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Some applications of interaction domains to pile foundations design

Quelques applications des domaines d'interaction à la conception de fondations sur pieux

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ABSTRACT: Pile foundations are generally checked against eccentric vertical loads by referring to the most loaded pile in the group, whose length is set to achieve a design bearing capacity at least equal to its design vertical load. All other piles in the group are then assigned the length obtained in this way. Intuitively, any pile group designed with this method is left with plenty of spare bearing capacity, well beyond the demand from minimum safety factors. In contrast, interaction domains allow to treat a pile group as a whole system and to include the contribution of each pile into the overall bearing capacity of the foundation, allowing the mobilisation of limit bearing capacity for most piles in the group. The lack of closed-form solutions made in the past the use of interaction domains impractical. However, some recent advances now provide analytical relationships for the full shape of the domain, without limitations to the pile group geometry.Some applications of interaction domains are presented in the paper for two Italian High Speed Railway projects, currently under construction.

RÉSUMÉ: Les fondations sur pieux sont généralement vérifiées contre les charges verticales excentriques en se référant au pieu le plus chargé du groupe, dont la longueur est définie pour atteindre une capacité portante de conception au moins égale à sa charge verticale de conception. Tous les autres pieux du groupe se voient ensuite attribuer la longueur ainsi obtenue. Intuitivement, tout groupe de pieux conçu avec cette méthode dispose d'une grande capacité portante disponible, bien au-delà de l'exigence des facteurs de sécurité minimaux. En revanche, les domaines d'interaction permettent de traiter un groupe de pieux comme un système global et d'inclure la contribution de chaque pieu dans la capacité portante globale de la fondation, permettant ainsi de mobiliser la capacité portante limite pour la plupart des pieux du groupe. Le manque de solutions de forme fermée a rendu par le passé l'utilisation de domaines d'interaction peu pratique. Cependant, certaines avancées récentes fournissent désormais des relations analytiques pour la forme complète du domaine, sans limitations à la géométrie du groupe de pieux. Certaines applications des domaines d'interaction sont présentées dans l'article pour deux projets de chemin de fer italien à grande vitesse, actuellement en construction.

Keywords: Pile groups; interaction domains; pile capacity.

1 INTRODUCTION

Axially loaded pile foundations shall be designed to provide adequate strength against a bearing capacity failure.

Routine design approach is typically based on three fundamental steps:

- Assessment of the compression (F_c) or tension (F_t) load acting on each pile belonging to the pile foundation,
- Evaluation of the individual axial capacity of the single pile under compressive (R_c) or tensile (R_t) loads,
- Estimate of the most probable failure mechanism (individual pile failure mechanisms or block failure mechanism).

With the only exception of groups with piles embedded in fine-grained soils at spacing s smaller than some critical value (say 2–4 times the pile diameter d; de Sanctis and Mandolini, 2006), individual pile failure mechanism occurs, and the axial pile resistance of the pile group R_g is evaluated as follows:

$$R_g = \sum_1^N R_i \qquad (1)$$

Checks against ULS (Ultimate Limit State) are then generally made with reference to the most loaded pile within the group, in practice selecting pile length L and diameter d for all the piles in order to satisfy the following inequality according to EC7:

$$R_{i,d} \geq F_{i,d,max} \tag{2}$$

where: $R_{i,d}$ = single pile design resistance; $F_{i,d,max}$ = maximum design action on single pile.

However, it is all too evident that achievement of the axial capacity on the most loaded pile does not represent a failure condition for the whole group and can be viewed just as the onset of yielding. At this point, the pile group is still capable to carry a further increase in the external load taking advantage from the ductility of the system.

To consider this aspect, in the past attention has been placed on the assessment of interaction diagrams of pile groups under vertical eccentric loads, although limited to experimental observations on reduced scale pile groups resting on homogeneous soils (for instance, Meyerhof et al., 1983; Meyerhof and Yalcin, 1984). Recently, a closed-form exact solution for the interaction domains of pile groups under vertical eccentric loads has been proposed by Di Laora et al. (2019) to describe the failure of a group of piles considered as a whole, then also extended to the case of inclined eccentric load (Di Laora et al., 2022).

In the following, the advantages coming from the applications of the interaction domains approach will be shown with reference to examples taken from two Italian High Speed Railway Line (HSRL) projects, currently under construction. Both projects constitute an important part of the European TEN-T program for sustainable transport, which aims to transfer 50% of the currently road freight traffic to railway by 2050, triple the high-speed rail network and connect the main seaports to the railways and reduce emissions from transport by 60%.

2 VERONA-PADUA HSRL PROJECT

Figure 1 shows the pile group layout for Pier 3 of one of the viaducts crossing the HSRL. The group is composed by eight bored cast in situ piles with d=1.2m, installed at spacing s=3.6m=3·d. Piles are connected to a stiff rectangular raft having B_{max}=13.2m and B_{min}=6m.

Local ground conditions feature predominantly cohesive soils, as summarised in Table 1 (unit soil weight, γ; friction angle, ϕ).

Compression conditions were found to govern single pile sizing. In particular, the design maximum compression load on a single pile was found to be equal to $F_{c,d}$=4900kN, which from single pile bearing capacity check would have required a pile length of 44m ($R_{c,d}$=4910kN). This design bearing capacity value was calculated according to the ULS approach in the Italian Building Code (shaft for compression, $\gamma_{s,c}$=1.15; shaft for tension, $\gamma_{s,t}$=1.25; base, γ_b=1.35; number of soil profiles n=1 → $\xi_3=\xi_4$=1.70)

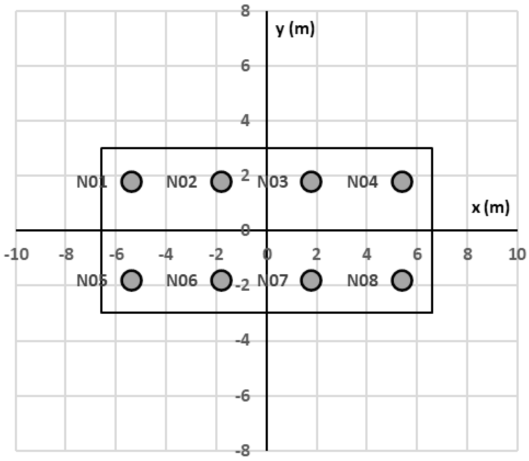

Figure 1. Pile group layout for Verona-Padua HSRL.

Table 1. Soil properties for Verona-Padua HSRL.

Soil	Thickness [m]	γ [kN/m^3]	ϕ [°]
Gravels	3	19	40
Clayey silts	18	19	26
Silty sands	2	19	35
Clayey silts	>25	19	26

The design was then optimised iteratively by means of the interaction domains, by investigating pile group capacity for shorter pile lengths. Figure 2 shows the interaction domains with respect to the symmetry axes of the group and for piles length of 38m (i.e. based on $R_{c,d}$ and $R_{t,d}$ values of 4395kN and 3818kN, respectively). Also shown are the total external loads on the pile group, in terms of axial force and moment (N_d=25.2MN, $M_{x,d}$=4.6MNm, $M_{y,d}$=4.3MNm), which fall into the two domains and prove that the design bearing capacity of the group is sufficient to carry the design external loads.

Implementing the interaction domains led then to a net reduction of 6m length for each of the piles of the group.

3 NAPLES-BARI HSRL PROJECT

In Figure 3 is reported a typical solution adopted for one of the many piers of the project. Twelve bored cast in situ piles with L=30m and d=1.5m were installed at spacing s=4.5m=3·d. Piles were connected to a stiff rectangular raft having B_{max}=16.5m and B_{min}=12m.

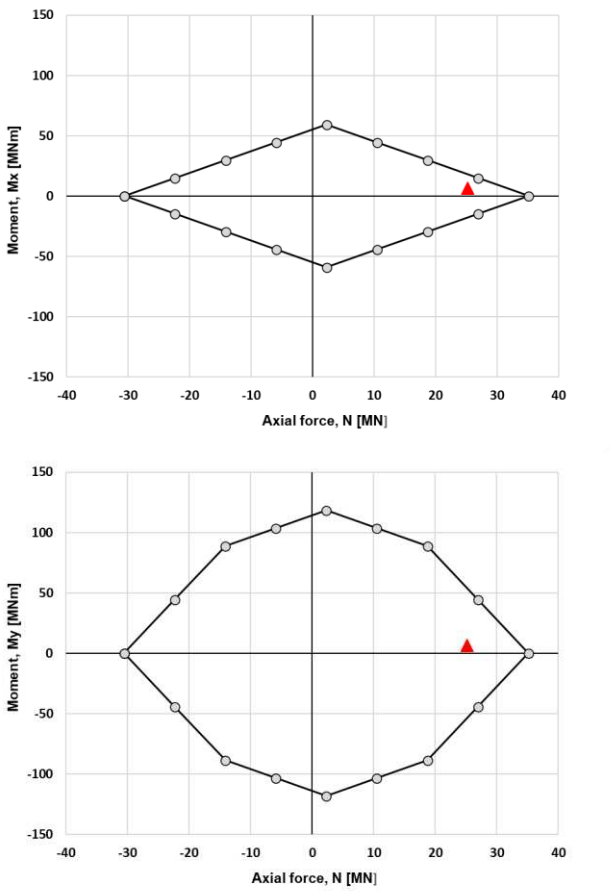

Figure 2. Interaction domains (L = 38m) for Verona-Padua HSRL.

Boreholes and in situ tests revealed the presence of a thick deposit of pyroclastic cohesionless soils up to 50m depth from ground surface, whose main properties for bearing capacity evaluation are listed in Table 2.

According to the evaluation made by designer, the calculated single pile bearing capacity under compressive load is $R_{c,cal}$ = 9.98MN. Adopting the partial factors according to Italian Code (shaft for compression, $\gamma_{s,c}$=1.15; shaft for tension, $\gamma_{s,t}$=1.25; base, γ_b=1.35; number of soil profiles n=1 → ξ_3=ξ_4=1.70), the design compressive resistance is $R_{c,d}$=5.08MN. Since the design action $F_{c,d}$ for the most loaded pile is 5.02 MN, ULS check (eq. 2) is satisfied with a ratio $R_{c,d}/F_d$=1.01.

In Figure 4 is reported the interaction domain evaluated on the basis of the design resistances. In the same figure is also reported the point representative of the worst loading design condition for the pile group (N_d=49MN, $M_{x,d}$=18.1MNm, $M_{y,d}$=19.5MNm), clearly falling within the domain.

During the installation of piles, some construction issues occurred. Non-destructive ND tests carried out on all piles revealed that problems occurred near the pile base with a maximum length of 4m, thus reducing in this case the effective length to 26m from the original 30m.

In such situations, typically the first practical solution aimed to re-establish the desired safety margin against failure is that of replacing defective piles with additional piles installed close to the original position of the defective ones.

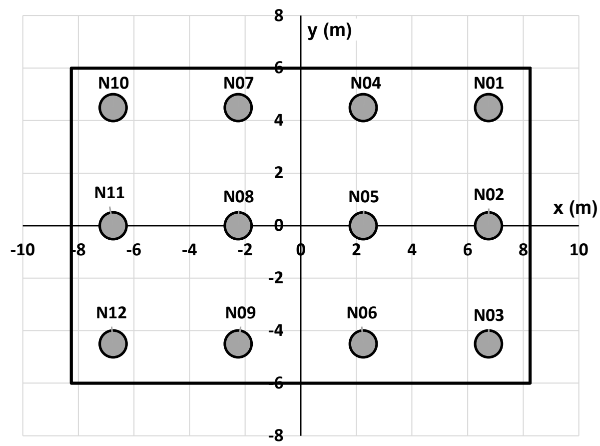

Figure 3. Pile group layout for Naples-Bari HSRL.

Table 2. Soil properties for Naples-Bari HSRL.

Soil	Thickness [m]	γ [kN/m³]	ϕ [°]
Remoulded pozzolana	4	16.0	30
Silty sand with interbedded pozzolana layers	7	16.0	34
Medium dense pozzolana	7	15.0	37
Dense pozzolana	32	16.0	39

The use of interaction domains, on the contrary, allows to accept the pile group with defects because, although reduced, it was found that the point representative of the worst loading condition kept inside the interaction domain (Figure 5).

Adopting this approach for all those piled foundations where ND tests revealed defects of different types, the number of cases where additional piles had to be installed reduced significantly.

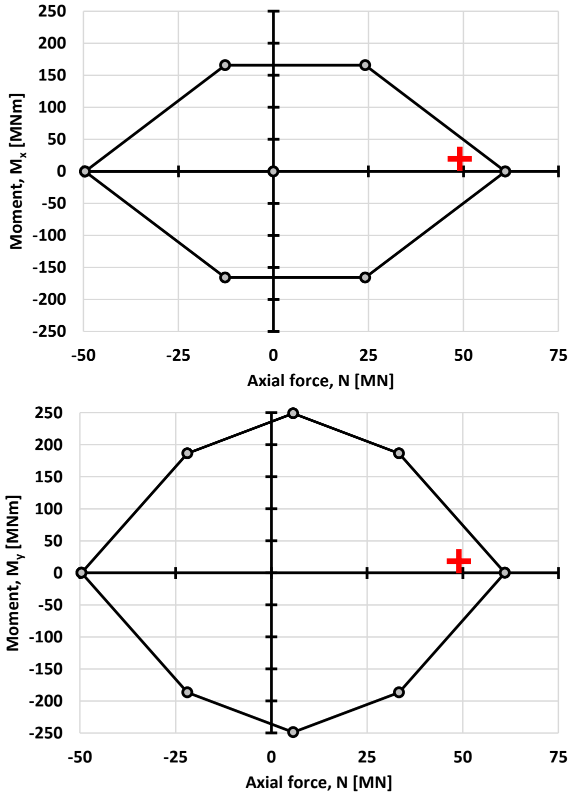

Figure 4. Interaction domains (L = 30 m) for Naples-Bari HSRL.

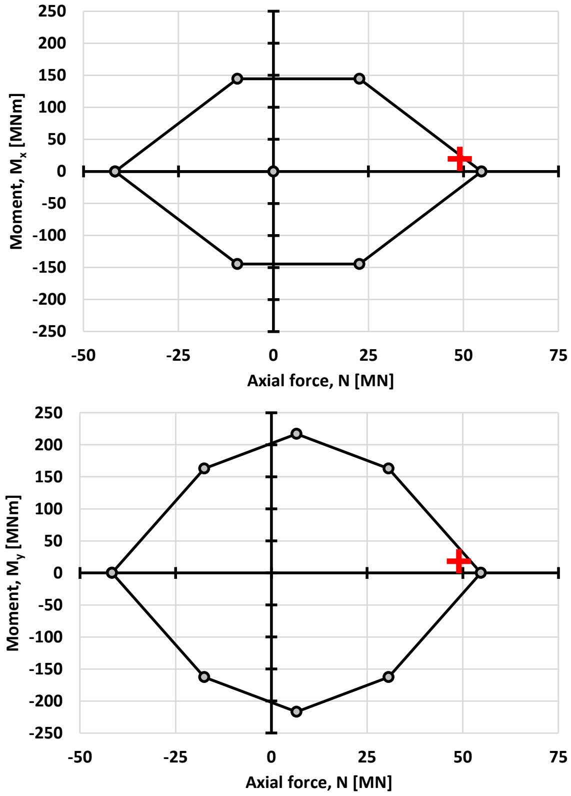

Figure 5. Interaction domains (L = 26 m) for Naples-Bari HSRL.

4 CONCLUSIONS

Pile sizing through single pile bearing capacity checks generally leads to overdesigned pile groups, which are left with some supplementary bearing capacity. On the contrary, interaction domains allow direct comparison between overall group capacity and total external loads on the group by taking into consideration the contribution from all piles.

Two example applications of interaction domains have been presented, one for the optimisation of design obtained from a traditional single pile bearing capacity check and one for the closure of non-conformities that resulted from construction issues.

The benefits from the method are evident. The routine adoption of interaction domains in pile foundation design would allow for more efficient design and avoid in some cases unnecessary re-work.

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