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## DYNAMIC RESPONSE OF SHALLOW FOUNDATIONS ON REINFORCED SOIL WITH RIGID INCLUSIONS

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### **Abstract**

The soil-improvement technique by rigid inclusions represents today a practical, economical and time-saving solution that allows the use of shallow foundations on compressible soils. Several studies have recently focused on the static behavior of this reinforcement system (i.e. ASIRI French national project), however, its seismic performance has not yet received the same amount of attention. This paper presents a state of the art in the dynamic soil-structure interaction (SSI) analysis of structures supported on shallow foundations on reinforced soil with rigid inclusions. Special attention is given to the calculation methods that are currently being used in design offices. A parametric study is conducted by means of 3D numerical models and the hybrid BEM-FEM method in order to highlight the possibilities and limitations of these methods, especially for the study of inertial and kinematic interaction effects. Different configurations of rigid inclusions are studied, including several lengths, spacing and foundation layout. The results of this parametric study are compared to those obtained for equivalent shallow and deep foundations in terms of impedance functions and kinematic interaction factors. Finally, a discussion on different aspects that may control the dynamic linear and non-linear response of these foundation systems is undertaken.

*Keywords: soil-structure interaction; numerical modelling; rigid inclusion; inertial and kinematic interaction*

## 1. Introduction

The soil reinforcement technique using rigid inclusions is a practical, economical and time saving solution that allows the use of shallow foundations on compressible soils and is more likely to be reserved for structures with a large footprint and loads primarily of the distributed type [1]. Compared with the pile foundation, the technique of soil reinforcement by rigid inclusions constitutes a good compromise between reducing effective settlements and decreasing construction costs.

The mechanisms that control the response of the rigid inclusion soil improvement under static loading can be generally divided in three main parts as illustrated in Fig. 1. Firstly, the interaction between the foundation and the load transfer platform. Secondly, the interactional behavior, such as the arching effect, between the load transfer platform and the reinforced zone consisting soft soil and rigid inclusions. Thirdly, a rigid inclusion reacts as a pile mobilizing ending bearing capacity and shaft friction. This shaft skin friction at the inclusion-soil interface varies especially from negative to positive along with depth.

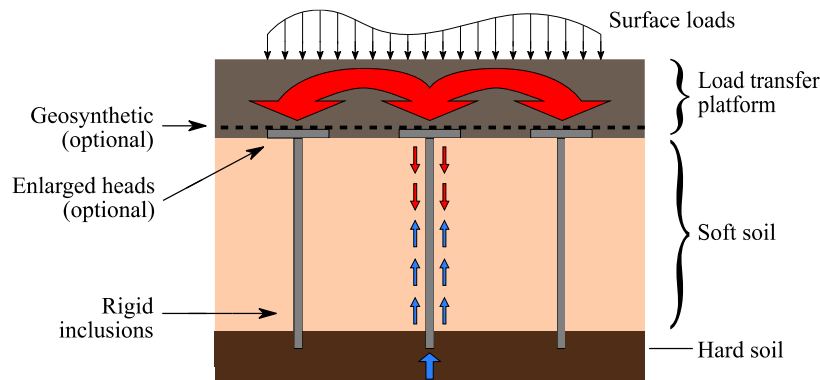


Fig. 1 – Rigid inclusions system (modified from Briançon et al. [2])

The seismic design of structures generally requires the consideration of soil-structure interaction effects. Over the last two decades, several numerical and experimental studies have focused on the understanding of the operating mechanisms of the soil reinforcement technique with rigid inclusions under vertical static and cyclic loading [1]. However, the behavior of the same foundation under seismic loading have not yet received the same amount of attention. Therefore, the understanding of the performance and of the mechanisms that control the foundation response is still limited. The utilization of rigid inclusions in ordinary projects have not yet been generalized and the design practice for similar projects under seismic loading needs to be developed [3].

In this study, a state of the art regarding the dynamic SSI study of shallow foundation over reinforced soil with rigid inclusions is firstly presented. Secondly, special attention is paid to the calculation methods that are currently being used in design offices. Then, a parametric study is conducted by means of 3D numerical BEM-FEM models within the so-called substructuring approach, so as to explore the inertial and kinematic interaction effects by using different configurations including several lengths, spacing and diameters of the rigid inclusions. A comparison with equivalent shallow and deep foundations is equally made in terms of impedance functions and kinematic interaction factors. As a conclusion, different aspects controlling the dynamic linear and non-linear response of rigid inclusion-reinforced foundation system are discussed.

## 2. State of the art

The rigid inclusion reinforcement technique has progressively gained more and more interest from the geotechnical engineering and research domain. However, in the literature, most research focused on the vertical behavior of the foundation over the rigid inclusions improved soil under static loading or cyclic loading (i.e. ASIRI French national project [1]). Only a few attentions were paid to the response of a rigid slab over inclusion-reinforced soil under dynamic loading.

Many experimental researches exist on the study of static and cyclic behavior of inclusion systems by means of small-scale tests [4-6], full-scale in-situ tests [7] and centrifuge tests [8]. Several dynamic experimental tests can be found in the literature. Garnier and Pecker [9] conducted centrifuge tests to validate an innovative foundation concept for the Rion-Antirion bridge. The performance of this foundation has since been demonstrated at full scale under a real earthquake. As part of the ICEDA project (Installation de Conditionnement et Entreposage des Déchets Activés), EDF (Electricité de France) [10] carried out a series of dynamic tests on two experimental plots obtaining the vertical and horizontal dynamic foundation response. The purpose of the tests was to examine the practical methods under real site conditions and to validate the methodology adopted to perform the numerical calculations. Santruckova [6] attempted to study the seismic behavior of the rigid inclusion soil reinforcement by 3D small-scale experimental studies under seismic loading. The response of the reinforced soil was measured, and the energy evaluation was conducted to understand the energy dissipation mechanism.

Concerning the numerical studies, the SSI response for the structures supported on shallow foundation over reinforced soil with rigid inclusions is a complex problem which requires the adapted numerical calculation approaches such as Finite Element Method (FEM), Finite Difference Method (FDM), Discrete Element Method (DEM), Boundary Element Method (BEM) and Material Point Method (MPM) [11].

Certain researches concentrated on the foundation dynamic responses in terms of flexibility. Okyay et al. [10] studied the foundation system consisting of an earth-platform over a soft ground reinforced by rigid inclusions as part of the ICEDA project. The vertical and horizontal flexibility for the slab foundation with or without rigid inclusions were obtained from experimental in-situ tests and compared with the FEM numerical results. Messioud et al. [12] compared different geometrical configurations in terms of flexibility, in order to interpret the influence of the load transfer platform stiffness, the geometrical parameters and the head/tip connection condition by using a 3D FEM dynamic analysis.

Rangel et al. [13] utilized a 2D FEM dynamic analysis to study the seismic performance of shallow foundation over soils improved by rigid inclusions, focusing on soil deposits that may amplify seismic movements which is a typical stratigraphical condition of Mexico City. Mánica et al. [14] studied the seismic ground response affected by the installation of a group of rigid inclusions embedded in deposits of Mexico City as well. The 3D FDM in temporal domain was utilized to analyze different configurations of rigid inclusions with the presence of the superstructure under real seismic loading. The results confirmed that the inclusions of small diameter (still considered as flexible inclusion) are not capable of greatly affecting seismic ground motion and that the superstructure dynamic characteristics dominate the soil-structure interaction phenomena more significantly than variations in the support conditions, lengths and spacing of inclusions.

Jiménez et al. [15] analyzed the FDM models with 3-storey reinforced concrete frame structure founded on inclusion system and pile system with the presence of liquefiable soil in seismic zone. Two natural earthquake accelerograms were applied to study the dynamic responses in terms of shear forces in the superstructure and the efforts and displacements of rigid elements.

Nguyen [16] modeled the reinforced soil masses under the elastic linearity hypothesis as a homogeneous medium in 2D or 3D but anisotropic due to the presence of inclusion reinforcement taking into account the soil-inclusions interaction as well as bending and shear effects of inclusions. This homogenization approach simplified the numerical implementation and greatly reduced computation time and computer memory space compared to the direct method. It was qualified and verified by comparison with the results of parametric studies using the FEM analysis combined with the BEM analysis.

This brief state of the art review shows that there are still few studies on the dynamic response of foundations on rigid inclusions reinforced soil. More research on this topic is therefore indispensable to better understand the main phenomena controlling the linear and nonlinear dynamic response of these kinds of systems. Furthermore, practical engineering design methods need also to be implemented.

### 3. Methodology

Several methods may be used to study the dynamic SSI problem of foundations on rigid inclusions, such as the direct method, the substructuring approach, Winkler-type models, or SSI macroelements.

In the direct method, the complete system (soil, foundation, and structure) is modelled which requires a huge computation time and computer memory space. However, this approach allows to introduce nonlinearity and a rigorous representation of the system. When the nonlinear behavior in the system can be approximated by means of a linear equivalent representation, the substructuring approach may be utilized. It permits to successively solve the SSI problem in several steps and is largely used in design offices. The advantage of this approach is that it allows a rigorous representation of dynamic phenomena provided that the linearity assumption remains valid. Winkler-type models are also used; however, they present, in general, some limitations such as the impossibility to consider group effects, etc. Finally, there is the SSI macroelement approach which is still in active development for foundations on rigid inclusions but has already proven its advantages in the design of remarkable structures such as the Rion-Antirion bridge [9].

#### 3.1 Substructuring approach

The substructuring method is commonly adopted in SSI analysis. It is generally based on the Kausel superposition theorem [17], that allows, under the linearity hypothesis, to successively solve the interaction problem in three steps: 1) Calculation of kinematic interaction to determine the seismic action applied at the base of the structure; 2) Calculation of dynamic impedance functions; 3) Calculation of structural responses considering SSI effects, as illustrated in the Fig. 2.

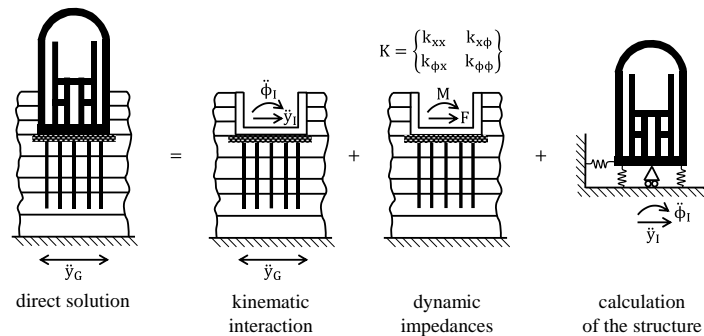


Fig. 2 – Substructuring approach

#### 3.2 Impedance functions

The dynamic impedances of a foundation are defined as the ratio between the harmonic force (or moment)  $F$  and the resulting harmonic steady-state displacement (or rotation)  $U$  at the centroid of the base of the massless foundation [19]. The dynamic impedance function  $Z$  is expressed as:

$$Z = \frac{F}{U} \quad (1)$$

Due to the presence of radiation and material damping in the soil-foundation system, the resulting displacement  $U$  is generally out of phase with respect to the applied force  $F$ . The impedance functions are therefore usually defined in complex notation as the following form:

$$Z(\omega) = K(\omega) + i\omega C(\omega) \quad (2)$$

where  $K(\omega)$  and  $C(\omega)$  are functions of the angular frequency  $\omega$ . The real part  $K$  is called “dynamic stiffness” and the imaginary part  $\omega C$  reflects the radiation and material damping generated in the foundation system.

#### 3.3 Kinematic interaction and interaction factor

A kinematic interaction factor  $I$  is introduced to better comprehend the kinematic effects in the interaction between soil and foundation system.

$$I = \frac{u_z}{u_f} \quad (3)$$

with  $u_z$  as the absolute value of the kinematic displacement at any depth and  $u_f$  as the free-field displacement at the surface of the soil profile.

#### 4. Parametric study

Aiming to understand the dynamic behavior of the rigid inclusion-supported foundation, a parametric study is presented in this section. The chosen geometrical configurations correspond to the cases which may be found in real projects.

The calculations have been conducted using the hybrid BEM-FEM analysis computer code SASSI2010 [19]. The substructuring approach is used and three steps (see Fig. 2) are calculated in the frequency domain to assess the response of the foundation under inertial and kinematic loading. The objective of the analysis is, on the one hand, to understand the phenomena determining the dynamic response of foundations on rigid inclusions and, on the other hand, to check the capabilities and limitations of this calculation approach that is nowadays largely adopted by design office.

##### 4.1 Foundation system model

The foundation and the structure are simulated by finite elements. The slab is represented by a rigid beam grid without mass. The inclusions are modeled by two-node beam elements with six degrees of freedom per node (three translational and three rotational components). The axial and bending stiffness of the beams are calculated from the geometry of the cross-section, and the Young's modulus and Poisson's ratio of concrete (see Table 1). According to the studies [10,14], the choice that inclusions are modelled by beam elements or volume elements has a weak impact on the dynamic response of the groups of inclusions.

The load transfer platform is modeled by hexahedral volume elements. The size of the load transfer platform exceeds 0.5m from the slab edges. The mechanical properties are given in Table 1. As a reminder, model elements are linear viscoelastic in these calculations.

In order to guarantee the correct propagation of dynamic wave over the frequency range of interest and to improve accuracy of results, a size mesh lower than one eighth the shorter wavelength is used in all calculations.

Table 1 – Geotechnical and mechanical characteristic used in the numerical analyses

Dynamic characteristic	Symbol	Soft soil	Hard soil	Bedrock	Transfer platform	Inclusions
Shear Modulus (MPa)	$G$	45	320	2 500	125	12 500
Poisson ratio (-)	$\nu$	0.45	0.45	0.45	0.35	0.2
Mass density (t/m <sup>3</sup> )	$\rho$	2.0	2.0	2.5	2.0	2.5
Damping ratio (-)	$\xi$	0.05	0.05	0.05	0.05	0

##### 4.2 Soil deposit characterization

In this study, a soil profile consisting of three isotropic and viscoelastic layers is used, which is composed of a 10-m-thick soft soil at the top, followed by a 5-m-thick hard soil over the bedrock half-space. Their properties are shown in Table 1.

In these simulations the soil is not modeled by volume elements but boundary elements. These transmitting boundaries are formulated by using exact analytical solution in the horizontal direction and a displacement function consistent with the finite element representation in the vertical direction [19]. It is supposed that the soil layers are horizontal in a semi-infinite medium.

### 4.3 Reference case and parametric study

The reference case consists of the rigid slab of 10 m × 10 m installed on a transfer platform with a thickness of 0.5 m. The rigid inclusions have a length of 10 m and are embedded of 0.5 m in the hard soil under the soft soil atop. They have a diameter of 0.42 m (this corresponds to a typical dimension used in France for inclusions and the rigid inclusion with this diameter is still considered flexible when the ratio of the inclusion elastic modulus  $E_p$  to that of the soil  $E_s$  satisfies  $E_p/E_s \leq (L_p/1.5d)^4$  where  $L_p$  and  $d$  are the inclusion length and inclusion diameter) and an axis-to-axis spacing of 2 m. This configuration is denoted A-01 and is selected as the reference case for the comparisons in this study (see Fig. 3). The other configurations are based on the reference case by varying certain parameters of the foundation system.

The parametric analyses are arranged into five groups, which are listed in Table 2. The principal characteristics of the different configurations studied are demonstrated in Fig. 3, Fig. 4 and Fig. 5.

Table 2 – Main characteristics of configurations used in the parametric study

Configuration	Description	Number of inclusions*	Length of inclusions*[m]	Spacing of inclusions*[m]	Diameter of inclusions*[m]
A-00	Free field	-	-	-	-
A-01	Foundation over rigid inclusions with transfer platform	25	10.0	2.0	0.42
A-02	Shallow foundation	-	-	-	-
A-03	Shallow foundation with transfer platform	-	-	-	-
B-01	Pile foundation	25	10.5	2.0	0.42
B-02	Pile foundation with transfer platform	25	10.5	2.0	0.42
C-01	Foundation over rigid inclusions with variable diameter	25	10.0	2.0	0.32
C-02	Foundation over rigid inclusions with variable diameter	25	10.0	2.0	0.52
C-03	Foundation over rigid inclusions with variable diameter	25	10.0	2.0	0.62
D-01	Foundation over rigid inclusions with variable spacing	49	10.0	1.5	0.42
D-02	Foundation over rigid inclusions with variable spacing	25	10.0	2.5	0.42
E-01	Foundation over rigid inclusions with variable length	25	5.0	2.0	0.42
E-02	Foundation over rigid inclusions with variable length	25	2.0	2.0	0.42

\* piles in case of pile foundation and rigid inclusions in case of inclusion-reinforced foundation system

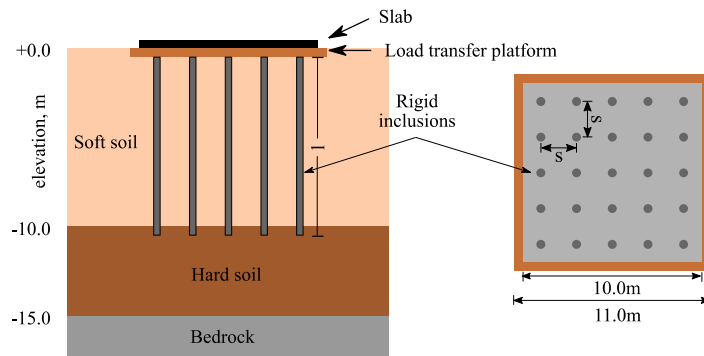


Fig. 3 – Scheme of the reference configuration (A-01) used in the parametric study

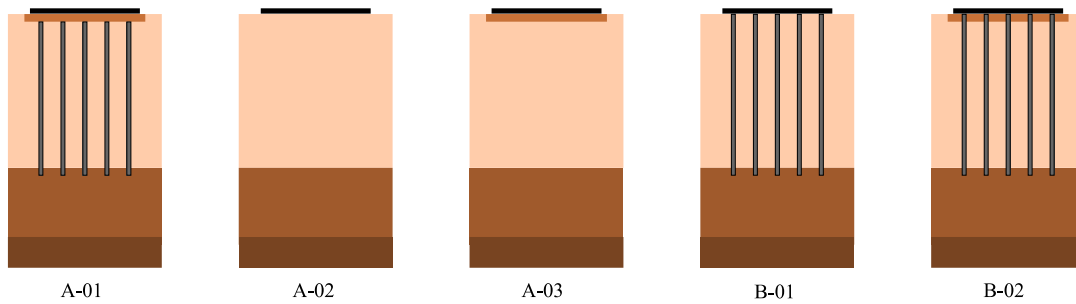


Fig. 4 – Schema of alternative configurations

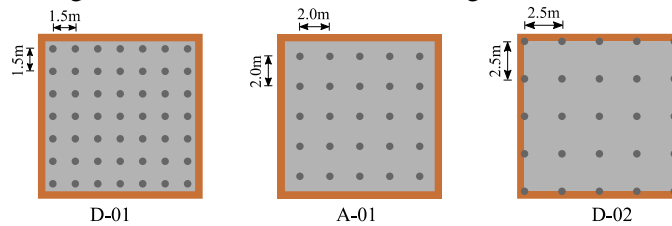


Fig. 5 – Distribution of inclusions for several configurations

#### 4.4 Inertial effects

In this section, the analysis is focused on the comparison of the dynamic stiffness and damping ratio curves calculated for the different configurations. The system being symmetric along both horizontal directions, the same response is obtained for both horizontal axes in terms of the dynamic stiffness and of damping ratio. The horizontal stiffness is denoted  $K_H$ , the rotational stiffness around horizontal axes  $K_R$  and the translational stiffness along vertical axis  $K_V$ . The corresponding damping ratios  $\zeta_H$ ,  $\zeta_R$  and  $\zeta_V$  are capped at 100%.

##### 4.4.1 Group A

This group of analyses aims to compare the response of a foundation over rigid inclusion-reinforced soil to that of a shallow foundation with or without a transfer platform. This comparison, illustrated in Fig. 6 et Fig. 7, concerns the reference case (A-01), a configuration with a shallow foundation without the inclusion reinforcement nor the transfer platform (A-02) and a configuration combining the shallow foundation with a transfer platform (A-03).

With regard to the horizontal stiffness, it is observed that the same variation of the dynamic stiffness values is obtained for configuration A-01 and A-03 before 9 Hz. It appears that the presence of rigid inclusions does not influence the horizontal dynamic response of the foundation system in the low frequency range as observed in the study of Okyay et al. [10]. The similar variation trend occurs for three foundation systems. The first trough situates at 3.5 Hz coinciding the first natural frequency of the free field. The stiffnesses at zero frequency for configuration A-01 and A-03 are 15% larger than that for configuration A-02 because of the presence of load transfer platform.

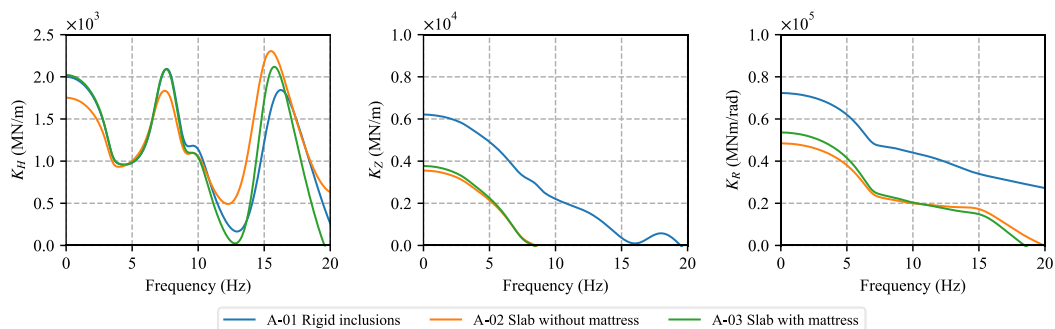


Fig. 6 – Dynamic stiffness for Group A



As concerns the vertical direction, the vertical stiffness decreases with the frequency. The vertical stiffness at zero frequency of configuration A-01 is nearly 1.5 times larger than configuration A-02 and A-03. The inclusion group effectively affects the vertical dynamic behavior. The rotational stiffness of configuration A-01 is greater than other two analyses for the entire frequency range thanks to the support of inclusions.

The damping ratio is equally analyzed in Fig. 7. It is observed that the damping ratios increase rapidly once the fundamental frequency of the soil deposit is attained. The same observations already made in terms of stiffness are found for the different degrees of freedom. Regarding the vertical and rotational damping, the evolution of damping ratio in configuration A-02 takes place later than in configuration A-01 and A-03.

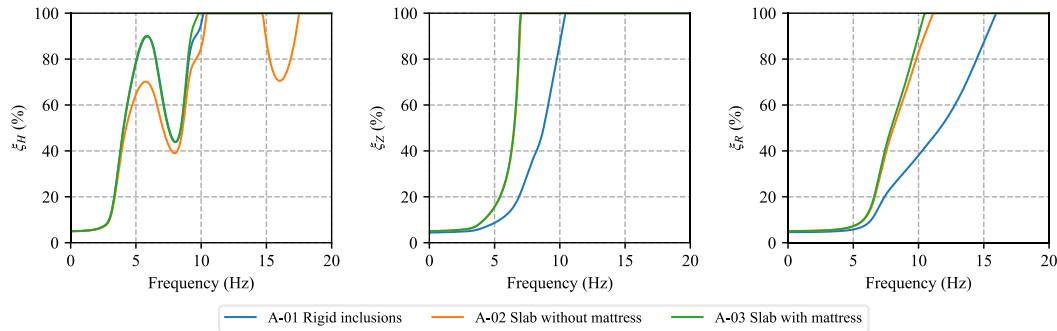


Fig. 7 – Damping ratio for Group A

#### 4.4.2 Group B

This group of analyses aims to compare the response of a foundation on rigid inclusions to that of a piled foundation. In addition to the reference case (A-01), a configuration with a pile foundation (B-01) and a configuration with the same pile foundation including the transfer platform atop (B-02) are compared as displayed in Fig. 8 and Fig. 9.

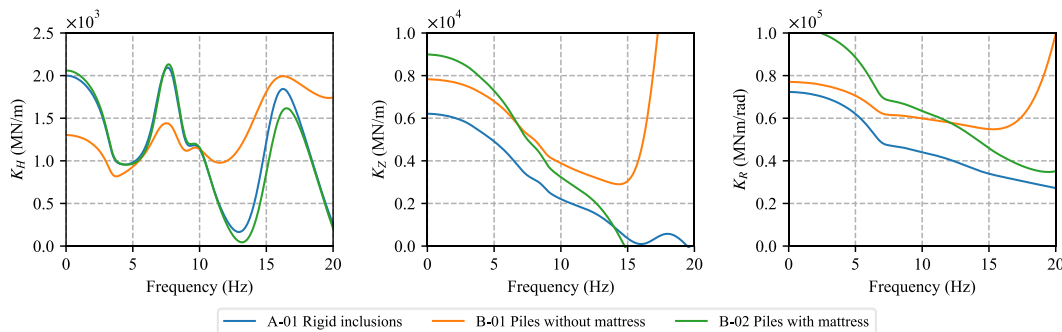


Fig. 8 – Dynamic stiffness for Group B

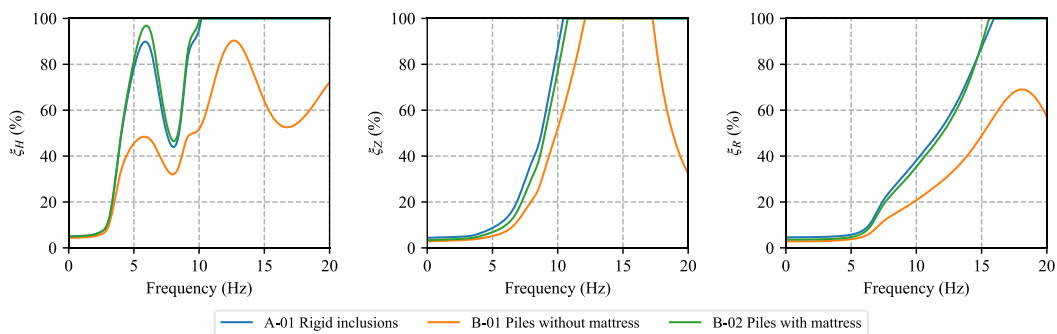


Fig. 9 – Damping ratio for Group B

Regarding horizontal stiffness, the result of configuration A-01 are noticeably similar to configuration B-02. These two analyses process the same tendency and the almost identical stiffness value before 13 Hz with

an ignorable difference at zero frequency. An interesting conclusion can be given that the connection condition does not influence the horizontal dynamic impedances. In the vertical and rotational directions, pile foundation with transfer platform in configuration B-02 seems to be stiffer than rigid inclusion foundation system. The connection condition indeed changes the vertical dynamic performance, unlike the horizontal directions. The configuration B-01 is undoubtedly different from other two analysis in all directions due to the absence of load transfer platform.

The damping ratio is equally analyzed for Group B in Fig. 9. As to the horizontal damping, the variation with the frequency is found. The damping ratios quickly arrive at 30% before 4 Hz. The damping ratio of configuration B-01 is more variable and generally smaller than configuration A-01 and B-02. Regarding the vertical and rotational damping, the pile foundation system without transfer platform is less damped than other two foundation systems at most of frequencies.

#### 4.4.3 Group C

Similar to the reference configuration (A-01), the configurations C-01, C-02 and C-03 are obtained by changing the inclusion diameter to 0.32 m, 0.52 m and 0.62 m, respectively. The comparison of their dynamic stiffness is shown in Fig 10. With regard to the horizontal stiffness, it can be seen that the same variation and the dynamic stiffness are obtained for the configurations with different diameter, for frequencies lower than 12 Hz. It shows that the diameter of rigid inclusions does not influence the horizontal dynamic response of the foundation system in this frequency range, provided that inclusions remain flexible. The influence of the diameter is more visible for the high frequency where the presence of rigid inclusions starts to modify the response of the system.

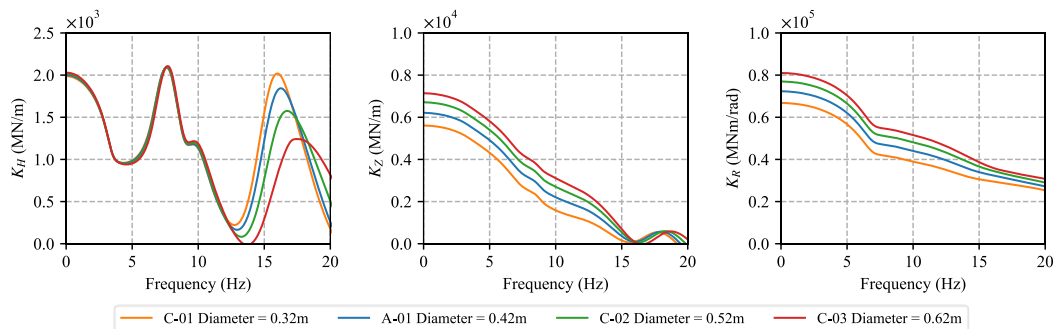


Fig. 10 – Dynamic stiffness for Group C

#### 4.4.4 Group D

Similar to the reference configuration (A-01), the configurations D-01 and D-02 are obtained by changing inclusion spacing to 1.5 m and 2.5 m, respectively (see Fig. 5). The influences of the inclusion spacing in the dynamic stiffness are analyzed by the comparison among the group D as illustrated in Fig. 11. The inclusion spacings do not change the horizontal dynamic impedances at low frequencies, while the number and the spacing of inclusion group play a more important role in the vertical and rotational directions.

#### 4.4.5 Group E

Similar to the reference configuration (A-01), the configurations E-01 and E-02 are obtained by changing the inclusion length to 5 m and 2 m, respectively. These two cases correspond to floating inclusion configurations. Only the supporting condition at the ending of inclusions in the configuration A-01 is anchored in the hard soil layer. The comparison between these configurations is focused on the dynamic stiffness as illustrated in Fig. 12.

Regarding horizontal directions, not many differences are observed among the analysis case. This is consistent to the fact that only the first meters of the rigid inclusions are mobilized under horizontal loading applied at the top. The embedding in hard soil layer does not provide a larger horizontal stiffness. As concerns the vertical direction, the existence of the tip bearing stiffness conducts to a stiffer vertical behavior. The configurations with floating inclusions are comparable with the shallow foundation with transfer platform (A-

03). It can be also concluded that floating inclusion reinforcement is not capable of improving the vertical dynamic stiffness unlike the configuration with the inclusion embedding in the hard soil layer.

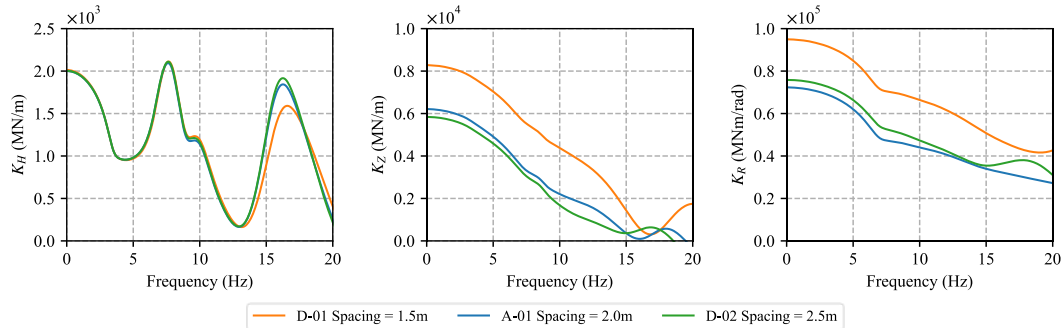


Fig. 11 – Dynamic stiffness for Group D

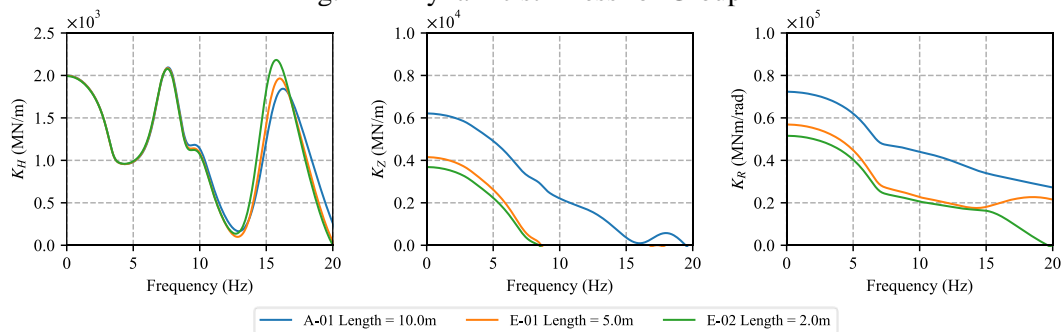


Fig. 12 – Dynamic stiffness for Group E

#### 4.5 Kinematic effects

The presence of the foundation may conduct to an amplification or degradation of the input motion which arrives at the base of the structure compared to the free-field motion at the soil surface. This phenomenon is known as kinematic interaction. In the following, kinematic effects are evaluated for three groups of configurations (Group A, B and C as utilized in the study of dynamic impedances) by comparing the kinematic interaction factor introduced in Eq. 3. The loading is applied by means of shear waves propagating vertically.

Fig. 13 indicates the kinematic factor of the foundation systems in Group A. The kinematic factor of the configuration A-02 is equal to 1 for the selected frequency range as expected. In addition, the presence of the transfer platform in the configuration A-03 translates into a slight decreasing of the kinematic interaction for frequencies higher than 10 Hz. By contrast, in the reference case (A-01), a more important variation is observed with a decline of 10% at 17.5 Hz.

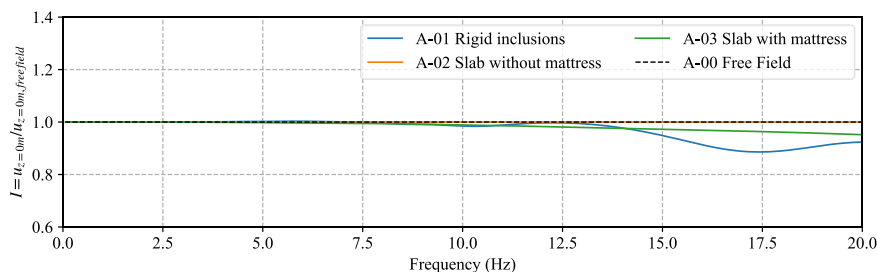


Fig. 13 – Kinematic interaction factor for Group A

The kinematic factor calculated for Group B varies with frequency as illustrated in Fig. 14. Three analyses seem to have the same variation trend. The field surface displacement is more degraded in the pile foundation case, which can be explain by the connection condition. The influence of inclusion diameter is studied in Fig. 15. Although the four analyses follow the same trend, the foundation system with a greater

diameter (0.62 m) shows a more important decline of the kinematic interaction factor, especially in the high frequency range, with a 30% decrease at 17.5 Hz.

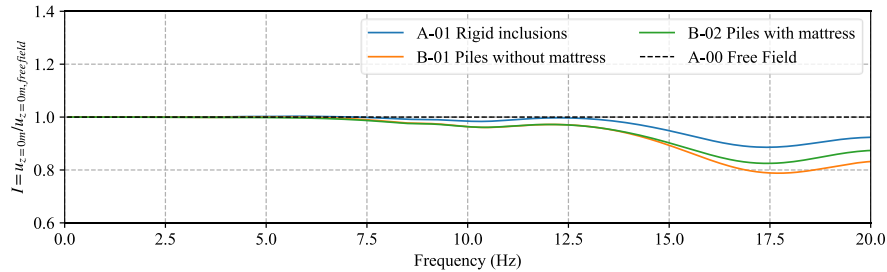


Fig. 14 – Kinematic interaction factor for Group B

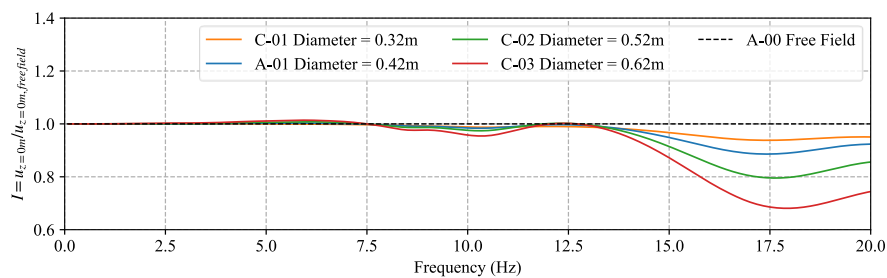


Fig. 15 – Kinematic interaction factor for Group C

## 5. Conclusion and perspective

The brief state of the art on the dynamic SSI studies of shallow foundations over rigid inclusion reinforced soil highlights that there are still few experimental and numerical studies regarding this topic and the absence of practical engineering design methods for this type of foundations under dynamic loading. The work in this article has been done in the framework of ASIRI+ French national research project and intends to explore the capabilities of actual design approaches and the main phenomena involved in the dynamic response of these foundations. Also, the limitations of these approaches are intended to be noted in order to feed future studies.

The 3D numerical study demonstrates the complicated phenomenon of the dynamic performance of shallow foundation on rigid inclusions. From the results of the comparison among equivalent shallow and deep foundations, it is found that the presence of inclusions influences the vertical and rotational directions in low frequency range, whereas the presence of load transfer platform influences, in general, all the directions throughout all the studied frequency range. In the horizontal directions, the dynamic behavior of the inclusion system resembles the shallow foundation with transfer platform. Different configurations of rigid inclusions include several diameters, spacing and lengths. These parameters related to inclusions do not modify the horizontal behavior, especially in the low frequency range. The kinematic effects have also been studied by means of kinematic interaction factors. The results confirm that the kinematic interaction effects have no significant impact in the low frequency range.

Future work will extend this study to the seismic response of rigid inclusion-improved foundation systems using a set of real earthquake recordings with different characteristics and levels of amplitude. The objective is not only to better understand the linear performance of these foundations, but also their non-linear behavior by introducing nonlinearities in the numerical model.

The concept of macroelement already utilized for shallow [20] and pile [21] foundations can be equally adopted in the non-linear analysis of inclusion-reinforced foundations, which makes it possible to concentrate the overall multidirectional response of the soil and the foundation in a single point as a multidirectional nonlinear spring. In order to realize this concept, a better understanding of the linear and non-linear dynamic phenomena that control the foundation responses is necessary and the presented work may largely inspire the future development of a macroelement for shallow foundation on soft soil reinforced with rigid inclusions.

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