Macroelement approaches in Geotechnical problems: a promising design framework?

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Abstract: Macroelement approaches in Geotechnical Engineering have been developed since late '80 of the past century with the aim of getting a simplified – yet accurate – description of the mechanical response of shallow foundations to complex loading histories. From that starting point, borrowed by analogue approaches for other Civil Engineering applications, a number of successive extensions to other foundation typologies and geometries, and modifications towards more and more complex constitutive assumptions have been introduced, making nowadays the "macroelement" concept a very versatile and efficient approach. Despite such an important development at the scientific and research level, macroelement theories do not yet represent standard interpretative and design frameworks in Geotechnical applications, albeit the implementations of such simplified generalized constitutive relationships would imply substantial benefits, mainly in terms of reduction of computational effort. In the paper, after a brief recall (without any claim of completeness!!) of the fundamental steps in the macroelement theory's developments, some field applications to large real scale soil-structure interaction problems as well as to possible extensions to advanced modelling issues will be presented, together with some weak modelling points who still need further scientific investigation. By taking advantage of such critical discussion, the paper is intended to fruitfully contribute to the development of a "macroelement perspective" which – at author's feeling – could be largely beneficial not only for design purposes but, more in general, for the scientific transfer of Geotechnical expertise.

1 Introduction

Soil-structure interaction (SSI) is of course one of the most important fields of interest in Geotechnical Research, with potentially positive outcomes in a large variety of Civil Engineering problems. Despite the large amount of theoretical, numerical and experimental works published in these last decades, SSI problems still represent an open issue for many geotechnical applications, and a challenging problem for designers. SSI problems are in fact inherently multiscale (in space, but sometimes even in time), requiring in general important computational resources and advanced theoretical skills to be tackled by means of traditional numerical approaches. In this perspective, where direct and time-saving applicability to real engineering problems is a fundamental issue, macroelement approaches often represent a possible alternative modelling option. The key point is to provide a description of the soil-structure interaction in terms of generalized stress and strain variables, i.e. by lumping soil stress distributions at soil-structure interface into the resulting force components (or moments), and soil strain fields into kinematic variables, representing soil-structure relative displacements (or rotations).

Macroelement approaches allow then to upscale the problem from the local scale of the representative element volume (REV; which is usually the typical working scale of the most used numerical geotechnical codes), to the enlarged scale of the structure, and to relate it to the global scale of the entire considered domain (the so-called "far field"). Ad hoc "generalized" constitutive relationships, relating the abovementioned generalized stress and strain variables, can then be defined, thus actually considering the structure and the soil interacting with it as a unique "macro"element, whose behavior is fully described by means of only few degrees of freedom. In the following, several examples of macroelement approaches will be briefly recalled, mainly pointing out three lines of interest: (i) geometry of the problem, (ii) inclusion of advanced constitutive modelling and (iii) application to real case studies. Some concluding remarks will then be added, together with possible suggestions about innovative fields of applicability for macroelement theories.

2 Foundations

The response of foundations to applied loads is a core field of application of Geotechnical expertise, and traditional solutions for computing foundation settlements under known stress distributions (e.g. those based on simple linear elasticity models, Boussinesq, 1885, or on semi empirical approaches like the well-known methods of Burland and Burbidge, 1984, Schmertmann, 1970, Schmertmann et al., 1978, Berardi and Lancellotta, 1991 and others), already actually achieved the idea of upscaling the description of the system from the local REV scale towards the abovementioned structural scale. The key concepts making the difference between such techniques and the so called macroelement approaches, involve at least three points:

(a) the aim of fully describing the behavior of the system not only with reference to exercise loads, but even in its ultimate (limit) condition, through the definition of a proper failure criterion expressed in terms of generalized stress variables;
(b) the capability of capturing the effects of combined loading components acting on the foundation, and of the coupling effects arising among them;
(c) the formulation of a comprehensive generalized constitutive rule, capable of taking into account complex loading histories.

With respect to shallow strip footings, for example, Nova and Montrasio (1991) defined the set of the three generalized stress variables as the vertical, V, and horizontal, H, loads acting on the foundation, together with the global overturning moment M. The corresponding work-conjugate kinematic variables are represented by the vertical and horizontal displacements of the foundation and by its rigid rotation. An analytical description of failure criterion $f(V,H,M,V_M)=0$ was introduced in the generalized stress space by interpolating experimental results on small scale 1g prototype system, where parameter V_M represents the usual bearing capacity of a shallow foundation under pure vertical load. In its original version, this macroelement model was only based on a classic rigid-plastic constitutive approach, fully described once a yielding function $f(V,H,M,V_C)=0$ (characterized by the same shape of the failure criterion, but with a reduced size represented by the variable V_C), a plastic potential g, and an isotropic hardening rule are introduced, and the classic consistency condition is stepwise enforced.

Starting from this point, several extensions have been proposed, moving towards directions (i), (ii) and (iii) synthetically outlined in §1. Butterfield and Gottardi (1994), for example, studied the influence on the failure criterion of positive and negative values of H and M, working in conjunction $(\pm H, \pm M)$ or in opposition $(\pm H, \mp M)$, respectively; Crèmer et al. (2001, 2002), Bienen et al. (2006), Grange et al. (2008) generalized the macroelement approach to 3D problems (e.g. an isolated foundation) where generalized stress and strain variables are characterized by 6 components. The same authors accounted even the possible development of geometrical effects and complex interaction mechanisms, remarkably affecting the overall behavior, like e.g. the detachment of the foundation from the underlying soil for highly eccentric loads (uplift effect). This is one of the most important consequences of the adopted upscaling framework: with respect to classical modelling approaches (based on a description of soil behavior at the local level), in macroelement approaches geometrical variables actually play the role of generalized constitutive parameters, directly affecting the global mechanical response. In this perspective, Pisanò et al. (2016) have recently proposed a macroelement model for shallow foundations accounting for the change in geometry, namely represented by the increase in the embedment of the foundation base with respect to ground level; whilst Galli and di Prisco (2014), numerically investigated the influence of the ground level inclination on the shape and rotation of the failure criterion in the generalized stress space, with the aim of extending the applicability of macroelement approaches to the design of anchored walls as stabilizing structures for potentially unstable slopes (an example of a real case study is provided in di Prisco et al., 2010). Li et al. (2016) proposed even a macroelement specifically conceived for deep foundations (i.e. single pile), thus extending again the applicability of such approach to other geometries than the traditional shallow foundation.

Following direction (ii), di Prisco et al. (2003) proposed an improved version of the original model accounting for the cyclic behavior of the system, by introducing a bounding surface approach and a mapping rule, thus allowing to develop permanent strains even within the yielding locus $f(V,H,M,V_C)=0$. In the same context, a very rich scientific literature (not reported here for the sake of brevity; interested readers will find further details in the final paper) is available on the application of macroelement approaches for shallow foundations in dynamic problems, especially taking into account non-linearity in SSI problems.

A specific application to rock boulder impacts on soft soil strata was instead proposed by di Prisco and Vecchiotti (2006), who developed a viscoplastic version of the macroelement model (BIMPAM, standing for "boulder impact model"), based on the concept of delayed plasticity and capable of taking into account even the evolution of the boulder-soil contact area along with the penetration of the rock into the granular layer. More recently, Salciarini and Tamagnini (2009), introduced a hypoplastic version of the macroelement constitutive rule, thus bypassing the classic strain decomposition into an elastic (reversible) and a plastic (irreversible) part and assuming a continuous evolution of the plastic part along with the loading and unloading phases of the imposed stress paths. In the very recent years, some specific applications of the macroelement approaches on historical towers (as in Pisanò et al., 2014) or on offshore structures (in particular the foundation of wind turbines, either on suction caisson of monopile; see e.g. Page et al., 2018, or Skjolden Skau et al., 2019) have even been proposed, witnessing the progressively increasing interest and awareness of the efficiency of this interpretative framework.

3 Buried structures and "other" Macroelement problems

Starting from the original idea of a macroelement for shallow foundations, Calvetti et al. (2001, 2004), on the basis of micromechanical numerical investigations and small scale 1g experimental results, defined the shape of a more general interaction domain, with specific reference to a buried structure like a pipeline. In this context, under the hypothesis of a rigid circular cross section of the pipe, a set of generalized stress variables can still be defined as V, H, N, where V and H keep the original meaning of the vertical and horizontal interaction forces arising between the pipe cross section and the surrounding soil, and the variable M is substituted by the axial drag force N at the soil-pipe interface (distributed bending components, as well as the torque induced by the soil on the pipe are in general neglected). In this context, of course, the pipeline is no longer thought as a "foundation", but simply as a buried structure that must resist the loads exerted by the soil. Typical examples are those involving the interaction of pipelines and active landslides, or the effects of earthquake induced permanent ground displacements due strike-slip fault activation. In such applications, real boundary value problems are modelled by discretizing the pipeline as a series of beam elements resting on a bed of non-linear springs, lumping soil reactions in each node of the pipeline. Each non-linear spring is governed by a 3D generalized macroelement constitutive rule. With respect to other traditional uncoupled approaches for the evaluation of the ultimate soil-pipe interaction forces (see e.g. Audybert and Nyman, 1977, Trautmann and O'Rourke, 1985, Trautmann et al., 1985, Scarpelli et al., 2005), the coupled macroelement approach allows to get a safer and more accurate description the soil-pipe interaction force, and hence of the internal state of stress in the pipeline (Galli, 2005, Cocchetti et al., 2008, 2009a). This perspective of numerically modelling real 3D boundary value problems by means of macroelement approaches (direction (iii), as cited in §1) introduces even the fundamental possibility of switching to displacement-based modelling approaches, since the "loading" history of the system is actually represented by the global soil displacement profile (i.e. the far field, with respect to the pipe) observed for the landslide under investigation.

A couple of brief citations can finally be introduced. An interesting application of the macroelement concept is presently under investigation with respect to the agronomy field, with specific reference to the stability of trees. For these problems, as synthetically described by Dattola et al. (2019), the definition of a specific macroelement formulation can fruitfully improve the understanding of the mechanical response of root systems under combined actions and complex loading histories, as those given by wind effects on tall trees. More in general, the macroelement conceptual framework results to be very effective in boundary value problems involving several mechanical components. In this case, following a classical substructuring approach, the behavior of each single component can be described by mean of a generalized constitutive rule, and the global mechanical response of the system can then be obtained in terms of its generalized governing variables, once equilibrium equations and compatibility conditions are incrementally enforced among all the components. An interesting application of such approach has recently been proposed by Galli and di Prisco (2013), Galli et al. (2017), Galli and Bassani (2018) with reference to the design of slope stabilizing piles (thus overcoming the limitations of traditional limit equilibrium methods, based on an Ultimate Limit State framework, ULS), and by di Prisco et al. (2019) with reference to a displacement based approach for the design of earth embankments on soft soil strata, reinforced by means of piles or granular columns.

4 Comments and perspectives

Despite the well-established theoretical framework supporting the formulation of macroelement models, and the richness of contributions nowadays existing in Literature proving the validity of such approaches, macrolement formulations do not still represent a standard design tool in engineering practice. At Author’s feeling, the reason of such limited application is twofold: on one hand, the lack of numerical codes implementing macroelement constitutive rules among the usual relationships describing the interaction between a structural element embedded in a surrounding “hosting” material (as it is, for example, for embedded piles in design codes for deep foundations). Except for some examples of real boundary value problems solved by means of ad hoc numerical codes developed for research purposes (see e.g. the seismic analysis of Noto Cathedral described in di Prisco et al., 2006, or the analyses of long pipelines presented in Cocchetti et al., 2009b), usual engineering codes still model SSI by means of simplified interaction elements (like e.g. non-linear 1D uncoupled springs) rather than by implementing a fully coupled macroelement model (see in this respect the works of Zani et al., 2019, where an interesting analysis of an historical masonry arch bridge is discussed). On the other hand, the non-trivial calibration procedure often required by macroelement models is of course a crucial point for their wide applicability. For example, being these generalized constitutive relationships geometry-dependent, a change in the geometry or the inclusion of additional mechanical components would in principle require a recalibration of the constitutive rule. Moreover, some very peculiar aspects of the system behavior, deeply characterizing even the exercise conditions, are still under investigations, like the accurate description of the ratcheting phenomenon or the loading path dependency under low number of loading cycles (see on this latter point the work of Galli et al., 2015).

Nevertheless, given the high computational efficiency, macroelement approaches are in principle mainly indicated whenever a large number of rapid single analyses is required. Typical cases are represented by the predimensioning phase of a design process, where the main geometrical and mechanical properties have to be optimized often by comparing different alternative solutions. On the opposite side, similar needs are required by territorial surveying systems for lifelines networks, where rapid (and possibly real time!) calculations of SSI problems are required. Such examples directly involve risk mitigation strategies against natural hazards (see e.g. Ni et al., 2018, and Hu et al., 2019).

Beyond the – still limited – application of macroelement theories to standard design problems, it is worth notice that such approaches are particularly important on a cultural point of view. As previously said, they represent in fact a powerful interpretative tool, assembling together a description not only of the ultimate limit condition of the system (i.e. its failure criterion), but even of its pre-failure response, thus making them suitable to be implemented in complex analyses respecting both equilibrium and compatibility conditions (bypassing e.g. the limits of usual ULS approaches). Two main consequences could in principle be outlined: the availability of an accurate description of the pre-failure phase at the design level would allow consistent displacement estimations (which often represent a performance measure), thus facilitating the introduction of Displacement Based Design approaches (DBD). Furthermore, the comprehensive description of all the possible failure mechanisms in a unique failure criterion accounting for the coupling effect among the different loading components, gives even the possibility of a meaningful measurement of the safety of the system for each given set of applied loads, thus bypassing some limitations of the usual verification criteria based on uncoupled approaches.

In an engineering perspective, these points could potentially (and hopefully?) lead to remarkable improvement of the design process, and represent an important tool for the diffusion of Geotechnical competences.

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