The contribution of constitutive modelling to sustainable geotechnical engineering: examples and open issues

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Extended Abstract

This extended abstract summarises the contents of the keynote lecture to be delivered during the final day of the VII CNRIG 2019. The title highlights the aim of the talk, that will be focused on the interplay between sustainability in geotechnical engineering and the research outcomes in the specific field of constitutive modelling of soils. If, on one hand, the role of sustainability in engineering in general, and in geotechnical engineering in particular, has already been explored in the scientific literature (e.g. Basu et al., 2014; Pantelidou et al., 2012), no such a focus has been put on the specific contribution of the research in constitutive modelling to a more sustainable geotechnics. This lecture aims at taking some steps in this direction.
The structure of the presentation reflects the above aim. In its first part the definition of sustainability will be recalled, briefly focusing on the consistencies and conflicts between environmental, economics and development-related issues. These concepts will be framed within the civil engineering context, bringing in the more specific notions of reliability and resilience, which will be further specialised to the geotechnical field, identifying the necessary ingredients for a modern definition of sustainable geotechnical engineering.

The following step will be that of linking sustainable geotechnical engineering concepts to the specific research aspect of constitutive modelling of the soil behaviour. This objective is first achieved by illustrating the outcomes of the analyses of two boundary value problems which clearly show how a slight improvement in the constitutive assumptions can lead to a rather more realistic, instructive and thus sustainable representation of reality. Both investigated cases rely on basic (elastic or linear elastic-perfectly plastic) or slightly more advanced (Cam-clay like) constitutive models, thus not representing the outcomes of the front-line of the research on the selected topic. Nevertheless, they are two effective examples to highlight how constitutive modelling

can help enhancing our predictive capabilities with reference to the reliability of an earth dam under construction or the resilience of a tunnel subjected to an earthquake.
In detail, the first example is inspired by a real case history, involving the design of a 33m high zoned earth dam, sitting on heterogenous foundation deposits, including a shallow fine-grained stratum of low undrained strength. This case was selected as representative of a typical geotechnical problem that, in similar conditions, has been solved in the past adopting a rather different design solution: in fact, the design of other dams in the close by area involved the complete excavation of the alluvial soft layer down to the stiff clayey deposit, i.e. the bedrock stratum for such geotechnical setting. The obvious economical and environmental implications of such a drastic solution has triggered the interest in analysing the alternative scheme where the dam sits directly onto the alluvial deposit (Amorosi et al., 2006; Amorosi and Boldini, 2015). The numerical analyses, based on a Cam-Clay family model, highlight the progressive increment of the available shear strength of the fine grained subsoil during the construction stages of the dam, due to the ongoing consolidation process, such that both short and long term stability conditions are satisfied, differently from what indicated by more conventional analysis approaches. The overall enhanced representation of the reliability of the system allows for a more sustainable solution to be accounted for in the design of the dam.
The second example is that of an ideal, though realistic, circular tunnel subjected to an earthquake, analysed along its transversal section (Amorosi and Boldini, 2009). When tackling this problem, standard engineering practice still relies on elastic solutions (e.g. Wang, 1993; Penzien and Wu, 1998) to evaluate the seismic-induced loads, which are assumed to act in the lining only during the seismic event, thus neglecting any post-earthquake effect on the system. The numerical exercise has been carried out first to reproduce the elastic solutions under the same assumptions, and then adding a simple plasticity hypothesis for the soil, to highlight its overall effects on the loads acting in the lining during the shaking and after the event. The good news was that a less intense magnitude of the seismic-induced hoop forces and bending moments, as compared to the elastic one, was predicted during the seismic stage, possibly due to the irreversibility-induced dissipative character of the surrounding soil, at the cost of the permanent accumulation of displacements and distortions of the structure, complemented by a substantial increase of the post-seismic static loads acting in the lining. This insight into the resilience of an ideal tunnel, achieved by a relatively small improvement of the constitutive assumptions, suggests that, nowadays, more informed design approaches could be adopted for similar underground structures, leading to more sustainability-oriented engineering solutions.

The third part of the lecture will be devoted to the discussion of some specific issues related to more recent advances in constitutive modelling of soils.
At this scope, a brief introduction is first proposed to outline two of the main features successfully accounted for, in the last three decades, in constitutive models for soils, in general, and clays, in particular: structure, and its degradation, and anisotropy, and its evolution. Both these ingredients have led to a substantial increase in the number of models' parameters: nonetheless, in the (provocative) opinion of this lecturer this is a

false problem, once a well-defined calibration strategy is provided for each of them. A far more subtle and underestimated problem is represented by the increase in number of internal variables, controlling the evolving character of the soil behaviour. These scalar or tensorial entities, which include, for example, those controlling the dimensions, positions or distortions of the – often more than one – yield-like surfaces, require to be first initialised each time the model is used to carry out a simulation. This is easier when reproducing the response of single element tests, while becomes cumbersome when setting up the numerical analysis of a boundary value problem, as each single internal variable must be initialised at each depth and location of the deposit. The scientific literature does not provide clear indications on how to proceed in this sense, while it can easily be proved that different assumptions in terms of initialisation can lead to noticeably different results, obviously for the same problem analysed with the same set of parameters.

Along this line, a first example is outlined where the construction of an embankment on a 15 m deep structured clayey deposit is analysed by a 2D FE analysis, adopting an advanced constitutive model for the foundation soil. While the same set of parameters is adopted in each analysis, two different assumptions are made on the profile with depth of the initial dimension of the bounding surface, this latter being controlled by the interplay between the deposition stages of the clay and its gain of interparticle bonding due, for example, to percolation of calcium carbonate. In detail, the first scenario assumes that the cementation occurs only after the clayey stratum had already been fully deposited, while concurrent deposition and cementation processes characterise the second case. Both scenarios are compatible at one depth, where a single ideal sample is assumed to be available for the characterisation of the material. The results are compared in terms of settlements, horizontal displacements and volumetric strain contours at the foundation deposit: as expected, the different initialisation strategies lead to rather different patterns of deformation of the clay, highlighting the need for more detailed experimental investigations to be carried out on samples retrieved at more than one depth within the deposit.

The discussion is then extended to plastic anisotropy and its evolution in terms of rotation/distortion of the yield surfaces: once again, the problem is that of establishing a procedure to initialise the related internal variables when dealing with a whole deposit of natural clay. A promising approach is discussed, based on what recently proposed by Amorosi et al. (2019). The initialisation strategy is based on the idea that, instead of retrieving a large number of samples at different locations of the deposit, to then directly detect the orientation and distortion of their yield domains by carefully probing the soil specimens in laboratory tests, a far more simple and economic procedure could be adopted limiting the number of laboratory tests by complementing them with Cross-Hole *in situ* tests polarised to obtain direct profiles of the elastic stiffness anisotropy (e.g. Clayton, 2011). The key theoretical hypothesis behind this procedure is that both elastic and plastic anisotropies are assumed as the macroscopic manifestation of the unique directional properties that characterise the fabric of the material at the micro scale. The evolution of the fabric, as induced by the stress-strain history experienced by the soil throughout its entire life, leads to corresponding evolutions of the anisotropy ratio G_{hh}/G_{hv} and of the degree of orientation/distortion of the yield surfaces.

To illustrate this relationship, various experimental investigations carried out on different natural clayey deposits, have been re-analysed adopting a mathematical tool based on the combination of a well-known constitutive model for plastic anisotropy, that of Dafalias and Taiebat (2013), and a recently published anisotropic hyperelastic formulation (Amorosi et al., 2019). Both models account for anisotropy via second order fabric tensors: an experimental-based relationship between the elastic and plastic fabric tensors is proposed and then used to link these two evolving internal variables, providing a mean to obtain quantitative indications on the degree of rotation/distortion of the yield surface simply by detecting the elastic anisotropy. A first attempt to illustrate the potentialities and limitations of this wave propagation-based approach to initialise the orientation/distortion of the yield surface is finally outlined.

In the closing part of the talk some conclusions will be addressed, not only aiming at summarising the key elements emerged during the presentation but also highlighting further sustainability-related issues, possibly not touched during the talk but deserving further deepening in future. Some of these aspects could then be adopted to trigger the collective discussion during the final Round Table session of the conference.

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