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Editorial

Soil–Water–Structure Interactions

Alba Yerro [1,*] and Francesca Ceccato [2]

[1] Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 111-A Patton Hall, Blacksburg, VA 24061, USA
[2] Department of Civil, Environmental and Architectural Engineering, University of Padua, 35129 Padua, Italy; francesca.ceccato.1@unipd.it
* Correspondence: ayerro@vt.edu

Abstract: Interactions between soil, fluids (e.g., water), and structures are intrinsic to most geotechnical problems. However, these can be extremely complex and further understanding is needed in this field. Soil–water–structure interactions can be studied on many different scales (micro to macro) and perspectives (experimental, numerical, and theoretical). In any case, the consequences of these interactions control soil behaviour, the stability of civil infrastructure, and, ultimately, the safety of our communities. This Special Issue consists of five papers (three research papers and two literature reviews) that highlight the importance of soil–water–structure interactions in a broad range of different applications. The topics addressed in the research contributions include (a) the performance of shallow footings under oblique loads, (b) the assessment of nonlinear base-isolated building systems under dynamic loading, and (c) the applicability of lightweight materials as fill for retaining wall systems. The other innovative papers, on the other hand, provide comprehensive reviews on (d) the role of the clay content in the interface characteristics between sand–clay mixtures and structures and (e) the latest developments in the understanding and measurements of the Atterberg limits.

Keywords: soil–water–structure interaction; shallow footings; base-isolation systems; lightweight fill; interface direct shear test; Atterberg limits

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1. Introduction

Geotechnics is inherently characterised by problems involving soil–water–structure interactions. Relevant examples of the importance of the interactions between soil and water in geotechnical applications are the stability of water-retaining structures subjected to changes in the water table, rainfall- or seepage-induced landslides, and scour and erosion around offshore structures. The interaction between soil particles and water is investigated from the micro-scale to the macro-scale. At the micro-scale, the soil's hydromechanical behaviour is determined by the electro-chemical interactions between solid grains and liquid, especially for clay particles. This can be easily determined by observing the change in the consistency of clay mixed with different water contents, which led to the definition of the well-known Atterberg limits more than one century ago. At the meso-scale, considered as the scale of the representative elementary volume, soil mechanical behaviour is characterised by the interactions between pore fluid and solid grains. In saturated soils, the famous Terzaghi's principle of effective stresses establishes that the total stress applied to the mixture is divided between pore pressure on the fluid and effective stress on the solid skeleton. The latter is responsible for all measurable effects in the soil. In unsaturated soils, the concept is even more complex. The interactions between the coexisting porous fluids (i.e., air and water) is controlled by the water surface tension and resulting capillary forces acting at the inter-particle contacts. This allows the development of suction. Suction and the degree of saturation rule the mechanical behaviour of unsaturated soils. Internal erosion processes resulting from seepage are also the result of water–soil interactions at the particle level. In general, the soil's hydromechanical behaviour is fully coupled, meaning that changes in liquid pressure generate changes in effective stress and thus material deformations, and, vice versa, soil deformations generate changes in liquid pressure. For these reasons, we need to be able to quantify stresses acting on the solid skeleton and the pore fluid, meaning that the governing equations of both phases as well as the interactions between them should be considered. In practice, these complex aspects can sometimes be simplified by assuming drained or undrained conditions.

Another relevant topic in geotechnics is related to the fact that we deal with granular materials that, under certain conditions, can exhibit a phase transition. This means that even when completely dry, they may behave like a solid, liquid, or gas, depending on the void ratio, stress state, and strain rate. This can be observed in flow-like landslides, where the material initially behaves like a solid during the pre-failure stage when the soil mass is in static conditions; then, the failure surface develops, the shear rate increases, and the material behaves like a liquid flowing for long distances. Finally, it comes to rest in a deposition area and solid-like behaviour is recovered. Other examples of liquid-like behaviour of soil are dynamic liquefaction occurring during strong earthquakes in saturated sands and static liquefaction due to seepage effects, e.g., sand boils. One of the explanations for this phase transition is related to the nature of soil packing and the fact that loose soils tend to contract or suffer internal collapse when sheared. A desirable constitutive model of the material should be able to capture these aspects, which is extremely challenging, but several steps have been taken in this direction.

In addition to the multi-phase nature of soils, geotechnical problems are often characterised by the interaction with structures. This is, again, a problem that can be addressed at different scales. At the micro-scale, soil–structure interactions can be treated as contact problems. The behaviour of soil at the interface is affected by the composition and size of the soil particles, the material of the structure, and the presence of water, among others, and still deserves to be thoroughly investigated, especially when considering different mixtures of coarse and fine-grained soils. Contact problems are important, for example, in deep and shallow foundations, where interface friction is related to installation problems and bearing capacity, earth retaining structures, and buried objects such as pipelines. At the macro scale level, soil–structure interactions can be interpreted as the coupled response between the superstructure and its foundation system. This is particularly important in dynamic conditions, where accounting for soil–structure interactions can completely change the response of the building during earthquake excitation. Furthermore, the realm of soil–structure interactions is even broader if one accounts for the study and design of structures made of soil and soil reinforcements (e.g., geosynthetics, soil–cement mixtures, biosoils, etc.).

The mechanics of soil–water–structure interactions are generally complex due to multi-body contact, soil non-linearities, and multi-phase coupling effects. In addition, large deformations of the soil are commonly encountered in such processes with a large variability of strain rates, making their numerical modelling extremely challenging. Advanced numerical tools in the frameworks of continuum and discrete mechanics are being developed to address these challenges. The validation of these tools is even more essential when experimental data are limited.

The overall understanding of these interactions is required to improve the design of geotechnical systems and to have safer and more resilient communities in a global warming scenario where climate conditions can dramatically change the external agents affecting our civil infrastructure. This Special Issue encouraged original submissions that provide innovative solutions to study soil–water–structure interaction problems. We received five papers, including two review papers. The following section briefly highlights the key aspects of the contributions.

2. Summary of the Special Issue

The paper by Savvides and Papadrakakis [1] presents a probabilistic failure estimation in terms of bearing capacity and settlement of a shallow footing subjected to oblique loading on saturated cohesive soil. This work addresses a classic geotechnical problem—the performance of shallow footings—and provides a numerical framework to assess the uncertainty in material properties for different loading orientations, which are typically assumed constant using simple constitutive models. A 3D finite element model is adopted in combination with an advanced, modified Cam Clay constitutive model with a bound stress envelope influenced by the structure development and degradation of the clay. The load is applied linearly in quasistatic conditions until the first yielding is observed. The effects of porous water in the results are incorporated using a fully coupled hydromechanical formulation. The effects of spatial random distribution of key soil properties, i.e., the soil compressibility, permeability, and critical friction angle, compared to constant and linear distribution, are assessed with Monte Carlo simulations. The algorithm is accelerated by using Latin hypercube sampling. The results show that both the bearing capacity and ground settlement follow a Gaussian normal distribution despite the excessive non-linear soil behaviour. In addition, the authors conclude that the bearing capacity and settlement increase with the obliquity of the applied load, while the uncertainty of the results remains the same.

The paper by Akehashi and Takewaki [2] focuses on assessing the performance of non-linear base isolation systems as structural vibration control solutions of superstructures. In order to provide safe structure designs, the accurate behaviour of the connections between the shaking ground and the structure sitting above the ground is crucial. In particular, base isolation systems are highly effective for moderate-level ground motions, but they are inefficient for motions associated with large ground displacement (e.g., resulting from amplification effects on deformable ground). This original work investigates the critical response of this structural solution considering soil–structure interactions under double and multi-impulse loads to account for different ground motion durations. In the numerical model, the superstructure is assumed elastic, the base isolation system consists of lead rubber bearings and has a bilinear force deformation relation, and the soil—structure interaction is modelled by a swaying rocking spring-dashpot system that accounts for the ground stiffness nonlinearity. Two critical timings for an MDOF building are derived. Time history response analyses show that the two critical times are almost equal, which implies that the total input energy to the whole system and the instantaneous input energy to the base-isolated building are maximised at almost the same time. Finally, it is concluded that the duration of the ground motion plays a key role in the critical responses of base-isolated buildings on flexible ground. Large deformation triggers the failure of the isolation system, the collision of the structure with the retaining wall, and damage to the superstructure.

In the realm of soil–structure interactions, the challenge of designing safe retaining structures and embankments is a common geotechnical problem. In the paper by Abbasimaedeh et al. [3], the use of expanded polystyrene (EPS) particles mixed with clayey sand as uncemented lightweight earth fill is proposed for the purpose of reducing bearing pressures on the underlying foundations to minimise destabilising moments in the slopes of the earth and downscale the earth pressures acting on the retaining walls. The paper presents the outcomes of a testing program to assess the effects of EPS on the geomechanical and hydraulic behaviour of the compacted clayey sand (cs) soil. Data from standard Proctor compaction, direct shear, California bearing ratio, pedometer, and permeability tests are presented. Six clayey sand–EPS bead mixtures were tested with a range of volume percentages of EPS (21–73 v.%) using two different particle sizes of EPS. The results demonstrate that the compacted dry density effectively decreases (when compared with the CS soils themselves) with an increase in EPS bead content. However, substantial mechanical failure (i.e., severe settlement and decay of bearing capacity and compressibility) is observed for the investigated stress range (50–400 kPa), especially for the mixtures with larger-sized EPS beads. Finally, the paper provides a unique discussion on the environmental impact of this type of lightweight fill; it highlights the detrimental effects of leaving EPS (microplastics) mixed with soil forever, which can interact with plants and eventually transmit into the food chain. The authors conclude that particulate EPS–soil mixtures are unsuitable as uncemented lightened fill.

The next two contributions to this Special Issue are review papers. The first one, by Yin et al. [4] provides state-of-the-art sand–clay mixture and soil–structure interface direct shear tests. The soil–structure interface is a vital part of the design of civil engineering structures because it transfers the load from the structure to the soil. It is the zone where major stress and strain develop, although it is generally very thin, at just a few times the soil particle diameter. The document has two main parts. First, the role of clay in the mechanical behaviour of sand–clay mixtures is presented. Second, a comprehensive overview of the mechanical behaviour of soil–structure interfaces based on interface direct shear testing is discussed. The contribution of the paper is that it identifies where the lack of data is and defines new research lines. In particular, the authors emphasise that there are limited data on the mechanical behaviour of the interface between sand-–clay mixtures and structure materials. In addition, there is a lack of knowledge on how the clay content influences the mechanical behaviour of the interface and the soil particle arrangement. Further research should investigate the interface in terms of a reconstituted sand–clay mixture and structure by interface direct shear tests to highlight the influence of the clay fraction on the interface response under various loading conditions. Sand–clay mixtures fabricated in the lab are a simplified way to study natural soils, which are often too complex.

The plasticity of fine-grained soils is very important for geotechnical engineering. Fundamentally, it depends on the hydro-mechanical interactions between pore fluids and clay particles at the micro-scale, characterised by the liquid and plastic limits (LL and PL). The second review paper by O'Kelly [5] is an updated state-of-the-art review of the most relevant developments in the understanding and measurement of the Atterberg limits, which are the most widespread laboratory tests to classify and determine the consistency of fine-grained soils. It elaborates on different experimental methods used in practice to determine the LL and PL. There are various fundamental aspects and limitations for consistently determining the consistency limits. The paper discusses the limitations of strength-based approaches derived from standardised fall cone (FC) testing or extrusion approaches to determine the Atterberg original hand-rolling PL. Then, the authors propose a framework to derive strength variation with water content utilising strength-based FC-derived plastic limits. Finally, a discussion is presented on two recently developed plasticity-based fine-grained soil classification systems, which do not rely on the original Atterberg testing methods.

3. Conclusions

Most geotechnical engineering problems involve soil–water–structure interactions that can be viewed, studied, and assessed from many different perspectives. The aim of this Special Issue was to promote research on this topic and collect original contributions covering different aspects of the problem. Of the five accepted contributions, three were research-oriented, while two were literature reviews. A summary of each paper, including the most important contributions, has been provided.

Conflicts of Interest: The authors declare no conflict of interest.

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