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Review of the PhD thesis of

Jose Alejandro Duque Felfle, Charles University Prague

with the title

„Contribution to the experimental investigation and numerical description of soil cyclic behavior“

Topic and aim of the research

Many geotechnical structures are subjected to cyclic loading. Offshore wind turbine foundations under cyclic loading caused by wind and waves are a highly topical example. The repeated loading of soil deposits and foundations during earthquakes is another important field of application. For numerical studies of such loading conditions sophisticated constitutive models for different types of soils, in particular sand and clay are needed. These models should be based on the results of high-quality laboratory tests and validated by the back-analysis of element tests, model tests or field measurements. Unfortunately, most constitutive models proposed so far show some deficits in describing all aspects of the cyclic soil behaviour observed in laboratory tests. Therefore, the thesis of Mr. Duque aims 1) to provide data from high-quality laboratory tests with monotonic and cyclic loading on sand and clay, 2) to experimentally investigate the soil behaviour under more complicated loading conditions including preloading and sequence effects, 3) to inspect some of the most advanced constitutive models for the cyclic soil behaviour based on the own element tests or available experimental databases, and to clearly work out the models' shortcomings and possible remedies, 4) to contribute to the further development of these models, 5) to validate the models by the back analysis of element and model tests and 6) to apply the models in numerical simulations to study the behaviour of different types of offshore wind turbine foundations.

Content of the thesis, applied methods and main results

The thesis of Mr. Duque is a cumulative one, composed of seven publications, of which three are already published and the remaining are submitted to high-quality journals in the field of geotechnical engineering (Computers and Geotechnics, Acta Geotechnica, Géotechnique Letters). Mr. Duque is the first author of all papers except one. Each chapter of the thesis contains one of these publications, preceded by a short summary. The chapters are embraced by a general introduction and a summary and outlook chapter.

The first article in Chapter 2 summarizes an experimental investigation on Malaysian kaolin using oedometer tests with un- and reloading phases and undrained triaxial tests with monotonic or cyclic loading. The influences of stress amplitude, soil plasticity (by a comparison with literature data), anisotropic consolidation, sequence effects (tests with packages of cycles varying in amplitude) and drained cyclic preloading are studied. The tests reveal a decrease of the rate of pore water pressure accumulation with increasing soil plasticity and due to drained cyclic preloading. It is demonstrated that Miner's rule is not applicable to clay under undrained cyclic loading conditions. To handle a cyclic loading composed of several packages with different amplitudes a modification of Stewart's approach was developed and proven suitable.

The second paper in Chapter 3 deals with an experimental study on Zbraslav sand, containing undrained monotonic triaxial tests, oedometer tests with un- and reloading cycles and undrained cyclic triaxial tests. Beside a variation of amplitude the focus of the cyclic tests is laid on the effect of a drained or undrained cyclic preloading. It is demonstrated that a drained cyclic preloading always leads to an increase of the liquefaction resistance, while for undrained cyclic preloading with a subsequent reconsolidation a threshold related to the exceedance of a certain pore water pressure ratio or strain, respectively, was identified. An undrained preloading staying below this threshold increases the liquefaction resistance, while the opposite tendency is observed if the threshold is surpassed.

In the third article provided in Chapter 4 four advanced constitutive models for fine-grained soils are inspected based on the kaolin database of the reviewer. The models comprise 1) an anisotropic hypoplastic model extended by the Intergranular Strain Anisotropy approach (HP + ISA), 2) the Saniclay-B model, 3) the anamnesis model (CAM) and 4) a three surface kinematic hardening model (A3-SKH). Element test simulations with the models are compared to the experimental data. The shortcomings of the different models in reproducing certain aspects of the cyclic soil behaviour are addressed and discussed against the background of the mathematical formulation of the models. It is demonstrated that none of these models succeeds to describe all experimental observations well with a single set of parameters, but some models seem more suitable for the application on boundary value problems with cyclic loading than others.

Paper No. 4 in Chapter 5 works out characteristic limitations of advanced constitutive models for sands with respect to cyclic behaviour. The considered models are the Sanisand model in the version of 2004, the modified Sanisand model with memory surface and the hypoplastic model with two different formulations of the intergranular strain. The seven identified limitations refer to an over- or undershooting during reloading, an unrealistic bias in the shear strain accumulation during cyclic mobility, the reproduction of the CSR-N curves describing the relationship between amplitude ratio and the number of cycles to liquefaction, the reaching of a liquefaction state in case of dense samples subjected to cycles with constant strain amplitude, an accumulation of strain by closed stress cycles, a wrong oedometric striffness and the effect of drained preloading on the response during undrained shearing. The analysis of the four models based on different types of element tests reveals that none of them adequately describes all seven aspects of soil behaviour. Necessary components of a constitutive model to overcome these deficits are discussed.

In Paper No. 5 presented in Chapter 6 the intergranular strain approach for enhancing a hypoplastic model with respect to cyclic soil behaviour is further improved. The new formulation is able to reproduce the decrease of the pore water pressure accumulation rate with increasing number of cycles at the beginning of an undrained cyclic triaxial test, and the re-increase accompanied by increasing strain amplitudes close to the cyclic mobility phase. The improved prediction is confirmed by means of a comparison with laboratory test data for sand and contrasted with the worse performance of two previous formulations of intergranular strain.

The sixth paper in Chapter 7 documents a finite element back analysis of centrifuge tests on monopiles in Malaysian kaolin. In these tests the piles were subjected to three packages of cycles with consolidation periods in between. For the numerical simulations a hypoplastic model with intergranular strain for clay was used and calibrated based on laboratory tests. The simulations approximately replicate the load-displacement curves under monotonic and cyclic loading, whereas the increase in soil-pile stiffness during the reconsolidation phases observed in the experiments could not be reproduced numerically.

The last paper in Chapter 8 concentrates on finite element simulations of a tripod suction caisson foundation for offshore wind turbines. A back analysis of a centrifuge model test is preformed, in which six packages of 1000 cycles with increasing amplitude were applied. In the finite element simulations the number of cycles per package had to be reduced to 100 due to restrictions on the computational capacities. The simulations could reproduce some aspects of the foundation behaviour observed in the model tests, in particular the “self-healing” i.e. back rotation of the foundation against the loading direction at larger numbers of cycles. This observation is explained based on the predicted development of the soil state in the vicinity of the caissons.

Evaluation of the thesis

In his thesis Mr. Duque has significantly contributed to the challenging topic of experimentally investigating and modelling the complex behaviour of sand and clay under monotonic and especially cyclic loading, which is of high importance for many practical applications in geotechnical engineering. The thesis covers a comparably large bandwidth of topics, from laboratory experiments over constitutive modelling work to applications in numerical simulations. Mr. Duque has performed and carefully analysed a significant number of well-designed advanced laboratory tests with monotonic or cyclic loading, where in particular the tests on clay are very time-consuming. The results of these tests are of high quality, show low amount of scatter and high reproducibility and thus reflect a careful handling of the samples and performance of the tests. While some parts of the experimental results confirm previous findings in the literature, other test series extend the current state of knowledge, e.g. regarding clay behaviour under a loading composed of packages of cycles, changes in clay cyclic response due to a drained cyclic preloading, or the effect of an undrained cyclic preloading of varying intensity on the undrained cyclic behaviour of sand. The presentation of the test results is well ordered, and the analysis covers all relevant aspects. Since the data are provided online they can also be used by other developers of constitutive models in future.

The high quality of the papers covering constitutive modelling work reflect the strong background of Mr. Duque on this field. The inspection of the prediction quality of different constitutive models for clay and sand based on element test simulations of various types of laboratory tests (also “non-standard” ones) goes beyond a simple comparison of predicted and measured curves, but seriously discusses the merits and deficits of the models against the background of the underlying constitutive equations. Some of the models are investigated under various types of cyclic loading conditions for the first time, and show serious deficits, which were not clearly communicated by the developers, or not even realized because only a limited number

of “standard” cyclic test conditions were analysed so far. The improvement of the intergranular strain approach presented in article No. 5 looks very promising, providing a realistic description of the change of the rate of pore water pressure accumulation with increasing number of cycles for the first time. With the finite element back analysis of centrifuge model tests on different types of offshore wind turbine foundations presented in the last two articles Mr. Duque also inspects selected constitutive models on boundary value problems with larger scale. Beside an overall good agreement between the experimental results and the numerical prediction, Mr. Duque identifies aspects of the foundation behaviour, which are not fully captured by the simulations and may necessitate a further inspection and possibly modifications or extensions of the constitutive models applied.

The papers constituting this cumulative thesis are well written, logically structured and easy to follow, despite the challenging topics. All illustrations showing experimental or simulation results are of high quality and support the statements in the text. The collection of papers represents an impressive mixture of experimental, constitutive and numerical work, documenting the comprehensive knowledge and deep understanding gained by Mr. Duque on these fields.

With his excellent thesis Mr. Duque has demonstrated that he is able to work independently and scientifically on ambitious problems of actual geotechnical research and to communicate his results in a clear and understandable way. With his research he has extended the current state of knowledge on the field of soil behaviour under cyclic loading and laid the foundations for further enhancements of constitutive models for soils.

Considering the very good achievements of Mr. Duque I recommend the acceptance of the thesis and, following its successful defence, the awarding of the title PhD.

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