Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 4055-4065

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

EFFECT OF THE SOIL PILE STRUCTURE INTERACTION IN A DYNAMIC ANALYSIS CONSIDERING A LINEAR BEHAVIOR

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Abstract

The present work aims to evaluate the kinematic interaction effects of a rigid inclusion reinforced soil mass under seismic waves. In order to understand the seismic behaviour of the system, a three-dimensional finite element code (FEM) is used (code Aster). Two numerical studies are presented. The first is a simple case study of a single Rigid Inclusion (RI), carried out to evaluate the influence of the RI modelling taking into account a beam element or a pile void element (called hybrid method). This technique consists of modelling the vertical reinforcements as void elements with the introduction of a beam element in their central axis. The use of this method makes it easier to determine the internal forces in the vertical reinforcements, taking into account the element rigid section. The second numerical work is a parametric study to highlight the effect of parameters such as the soil stiffness, mattress stiffness and RI diameter on the seismic response of a 5x5 rigid inclusion group considering a linear elastic behaviour.

Keywords: Rigid inclusions; dynamic analysis; numerical modelling; Kinematic interaction, Hybrid method

doi: 10.7712/120123.10702.20245

INTRODUCTION

Soils with low bearing capacity can cause problems in the construction of civil engineering works due to differential settlements. Reinforcement of compressible soils by vertical rigid inclusions (RI) is a technique used to improve the soil quality by combining a network of inclusions with a mattress made up of granular soil (Figure 1). The various elements of this system interact in a complex manner, and a particular attention should be paid to the response of soils reinforced by rigid inclusions under complex and dynamic loads [1,2]. Compared to pile foundations, this technology represents a good compromise between an effective settlement reduction and a reduced construction cost.

Previous studies, in particular the ASIRI national project, have focused on the behaviour of compressible soils reinforced by rigid inclusions, subjected to uniform static loadings, leading to practical recommendations for the profession. A smaller attention has been paid to the study of the behavior of this type of foundation under seismic loading. Therefore, this paper proposes to quantify the response of a group of RI under dynamic loading. This work is supported by National Project ASIRI+.

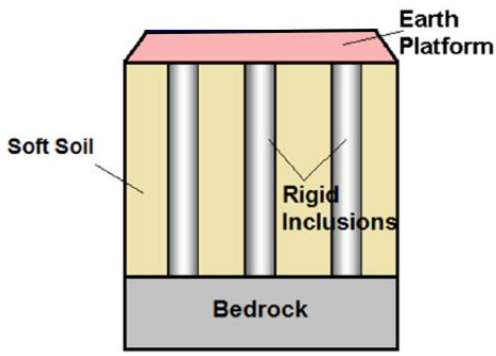


Figure 1: Rigid inclusion system [3]

The use of a rigid inclusion in a seismic zone is an interesting concept, and in terms of seismic stresses this reinforcement system is similar to the isolation system at the structure base . A load transfer platform (LTP) represents an energy dissipation zone that is transferred between the structure and the rigid elements, reducing the inertial effects of the structure [4-6]. This type of reinforcement has been implemented in the Rion-Antirion bridge [7].

This study is aimed at analyzing the kinematic interaction of a soil-mattress-inclusion-structure system. The analysis consists in calculating the response of all the elements of the system to the seismic loads. It is conducted using a three-dimensional finite element code (Code Aster). Particular attention is paid to studying the effect of the presence of RI on the modification of response of the system.

1. Kinematic interaction

Kinematic interaction is a soil-structure interaction mechanism related to the stiffness contrast between the soil and the foundation elements it contains. In particular, for soils reinforced by rigid inclusions, it can influence the seismic wave propagation and modify the incident seismic action on structures (amplitude and frequency content). It can also induce additional stresses (bending, shear) in the rigid inclusions in addition to the vibration stresses inherent in the supported structure.

In order to understand this phenomenon, this paper study is based on a dynamic model covering different configurations and aims to understand the effect of dynamic interaction between the inclusions and the soil.

2. Three-dimensional rigid inclusion modelling.

In order to study the influence of the rigid inclusion modelling on the response of the system, a special analysis is performed where the inclusion is modelled as a solid element combined with beam elements, which we call the "hybrid method", and only the beam element connected to the ground is considered.

2.1. Hybrid method

This technique consists of modelling the vertical reinforcements as void elements with the introduction of a beam element in their central axis. For each depth, connection conditions are defined between the inclusion nodes and the nodes of the boundary of the void, as shown in (Figure 2a). The use of this method makes it easy to determine the internal forces in the vertical reinforcements, taking into account the rigid element section [8].

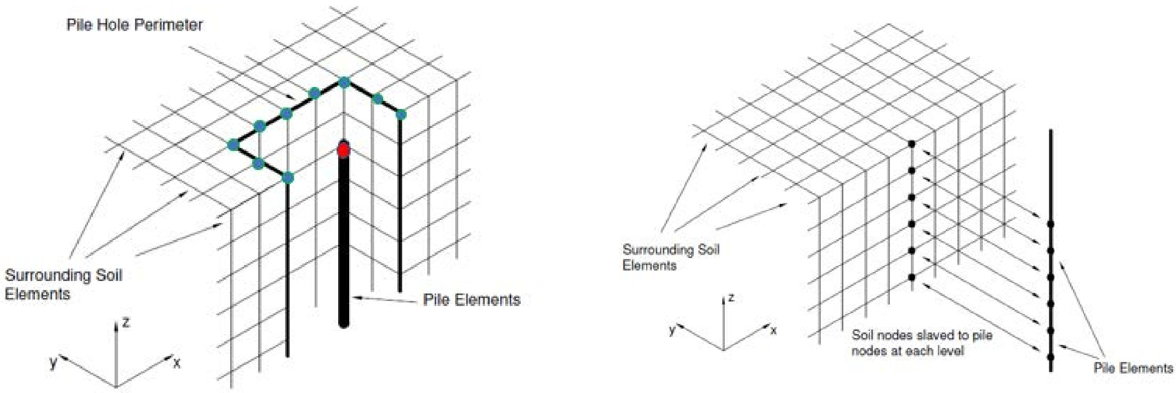


Figure 2:Isometric view a) Hybrid model, b) Beam element model

2.2. Beam element modeling

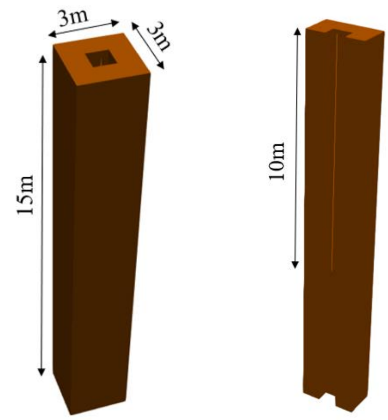
This technique, (Figure 2b), consists of representing the inclusions by beam elements, which are later rigidly connected to the soil. Loads were transferred between the inclusions and the soil through the nodes connected at different depths. The advantage of this method is that the internal forces can be easily determined without considering the solid element.

2.3. Geometry of the one inclusion Model

The first analyzes focused on a simple model 3mx3mx15m containing one rectangular rigid inclusion of dimensions 0.3mx0.3m and a length L=10 m placed in the centre of the model figure 3. This analysis considers a damping ratio of 5% under the Friuli earthquake, (Figure 7), applied as an imposed velocity at the model base.

The soil is modelled with 8-node hexahedral elements and the inclusion is modelled with both the beam element method and hybrid method. The soil Elastic modulus is Es = 97.6 MPa, Poisson's ratio υ= 0.35 and density ρ= 1610 kg/m^3. The inclusion has the following properties: Elastic modulus Em = 30 MPa, Poisson's ratio υ = 0.2, density ρ = 2500 kg/m3.

The fundamental frequency of the soil is 2.5 Hz, and the soil and rigid support is assumed to behave elastic.



a)Basic geometry b)Longitudinal section

Figure 3: Basic geometry of the numerical model

(Figure 4) shows the variation of the normalized bending moment for different pile dimension 0.3mx0.3m, 0.6mx0.6m and 0.9mx0.9m with depth.

$$M\ normalized = \frac{M\ \text{"beam element"}}{M\ \text{"Hybrid method"}} \quad (1)$$

$$Displacement\ normalized = \frac{d\ \text{"beam element"}}{d\ \text{"Hybrid method"}} \quad (2)$$

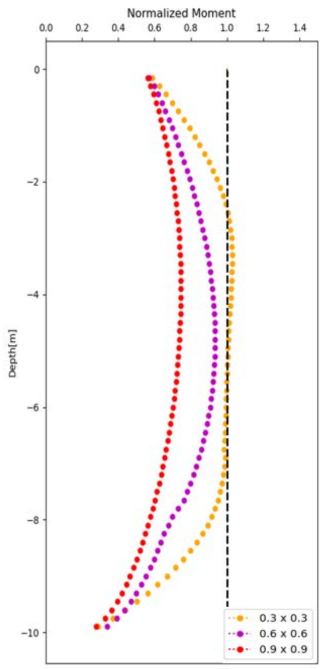


Figure 4: Normalized bending moment

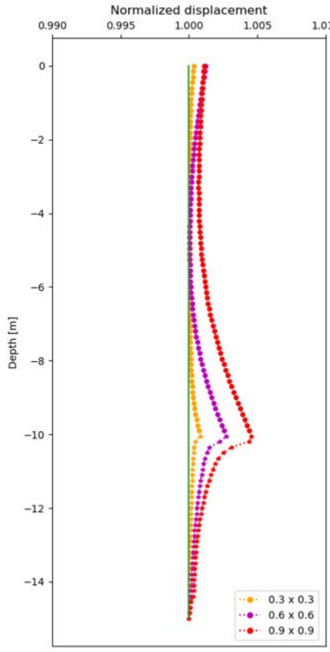


Figure 5: Normalized horizontal displacement

The results show that there is no significant difference, between the moment derived from the beam element method and the hybrid one for the depth between 2m and 8m where the moment is maximum, for a small dimension of 0.3m. The Results show that this variation increases as the inclusion dimension increases. For dimensions 0.6 x 0.6 and 0.9 x 0.9 there is a difference of 20 % and 50% respectively with the 0.3 x 0.3 dimension. Therefore, for large inclusion dimensions the modelling method should be taking into account.

(Figure 5) shows a small influence of the modelling method on the normalised displacement at the top and the base of the inclusion. However, this different is still negligible and does not exceed 0.5%.

In this case study, modelling the inclusions with beam elements or hybrid elements has little effect on the response of the inclusion for a dimension less than 0.4m, but it should be considered for larger dimensions.

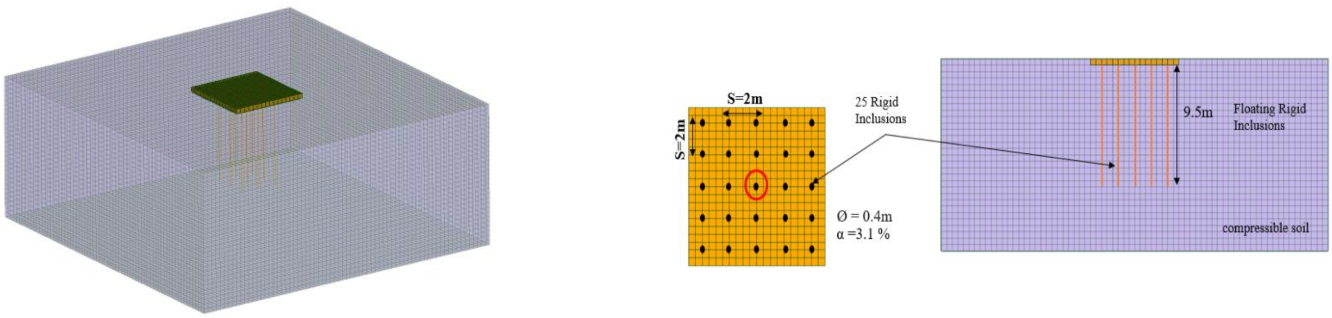
3. NUMERICAL MODEL

The numerical method used in this study is the Finite Element Method (FEM) with code Aster. A full FEM 3D model is proposed. The geometry of the domain is provided by the software Salome-Meca, where we can define the external boundaries of the domain, the soil properties, the pile diameter, and the pile length.
In terms of finite elements, the model consists of 3D 8-node hexahedral elements representing the soil and the mattress, and beam elements representing the inclusions.
The particular choice of beam elements to represent the inclusion behaviour is based on the previous analysis which showed no difference between the two modelling methods for the small

inclusion dimension of 0.4m. And because the beam element facilitates the calculation of internal forces in the inclusion, compared to 3D volumetric elements.

3.1.Case study description

The dimensions of the soil volume considered in this study are 35 m x 35 m x 15 m. The model studied concerns a group of 5x5 rigid inclusions of length L=9.5 m, in a layer of soil with uniform mechanical properties. The diameter of the inclusions is 40 cm. They are floating inclusions modelled by beam elements. The spacing between inclusions is S = 2 m (S/D = 5, D is the inclusion diameter). A 0.5m thick load transfer platform (LTC) is placed directly above the rigid inclusions. The rigid inclusions are not connected to the LTP Figure 6. The cover ratio α is expressed as the ratio of the area of the rigid inclusion to the area of the reinforcing soil. Boundary conditions, called "paraxial elements" [9], are considered at the bottom and lateral boundaries of the model.



a)3D Model b) Plan view of the mattress and cross section

Figure 6: Basic geometry of the numerical model

The soil, the mattress and the rigid inclusions are assumed to behave in a linear elastic manner. The properties of the different element constituting the model are summarized in table 1. A Rayleigh damping ratio of 5% was assigned to the soft soil.

Parameters	Rigid inclusion	LTP	Soft soil
Young Modulus E (MPa)	40000	200	97.6
Volumetric weight (kg/m³)	2500	1800	1610
Poisson's ratio	0.2	0.3	0.35

Table 1 : Parameters used for the numerical model.

3.2.Dynamic loading

The load was applied as an imposed velocity at the base of the soil mass. Calculation is performed using the record of the Friuli earthquake that occurred in Italy, with maximum acceleration = 0.25g. (Figure 7) gives the details of this record. The fundamental frequency of the soil layer is 2.5 Hz. The earthquake is applied in the form of velocity to the base of the model.

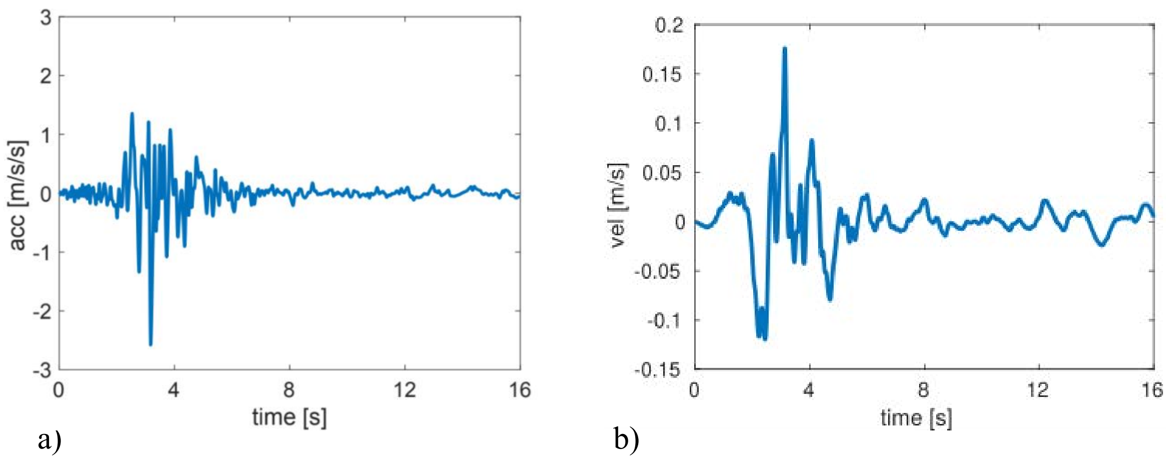


Figure 7: Dynamic input motion: a) Acceleration time history record, b) Velocity time history record for Friuli Earthquake

3.3.Case studies

In order to highlight the effect of some parameters on the response of the reinforcement system, a parametric study was initiated for the RI diameter, the soil and mattress parameters, the RI length and the group effect.

3.3.1. Influence of the Diameter of the RI

The diameter of rigid inclusions is known to be an important parameter for the load transfer mechanisms. (Figure 8a) shows the variation of the horizontal displacement of the central rigid inclusion starting from a depth of 0.5m to 10m normalised to the free field displacement as a function of depth. At depths greater than 10 m (ie. under the inclusion), it represents the horizontal normalized displacement of the soil. The displacement within the inclusion follows a linear relationship, with a maximum at the head and then decreasing to a minimum at the end. The values obtained from the displacement show the influence of the diameter on the variation of the displacement. The displacement of the inclusion head increases as the diameter of the RI increases. The results show that there is no significant variation of the displacement of the rigid inclusion. However, this isn't the case for the bending moment. (Figure 8b) shows the envelope of the bending moment which reaches its maximum of 12 kN.m for the reference case of Φ = 0.4m at depth = 4m. The results show that with increasing the diameter, the moment increases by approximately 4 times the reference case for Φ = 0.6m to reach 50 kN.m. The bending moment graph starts at depth -0.5m corresponding to the position of the inclusion in the model.

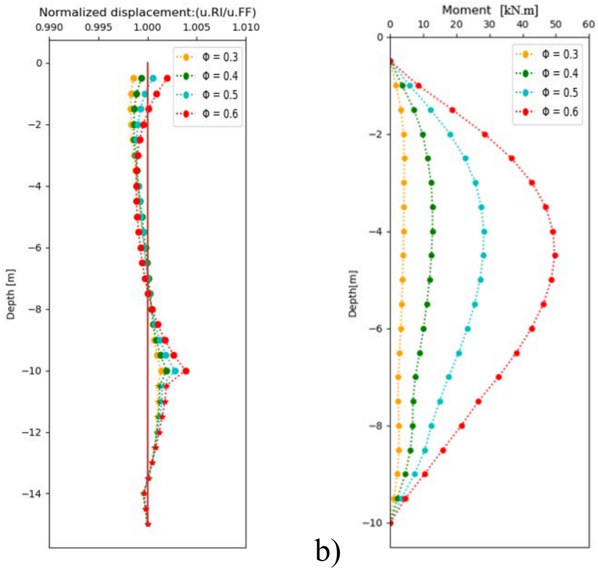


Figure 8: Influence of the diameter of the inclusion on a) the normalized displacement and b) the normalized bending moment along the rigid vertical elements.

3.3.2. Influence of the soil parameters

(Figure 9) shows the bending moment distribution of RI with two different young's modulus. It is noted that the bending moment presents a classic profile with a maximum near the central part of the inclusion reaching 13 kN.m for the reference case of E = 98 MPa. This result decreases to reach the value of 9kN.m for E = 174MPa because of the stiffer soil surrounded the inclusions which provides lateral support.

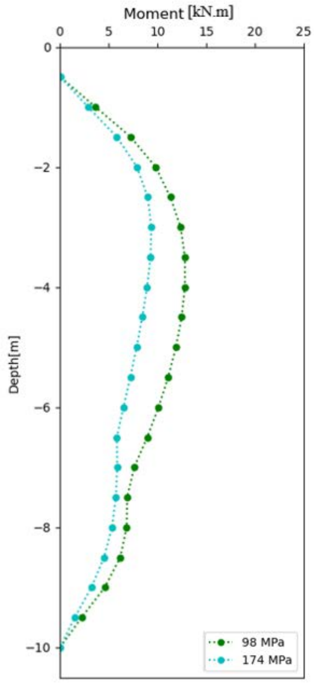


Figure 9: Influence of the soil property on the normalized bending moment along the rigid vertical elements.

3.3.3. Influence of the mattress stiffness

(Figure 10) compares the moments for three different mattress properties. Results show that, as the properties of the mattress increase, the moment experienced in the first three meters increases. Varying the elastic modulus from 200 MPa to 400 MPa induces an increase in the bending moment from 9 to 10.5 kN.m respectively at depth of 2m.

This result indicates that the mechanical properties of the mattress have an important effect on the response of the system.

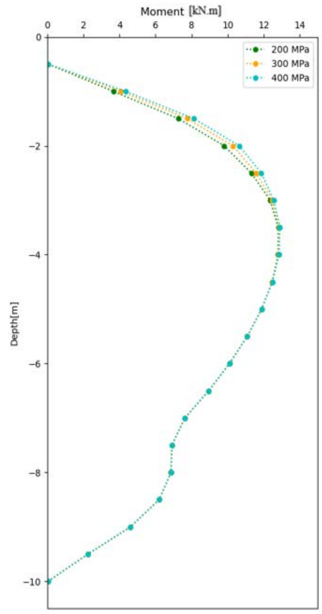


Figure 10 : Influence of the mattress property on the normalized bending moment along the rigid vertical elements.

3.3.4. Influence of the inclusion's position

In fact, the distribution of seismic forces between different rigid inclusions is not regular as it depends on the position of the elements within the group. (Figure 11) shows the bending moment envelopes for the center and outer inclusions. The RI are spaced by 5D. The results show that the corner inclusion experiences a greater moment, so it's more exposed to damage than the central inclusion, which has the least bending moment and is better protected (shadow effect).

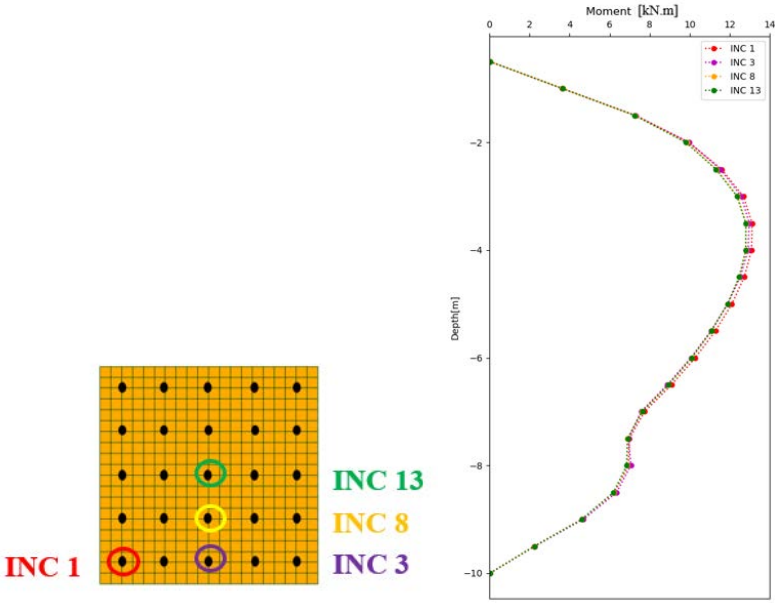


Figure 11: Influence of the RI position on the normalized bending moment.

Conclusion

A numerical study is presented to evaluate the effect of the kinematic interaction for a soil reinforced by reinforced by rigid inclusions under the passage of seismic waves. The calculations were performed using a 3D FEM.

The results obtained show that considering a beam element for the rigid inclusion gives similar results to the hybrid method in terms of horizontal displacements and bending moments in the RI for a pile dimension lower than 0.4m. The results become different when the diameter is greater than 0.4m. The results of the parametric study show that inclusions modify the seismic ground response and that the RI system "diameter and position", soil and mattress characteristics have a great influence on the efforts and displacements of the rigid elements.

The research will continue by investigating the soil non-linearity considering more complex constitutive models.

REFERENCES

[1] Jenck O., "Le renforcement des sols compressibles par des inclusions rigides verticales. Modélisation des sols par inclusions rigides ». Symp. Int. Sur l'Amélioration des Sols en Place. ASEP-GI, 9-10 septembre 2004, Paris, Presses de l'Ecole Nationale des Ponts et Chaussées, 2004, pp 15-44

[2] Briançon L., Kastner R., Simon B., Dias D. "Etat des connaissances - Amélioration des sols par inclusions rigides ". Symp. Int. Sur l'Amélioration des Sols en Place. ASEP-GI, 9-10 septembre 2004, Paris, Presses de l'Ecole Nationale des Ponts et Chaussées, 2004, pp 15-44.

[3] LOPEZ JIMENEZ G.A., "Static and dynamic behavior of pile supported structures in soft soil" PHD thesis 2019. Université Grenoble Alpes.

[4] Dobry R., Pecker A., Mavroeidis G., Zeghal M., Gohl B., Yang D., “Damping/Global Energy Balance in FE Model of Bridge Foundation Lateral Response”, J. of Soil Dynamics and Earth.Eng, 23(6), (2003), 483-495

[5] Pecker A., Garnier J. (1999). “Use of Centrifuge Tests for the Validation of Innovative Concepts in Foundation Engineering”. Proc. 2nd Int. Conf. on Earthq. Geotech. Eng., Lisbon, 433-439.

[6] Pecker A, Salençon J. (1999). “Ground Reinforcement in Seismic Area”. Proc. of the XI Panamerican Conf. on Soil Mech. and Geotech. Eng., Iguasu, 799-808.

[7] Pecker A., Teyssandier J.P. 1998, “Seismic design for the foundation of the Rion-Antirion bridge”, Geotechnical Engineering, vol.131, p.4-11

[8] L.M. Wotherspoon. “Three-dimensional pile finite element modelling using OpenSees”. 2006 NZSEE Conference.

[9] Code Aster: [R4.02.05] Absorbing boundary elements