NONLINEAR SOIL-STRUCTURE INTERACTION: HOW SOIL PLASTICITY AFFECTS STRUCTURAL NONLINEARITY AND VICE VERSA

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Abstract

Geotechnical and structural engineering are generally perceived worldwide as different academic disciplines, characterized by quite different nomenclature, approaches and models. In Italy, this distinction is emphasized by the current academic system, organizing disciplines within different scientific disciplinary sectors. Is this practical distinction always representative of reality? This paper suggests that it is not always the case and that removing the fences between these two disciplines could help to optimize the solution of different problems. First, this paper will show the successful implementation in structural engineering of crucial concepts of one of the most influential and elegant formulations of geotechnical engineering (i.e. critical state theory), to interpret direct shear tests of structural materials. Then, evidence of the coupling effects of soil and structural plasticity in the solution of nonlinear SSI problems will be provided, showing that structural nonlinearity (i.e. damage) influences soil plasticity and vice versa. In particular, it will be shown that soil properties, and the evolution of soil plasticity, affect structural nonlinearity with consistent implications in the assessment of structural demand, capacity and damage.

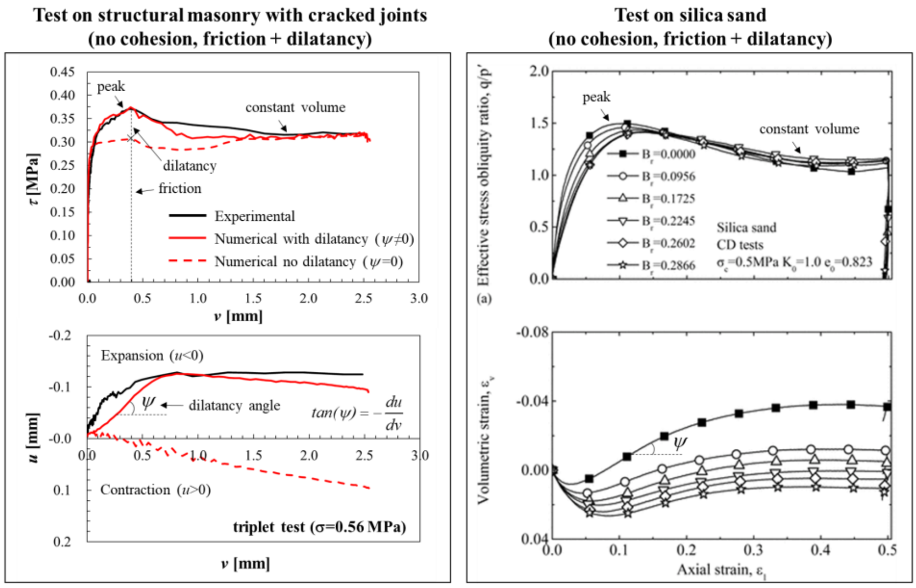
1. Introduction

Earthquake engineering is a field of research that requires knowledge in different disciplines such as seismology, structural engineering and geotechnical engineering. The study of dynamic soil–structure interaction (SSI) requires the integration of key concepts of both structural and geotechnical engineering, which appears to be more than the simple sum of the knowledge of the two disciplines. In fact, it will be shown that the complex geometrical and material nonlinearities of soil and the structural components tend to be coupled. In the current practice, this interplay role of nonlinearities is generally disregarded because SSI problems are often solved using the so-called substructure method based on decomposing the superstructure-foundation-soil system into two subsystems: (*i*) the above-ground subsystem, typically addressed by structural engineers, and (*ii*) the underground parts, addressed by geotechnical engineers. With this approach, the response of the system is determined by solving the two subsystems independently. Since the response of the overall system is obtained from the application of the superposition's principle, linearity is the underlying assumption of the substructure approach. Thus, this method provides the exact solution only if the structural components and the ground behave linearly or weakly nonlinearly. The direct method is a more general procedure to tackle SSI problems which is in principle capable of accounting for both soil and structural nonlinearities. The stiffness contrast between soil and structural elements is one of the most influential parameters in the assessment of kinematic and inertial SSI effects. During earthquakes, the differential evolution of soil and structural plasticity alters the initial stiffness contrast (i.e. linear SSI), making the evaluation of nonlinear SSI effects more complex. This aspect emphasizes the need to lower the barriers between structural and geotechnical engineering, laying the foundations for common didactic and research activities.

The first case study presented in the article aims to highlight that geotechnical and structural engineering are not so far apart because key concepts of one of the most influential and elegant formulation of geotechnical engineering (i.e. critical state theory) have been successfully implemented in structural engineering to interpret direct shear tests of structural masonry. Then, evidence of the coupling effects of soil and structural plasticity in the solution of nonlinear dynamic SSI have been provided in the second case study, showing the mutual influence of soil and structural plasticity (i.e. damage).

2. Case study 1: Implementation of the critical state theory in structural engineering

The concept of dilatancy is central in the critical state theory, which is one of the most appealing formulations of geotechnical engineering. In general terms, dilatancy is related to the volume change observed in granular materials when subjected to shear displacement. The term "dilatancy" was originally introduced in 1885 by Osborne Reynolds to denote a particular type of behaviour exhibited by a collection of particles in contact. Donald Wood Taylor, in Fundamentals of Soil Mechanics (1948), puts in relation dilatancy to friction and strength. Taylor, who was an early contributor to the emerging field of soil mechanics, used the term "*interlocking*" to describe the effect of dilatancy. A similar term "*aggregate interlock*" is used today in the field of structural engineering to identify the same mechanism in the definition of the shear strength of reinforced concrete structural elements (e.g. Bazant and Tsubaki, 1979), while the term dilatancy is used for structural masonry (e.g. Zijl, 2004). Despite the nomenclature, the interpretation of this phenomenon in structural engineering seems to be less refined than in geotechnical engineering. This case study shows the successful transfer of key concepts of the critical state theory to interpret the direct shear test of structural masonry.
The tendency of mortar joints to dilate during direct shear tests has already been described for masonry by various researchers (e.g. Lourenço, 1996). Figure 1 shows that the mechanical response of structural masonry is similar to that of silica sand, highlighting the presence of a peak and constant volume shear strength, also for cracked masonry specimens with initial cohesion equal to zero. During shear failure, the shear displacements tend to increase the volume of the sample. When normal compression is present, the mechanism of dilatancy increases the shear resistance because the work generated by the expansion opposes the work done by the compression force. Dilatancy can be measured experimentally as $\tan\psi = -du/dv$, where ψ is the dilatancy angle, dv and du are respectively, the plastic displacement in the shear direction and in the direction perpendicular to shear displacement, expressed in incremental terms (see Fig. 1a).

(a)


(b)

Fig 1. Comparison between structural and geotechnical material subjected to shear strain: (a) structural masonry with cracked joints and (b) silica sand (modified from Yu, 2017).

Several direct shear tests were executed on several specimens under different initial states and levels of compression (σ), which were defined before the execution of the shear test. Each direct shear test started with the application of the shear force on the intact specimen (i.e. uncracked joints) and then the test was repeated on the same specimen with cracked joints, for the definition of the constant volume properties (Andreotti et al., 2018; 2019). The multi-step approach was instrumental for the

characterization of different resisting mechanisms that in the definition of the peak shear strength are simultaneously active. The numerical research has been conducted in order to verify the consistency of the proposed analytical formulation. Differently from soils, when the mortar joints of masonry specimens are uncracked, the "true" cohesion is not negligible, with three mechanisms that contribute to the definition of the peak shear strength: cohesion, friction and dilatancy. When joints are cracked (e.g. Fig. 1a), cohesion is not present therefore, the active mechanisms remain friction and dilatancy. The expansion of masonry specimens tends to vanish at large shear displacements and/or with large value of compression. This phase is called "*constant volume*" because it is characterized by a dilatancy angle that approaches zero. The numerical results show that the amount of shear strength due to the dilatancy angle is not negligible (Fig. 1a). When dilatancy angle is zero, the effects of dilatancy vanish and the shear strength is only controlled by friction angle at constant volume.
A simple friction model for mortar joints that include these mechanisms has been developed based on experimental results (see Andreotti et al., 2018; 2019). This formulation extends the friction model currently used in masonry standards that neglect dilatancy (e.g. Eurocode 6 and ASTM C1531). The proposed model has been implemented in Abaqus and it has been used to simulate the experimental tests, with evaluation of the role of the dilatancy mechanism. The friction model used for masonry is based on the Coulomb's law, which is characterized by two parameters: the initial shear strength in absence of compression (i.e. t_o or cohesion), constant volume friction angle (ϕ_{cv}) and dilatancy (ψ).
Based on this formulation, a methodology to eliminate the Terzaghi's Mohr-Coulomb error due to dilatancy (Schofield, 1998), has also been proposed for masonry (Andreotti et al., 2019).

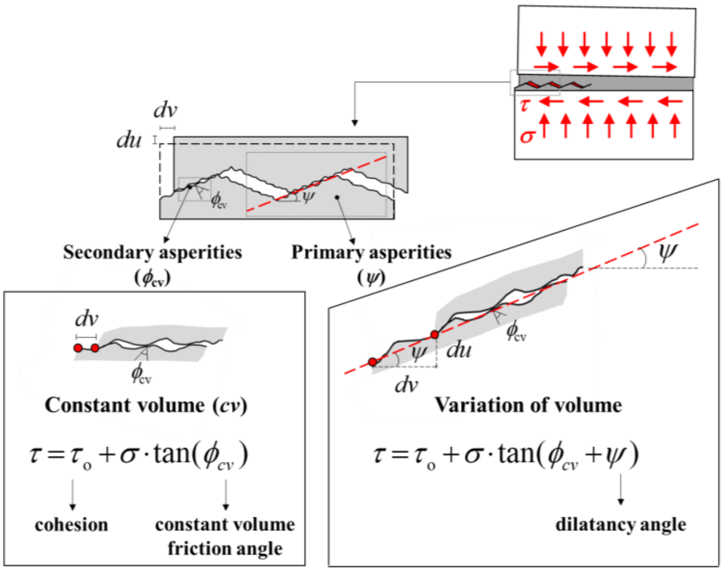


Fig 2. Proposed mechanical model for structural masonry based on key concepts of the critical state theory.

3. Case study 2: how structural nonlinearity affects soil plasticity and vice versa

This case study has the main objective to underline the coupled role of structural and soil plasticity within nonlinear SSI problems, also discussing the implications in the evaluation of structural damage. The selected case study is a full-scale test executed on a reinforced concrete large diameter (1.8 m) cast-in-drilled-hole (CIDH) pile-column with free end and flagpole configuration that has been subjected to cyclic lateral load (Janoyan et al., 2006). This case study has been selected because, unlike most of the experimental tests on piles, the full-scale test is characterized by extensive structural damage and the availability of high-quality data on both the structural and geotechnical part of the system is essential for the calibration of the structural parameters independently from the geotechnical parameters. Moreover, it is worth noting that the distinction between structural and geotechnical engineering duties in the solution of this nonlinear SSI problem is not clearly definable.
First, the numerical model has been validated using the full-scale experimental data as benchmark (Fig. 3). Then, the results of the model with varied structural and geotechnical parameters have been compared. Two types of approaches and programs have been selected: (*i*) the direct method using Abaqus and (*ii*) the p-y curves method using SeismoSstruct. Abaqus is a general-purpose software capable of solving coupled structural and geotechnical problems whereas SeismoStruct is oriented to solve structural engineering problems. As shown in Fig. 3, the numerical models consider the inelasticity of both the soil and the structural elements. Interface elements have been introduced in the

Abaqus model to consider the contact-slip-gap effects at the soil-pile interface. More detailed information about the experimental tests and numerical simulations can be found in Wallace et al. (2001) and Andreotti and Calvi (2021), respectively.

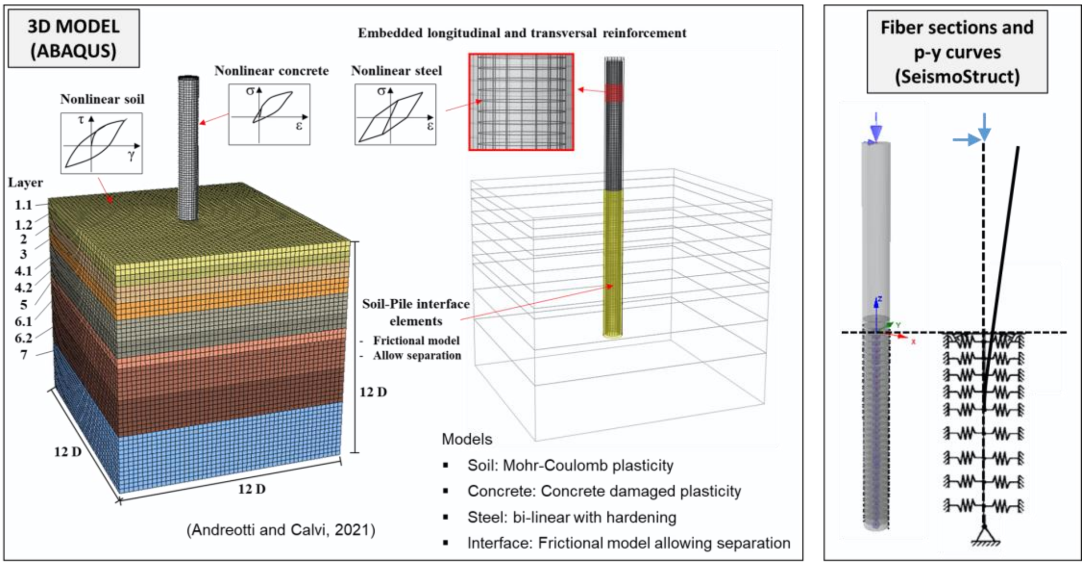


Fig 3. Numerical models used to simulate the full-scale experimental test on CIDH reinforced concrete pile.

Figure 4 shows the comparison between the experimental and numerical results in terms of load-displacement at top of the column and displacements profiles, considering three levels of lateral displacement at the top of the column (Δ): (*i*) half the yielding displacement (ΔI=0.5Δ_y), (*ii*) equal to yielding displacement (ΔII=Δ_y) and (*iii*) two times the yielding displacement (ΔIII=2Δ_y). This comparison shows that the models are capable to accurately reproduce the experimental results in terms of both lateral forces and displacement profiles, for all levels of lateral displacements.

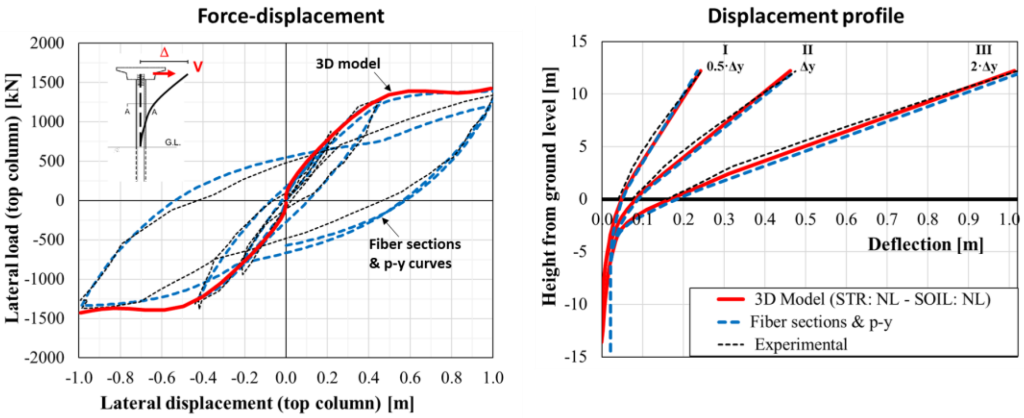


Fig 4. Comparison between experimental and numerical results.

The role that structural and soil properties have on the system response have been studied by varying the geotechnical and structural parameters. First, the parameters of the nonlinear constitutive model of soil have been fixed, repeating the analysis with linear-elastic and plastic structural elements (Figure 5). Then, the exercise has been repeated, this time fixing the parameters of the nonlinear structure, repeating the analysis with linear-elastic and plastic constitutive models for layered soil (Figure 6). Figure 5 shows that the fully nonlinear model is capable to accurately reproduce the experimental results for all levels of lateral displacements. The model with linear-elastic structure and nonlinear soil is consistent with the experimental results when the pile-column specimen is within the linear elastic phase ($\Delta<\Delta_y$). Beyond this level, the physical structure enters in the plastic stage and the results of the linear-elastic numerical model deviate significantly from the experimental data, showing a significant overestimation of the lateral load and displacement profile below the ground line. Moreover, in the linear-elastic model the volume of plasticized soil is greater and soil nonlinearity reaches greater depths from the ground level because the activation of the plastic hinge (i.e. damage) in the nonlinear pile-column tends to isolate the deeper soil layers.

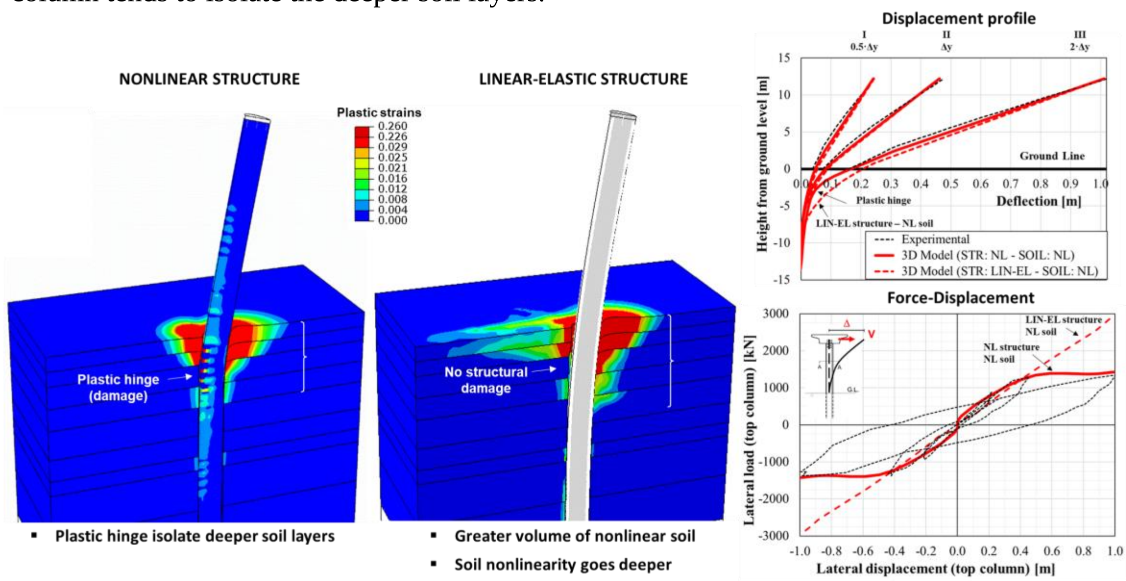


Fig 5. Influence of structural nonlinearity on soil plasticity.

Figure 6 shows the influence that soil properties, and the evolution of soil plasticity, have on structural nonlinearity and damage assessment. This figure reports the results obtained considering two different configurations of soil parameters within the site-specific variability: (*i*) stiff soil and (*ii*) soft soil. The initial soil stiffness has implications on both the evolution of soil and structural plasticity. In stiff soil, the length of plastic hinge is significantly shorter than in soft soil. This numerical result is consistent with the study of Budek, Priestley and Benzoni (2000).

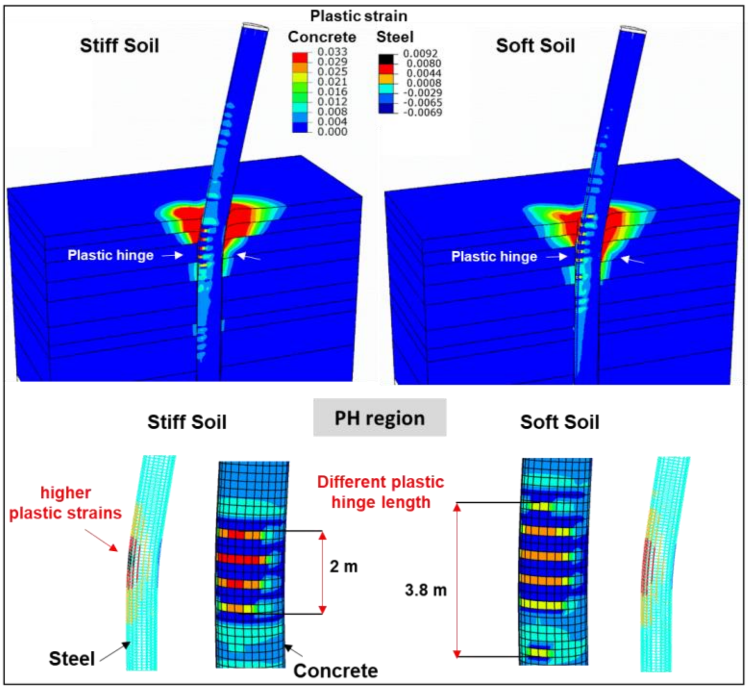


Fig 6. Influence of soil properties and evolution of soil plasticity on structural nonlinearity and damage.

Figure 6 also shows that the plastic strains in concrete and steel are greater in stiff soil. This aspect is also confirmed by the curvature profiles (Andreotti and Calvi, 2021), indicating that stiff soil generated a higher curvature demand. By looking at the distribution of the soil plasticization it can be noted that the vertical distribution of plastic strains (i.e. red color) is more uniform in soft soil while, in stiff soil, it is more concentrated in the superficial layers. The interpretation of the results indicates that soft soil distributes the pressures over a greater length of the pile-column, reducing the concentration of stresses. This situation extends the length of the plastic hinge region (i.e. damaged zone) with the formation of a greater number of cracks that are characterized by smaller widths and lower strains in the reinforcement. In contrast, stiff soil tends to concentrate the stresses with the formation of a lower number of cracks which are characterized by a greater width. This situation generates: (*i*) a shorter length of the plastic hinge, (*ii*) greater peak strains in the reinforcement and (*iii*) a higher curvature demand. This case study shows that soil properties and the evolution of soil plasticity have implications in the evaluation of both the structural demand and capacity.

4. Conclusions

Geotechnical and structural engineering are generally perceived as different academic disciplines. This paper suggests that the lowering of barriers between these two disciplines could help to optimize the solution of different problems. The first case study shows the implementation in structural engineering of one of key concepts of one of the most influential and elegant formulations of geotechnical engineering (i.e. critical state theory). Then, evidence of the coupling effects of soil and structural plasticity in the solution of nonlinear SSI problems has been provided, showing that structural nonlinearity (i.e. damage) influences soil plasticity and vice versa. In particular, soil properties and the evolution of soil plasticity affect the assessment of both structural demand and capacity, with significant implications in the evaluation (i.e. amount and position) of structural damage.

Acknowledgements

The Author would like to thank Prof. Carlo G. Lai and Prof. Gian Michele Calvi for their support in the research fields of geotechnical and structural engineering, respectively. The contribution of Prof. Guido Magenes and Dr. Francesco Graziotti in the first case study and Prof. Gian Michele Calvi in the second case study are also gratefully acknowledged. This paper has been developed within the framework of the project "Dipartimenti di Eccellenza", funded by the Italian Ministry of Education, University and Research at IUSS Pavia.

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