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THE EFFECT OF TIE BEAMS ON THE KINEMATIC RESPONSE AND IMPEDENCE FUNCTIONS OF MONOPILE FOUNDATIONS

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ABSTRACT

The paper focuses on the effect of tie beams on the kinematic response and impedance functions of monopile foundations. Considering a foundation system of a regular framed structure, constituted by monopiles connected with tie beams, a representative portion of the foundation is isolated by suitably modelling its boundary conditions, and kinematic Soil-Structure Interaction analyses are performed exploiting the numerical formulation proposed by Dezi et al. (2009) for the soil-pile system modelling. The model assumes a linear behaviour for the pile and is able to include the soil non linearity in a linear equivalent manner; this allows formulating the problem in the frequency domain where elastodynamic Green's functions are used to account for the soil-pile interaction and for both the hysteretic and radiation damping. Tie beams are included into the formulation and the problem is solved by means of the finite element approach. A non dimensional parametric investigation is performed by varying the main geometrical and mechanical parameters affecting the whole system response. Results are presented in terms of impedance functions and kinematic response parameters, focusing on the effects of the foundation tie beams on the system response.

INTRODUCTION

Monopile foundations are increasingly used in reinforced concrete frame structures due to their ease of execution and to the low cost associated to manpower for the concrete forming and the assembling of the reinforcement cages. They are constituted by single piles, located beneath each column and generally characterized by a large diameter, embedded in the soil deep enough to support all the loads transmitted by considerable superstructures. In order to guarantee an adequate rotational degree of restraint, consistent with the usual fixed base assumption in the superstructure design, stiff tie beams are commonly provided to connect monopiles. However, the conventional fixed base model developed for the structural design cannot provide information about the actual effectiveness of tie beams in preventing the column base rotations. In order to obtain a reliable prediction of the structural seismic response, especially when tie beams are adopted, Soil Structure Interaction (SSI) analyses have to be performed accounting for the soil-foundation frequency dependent compliance and the actual seismic input transmitted by the foundation (Carbonari et al., 2011, 2012)

According to the substructure approach, SSI analyses may be performed by means of a stepped procedure by studying separately the soil-foundation system and the superstructure on compliant-base

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subjected to the Foundation Input Motion (FIM). In this framework, the analysis of the soil-foundation system has a twofold aim: (*i*) to evaluate the kinematic soil-foundation interaction (e.g. FIM and stress resultants due to the propagation of seismic waves) and (*ii*) to define the soil-foundation dynamic impedance functions, namely the complex-valued relationships between forces and displacements which have to be used in the inertial interaction analysis of the superstructure to define the foundation compliance.

In the frame of the substructure approach, that allows considering the superstructure and the soil-foundation system as an integrated system, this paper focuses on the role of grade beams, acting as horizontal ties between pile caps, in the kinematic response and dynamic behaviour of monopile foundations. Analyses refer to a generic foundation system of a multi-bay regular frame, constituted by monopile foundations connected by tie beams embedded in homogeneous soil profiles and are performed by means of a specific procedure developed by the authors.

The problem is formulated in the frequency by considering a linear behaviour for both piles and tie beams and by including the non linear behaviour of the soil in a linear equivalent manner, and the solution is obtained through a finite element approach. The soil-pile system is modelled by means of the numerical procedure proposed by Dezi et al. (2009) in which beam elements are used to represent piles and the soil is schematized with infinite independent horizontal layers (unbounded domain). The soil-pile interaction as well as the hysteretic and radiation damping are taken into account by means of elastodynamic Green’s functions. Tie beams, schematized as beam elements, are included in the model in order to obtain the whole soil-foundations dynamic stiffness matrix.

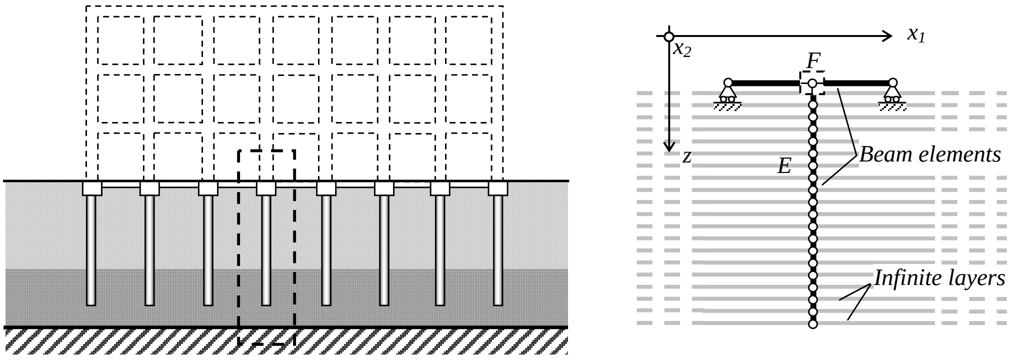
A dimensional analysis is adopted identifying the main geometrical and mechanical parameters affecting the system response and a wide parametric investigation is carried out by varying parameters within realistic ranges. Results, presented in terms of impedance functions and kinematic response parameters, are compared with those achieved considering monopile foundations without tie-beams.

ANALYSIS APPROACH

In this section a numerical approach for the dynamic kinematic interaction analysis of generic monopile foundations connected by tie beams is presented. Assuming piles to behave linearly and considering the non linear behaviour of the soil in a linear equivalent manner, the problem is conveniently formulated in the frequency domain. The soil-monopile system is modelled by means of the numerical model proposed by Dezi et al. (2009) for the dynamic interaction analysis of piles in layered soil profiles; tie beams, schematized as beam elements, are considered as part of the foundation system and included into the formulation to obtain the whole soil-foundation dynamic stiffness matrix. In particular, piles are modelled as beam elements, and the soil is considered as a visco-elastic medium consisting of infinite independent horizontal layers. The dynamics of each layer is a key point for the modelling of soil-structure interaction problem, and it is defined through elastodynamic Green’s functions, which enable to catch automatically both radiation and hysteretic damping.

Analytical model

The soil-foundation system of a generic multi-bay framed structure constituted by monopile foundations connected by tie beams is considered (Fig. 1a). Piles are embedded in a generic horizontally layered half-space subjected to seismic excitation. Piles, having length L_p and diameter d, are modelled as Euler-Bernoulli beams and the soil is considered to be a non-homogeneous visco-elastic medium. Tie beams, schematized as beam elements, are included into the finite element formulation. By considering a regular frame with equally spaced columns, the problem symmetry allows considering a simplifyed scheme for the analysis of the translational and rotational dynamic response of the soil-foundation system. In particular, the simplified sub-model depicted in Fig.1b, which considers half tie-beams at each side of the monopile foundation and has the vertical displacements restrained at the end sides of tie beams, is adopted to investigate the influence of tie-beams on the translational and rotational behaviour (dynamic stiffness and kinematic response) of the whole soil-foundation system under asymmetrical horizontal actions (seismic actions).



(a) (b)

Figure 1. (a) Soil-foundation system; (b) simplified finite element model

The solution of the problem is achieved numerically with the finite element method by including the contribution of tie beams to the numerical model of the soil-pile system, developed according to Dezi et al. (2009). The following complex linear equation system governs the problem dynamics:

$$\left(\begin{bmatrix}\mathbf{K}^{P}_{FF}+\mathbf{K}^{T}_{FF} & \mathbf{K}_{FE}\\ \mathbf{K}_{EF} & \mathbf{K}_{EE}\end{bmatrix}-\omega^{2}\begin{bmatrix}\mathbf{M}_{FF} & \mathbf{M}_{FE}\\ \mathbf{M}_{EF} & \mathbf{M}_{EE}\end{bmatrix}+\begin{bmatrix}\mathbf{D}_{FF} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}_{EE}\end{bmatrix}^{-1}\right)\begin{bmatrix}\mathbf{u}_{F}\\ \mathbf{u}_{E}\end{bmatrix}=\begin{bmatrix}\mathbf{D}_{FF} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}_{EE}\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{u}_{ff,F}\\ \mathbf{u}_{ff,E}\end{bmatrix} \tag{1}$$

where all matrixes are partitioned consistently with the displacement vector **u**, in order to highlight components relevant to the pile cap (*F*) and the embedded piles (*E*). It is worth noting that, since the model aims at investigating the in-plane translational and rotational response of the system, sub-vectors $\mathbf{u}_F$ and $\mathbf{u}_E$ only collect the horizontal displacements along x_1 and rotations around x_2 of the cap and piles embedded sections, respectively. Furthermore, **K** is the real stiffness matrix of the system obtained by assembling the pile cross sections and tie beams contributions (*T*); according to the scheme of Fig. 1b, the latter only contributes to the rotational stiffness term of sub-matrix $\mathbf{K}_{FF}$. Tie beams are assumed to be massless, so that the consistent mass matrix **M** is obtained by only assembling contributions of the pile. In addition, matrix **D** is the dynamic compliance matrix of the soil which reflects the overall dynamic characteristics of the soil medium and allows modelling the soil-pile interaction phenomena. Furthermore, matrix **D** allows including the hysteretic and radiation damping developing in the soil medium; these are the only source of damping as structural damping in the soil-foundation system is neglected. Finally, the right-hand side of equation (1) is obtained by multiplying the complex compliance matrix of the soil by vector $\mathbf{u}_{ff}$, collecting the soil free-field motion, which constitutes the seismic input; the product furnishes the soil-pile interaction forces developing as a consequence of the seismic motion propagating thought the foundation soil. The free-field ground motions at different depths, corresponding to the nodes of pile finite element discretization, may be obtained by means of site response analysis while the complex compliance matrix of the soil is obtained by assembling contributions of all finite elements, according to

$$\begin{bmatrix}\mathbf{D}_{FF} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}_{EE}\end{bmatrix}=\sum_{e=1}^{n_E}\int_{0}^{L_e}\mathbf{N}^{T}\left(\frac{k_h-i\omega c_h}{k_h^{2}+\omega^{2}c_h^{2}}\right)\mathbf{N}dz \tag{2}$$

In equation 2, n_E and L_e are the total number of finite elements adopted to discretize the pile and the finite element length, respectively while **N** is the matrix of the interpolating polynomials. The local soil dynamic compliance, which constitutes the kernel of equation 2, is obtained starting from expressions proposed by Makris and Gazetas (1992, 1993). These furnish the following soil frequency-dependent stiffness and damping in the horizontal (*h*) direction

$$k_h(\omega;z)=1.2E_s \tag{3}$$

$$c_h(\omega;z) = 2d\rho_s V_s\left(1+\frac{3.4}{\pi(1-\nu)}\right)\left(\frac{\omega d}{V_s}\right)^{-0.25} + 2\xi\frac{k_h}{\omega} \tag{4}$$

where ξ is the soil hysteretic damping ratio, V_s is the velocity of the shear waves and ν is the Poisson's ratio of the soil.

Equation 1 may be rewritten in the form

$$\begin{bmatrix} \mathbf{Z}_{FF}+\mathbf{K}_{FF}^T & \mathbf{Z}_{FE} \\ \mathbf{Z}_{EF} & \mathbf{Z}_{EE} \end{bmatrix}\begin{bmatrix} \mathbf{u}_F \\ \mathbf{u}_E \end{bmatrix} = \begin{bmatrix} \mathbf{D}_{FF} & \mathbf{0} \\ \mathbf{0} & \mathbf{D}_{EE} \end{bmatrix}^{-1}\begin{bmatrix} \mathbf{u}_{ff,F} \\ \mathbf{u}_{ff,E} \end{bmatrix} \tag{5}$$

that, opportunely manipulated, provides

$$\left(\mathbf{Z}_{FF}-\mathbf{Z}_{FE}\mathbf{Z}_{EE}^{-1}\mathbf{Z}_{EF}+\mathbf{K}_{FF}^T\right)\mathbf{u}_F = \mathbf{D}_{FF}^{-1}\mathbf{u}_{ff,F}-\mathbf{Z}_{FE}\mathbf{Z}_{EE}^{-1}\mathbf{D}_{EE}^{-1}\mathbf{u}_{ff,E} \tag{6}$$

In equation (6)

$$\Im(\omega) = \left(\mathbf{Z}_{FF}-\mathbf{Z}_{FE}\mathbf{Z}_{EE}^{-1}\mathbf{Z}_{EF}+\mathbf{K}_{FF}^T\right) \tag{7}$$

is the impedance matrix of the soil-pile tie beam system and

$$\mathbf{u}_F = \Im^{-1}\left(\mathbf{D}_{FF}^{-1}\mathbf{u}_{ff,F}-\mathbf{Z}_{FE}\mathbf{Z}_{EE}^{-1}\mathbf{D}_{EE}^{-1}\mathbf{u}_{ff,E}\right) \tag{8}$$

is the FIM, constituted by both a translational (in x_1 direction) and rotational component (around axis x_2).

EFFECTS OF TIE BEAMS ON MONOPILE FOUNDATIONS

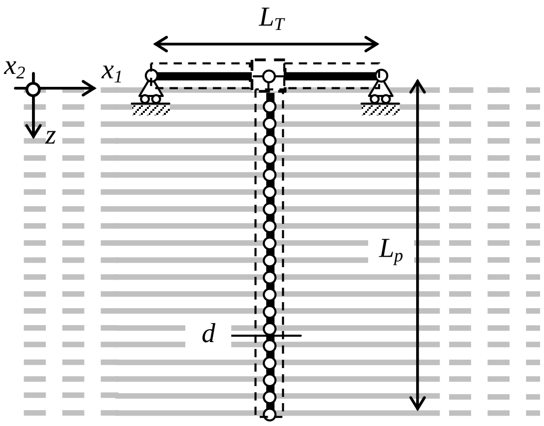
By considering the foundation system of a multi-bay framed structure with equally spaced columns, the approach presented in the previous section is adopted to investigate the effects of tie beams on the dynamic response of monopile foundations (Fig.2). A homogeneous soil profile is considered and the excitation along the pile ($\mathbf{u}_{ff}$) is obtained by vertically propagating harmonic shear waves with amplitude U_{ff} at the deposit surface. To guarantee a satisfactory accuracy of results, the pile is discretized with finite elements having length-pile diameter ratio $L_e/d = 0.5$, according to Dezi et al. (2010). The system response is evaluated in terms of impedance matrix and FIM that are specified, according to equations (7) and (8), in the following expressions

$$\Im(\omega) = \begin{bmatrix} \Im_t & \Im_{tr} \\ \Im_{rt} & \Im_r \end{bmatrix} \qquad\qquad \mathbf{u}_F = \begin{bmatrix} U \\ \Phi \end{bmatrix} \tag{9a, b}$$

A dimensional analysis is performed to identify the main geometric and mechanical non dimensional parameters governing the system response. According to the Buckingham's π-theorem (1914), the i-th components Π_i and I_i of the non-dimensional impedance matrix and FIM, respectively, depend on the following quantities, schematically depicted in Fig. 2:

$$\Pi_i = f\left(\frac{J_T}{J_p},\frac{L_T}{d},\frac{L_p}{d},\frac{E_c}{E_s},\frac{\rho_c}{\rho_s},\nu_c,\nu_s,\xi,\frac{\omega d}{V_s}\right) \tag{10a}$$

$$I_i = f\left(\frac{J_T}{J_p},\frac{L_T}{d},\frac{L_p}{d},\frac{E_c}{E_s},\frac{\rho_c}{\rho_s},\nu_c,\nu_s,\xi,\frac{\omega d}{V_s},\frac{U_{ff}}{d}\right) \tag{10b}$$



d	Pile diameter [m]
L_p	Pile length [m]
J_T	Inertia of tie beam section around y axis [m^4]
L_T	Tie beams length [m]
E_c	Concrete Young's modulus [Mpa]
ρ_c	Concrete density [kg/m^3]
ν_c	Concrete Poisson's ratio [–]
V_s	Soil shear wave velocity [m/s]
ρ_s	Soil density [kg/m^3]
ν_s	Soil Poisson's ratio [–]
ξ	Soil damping [–]

Figure 2. Main parameters governing the problem

Table 1. Set of value adopted for analyses

$\frac{J_T}{J_p}$	$\frac{L_T}{d}$	$\frac{L_p}{d}$	$\frac{E_c}{E_s}$	$\frac{\rho_c}{\rho_s}$	ξ
0.2	3	5	10	1.0	0.02
0.5	6	10	100	1.5	0.05
1	9	15	1000	2.0	0.10
2	12	20	10000		
5		30			
10					
20					

which include geometric and mechanical parameters, as well as the non-dimensional frequency factor $a_0 = \omega d/V_s$. The non dimensional components appearing in equations (10a, b), which will be used in the sequel to describe the system behaviour, assume the form:

$$\Pi_t = \frac{\Im_t}{\rho V_s^2 d} \qquad \Pi_r = \frac{\Im_r}{\rho V_s^2 d^3} \qquad \Pi_{tr} = \frac{\Im_{tr}}{\rho V_s^2 d^2} \tag{11a, b, c}$$

$$I_U = \frac{U}{U_{ff}} \qquad I_\Phi = \frac{\Phi d}{U_{ff}} \tag{11d, e}$$

Notice that absolute values of expressions (11d, e) are the well-known non dimensional kinematic response factors (Fan et al. 1991).

Analyses cases

A comprehensive parametric investigation is carried out by varying the main geometrical and mechanical parameters affecting the system response. The ratio of pile and tie beam cross section moment of inertia (J_T/J_p), the tie beam length-pile diameter ratio (L_T/d), the pile-soil Young's modulus ratio (E_c/E_s), the pile length-diameter ratio (L_p/d) and the pile-soil density ratio (ρ_c/ρ_s) are varied within realistic ranges evaluated by considering both short and long piles embedded in homogeneous soil deposits. Furthermore, the behaviour of the system is studied for both stiff and deformable tie beams conditions. The soil and concrete Poisson's ratios (ν_s and ν_c) are assumed to be constant and equal to 0.4 and 0.2 respectively. Finally, the non dimensional frequency factor a_0 is varied between the range $0 \div 1$, which is usually considered to be of practical interest in earthquake engineering. A complete survey of the sets of values adopted in the analyses is presented in Table 1; their combination produces a total amount of 5040 dynamic kinematic interaction analysis.

Main results

Given the great number of analyses performed, an extensive result database has been obtained. For the sake of brevity, in this section only some results will be shown in order to highlight effects of tie beam stiffness on the system compliance and kinematic response.

Dynamic compliance of the monopile-tie beam system

In order to show the effects of tie beam stiffness on the system compliance, results obtained by alternatively varying J_T/J_p and L_T/d are shown, while keeping the other parameters fixed. In particular, Fig. 3 shows the non dimensional real and imaginary parts of the translational, rotational and coupled roto-translational components of the impedance matrix (equation (11a, b,c)) as functions of the frequency factor a_0. Results are obtained by considering $L_p/d = 10$, $E_c/E_s = 1000$, $J_T/J_p = 0.5$, $\rho_c/\rho_s = 1.5$, $\xi = 0.05$ and varying L_T/d. Fig. 4 shows the real and imaginary parts of the same components of the impedance matrix obtained by considering $L_p/d = 10$, $E_c/E_s = 1000$, $L_T/d = 9$, $\rho_c/\rho_s = 1.5$, $\xi = 0.05$ and varying J_T/J_p. Results obtained for the case of monopile foundation without tie beams is always reported for comparisons. With reference to both figures, it should be noted that only the real part of the rotational impedance is affected by the presence of tie beams. As expected, the rotational stiffness increases with the tie beam stiffness, i.e. by reducing the tie beam length-diameter ratio (L_T/d) or increasing the ratio between the tie beam and pile cross sections moment of inertia (J_T/J_p). Furthermore, the real components of the non dimensional impedances are almost constant with the frequency factor, while imaginary parts increase.

Since the real component of the normalized rotational impedance is almost constant with frequency, the influence of tie beam stiffness on the system compliance is hereafter analyzed with reference to the non dimensional static rotational stiffness (i.e. $a_0 = 0$). Fig. 5 shows, for different E_c/E_s rations, the non dimensional rotational stiffness obtained by varying the J_T/J_p ratio. In each graph results obtained for $L_p/d = 5$ and 10 are shown with dashed and continuous lines, respectively, while the variability with L_T/d ratios is shown with different colours. Given that results are presented on the logarithmic scale, it can be observed in all cases that the rotational stiffness increases almost linearly with the J_T/J_p and the E_p/E_s ratios. On the other hand the L_p/d ratio slightly affects the rotational stiffness; the contribution of the pile length is only evident in the case of very soft soils ($E_p/E_s = 10^4$) for which the active pile lenght increses. Finally, it can be observed that the effects of tie beams on the static rotational stiffness are more and more evident by increasing the E_p/E_s ratio, namely by reducing the soil stiffness.

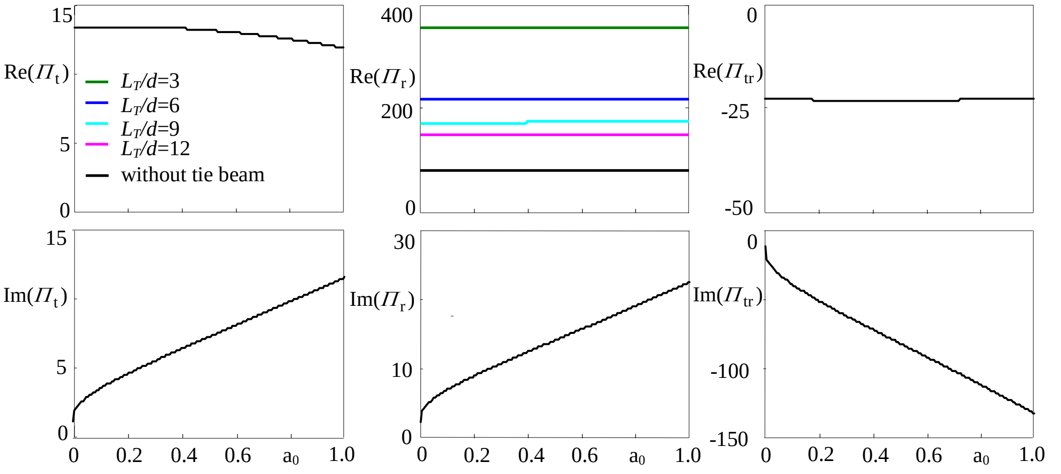


Figure 3. Traslational, rotational and roto-traslational non dimensional components of impedances for different values of L_T/d and for $E_p/E_s = 1000$, $L_p/d = 10$, $J_T/J_p = 0.5$

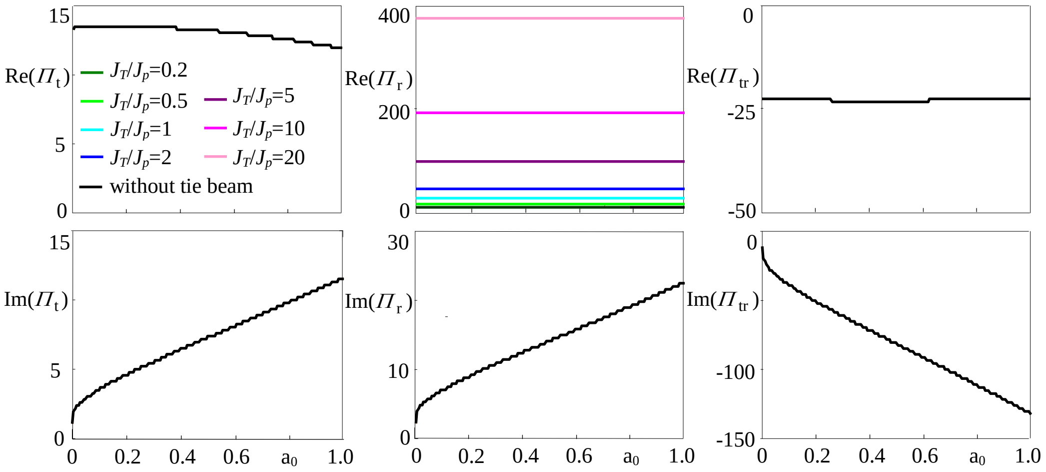


Figure 4. Traslational, rotational and roto-traslational non dimensional components of impedances for different values of J_T/J_p and for E_p/E_s = 1000, L_p/d = 10, L_T/d=9

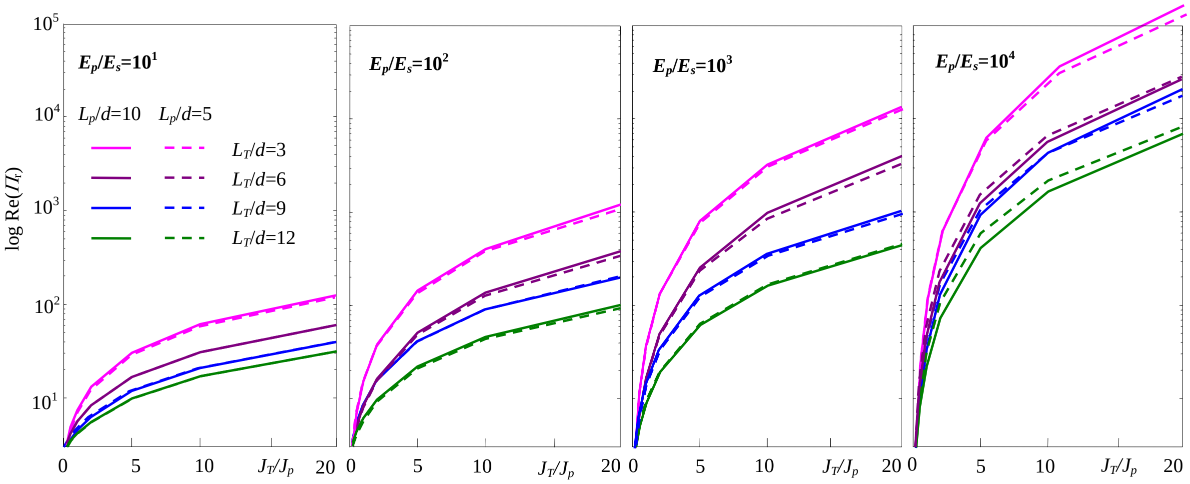
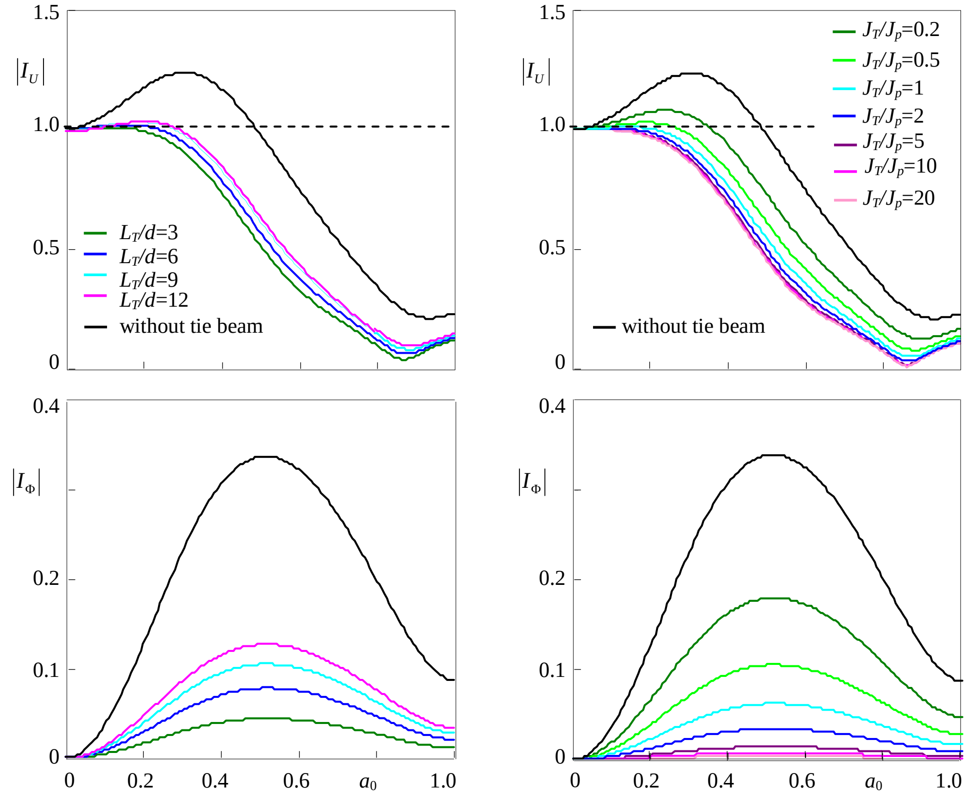


Figure 5. Non dimensional rotational component of impedance matrix at static conditions (a_0 = 0)

Kinematic response of the monopile-tie beam system

Effects of tie beam stiffness on the kinematic response of the system are presented in terms of kinematic response factors; these describe the foundation motion resulting from the modification of the free-field displacements, as a consequence of the filtering effect exerted by the deep foundation.

Fig. 6a shows the amplitude of the kinematic response factors I_U and I_Φ appearing in equation (10d, e) as function of the frequency factor a_0. Results are obtained by considering $L_p/d = 10$, $E_c/E_s = 1000$, $J_T/J_p = 0.5$, $\rho_c/\rho_s = 1.5$, $\xi = 0.05$ and varying L_T/d. Furthermore, Fig. 6b shows the same quantities obtained for $L_p/d = 10$, $E_c/E_s = 1000$, $L_T/d = 9$, $\rho_c/\rho_s = 1.5$, $\xi = 0.05$ by varying J_T/J_p. Again, results obtained for the case of monopile foundation without tie beams is reported for comparisons. With reference to both figures it can be observed that for the monopile foundation without tie beams (free-head pile) the amplitude of the pile head displacement is greater than that of the free-field motion up to a non dimensional frequency of about 0.4; for frequencies within the range 0.4 ÷ 0.8 the amplitude of pile head declines rapidly while at relatively high frequencies (greater than 0.8) an almost constant value is attained. The kinematic response parameter I_Φ presents an almost parabolic trend within the investigated frequency range; in particular, the pile head rotation increases with frequency attaining the maximum value at intermediate frequencies. Concerning foundations with tie beams it can be observed that $\left|I_U\right|$ and $\left|I_\Phi\right|$ sensibly decrease by increasing the tie beam stiffness (i.e. by reducing L_T/d or increasing J_T/J_p).



(a) (b)

Figure 6 Traslational and rotational kinematic response factors: (a) results obtained for different values of L_T/d and for E_p/E_s = 1000, L_p/d = 10, J_T/J_p = 0.5; (b) results obtained for different values of J_T/J_p and for E_p/E_s = 1000, L_p/d = 10, L_T/d = 9

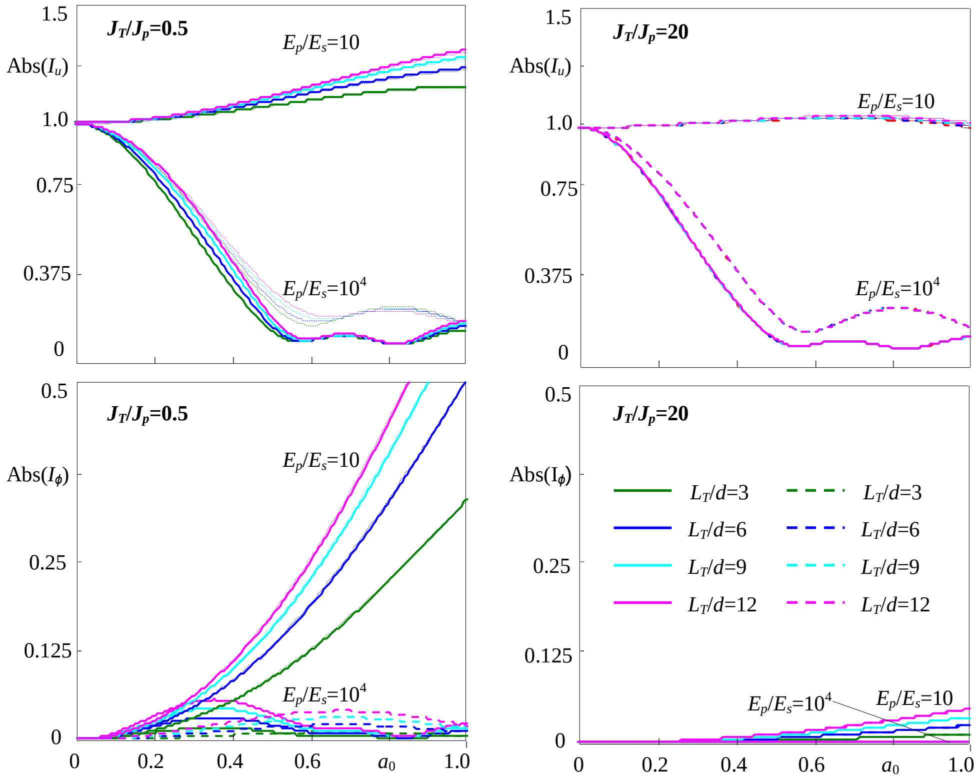


Figure 7. Traslational and rotational kinematic response factors for different values of E_p/E_s, L_T/d, J_T/J_p and L_p/d

It should be noted that the FIM is always characterized by a rotational component that should be carefully evaluated in the case of deformable tie beams. On the other hand, in the case of stiff tie beams the rotational component of the FIM reduces sensibly with respect to the free-head pile; with reference to the analyses herein presented, reductions of about 80÷90% have been achieved for $J_T/J_p = 2$ in the case of $L_T/d = 9$ (medium bay length) and for $J_T/J_p = 0.5$ in the case of $L_c/d = 3$ (short bay length).

Fig. 7 shows the amplitude of the kinematic response factors I_U and I_Φ obtained for two values of the J_T/J_p ratio (0.5 and 20) in the case of very soft and very stiff soil deposits ($E_p/E_s = 10$ and 10^4) and for different values of the L_T/d and L_p/d ratios. In particular, results obtained for $L_p/d = 5$ and 10 are shown with dashed and continuous lines, respectively, while the variability with the L_T/d ratios is depicted using different colours.

As previously observed, the effects of the L_p/d ratio is only slightly evident in the case of very soft soils ($E_p/E_s = 10^4$) for which the pile active length increases. On the other hand the L_T/d ratio mostly affects the pile head rotation, especially in the case of $J_T/J_p = 0.5$ (deformable tie beam).

Finally, the E_p/E_s ratio is the most important parameter affecting the system response. In the selected frequency range the absolute value of the translational component of the FIM is greater than the absolute value of the free-field motion for $E_p/E_s = 10$ while the opposite is observed for $E_p/E_s = 10^4$ for which an amplitude reduction of about 80% is observed for a_0 greater than 0.5. As for the rotational component of the FIM, in the case of stiff soils ($E_p/E_s = 10$) values greater than those obtained for soft soils ($E_p/E_s = 10^4$) can be observed for both the selected J_T/J_p ratios, starting from medium-high frequencies (a_0 greater than 0.3).

CONCLUSION

In this paper the influence of tie-beams on the kinematic response and impedance functions of monopile foundations has been discussed. With reference to a simplified scheme representative of the soil foundation system of a generic regular multi-bay framed structure, a numerical procedure has been developed exploiting the numerical formulation proposed by Dezi et al. (2009) for the soil-pile system modelling. Tie beams are included into the formulation and the problem is solved by means of the finite element approach. A non dimensional parametric investigation, involving 5040 analysis cases, has been performed by varying the main geometrical and mechanical parameters affecting the whole system response. Non dimensional graphs of impedances and kinematic response factors have been presented discussing effects of the tie beam stiffness and pile-soil Young's modulus ratio as well as the pile slenderness. The following main conclusions may be drawn:

- the tie beam stiffness strongly affects the rotational stiffness of the foundation system which is almost constant with frequency;
- the contribution of tie beams to the rotational stiffness is more and more evident by increasing the pile-soil Young's modulus ratio, namely in soft soil;
- the FIM is always characterized by a rotational component that should be carefully evaluated in the case of deformable tie beams; for stiff tie beams the rotational component reduces sensibly.
- for flexible tie beams, the rotational component of the FIM is strongly affected by the soil stiffness; in the case of stiff soils values greater than those obtained for soft soils have been obtained at medium-high frequencies.

REFERENCES

Carbonari S, Dezi F, Leoni G (2011) "Linear soil–structure interaction of coupled wall–frame structures on pile foundations", *Soil Dynamics and Earthquake Engineering,* 31(9):1296–1309

Carbonari S, Dezi F, Leoni G (2012) "Nonlinear seismic behaviour of wall-frame dual systems accounting for soil-structure interaction" *Earthquake Engineering & Structural Dynamics,* 41(12):1651–1672.

Dezi F, Carbonari C, Leoni G (2009) "A Model for the 3D Kinematic Interaction Analysis of Pile Groups in Layered Soils", *Earthquake Engineering & Structural Dynamics,* 38(11):1281–1305

Dezi F, Carbonari C, Leoni G (2010) “Static Equivalent Method for the Kinematic Interaction Analysis of Single Piles”, *Soil Dynamics and Earthquake Engineering*, 30(8): 679–690

Buckingham, E., (1914) “On Physically Similar Systems; Illustrations of the Use of Dimensional Analysis*”*, *Physical Review*, **4**, 345-376

Fan K, Gazetas G, Kaynia A, Kausel E, Ahmad S (1991) “Kinematic Seismic Response of Single Piles and Pile Groups”, *Journal of Geotechnical Engineering*, 117(12):1860–1879

Makris N, Gazetas G (1992) “Dynamic pile-soil-pile interaction. Part II: Lateral and seismic response,” *Earthquake Engineering & Structural Dynamics*, 21(2):145–162

Makris N, Gazetas G (1993) “Displacement phase differences in a harmonically oscillating pile,” *Geotechnique*, 43(1):135–150