Université Gustave Eiffel

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PhD thesis offer : Study of the behavior of granular materials under cyclic loading

Location : Université Gustave Eiffel, IFSTTAR, Campus de Nantes, laboratoire MAST/GPEM et laboratoire GERS/GMG, Allée des Ponts et Chaussées, 44344 Bouguenais ;

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Context: In many industrial applications and natural situations, granular materials are subject to cyclic loading. In civil engineering, this is the case, for example, with soils supporting geotechnical structures, pavement elements during initial compaction and in service conditions, or even railway ballast in service and in maintenance conditions. Despite the strong implications of the cyclic behavior of granular media on their mechanical response, this type of behavior is still poorly understood, and therefore poorly modeled, in particular when the number of cycles becomes important. This is even more true when the application presents interfaces with structures (walls, piles, rails, etc.), where heterogeneous and irreversible deformations can appear.

The discrete element method (DEM), originating from the work of Cundall & Strack (1979), is a numerical technique in which a granular medium is simulated as a collection of particles, interacting by means of contact laws accounting for the impenetrability of matter, friction, etc. Each body is treated as a separate object with its own degrees of freedom. The discrete numerical simulation makes it possible to obtain micromechanical information on the behavior at the grain scale and in particular on the possible mechanisms of energy dissipation (friction, internal dissipation, fracture, attrition), depending on stress level and confinement conditions.

The geotechnical centrifuge allows, on a reduced soil model (e.g. sand) with a free surface, to reproduce a stress field similar to that of a full-scale structure. By changing the speed of rotation, the centrifugal force is changed, which allows to achieve macrogravity up to 100 times the acceleration of Earth's gravity. It is thus possible to study, for example, a reduced-model foundation subjected to cyclic, vertical or horizontal, unidirectional or alternating loads (such as those that can be exerted on the foundations of offshore wind turbines). The centrifuge therefore allows to carry out parametric studies on reduced models by varying the gravity (and therefore the applied stresses), but also the applied loading signal (intensity, frequency, etc.), or even the characteristics of the soil (apparent density of sand).

Topic : This thesis will focus on the study of the behavior of granular materials under cyclic stress, by coupling (1) discrete numerical simulation, (2) macrogravity tests, (3) modeling with elastoplastic models. Two types of configurations will be studied. First, the rheology of the material in the case of simple cyclic loading (eg periodic shearing) and in homogeneous conditions will be characterized using discrete numerical simulations carried out on an elementary volume in a semi-infinite medium (tri-periodic conditions). Modeling choices of increasing complexity will be used, in particular by considering the polidispersity of the grains. The simulations will make it possible to quantify, for the chosen model materials, the evolution of the secant Young and shear moduli (E / Emax, G / Gmax) with the strain, and the typical hysteresis observed in cyclic loading, which results in dissipation of energy measurable with a hysteretic damping coefficient (damping ratio D).

Then, a heterogeneous configuration representing the interaction between a granular medium and a structure on which cyclic stresses act will be analyzed. For example, the case of a cylindrical body (similar to a pile) inserted vertically into the material will be implemented. The analysis of the simulation results, in particular through adapted averaging methods (Artoni & Richard 2015, 2019) will make it possible to characterize the forces transmitted to the structure, the evolution of displacements and the microstructure of the material, as a function of the physical parameters of the grains (friction, cohesion, polidispersity) and the characteristics of the loading (frequency, amplitude, waveform, number of cycles). The objective of these simulations will be to understand the effect of oscillations on the structuring of the granular medium, the evolution of its mechanical response, and the feedback on the behavior of the structure, taking into account the phenomena of effective internal friction and the material / structure interface.

Numerical simulations will be compared to macrogravity experiments in the geotechnical centrifuge at Gustave Eiffel University. These experiments will be designed by considering the need to reduce potential scale effects (e.g. Garnier et al. 2007). Discrete numerical simulations will be carried out in support to this design phase, by varying the gravity, the dimension of the system, the size of the grains and the initial solid fraction, in order to verify literature scaling laws and to reproduce reduced-model experiments corresponding to the same prototype foundation.

The experiments thus dimensioned will make it possible to study the effect of cyclic stresses on the soil-structure interaction. The geotechnical centrifuge tests will focus on a foundation configuration (pile, rigid inclusion or shallow foundation) or anchor (nail) on a reduced scale while being able to vary the state of stress thanks to macrogravity. The stresses will correspond to service loads with a frequency typically of the order of 1 Hz. The experimental device will be designed with a transparent wall allowing the recording of the movement of the particles by imaging. The force applied to the foundation will also be measured. The instrumentation will also possibly integrate optical fibers, strain and displacement sensors.

The results of discrete numerical simulations as well as centrifuge tests will be compared with the predictions of an elastoplastic model developed at the GPEM laboratory to describe the mechanics of soils under cyclic stresses (Cazacliu & Ibraim 2016). The results of the research carried out within the framework of this thesis will be published in international journals in physics (for the more fundamental aspects), granular materials engineering (for the technical aspects of simulations), geotechnics (for the applications), At least two articles should be submitted before the end of the thesis. It is also envisaged that the doctoral student will present his work at thematic conferences.

Profile : Applicants must hold a Master 2 in physics, mechanics, civil engineering, or equivalent. They must be motivated by approaches combining experiments with numerical simulations.

References :

Artoni, R., & Richard, P., 2015. Average balance equations, scale dependence, and energy cascade for granular materials. Physical Review E, 91(3), 032202.

Artoni, R., & Richard, P., 2019. Coarse graining for granular materials: micro-polar balances. Acta Mechanica, 230(9), 3055-3069.

Cazacliu B., Ibraim, E., 2016. Elasto-plastic model for sand including time effect. Géotechnique Letters 6.

Cundall, P. A., & Strack, O. D., 1979. A discrete numerical model for granular assemblies. Geotechnique, 29(1), 47-65.

Garnier J., Gaudin C., Springman S.M., Culligan P.J., Goodings D., Konig D., Kutter B., Phillips R., Randolph M.F., Thorel L. 2007 Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. Int. J. Physical Modelling in Geotechnics ISSN 1346-213X, vol7, n°3, pp 1-24.