Introduction:

Erosion is the gradual wearing away of solid matter due to natural agents such as wind, water, or ice. This can lead to the degradation of various types of soils and the generation of solid transport. Understanding and measuring the amount of soil erosion is crucial in many environmental and engineering areas. The phenomenon has been studied for years in fields like meteorology, seabed degradation, coastline erosion, and the morphological evolution of rivers and estuaries. In civil engineering, erosion can have a significant impact on the sustainability and safety of structures like dams, bridges, and offshore structures, and can interfere with human activities (Bollaert, 2003), (Bonelli S. , 2012) *and* (Bonelli, 2013). Soil erosion also has broader ecological consequences such as spreading heavy metals or radioactive particles through sediment transport and affecting the global carbon cycle (Van Oost, 2007) in agricultural soils.

In France, there are around ten thousand dams, with about 500 classified as large, as well as several thousand kilometers of hydraulic structures such as river dikes or waterway embankments. Their main purpose is to retain water over time, but they are also used to produce hydro-electrical power and for irrigation systems during the dry season. Many of those hydraulic structures are more than half a century old, which makes them particularly susceptible to failure (Foster, 2000). More than 70 incidents have been reported by the International Commission On the Large Dams (ICOLD) in France, particularly during strong flood periods (i.e. Aude in 1999, Gard in 2002, and Rhône-Alpes in 2003). Such failure of an hydraulic earthwork structure can lead to dramatic consequences in terms of human lives and economic losses. There is a growing demand for improving safety management of the existing structures and building more resistant ones for the future.

Erosion is by far the most common cause of failure of earth dams. Two different situations can be distinguished: External erosion, the degradation of the outer surface of the hydraulic structure in the event of overflow or over-topping, and internal erosion which takes place inside the structure or the foundation by seepage flow. In the latter case there may therefore be no external evidence that erosion is taking place until the phenomenon has progressed sufficiently to be visible and detectable by measuring devices. The susceptibility of a soil to erosion can be assessed with dedicated devices developed for the purpose and based on mainly empirical interpretation models. The understanding of the intrinsic physics of the mechanism underlying the specific processes of soil erosion has been extensively studied for the specific case of granular materials, but very few for coherent soils, for which many questions are still open.

This thesis deals with water flow induced erosion of geomaterials more complex than purely friction soil, which are often found in civil engineering hydraulic structures with significant socio-economic implications. More specifically, we focus here on cemented granular materials with solid inter-particle bonds. We aim to study the mechanical characterization of an artificial cemented granular system at different scales and the development of hydro-mechanical instabilities of this model soil, both by localized fluidization and hydraulic loading. This multidisciplinary research work involves different scientific communities, notably those of soil mechanics, geotechnics, and geophysics. This PhD thesis is part of a bilateral project funded by ANR-DFG, called COMET (Coupled micromechanical modeling for the analysis and prevention of erosion in hydraulic and offshore infrastructures).

Micro-macro mechanical characterization:

Our research first focused on the experimental micro-macro mechanical characterization of artificial cemented granular materials, made of spherical glass beads bonded with paraffin bridges. By varying the properties (particle size, surface finishing, and paraffin content) of this artificial material, we tested a large range of sample parameters. On the one hand, we investigated several solicitations at the micro-scale to study the bond strength, starting from tensile and shear forces to bending and torsion moments. Despite the large dispersion detected (standard error nevertheless less than 20%), the micro-tensile force was found to increase with both the paraffin content and the glass bead diameter. By means of X-ray tomography and specific experiments with image processing, we examined three different modes of bond rupture: (i) adhesive rupture, when a full debonding at the bead surface occurs; (ii) cohesive rupture, when the bridge itself is fractured; (iii) mixed rupture, which combines the two others. Typically, around 90% of the bond ruptures are adhesive ones for the polished particles, whereas, for the matt beads, the ruptures are mostly mixed. Only some rare cases of cohesive ruptures have been observed for matt beads with large diameter. An interesting finding was that, within the intrinsic dispersion, the micro-tensile strength does not seem to be affected neither by the size of the paraffin bridge nor by the type of the rupture. To interpret our measurements, we have succeeded in deriving a theoretical law that links the micro-tensile force to paraffin volume content, coordination number, and grain diameter. Finally, we proposed to linearly relate the critical values of shear force, bending moment, and torsion moment to the yield micro-tensile force, using coefficients obtained by fitting our whole set of data and thus offering a calibrated 3D model for grain cementation through solid bonds.

On the other hand, we performed macro-tensile tests for which high variability was measured, even larger than at the micro-scale. Beyond this dispersion, resulting from both the above scattering in the particle-particle cohesion strength and a suspected finite size effect related to the macro-devices, the macro-tensile strength was found, as expected, to increase with the paraffin content. A proposal of a theoretical law based on the micro-scale one was derived by the use of a homogenization law proposed by Richefeu and co-authors (Richefeu, 2006) and in the continuation of Rumpf's initial work. This theoretical expression suggests a dependence solely on the paraffin volume concentration and not on the size of the glass beads. An observation of an instantaneous brittle failure during several creep tests indicated the absence of damage progressing in the sample by bond ruptures. Finally, complementary tests showed that the macro-tensile force could be affected by the rate of loading, and the non-repeatability of the creep tests highlighted the random nature of the failure process.

Localized hydraulic failure of a cemented granular layer

In the second part of our work, we carried out several experimental campaigns on submerged cemented granular materials subjected to a localized flow loading from bottom injection. Globally, all of these experiments showed that cemented beds made of larger beads and higher paraffin content required a greater flow rate to be destabilized. Four distinct modes of hydraulic failure were observed: (i) a static regime, with no movement in the sample; (ii) a block rupture, characterized by the appearance of a median crack above the flow inlet; (iii) a fluidized path rupture, by progressive burrowing along the walls towards the inlet; and (iv) a block uplift rupture, when the sample slides upward at the lateral walls following prior bond breakage at its boundaries. To relate these experiments to our previous micro-mechanical characterization, we plotted the critical hydraulic pressure, acquired at each hydraulic failure experiment, as a function of the yield micro-tensile force. The resulting and rather speculative trend showed that the hydraulic threshold indeed increased with the cemented soil cohesion, regardless of the destabilization mode. Finally, in consistency with previous data from experiments on granular localized fluidization _(Mena, 2017), it was possible to satisfactorily gather all the data, approximately on Ergun's law, when considering the relevant dimensionless numbers, namely the inlet particle Reynolds number and the Archimedes number, the latter being adapted to the cemented case by considering the micro-tensile force instead of the grain buoyant weight.

In addition, we succeeded in simulating several types of localized hydraulic failures in cemented granular beds using a homemade 2D numerical code based on an LBM-DEM coupling method. The governing parameters for the onset of erosion were found to be the flow rate (regardless of the inlet velocity profile applied at the inlet injection), the particle diameter, the bond strength, and the bed height. A rather similar phenomenology was thus observed, including the following scenarios reminiscent to the experiments: (i) the so-called static regime, with possible partial damage by rupture of a fraction of the solid bridges; (ii) the fracture scenario, that refers to a destabilization of the cemented bed through almost symmetric inclined cracks initiating from the inlet ; (iii) the fluidized chimney scenario, that refers to a localized destabilization of the grains, from the inlet, in somehow the same way as with purely granular material; (iv) the mixed scenario, that is a combination of the two previous ones. Using phase diagrams, we finally discussed the influence of both inlet flow rate and bond strength on the failure modes. Overall, we got an interesting though limited agreement between the 2D numerical part and the experimental findings. However, the discrepancy provides an incentive to improve the modeling by pursuing a 3D extension. In collaboration with the BAM, some preliminary and rather promising 3D simulations using the WaLBerla framework have been successfully performed at the very end of this thesis.

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