatic contexts are needed.

Experimental approach

With the aim of characterising the behaviour of undisturbed samples with respect to overtopping (external erosion) and suffusion (internal erosion), two specific devices and interpretation methodologies have already been developed at the GeM institute of Nantes University. These devices will be used to compare the erosion behaviours of vegetation-treated soils against untreated soils. Also, vegetation-treated samples will be subjected to drying-imbibition cycles to mimic environmental conditions encountered during a drought. The root networks will be further characterized by X-ray microtomography to complete the study.

<u>1) Device and interpretation methodologies dedicated to overtopping</u>
The erosion behaviour of soil with respect to overtopping can be characterised using the jet erosion test (JET), which is designed to apply a submerged water jet on the face of a soil specimen. It consists of an adjustable head tank, a jet tube with a nozzle, a point gage and a jet submerged tank which contains the specimen. The point gage is adjusted to close off the nozzle and also to measure the depth of scour below the nozzle at increasing time intervals. Two existing interpretative methods for JET apparatus can be distinguished. The first method, which originates from Hanson and Simon (2001) is based on the increase in scour over time. The Hanson and Simon system recognizes five categories from very resistant to very erodible materials. However, as a same scour depth can correspond to very different eroded volumes, the GeM device also allows the loss of soil mass over time to be measured. Thanks to this eroded mass measurement, a second interpretative method was proposed by Marot et al. (2011). This method is based on the energy dissipation between the fluid and the soil, on one hand, and the cumulative eroded dry mass, on the other hand. From this energy-based approach, Marot et al. (2011) proposed six categories of soil erodibility: from highly erodible to highly resistant.

<u>2) Device and interpretation methodologies dedicated to suffusion</u>
Suffusion is indeed the result of the combination of three processes: dislodgement of fine particles, that are next transported by the flow, upon which some of these fluidized fine particles filtered by the soil's skeleton. These processes depend on the soil's stress state and on the hydraulic gradient path. Thus, to control with accuracy these parameters and to ensure the repeatability of suffusion tests, a triaxial permeameter was developed (Marot et al., 2024). This apparatus is designed to test specimens under a vertical downward flow in hydraulic gradient controlled condition while controlling the confining pressure and the stress deviator. The funnel shape base pedestal of the cell is connected to a collecting system to catch the eroded particles during testing. Marot et al. (2016) suggested to determine the cumulative expended energy and the cumulative loss dry mass at the end of the suffusion process (i.e., when the hydraulic conductivity stabilizes and the erosion rate decreases). From

this approach, six categories of suffusion susceptibility from highly erodible to highly resistant are defined.

3) Vegetation-treated tests

Using these two devices, several parametric studies were carried out to characterise the influence of different physical parameters on both erosion processes (Regazzoni and Marot, 2011; Le et al., 2018). However, all the tests were carried out on bare soil. The aim of the proposed study is therefore to characterise the erosion behaviour of samples composed by vegetation-treated soils. Clayed sand samples will be planted with two plant species (hybrid poplar and tamarisk), which are characterized by very different root development (Zanetti et al., 2015). For each specie, as the root network develops, pairs of samples will be tested. The erosion behaviour of the first sample will be tested using the jet erosion test, while a section of the second sample will be cut out and tested using the triaxial permeameter. For both samples, the root network is expected to fully develop in the whole volume, so as to guarantee representative elementary volumes.

4) Wetting-drying cycles

The development of the root network is highly dependent on the wetting-drying cycles that the soil and plants undergo. With the objective to study the influence of wetting-drying cycles, some samples will be exposed to these cycles with suction controlled from several kPa to several hundreds of MPa, refer to Li et al. (2018). Moreover, we will also study both healthy root networks and decayed ones, to challenge to limits of this vegetablization solution in dryness conditions.

5) Microstructural characterisation by X-ray microtomography

In ShanDong University, by using X-ray microtomography, Wang et al. (2024) investigated the root–soil interaction at a microscale level and examined the evolution of three-dimensional root parameters throughout the growth process. As part of this PhD-thesis, this process will be used to investigate healthy root networks and decayed ones, which are expected to create a number of preferential flow paths. This microstructural characterisation will help us to better understand the erosion behaviours and especially the influence of root networks, which might improve or worsen the soil's resistance towards erosion.

Time Plan:

Period 1: September 2025 - December 2025, in Nantes University

Literature review, familiarization with erosion processes, with JET and suffusion benches, with suction control, with root development of two plant species (hybrid poplar and tamarisk) and with tomography

Period 2: January 2026 - February 2027, in Nantes University

1. Designing the test program and placing the samples according to the different curing conditions required.
2. Application of wetting-drying cycles for several samples
3. Performing JET and suffusion tests on samples composed by: bare soil on one hand, vegetation-treated soils with a growing root network on the other hand.
4. Processing data and publish one Science Citation Indexed journal paper.

Period 3: March 2027 - February 2028, in ShanDong University

1. Placing the samples according to the different curing conditions required.

2. Application of wetting-drying cycles for several samples
3. Investigation the root–soil interaction at a microscale level according to sample curing conditions.

Period 4: March 2028 - August 2028, in ShanDong University

1. Summarize the research work during the doctoral period
2. Processing data and publish one Science Citation Indexed journal paper.
3. Finalize the thesis report and complete the graduation defence.

Skills required

- Expertise in experimental geomechanics is required
- Skills in physical, mechanical and hydraulic characterisations of soils are highly recommended.
- Ability to work in a team
- Ability to speak English

Additional information & Contacts

The thesis will be carried out:

- At Nantes University (on the Heinlex site in Saint-Nazaire, France) from September 2025 to February 2027 and
- At ShanDong University (China) from March 2027 to August 2028.

1st contact deadline: 17/04/2025

A Curriculum Vitae, covering letter and transcript of grades (M1, M2) should be sent by e-mail for all applications to:

Dr. ZhongSen LI: zhongsen.Li@univ-nantes.fr
Dr. Rachel GELET: rachel.gelet@univ-nantes.fr
Prof. Didier MAROT: didier.marot@univ-nantes.fr
Prof. Ji-Peng Wang: ji-peng.wang@sdu.edu.cn

1st hiring committee (Supervisors): 22/04/2025 or 23/04/2025

Upon your application, you may be contacted for a 20 to 30 minutes audition.
Details of this audition will be in the email.

Official application: before the 28/04/2025

All candidates have to apply on the Amethis portal
https://amethis.doctorat.org/amethis-client/prd/consulter/offre/1531

2nd hiring committee (Doctoral school): May 2025

Desired start date: 01/09/2025

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