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Finite Element Analyses of Piled Foundations: Interaction Domains Under Undrained Conditions

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Abstract. Most of the bridges in Europe countries are now approaching their design life. Therefore, at present crucial is the choice of the most suitable retrofitting solution taking the current design standards into account. From an economic point of view the costs related to the foundations adaptation are not negligible at all, even because design approaches are in general over-conservative. For instance, in case of piled foundations, the presence of the raft is conventionally disregarded in the calculation of the pile group bearing capacity under general loading. In this work a pile group foundation embedded in a silty-clay soil stratum is studied to emphasise how the use of a non-standard approach may allow to make more sustainable the interventions. An extensive 3D pseudo-static finite element numerical analyses campaign, under general loading, accounting for the non-linear soil mechanical behaviour, was performed. The results were interpreted in terms of interaction domains for the piled foundation system (raft + piles).

Keywords: Bearing capacity · Combined loading · Failure mechanism · Piled foundation · 3D finite element analysis

1 Introduction

Most of the bridges in Europe, are approaching or have already approached their design life. For this reason, they have to be reassessed in terms of safety and serviceability. This is also true for foundations, for which eventual retrofitting measures are often very expensive and technologically challenging.

For most of the tall bridges founded on piles, critical are the aspects related to seismic actions and, in particular, to the moment capacity of the foundation [1] along the bridge transversal direction. According to the current design approaches [2, 3], the moment capacity is calculated by on one side disregarding the presence of the raft and, on the other, assuming the global bearing capacity to be reached when the most loaded pile reaches its bearing capacity (under either tension or compression). The design standards recognize the current practice to be over-conservative and the limit state to occur only when a significant number of piles reaches its bearing capacity [3], but do not suggest any calculation method accounting for (i) the ductile redistribution of vertical forces among

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piles and (ii) the presence of the raft. Only recently, an approach to estimate the bearing capacity of pile groups under inclined and eccentric loads, accounting the first aspect for, was proposed [4, 5]. This approach, however, disregarding the presence of the foundation raft, is still over-conservative, especially in the typical case of existing bridges founded on a small number of piles. The role of both foundation raft and interaction mechanisms, involving the pile-raft-soil system, is rarely analysed and only very recently, [6], the beneficial role of the raft has been experimentally and numerically shown not to be negligible.

The goal of this paper is to put in evidence that finite element (FE) numerical analyses could provide a significant insight in the pile-soil-raft interaction, allowing a more aware design of both new foundations and retrofitting measures.

To this aim, a case study is numerically discussed by assuming the soil to behave under undrained conditions (Sect. 2). The mechanical response of the system is described by defining the interaction domains and by illustrating the failure mechanisms developing in the soil (Sect. 3). Finally, the foundation system is verified under design seismic actions by employing the interaction domains (Sect. 4).

2 Numerical Model

The viaduct considered in this paper, built at the end of the ‘70 s, is 13 m high and consists of three spans of 32 m and a 18 m-wide deck. The piers are founded on rectangular piled rafts (Fig. 1). The raft bases are at 4 m depth from the ground surface, whereas the 7 reinforced concrete bored piles, connected to the raft, are characterized by a diameter of 1.2 m and are 12 m long.

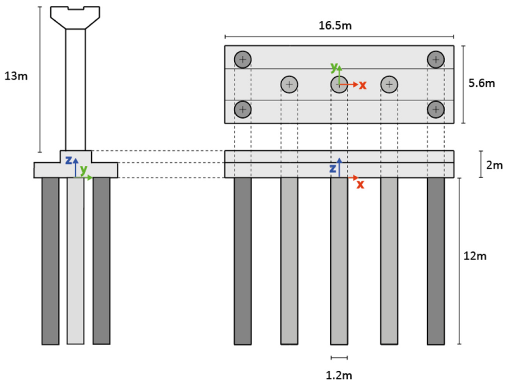

Fig. 1. Geometry of the piled raft foundation.

Recent restoration works made possible a geotechnical characterization of the site. The soil profile consists of (i) 1 m of landfill material, (ii) 5 m of coarse sand and sandy gravel and (iii) an underlying layer composed of fine-grained materials (clayey silt, silty and marly clay). To provide a safe side estimation, the granular material stratum is disregarded and the piled foundation is assumed to be positioned in a saturated homogeneous clay soil stratum of unit weight equal to $\gamma_{sat} = 20\,\mathrm{kN/m^3}$. The results of standard penetration tests [7] highlight a rather constant profile of undrained strength along depth ($S_u = 150$ kPa).

The mechanical response of the system is analysed by performing non-linear pseudo-static 3D FE numerical analyses by employing the commercial code MIDAS/GTS-NX. The geometry and spatial discretization of the FE model (for the sake of symmetry, only one half of the spatial domain has been discretized) are reported in Fig. 2.

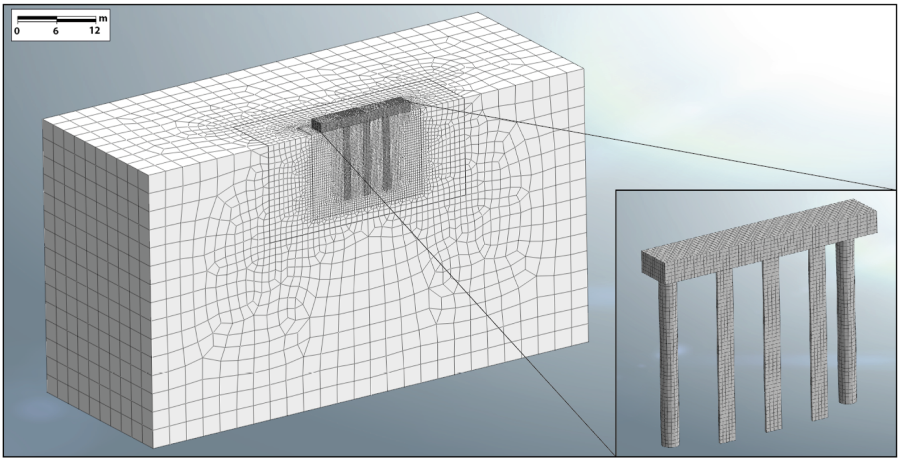

Fig. 2. Finite element discretization for 3D numerical analyses: full model with a zoom on the piled raft only.

Piles and concrete raft (with a unit weight is $25\,\mathrm{kN/m^3}$) are assumed to be elastic with a Young modulus of 30GPa and a Poisson ratio equal to 0.3. The soil is modelled as a 1-phase elastic perfectly plastic material, with a Tresca failure criterion and an associated flow rule. Elastic perfectly plastic interface elements have been set at both soil-pile and soil-raft interfaces. Along the normal direction, these elements are perfectly fragile under tension and "quasi-rigid" under compression (normal stiffness equal to 500 $\mathrm{MN/m^3}$). Along the tangential direction, a nil dilatancy Tresca failure criterion is adopted (the limit tangential stress is imposed to be equal to S_u) and tangential stiffness is assumed to be 50 $\mathrm{MN/m^3}$. Both vertical and horizontal displacements are constrained at the bottom boundary. Along the lateral sides, only vertical displacements are allowed. The lateral soil above the foundation plane is modelled as a uniform surcharge p = 80 kPa.

The initial conditions have been imposed as it follows: (i) the geostatic state of stress condition of the stratum is obtained by linearly increasing gravity, (ii) the pile construction is simulated by progressively changing mechanical properties and unit weight in the piles domain (from soil to piles properties), (iii) the raft construction is simulated by linearly increasing mechanical properties and unit weight in the raft domain. Finally, (iv) the vertical load (V of Fig. 3) is linearly increased up to a prescribed value.

To derive the interaction domain, two different sets of analyses were performed. In the former one, aimed at defining the M_y-V section, 7 prescribed V values are imposed

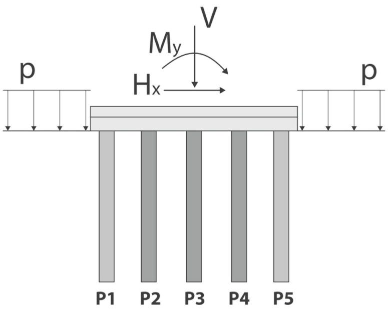

Fig. 3. Geometrical scheme (longitudinal section) with applied loads.

and during the numerical tests $\dot{V} = \dot{H}_x = \dot{H}_y = \dot{M}_y = 0$ whereas modulus of M_y is progressively increased up to failure (Fig. 4a). In the latter one, aimed at defining the M_y-H_x section, $\dot{V} = \dot{H}_y = \dot{M}_y = \dot{M}_x = \dot{e} = 0$ (where $e = M_y/H_x$) but modulus of M_y and H_x are progressively increased up to failure. In this case the prescribed V value coincides with the superstructure weight ($V = V_d = 24$ MN).

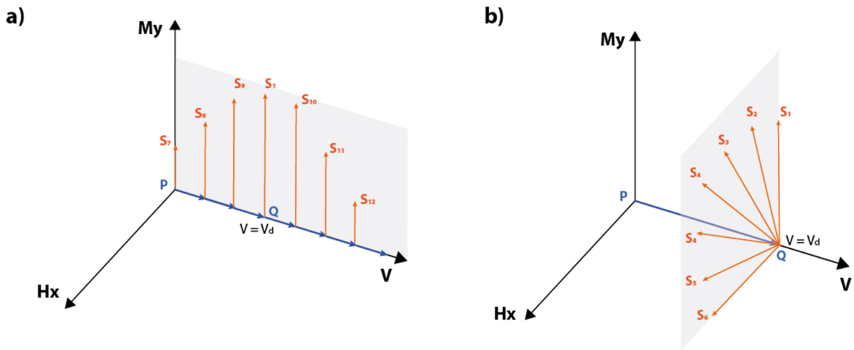

Fig. 4. Load paths in M_y-H_x-V space.

3 Numerical Results

The numerical results are discussed in terms of interaction domains (in Fig. 5 and 6 the straight lines represent the imposed generalized stress paths) and contours of irreversible deviatoric strains (A-D of Fig. 5 and A-H of Fig. 6).

The M_y-V section of the interaction domain, illustrated in Fig. 5, is characterized by a non-negligible upward vertical strength ($V < 0$), due to the pile shaft resistance. This resistance is significantly lower than the compression one due to the contribution of both pile bases and raft. The asymmetry in the interaction domain section is clarified by the plastic mechanisms in the foundation soil plotted in Fig. 5A–D, corresponding to points A-D in M_y-V plane of Fig. 5. In particular, for $V \leq 0$, the raft partially detaches from the soil and plastic strains mainly develop along the piles shaft and in the proximity of the compressed edge of the foundation (Fig. 5A and B). On the contrary, for positive V values, raft detachment does not take place and plastic strains develop both in the proximity of the piles (especially at the base) and at the foundation edges (Fig. 5C and D). It is worth mentioning that the "closed" failure mechanisms of Fig. 5C and D, differing significantly from the one expected in case of shallow foundations, seem to be a sort of punching in which lateral shear of the entire block and bearing capacity of each pile tip dominate the soil system interaction.

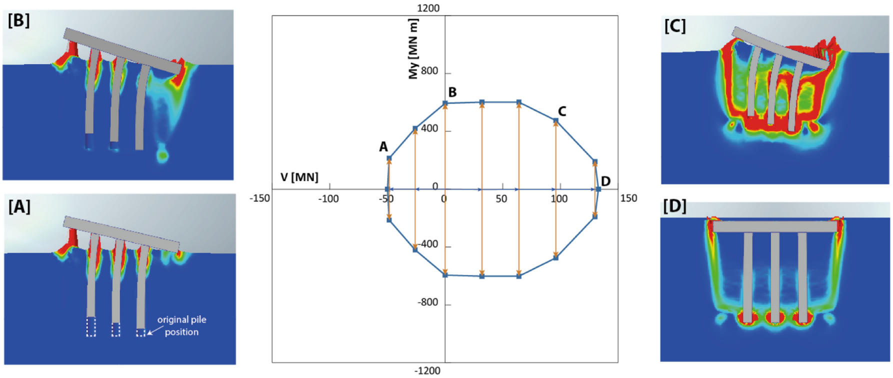

Fig. 5. Interaction diagram sections with load paths in M_y-V plane and plastic strains contours in points A-D.

The M_y-H_x section of the interaction domain (for $V = V_d$) is illustrated in Fig. 6. Analogously to what observed for shallow foundations [8] and for caissons [9], the M_y-H_x section shape is an ellipse whose principal axes are counter-clockwise rotated from the coordinate axes. The orientation of the ellipse principal axes depends on the plastic mechanism developing in the foundation soil: when H_x and M_y are opposite (Fig. 6E–G, corresponding to points E-G), large plastic strains develop in both sides of the foundation, whereas when H_x and M_y are concordant (Fig. 6H), large plastic strains develop only on the compressed side of the foundation.

4 Geotechnical Verification of the Foundation System

The interaction domains illustrated in Sect. 3 are here below employed for the pseudo-static seismic geotechnical verification of the piled foundation. The actions applied to the foundation are calculated, by following NTC2018 [3]: both kinematic interaction and soil inertia are disregarded, whereas the inertial forces transferred by the superstructure are calculated by using an uncoupled approach (the structural dynamic analysis for the viaduct was carried out by assuming the foundations to provide a rigid constraint). Different load combinations were accounted for but, for the sake of brevity, only the most critical one will be discussed.

The verification according to NTC2018 [3] requires the use of a partial coefficient γ_R, defining a reduction of the foundation system strength. The design code, however,

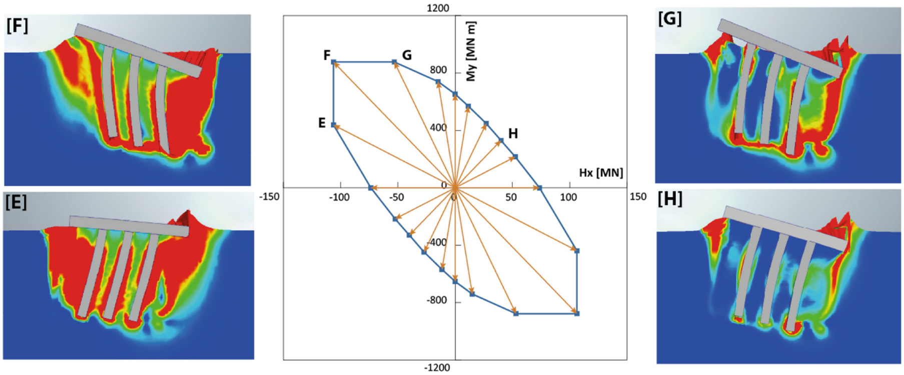

Fig. 6. Interaction diagram sections with load paths in M_y-H_x plane and plastic strains contours in points E-H.

does not provide a γ_R value to be used in case of interaction domain for the entire piled foundation. By following the philosophy of NTC2018 [3], the authors decided to homothetically scale the interaction domain by $\gamma_R = 2.3$ (solid line in Fig. 7). In Fig. 7, the cross, representing the design load, lies inside the scaled interaction domain, implying that, in its current state, the foundation system can be considered to be "safe" and does not require any retrofitting measure, at least in relation to soil limit conditions.

For the sake of completeness, in Fig. 7 are also reported the interaction domain sections obtained by using a conventional approach (dashed lines in Fig. 7), based on the following assumptions: (i) rigid raft not transmitting stresses to the soil, (ii) rigid-perfectly plastic behaviour of the soil, (iii) pile heads rigidly connected to the raft by means of hinges (piles are only axially loaded) and (iv) ultimate loads for each pile along horizontal and vertical directions independent to each other. According to these

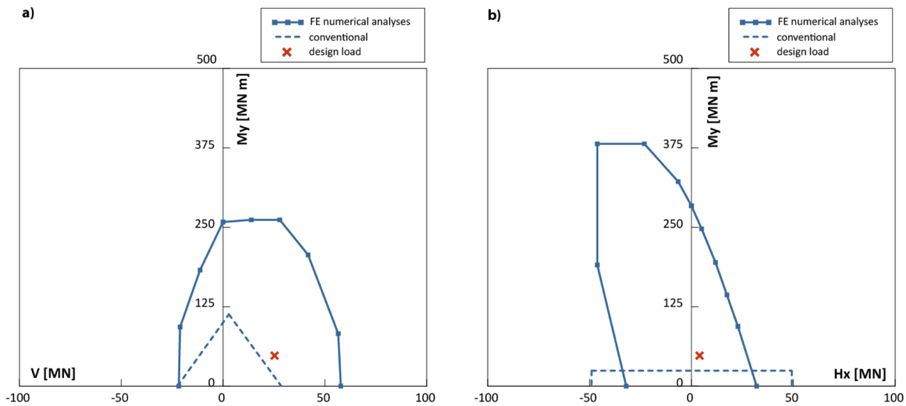

Fig. 7. Interaction diagram sections (partial factors of safety applied) and design load: comparison between numerical analyses results and conventional verification approach in (a) M_y-V plane and in (b) M_y-H_x plane.

assumptions, the interaction domain can be obtained: (i) by imposing a linear distribution for the vertical loads transmitted to each pile (Q_i), (ii) by imposing the vertical balance of momentum and the rotational equilibrium, (iii) by calculating the upward and downward pile bearing capacities [10], and (iv) by using the partial factors of safety of NTC2018 [3]. It is worth mentioning that the rectangular shape in the M_y-H_x plane is due to the assumption of independent ultimate pile load along horizontal and vertical direction.

The comparison in Fig. 7 of the interaction domains, obtained by using the FEM numerical results and the conventional simplified approach, puts clearly in evidence the role played by the raft in affecting the response of the system, in particular in cases like this, where the ratio L/B (where L is the pile length and B the raft width) is sufficiently small.

5 Conclusions

The verification of the safety of existing structures is nowadays a topic of great practical relevance since in Western countries many structures are approaching/have approached their design life. This is particularly critical in case of foundations since their retrofitting is very expensive and requires large investments in terms of time and raw materials.

In this paper, the authors numerically analysed the undrained response of the piled foundation of an existing bridge. The numerical results allowed to define an interaction domain, accounting both piles and raft for, to be used for the geotechnical verification of the foundation system. The definition of the interaction domains has been shown to be useful for the pseudo-static verifications of the foundation under seismic conditions; to this aim, particularly useful is the description of the interaction domain in overturning moment vs horizontal load plane. In this plane the shape of the interaction domain is elliptic, as was shown by other author with reference to shallow foundations or rigid caissons. The description of yielded zones in the soil has allowed to define the geometry of the failure mechanism, not accounting for soil inertia, associated with the different ultimate states corresponding to the different load paths imposed. The analysis of these mechanisms allows to capture the role of the raft-piles coupling, which is expected to dominate the response of the foundation system in all those cases characterized by short piles and large values of the raft width. In case of bridges, this geometry is quite common in the cross-section orthogonal to the bridge axis and, for this reason, the case here analysed may be considered to be quite general.

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