A class of thermodynamic inertial macroelements for soil-structure interaction

Davide Noè Gorini[1*] [0000-0001-6673-0071], and Luigi Callisto [1] [0000-0001-9795-7420]

[1] Sapienza University of Rome, ITALY
*corresponding author: davideno.gorini@uniroma1.it

Abstract. The seismic performance of structures can be significantly influenced by the interaction with the foundation soils, with effects that depend on the frequency content and the amplitudes of the ground motion. A computationally efficient method to include these effects in the structural analysis is represented by the macroelement approach, in which a geotechnical system is modelled with a single macroelement that describes the generalized force-displacement relationship of the system. While this method has been mainly developed for shallow foundations, the present study proposes a class of macroelements representing the macroscopic response of different foundation types, including abutments, piled and caisson foundations. The generalized force-displacement relationships for these models are elastic-plastic and are derived using a rigorous thermodynamic approach. The plastic responses of the macroelements are bounded by the ultimate capacities of the geotechnical systems, while the inertial effects associated with the soil mass involved in the dynamic response of the structure are simulated by introducing appropriate participating masses. The macroelements are implemented in OpenSees; in this paper they are applied to assess the seismic performance of a tall viaduct showing highly nonlinear features.

Keywords: *dynamic soil-structure interaction, nonlinear behaviour, inertial effects, thermodynamic framework, OpenSees.*

1 The response of geotechnical systems in structural analysis

During the last years the need to include the effects of soil-structure interaction in the assessment of the seismic risk of structures has gained increased interest worldwide. These effects are particularly evident for bridges because of the recurring presence of abutments and deep foundations, that imply a large participation of soil mass to the dynamic response of the structure [1-6].

It is well known that the dynamic behaviour of geotechnical systems is markedly nonlinear starting from small strain levels, showing amplification at the resonance frequencies of the soil-foundation system. This combined nonlinear and frequency-dependent response may increase the ductility demand for the structural members [5], and this effect cannot be evaluated through the usual substructure approach, which is based on linear behaviour. The strength and stiffness properties at the macroscopic scale, that refers to the entire soil-foundation system, are moreover affected by the loading direction. This effect reflects also on the mass participation of the soil, as demonstrated for foundations [7-8] and bridge abutments [9-10].

In this paper, a class of macroelements for geotechnical systems is proposed as constitutive relationships able to reproduce the soil-structure interaction phenomena discussed above with a minimal computational effort. The main ingredients of the adopted thermodynamic formulation are described below, and an illustrative example on the use of the macroelements in the structural analysis is finally shown.

2 A potential-based formulation

The macroelements (MEs) developed in this work are aimed at simulating the response of geotechnical systems, such as foundations and bridge abutments, in the numerical analysis of structures. Each ME relates the generalised forces Q_i (three forces and three moments), exchanged between the geotechnical system and the superstructure, to the corresponding displacements and rotations q_j through a second-order tangent stiffness matrix H_{ij}, such that $Q_i = H_{ij} \times q_j$.

The MEs are multi-surface plasticity models with kinematic hardening derived with a consistent thermodynamic approach, using hyperplasticity [11]. The constitutive response requires the definition of two potentials, namely the energy and dissipation functions, formulated to provide a multi-axial, frequency-dependent and hardening response. The dissipative response is based on some primary assumptions, that are the validity of Ziegler's principle [12], the additive decomposition of the elastic and plastic components of deformations and the associativity of the plastic flows, so that the dissipation function can be obtained by the yield surfaces.

The constitutive ingredients needed to compute the potentials are 1) the identification of the mass and stiffness tensors at small displacements (elastic response) and 2) the evaluation of the ultimate limit state surface bounding the plastic domain.

3 Energy function

The proposed MEs represent a multi-axial generalisation of the model developed in [5] for bridge abutments, shown in Figure 1. The energy function for all the MEs, expressed by Gibbs free energy g, therefore reads:

$$g\left(Q_i^{(l)}, q_i^{(n)}, m_i^{(n)}\right) = -\frac{1}{2} \cdot C_{ij}^{(0)} \cdot Q_j^{(0)} \cdot Q_i^{(0)} - \sum_{n=1}^{N} Q_i^{(n)} \cdot q_i^{(n)} + \frac{1}{2} \cdot \sum_{n=1}^{N} H_{ij}^{(n)} \cdot q_j^{(n)} \cdot q_i^{(n)} -$$

$$-Q_i^{(R)} \cdot q_i^{(R)} - \sum_{n=1}^{N} m_{ij}^{(n)} \cdot \sum_{h=n}^{N} \ddot{q}_j^{(h)} \cdot \sum_{k=n}^{N} q_i^{(k)} + \frac{1}{2} \cdot \sum_{n=1}^{N} m_{ij}^{(n)} \cdot \sum_{h=n}^{N} \dot{q}_j^{(h)} \cdot \sum_{k=n}^{N} \dot{q}_i^{(k)} \qquad (1)$$

According to Eq. 1, for sufficiently small displacements q_j the response is purely elastic and is controlled by the elastic free energy $0.5 \cdot C_{ij}^{(0)} \cdot Q_j^{(0)} \cdot Q_i^{(0)}$, that is proportional to the square of the elastic force vector $Q_j^{(0)}$ through the second-order compliance matrix $C_{ij}^{(0)}$. When the total force vector Q_i reaches the innermost yield surface the response becomes elastic-palstic. In this case plastic displacements occur with amplitude and direction that depend on the number of plastic flows activated. During plastic loading, the force $Q_i^{(n)}$ developing in the n^{th} plastic flow spends work in the respective palstic displacement $q_i^{(n)}$ (term $Q_i^{(n)}\cdot q_i^{(n)}$ in Eq. 1); moreover, by virtue of the kinematic hardening the macroelement stores energy through the second order kinematic tensors $H_{ij}^{(n)}$ (term $H_{ij}^{(n)}\cdot q_j^{(n)}\cdot q_i^{(n)}>0$). The term $Q_i^{(R)}\cdot q_i^{(R)}$ is associated with an additional irreversible displacement vector $q_i^{(R)}$ aimed at reproducing the ratcheting phenomenon, as already proposed in [13] for piles. The energetic contributions described so far define completely the nonlinear behaviour of the ME, while the frequency-dependent features are enclosed in the last two terms of Eq. 1, that are proportional to the second order mass tensors $m_{ij}^{(n)}$ associated with the plastic flows.

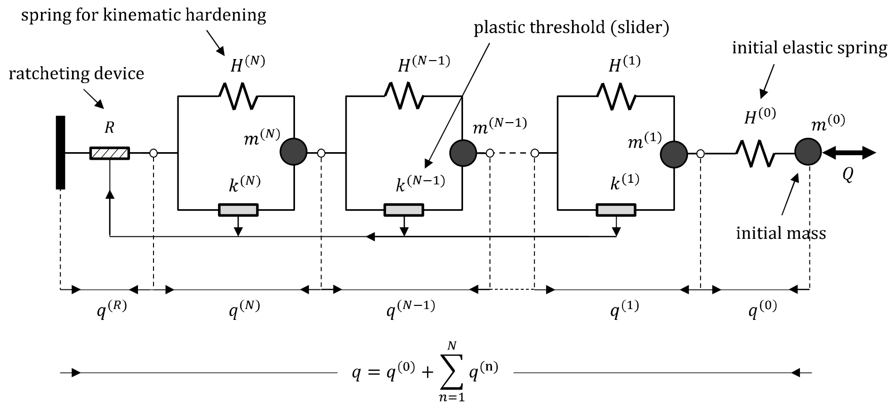

Fig. 1. One-dimensional layout of the inertial, multi-surface hyper-plastic macroelement.

4 Dissipative response

Energy dissipation occurs when the MEs exhibit a plastic response, that is when the force state is within the plastic domain. In the context of multi-surface plasticity, the plastic response is obtained through a series of yield surfaces $y^{(n)}$ (n=1,…, N) defined in the force space, that provide a multi-linear response up to the attainment of the ultimate conditions of the system, described by the ultimate limit state surface. Since the internal yield surfaces are homothetic to the ultimate locus, the definition of the plastic domain requires only the definition of the ultimate capacity of the geotechnical system under multi-axial loading. The following models of ultimate surface are here taken into consideration, as schematically shown in Figure 2:

- shallow foundations (Figure 2a): translated hyper-ellipsoid in the space of the forces, Q_1-Q_2-Q_3, and moments, Q_{R1}-Q_{R2}-Q_{R3}, exchanged between the foundation and the superstructure, as proposed by Martin et al. [14];

- deep foundations (Figure 2b): hyper-egg with super-elliptical generatrices describing the combinations of forces, Q_1-Q_2-Q_3, and moments, Q_{R1}-Q_{R2}, producing failure of a pile group [15];
- caisson foundations (Figure 2c): roto-translated hyper-ellipsoid in the generalised force space, Q_i (i=1, 2, 3, R1, R2, R3), relative to the force transfer between foundation and superstructure in presence of sloping ground (developed in this work);
- integral bridge abutments (Figure 2d): roto-translated hyper-ellipsoid in the generalized force space, Q_i, representing the force exchange at the deck-abutment contact, as an extension of the model by Gorini et al. [16] for semi-integral abutments.

The reader can refer to the papers above for the description of the calibration procedures and to [3,5] for the derivation of the incremental elastic-plastic response.

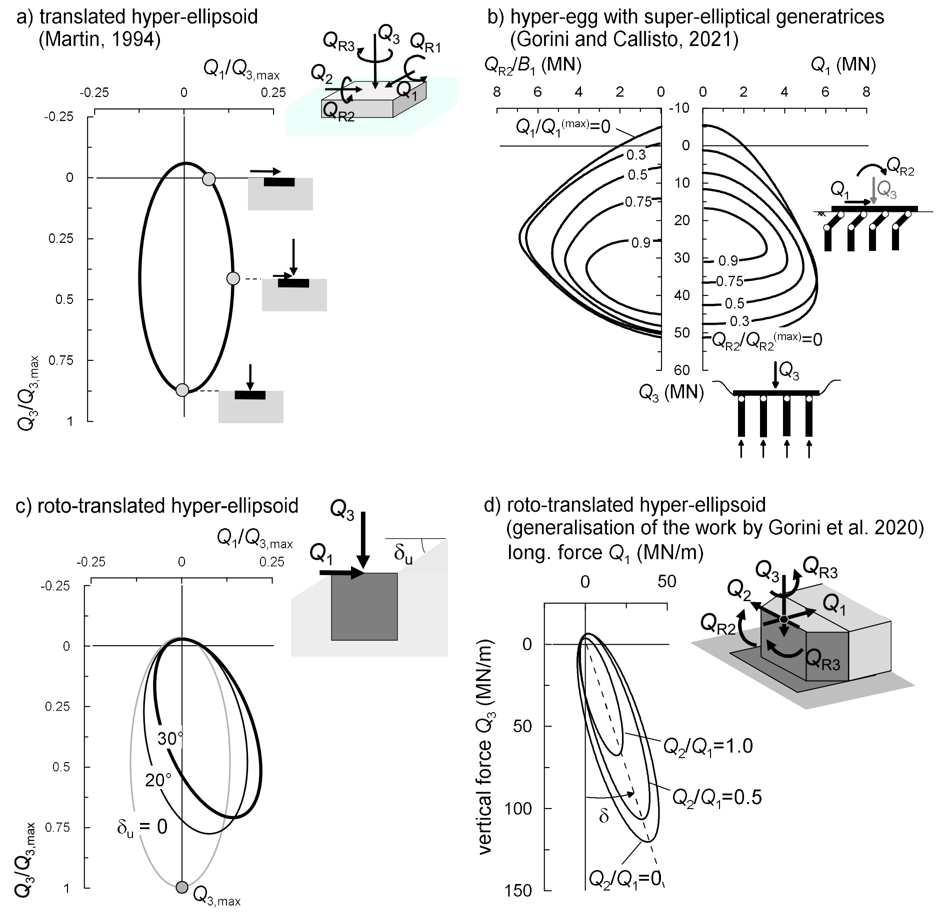

Fig. 2. Models used for the ultimate limit state surface of the macroelements, for the case of a) shallow foundations, b) deep foundations, c) caisson foundations, d) integral bridge abutments.

5 Implementation and analysis method

The MEs are implemented in the analysis framework OpenSees [17] as multi-axial materials. Each material can be assigned to a novel zero-length finite element, named *ZeroLength6D*, simulating the full translational-rotational coupling of the response between the two overlapped nodes. In the current version in OpenSees, the response of the new materials does not include inertial effects, hence only the effect of the first mass tensor $m_{ij}^{(0)}$ can be reproduced by assigning the corresponding masses to the soil-structure contact node in the global structural model. As a result, the MEs can reproduce with good accuracy the frequency-dependent response of the geotechnical system from small to medium strain levels, while they may somewhat underestimate the period lengthening towards failure [3,5].

The analysis procedure is the one proposed in [3,5], based on which the subsoil is considered as composed of two regions: the near field, intended as the soil zone interacting with the structure whose response is simulated by means of the ME, and the far field not influenced by the presence of the structure. In this view, the propagation of the seismic waves from the bedrock up to the lower boundary of the near field, called effective depth z_{eff}, can be studied separately through a free field site response analysis. The motion computed at z_{eff} represents the seismic input for the MEs in the global structural model to carry out dynamic analyses in the time domain. The effective depth can be taken as $z_{eff} = 10\times D$ for deep foundations (D is the pile diameter) and $z_{eff} = L_f$ or $\max\{L_f, 10\times D\}$ for bridge abutments with shallow and deep foundations, respectively (L_f is the width of the abutment foundation).

6 Illustrative example and discussion

The proposed MEs are now employed to analyse the seismic performance of the idealised case study shown in Figure 3a. The bridge rests on five supports and crosses a V-shaped valley whose subsoil reflects typical layering and mechanical features of the Apennine area of central Italy. The subsoil is composed of four layers, S1 to S4 in the figure, with shear wave velocity, V_s, increasing with depth. At the location of abutment A1, V_s ranges from 200 m/s at the foundation level to 1000 m/s at the bedrock, the latter encountered at a depth of 95 m. The strength of the soil layers is described by a cohesion of 10 kPa and angle of shearing resistance in the range 24°-26°.

The structural members were designed referring to Italian technical provisions (Italian Building Code, 2018), considering the seismic demand for the site at hand. According to the static scheme of the bridge, in the longitudinal direction the deck is connected only to piers P2 and P3. The abutment A2 is connected longitudinally to the deck using viscous dampers, while relative deck-abutment deformations at A1 are free. In the transverse direction, the deck is connected to all piers and abutments. The foundation piles have diameters ranging between 1.0 - 1.2 m.

The seismic performance of the bridge was investigated using a numerical representation of the bridge model with the MEs implemented in OpenSees. The results of this analysis are compared with the ones of a dynamic analysis of the structural system in which soil-structure interaction is neglected. As per the calibration of the MEs, here omitted for brevity, one can refer to [5,10] for the evaluation of the modal characteristics of the soil-abutment system, and for instance to the commercial software DYNA [18] for the identification of the dynamic behaviour of piled foundations; the definition of the plastic domain follows the rationale exposed in Section 4. The resulting dynamic responses at small displacements are characterised by fundamental vibration periods of 0.15 s to 0.25 s for the abutments and of 0.05 s to 0.11 s for the pier foundations. The piers were modelled as displacement-based beam elements with hollow sections reproducing the properties of the effective reinforced concrete cross section. The Kent-Scott-Park model [19] was assigned to the concrete fibers and an elastic-plastic material with kinematic hardening to the steel fibers. The P-δ transformation was used to account for geometric nonlinearity effects. The stiffness and strength of the bearing devices were simulated through the combination of nonlinear rheological elements. The deck was reproduced through equivalent elastic force-based beam elements.

In the numerical model with MEs, a staged analysis procedure was adopted, composed of a first gravitational stage and the subsequent application of a three-component seismic motion following the procedure in Section 5. The results shown in the following refer to a no-collapse earthquake scenario. The bridge performance is concisely quantified in terms of the shear force-drift responses of the bearing devices on the abutments A1 and A2, in Figures 3b and 3d, the shear force-drift response at the base of pier P2, in Figure 3c, the longitudinal force-displacement responses of the MEs of abutment A1, pier P2 and abutment A2, in Figures 3e and 3f. It is evident that the nonlinear response of the geotechnical systems magnifies the displacements of the superstructure compared to the fixed-base model, causing significant permanent effects that increase the displacement and ductility demands for the bearing devices and the piers members, respectively. The abutments show a more pronounced nonlinear response than the piers foundations because of the higher participation of the soil mass involved in the embankment. The abutments attain the active resistance (force cut-off in Figs. 3e,g) and accumulate irreversible displacements towards the centre of the bridge. However, this permanent effect is less evident for the strong abutment, A2, due to the smaller height and to the interaction with the superstructure.

The above results point to the need to account for a combined frequency-dependent and nonlinear response of the geotechnical systems in the assessment of the structural performance. The proposed macroelements may be employed in large parametric studies and for a direct verification of the preliminary design assumptions, as they require limited computational resources.

7 Acknowledgements

Part of this research was sponsored by the Italian Department of Civil Protection (Project RINTC 2019/21). The Authors acknowledge the contribution of Prof. P. Franchin and Dr. F. Noto for the development of the structural model of Figure 3.

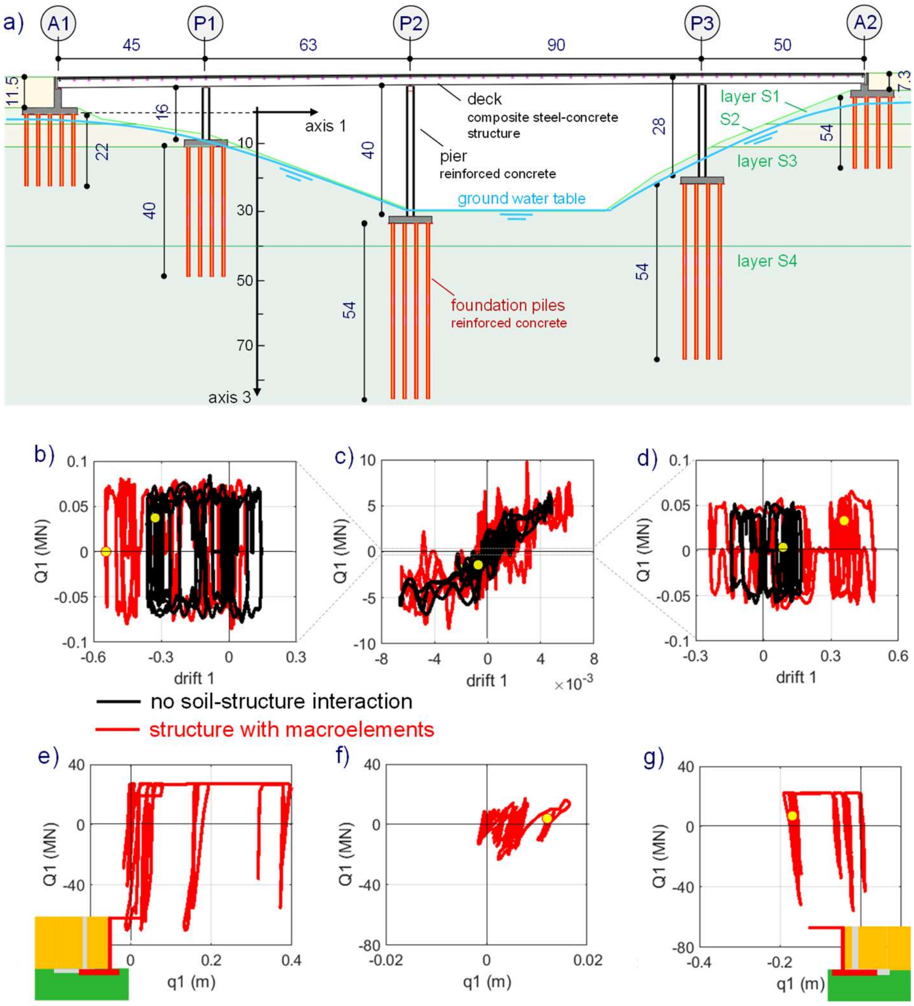

Fig. 3. a) longitudinal section of the reference soil-bridge system (lengths in meters), and representation of the seismic performance in terms of: b,d) shear force-drift responses of the bearing devices on A1 and A2, respectively, c) shear force-drift response at the base of P2, e,f,g) longitudinal, force-displacement responses of the MEs for A1, P2 and A2.

References

1. Elgamal, A., Yan, L., Yang, Z., Conte, J. P.: Three-Dimensional Seismic Response of Humboldt Bay Bridge-Foundation-Ground System. Journal of Structural Engineering, 134(7), 1165-1176 (2008). doi:10.1061/(ASCE)0733-9445(2008)134:7(1165).
2. Stefanidou, S. P., Sextos, A. G., Kotsoglou, A. N., Lesgidis, N., & Kappos, A. J.: Soil-structure interaction effects in analysis of seismic fragility of bridges using an intensity-based ground motion selection procedure. Engineering Structures, 151, 366-380 (2017).

3. Gorini, D. N.: Soil–structure interaction for bridge abutments: two complementary macro-elements. PhD thesis, Sapienza University of Rome, Rome, Italy (2019).
4. Gorini, D. N., Callisto, L.: A coupled study of soil-abutment-superstructure interaction. In: Geotechnical research for land protection and development - proceedings of CNRIG 2019 (eds F. Calvetti, F. Cotecchia, A. Galli and C. Jommi), pp. 565-574. Cham, Switzerland: Springer (2020).
5. Gorini DN, Callisto L, Whittle A.J.: An inertial macroelement for bridge abutments. Géotechnique (2020). doi.org/10.1680/jgeot.19.P.397.
6. Gallese, D., Gorini, D. N., Callisto, L.: On a novel seismic design approach for integral abutment bridges based on nonlinear static analysis. In: 4th International Conference on Performance-based Design in Earthquake Geotechnical Engineering, China (2022).
7. Paolucci, R., Pecker, A.: Seismic bearing capacity of shallow strip foundation on the dry soils. Soils Found. 37(3), 95–105 (1997).
8. Pane, V., Vecchietti, A., Cecconi, M.: A numerical study on the seismic bearing capacity of shallow foundations. Bull. Earthquake Eng. 14 (11): 2931-2958 (2016).
9. Kotsoglou, A. N., Pantazopoulou, S. J.: Bridge-embankment interaction under transverse ground excitation. Earthquake Engineering & Structural Dynamics, 36(12), 1719-1740 (2007). doi: 10.1002/eqe.715.
10. Gorini, D. N., Callisto, L., Whittle, A.J.: Dominant responses of bridge abutments. Soil Dynamics and Earthquake Engineering, 148:106723 (2021). doi: 10.1016/j.soildyn. 2021.106723.
11. Collins, I. F., Houlsby, G. T.: Application of thermomechanical principles to the modeling of geotechnical materials. Proc. R. Soc. Lond. Ser., A 453(1964), 1975–2001 (1997).
12. Ziegler, H.: An introduction to thermomechanics. Amsterdam, the Netherlands: North Holland (1977).
13. Houlsby, G. T., Abadie, C., Beuckelaers, W., and Byrne, B.: A model for nonlinear hysteretic and ratcheting behaviour." International Journal of Solids and Structures, 120, 67-80 (2017).
14. Martin, C. M.: Physical and numerical modeling of offshore foundations under combined loads. PhD thesis, University of Oxford (1994).
15. Gorini, D. N., Callisto, L.: Generalised ultimate loads for pile groups. Accepted for publication in Acta Geotechnica (2021).
16. Gorini, D. N., Whittle, A. J., Callisto, L.: Ultimate limit states of bridge abutments. J Geotech Geoenviron Eng, 146(7) (2020). https://doi.org/10.1061/(ASCE)GT.1943-5606.0002283.
17. McKenna, F., Scott, M. H., & Fenves, G. L.: OpenSees. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. Journal of Computing in Civil Engineering, 24, 95-107. doi:10.1061/(ASCE)CP.1943-5487.0000002 (2010).
18. El Naggar, M. H., Novak, M., Sheta, M., El-Hifnawy, L., El-Marsafawi, H.: DYNA6.1 - a computer program for calculation of foundation response to dynamic loads. London, Ontario: Geotechnical Research Centre, University of Western Ontario (2011).
19. Scott B. D., Park, R. Priestley, M. J. N.: Stress-strain behavior of concrete confined by overlapping hoops at low and high strain rates. ACI J, 79: 13–27 (1982).