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Investigation of the interaction between neighboring model structures at the Euroseis-Test site

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ABSTRACT: This paper examines numerically the dynamic interaction between neighboring structures for various excitation levels, frequency content and approaches adopted. In particular, the structure-soil-structure interaction is examined for the case of a 6-storey model structure and a model bridge pier at the Volvi – Greece European Test Site for Earthquake Engineering, a well controlled built environment both in terms of soil and structure configuration and characteristics.

1 INTRODUCTION

Within the last decade the demand and interest for reliable methods to analyze the dynamic Soil-Structure Interaction (SSI) has increased considerably. The challenge to construct long bridges, high-rise buildings at unfavorable geotectonic or geotechnical environment as well as the introduction of modern seismic codes all over the world posed the necessity of a better understanding of the dynamic behavior of these structures taking into account the interaction with the underlying soil.

Towards these objectives, a model bridge pier and a 6-story building have been constructed at the Volvi - Greece European Test Site for Earthquake Engineering within the framework of the currently running (http://euroseis.civil.auth.gr) Euroseis-Risk Project. Since one of the objectives of the European project Euroseis-Risk is the numerical and experimental study of the dynamic response of the 3D reinforced concrete structures built on site, numerous in-situ low level dynamic tests have been performed which were complemented by laboratory tests.

Apart from the study of the potential effect that soil flexibility and damping can have on on the dynamic and earthquake response of structures, Euroseis-Test Site provides the opportunity to study the dynamic interaction among neighboring structures as well. This is achieved not only on the basis of the well known and controlled structural and soil properties, characteristics and configuration but also of the validation of numerical results through a set of experimental campaigns and the subsequent in-situ observations.

Within this context and in order to simulate numerically, as a first stage, the above potential interaction, various methods have been used and compared in an ascending order of complexity. In particular, simplified methods are utilized like the Winkler-Spring and the Cone-Models of Wolf, Finite Element Method (FEM), as well as a new approach that couples Boundary Element Method (BEM) and Finite Element Method formulation; the latter is implemented into a finite element software package, that essentially incorporates the advantages of both methods. Through a comparative approach that utilizes various excitation levels and frequency content, the effectiveness of the aforementioned approaches is examined and the importance of accounting for the presence and the interaction of neighboring structures.

2 DESCRIPTION OF THE STRUCTURES AND THE TEST SITE

Two model structures have been built at the Volvi test; the first is a 6-story reinforced concrete frame model building with masonry infills, initially constructed in 1994. The second model structure is a single bridge pier and its foundation block. This bridge pier model structure was recently built (2004) at the Volvi test site and is similar to corresponding bridge piers that were tested at ELSA laboratories of the European Joint Research Center (Pinto 1996), but of larger dimensions and a different cross-section detailing as will be explained below. The layout at the Test Site is depicted in Figure 1; apart from the structural models and the network of strong motion accelerographs this facility also includes a crane, a store house and a power generated hydraulic system. The geometry and material properties of the model building can be found in Manos et al. (1995). For the bridge pier the geometry and material parameters of the laboratory test specimens as well as the reinforcement distribution are described in Manos et al. (2004). The geometry of the bridge pier, with a total mass of 18.89t (9.71t of which are concentrated at the deck level) is shown in Figure 2.

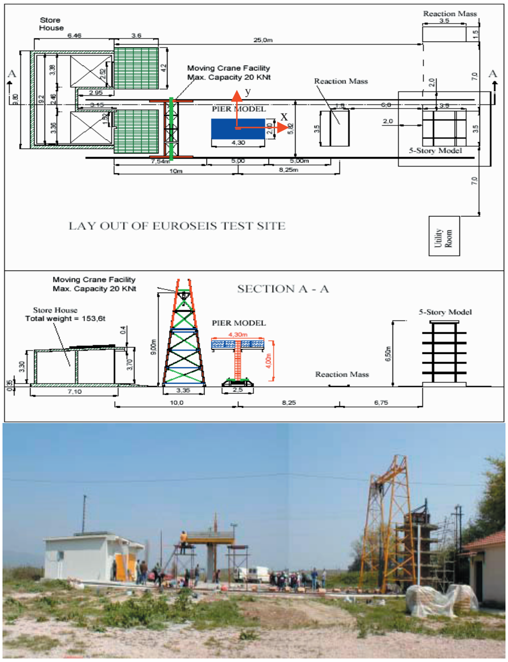

Figure 1. Layout of the Euroseis-Test site

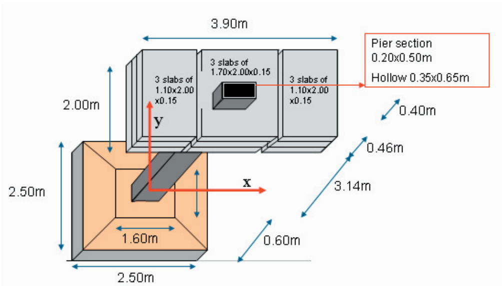

Figure 2. Geometry of the bridge pier

Table 1. Soil profile of the test site

Formation	Layer thickness [m]	Shear wave velocity [m/s]	Density [t/m^2]
A	3	130	2.05
B	19	200	2.15
C	30	300	2.00
C_w	26	300	2.15
D	45	450	2.10
E	60	650	2.15
F	11	800	2.20
G	15	1250	2.50

The soil conditions on the test site have been studied intensively during the last years. They can be found e.g. in Pitilakis et al. (1999) and are summarised in Table 1.

3 DYNAMIC CHARACTERISTICS OF THE IN-SITU MODEL STRUCTURES, WITH OR WITHOUT SOIL FLEXIBILITY

The dynamic characteristics of both the model structures are derived numerically taking into account the SSI effect and they are compared to the eigenfrequencies resulting from the corresponding fixed based systems. The dynamic characteristics of the coupled soil-bridge pier system as well as of the coupled soil-model 5-storey structure system are presented in Tables 2 and 3. As anticipated, the fundamental frequencies decrease due to the soft soil conditions. It is also notable that the measured eigenfrequencies of the model building on the test site match very well with the numerical results. It has to be noted that the analyzed configuration refers to the 5-story model building without masonry infills between the columns, without diagonals in each story and without the additional masses forming the 6-story building (Manos et al., 2000). A further numerical effort will deal with the latter.

Table 2. Eigenfrequencies of the bridge pier

Mode	On bedrock [Hz]	With SSI [Hz]
1. (transl. deck y)	1.31	1.23
2. (transl. deck x)	2.81	2.27
3. (rotation deck)	2.48	2.46
4. (2nd transl. deck y)	9.38	8.94
5. (2nd transl. deck x)	12.54	10.65
6. (vertical)	40.86	14.42
7. (transl. soil y)	-	19.89
8. (transl. soil x)	-	22.35
9. (rotation soil)	-	25.30

Table 3. Eigenfrequencies of the 5-story building (Manos et al., 2000)

Mode	On bedrock [Hz]	With SSI [Hz]	Measured [Hz]
1. (rotation)	2.87	2.738	2.71
2. (transl. y)	2.93	2.848	2.85
3. (transl. x)	2.94	2.871	2.87

4 STUDY OF ALTERNATIVE SSI APPROACHES

In order to extend the investigation to the influence of neighbouring structures, a first step is to study alternative SSI approaches in simplified soil-structure interaction conditions. A number of such SSI approaches, at an increasing level of complexity, are implemented and listed below:

a) simple spring model based on the Winkler theory (1867)

b) cone models developed by Wolf (1994)
c) finite element representation with solids
d) coupled Boundary Element Method and Finite Element Method formulation.

Despite the fact that the widely used approaches (a, b) cannot be utilized to deal with the neighbouring structures interaction problem, they are employed here to verify the more refined approaches (c, d) which will be implemented in the next step.

According to the simplest method, linear springs are assumed below the structure's foundation corresponding to the appropriate embedment modulus. For this purpose, a damping ratio of 5 % and a total stiffness of 170 MN/m is used while a spring with appropriately scaled stiffness is connected to each node of the interaction horizon. The cone model developed by Wolf (1994) provides a spring-damper system for all the six degrees of freedom. For time history analyzes a special time dependent formulation is proposed. This formulation was implemented into a FEM code in order to compare the results with the other methods. Therefore, the following input parameters are used: equivalent foundation radius 1.41 m, Moment of inertia of the foundation 3.26 m^4, Vs 100 m/s, soil density 2.1 t/m^3 and Poisson ratio 0.3. For the FEM (solid element model) approach, the material properties of the solid elements are the corresponding Young's-Modulus of 54.6 MN/m^2 and the Poisson ratio of 0.3. The extension of the modeled soil part is chosen in such a way, that the waves that are reflected at the boundaries of the model do not affect the behavior of the structure during the analysis time window.

The last model used to simulate the soil is a coupled BEM and FEM approach. The method is explained more detailed in Renault and Meskouris (2004). A similar approach for the investigation of SSI effects has already been used successfully by Savidis et al. (2000). The soil properties used are the shear wave velocity of 100 m/s, a shear modulus of 21 MN/m^2 and the Poisson ratio of 0.3.

The advantage of this approach is that the soil can be discretizised only in the interaction horizon, while the boundary conditions are consistent and hence, the wave propagation in the free-field can be calculated. In this formulation, the so called non-relaxed boundary conditions for the SSI problem are considered completely. As a first step of model validation and stiffness identification, the case of the immediate placement of the deck at the top part of the pier is investigated. This has been performed in situ by the removal of the components that supported the deck until complete assemblage. As a result, the 9.71t mass is assumed to be added all at once and the settlement is calculated. Figure 3 indicates that all the models lead to the same static vertical displacement (settlement) of approximately 0.6 mm under this vertical load.

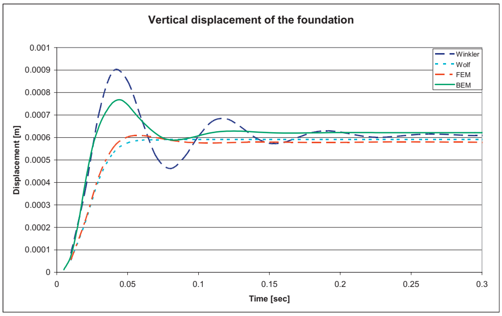

Figure 3. Comparison of the effect of different soil models on the vertical oscillation of the pier under the deck load

It is also seen that the calculated oscillation of the foundation under the aforementioned vertical load by means of the Winkler model is not damped fast enough and rather overestimates the actual amplitude of the time-varying vertical displacement. The results of the Wolf and FEM model on the other hand reflect a very stiff behavior of the soil. They yield similar results and reach the value of the static displacement quickly.

Finally the BEM method reproduces best the behavior of a soft soil. It has a relative peak at the beginning followed by a short and well damped numerical oscillation compared to the Wolf and FEM method. Several other simulations have confirmed the correctness of the different soil models used here. The above results therefore, provide a confidence that the latter methods can be utilized for the study of the coupled structure-soil-structure system in a realistic and feasible way.

5 LOW AMPLITUDE MAN-MADE EXCITATIONS AND SUBSEQUENT FREE VIBRATION

The main disadvantage of the simplified methods (such as the Winkler method) is the inability to analyze the interaction of neighboring structures as it cannot represent the propagation of the wave field in the surrounding soil. Finite element approaches on the other hand, in certain cases, introduce a level of uncertainty with respect to modeling (and the corresponding potential interference) of the reflected wave field at the boundaries of the modeled soil part, unless a refined mesh is adopted. In the past, several attempts have been made to circumvent this effect by introducing absorbing elements or infinite elements (e.g. Zhang et al. (1999), Pitilakis et al., 2004). Nevertheless, the demanding calculation effort, which depends on the volume of the soil simulated, poses a set of modeling difficulties especially with increasing number of degrees of freedom. Compared to this, the coupled BEM-FEM approach provides a relatively higher level of flexibility and accuracy at lower computational cost as it discretises the substructured part at the proximity of the pier.

For the evaluation of SSI effects on the test site in particular, two main sets of sequential low amplitude man-made excitation were conducted. In the first numerical simulation, the deck of the model pier is pulled in the y-y direction with a force of 1300N, utilizing an anchorage placed in the soil 21m from the center of the pier, and then suddenly released. In the second numerical simulation the deck is again pulled and suddenly released, with of force of 1950N. This time the anchor point is placed at the top of the store house and the direction of the pull is the in-plane (x-x) direction (see Figures 1,2). The above excitation procedure is also planned to be utilised in-situ. In order to predict the behavior of the bridge pier and especially the potential effect of the vibration of the neighboring building structures under this particular excitation force, numerical simulations were performed with the use of the aforementioned coupled BEM-FEM.

5.1 *Investigation of the soil properties*

Based on the geotechnical profile provided in Table 1 and on the level of stresses that are expected to develop below the foundation during the low amplitude tests, an additional soil layer (A*) was assumed for the first two meters of depth that essentially contribute to the system stiffness for the given load level. In the following, the soil conditions are simplified by the assumption of an average density of 2.1 t/m^3, a Poisson ratio of 0.3 and a damping ratio of 5 % for all the layers, but considering the different shear wave velocities of Table 1.

In order to compare the influence of different soil configurations, three simulations are performed. At first the structure is supposed to be bedded on bedrock. The second simulation assumes a homogeneous infinite half-space under the foundation with the material parameters of the layer A*. The third simulation was carried out considering all the nine layers described in Table 1.

In Figure 4, the resulting top displacements of the pier for the free vibration test along the in-plane (strong) axis of the structure are illustrated, while for the vibration test along the out-of-plane (weak) axis of the bridge pier the results are shown in Figure 5. As anticipated, the comparison of the structure assumed to be supported on the three different soil conditions (Figure 4) leads to the result that, the displacements of the structure are higher in the case of a flexible soil (i.e. homogeneous and layered soil condition) compared to the assumption of full foundation fixity. It is also notable and reasonable that the assumption of a layered soil profile results to an increase in the structural displacements due to the fact that the upper layers (which are represented more accurately in the case of a layered soil formation) contribute more significantly to the overall (and lower in this case) system stiffness. For the weaker axis on the other hand (Figure 5), the same conclusion can be drawn, but clearly, due to the higher relative flexibility of the system compared to the oscillation along the strong axis, the effect of foundation rocking is smaller.

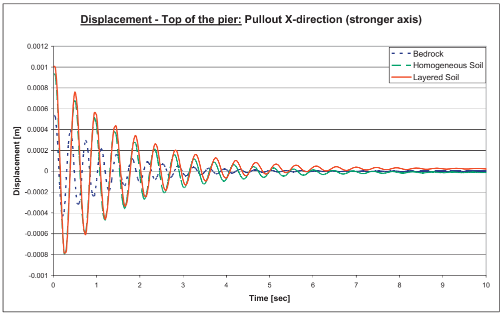

Figure 4. Comparison of different soil configurations for excitation along strong axis.

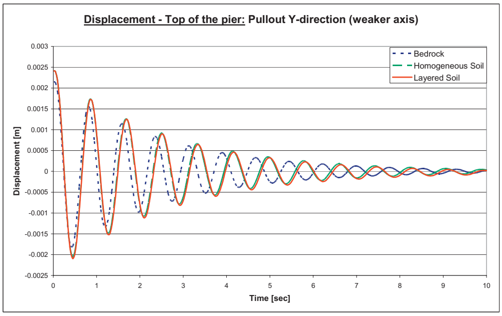

Figure 5. Comparison of different soil configurations for excitation along weak axis.

5.2 *Investigation of the influence of the surrounding structures*

Having identified the effect of different soil properties on the response of the soil-pier and soil-5 storey structure system, the influence of the presence and oscillation of neighboring structures on the bridge pier is analyzed as shown in Figure 6. For this analysis, all the surrounding structures are accounted for, except form the crane rails and the movable crane facility on the test site since it was found that they had no effect according to preliminary analyses.

The BEM formulation is again chosen with the assumption of the complete layered soil with respect to the subgrade. The discretizised volume of soil (corresponding to the surface area of 35 x 12 m - Figure 6) is modeled by 6720 regular boundary elements with an edge length of 0.25 x 0.25m. The foundations of the considered structures are thus dis-

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cretised with elements of the same size. The store house and the reaction masses for the low amplitude man-made excitations are only modeled as foundation slabs with appropriate weight, due to their high stiffness and the subsequent limited vibration at frequencies of interest.

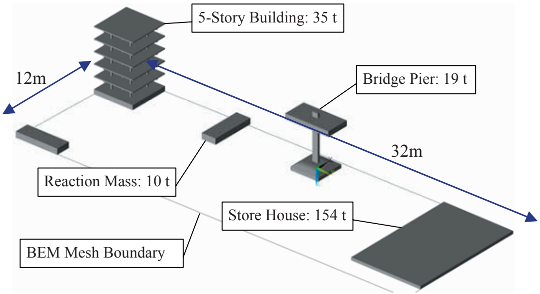

Figure 6. FEM models of the test site

The bridge pier and the 5-story building are modeled with solid, beam and shell elements. In order to demonstrate the possible interaction between the nearby structures first, a horizontal harmonic excitation with an amplitude of 0.1m, duration of 2.5 sec and a frequency of 2 Hz (which is close to the fundamental natural frequencies of the two models) is chosen. In order to compare the interaction between the nearby buildings, two simulations are performed, i.e. one of the pier analyzed alone and one by accounting for the effect of all the surrounding structures and soil as described above.

The comparison of the pier top displacements for both cases, along the strong axis shows a small, but not negligible increase in the movement of the pier top. Figure 7 also presents the ratio of the Fourier Transformations of the horizontal displacement that is derived at the top of the pier for the case that the neighboring structures are accounted for, with respect to the case that the pier stands alone. From this figure it is observed that for the range of frequencies of interest (2-3 Hz) the presence of the neighboring structures indeed affects the pier dynamic response, but to a relatively low degree (only by 6%). With respect to the sensitivity of the response of the 5-story building to the existence and consideration of the surrounding structures and soil formations, a small increase (6mm) is observed in terms of horizontal and vertical displacement when the neighboring built environment is accounted for (Figure 8).

It has to be noted though that, the above observations cannot be easily generalized. In fact, the overall superposition, reflection and refraction of the incoming waves at the soil boundaries, the foundations and the surface, as well as the coupling of the wavefield radiated by the oscillation of the superstructures is a complex phenomenon, especially in the presence of strong excitations and subsequent nonlinear material (soil and structure) behaviour.

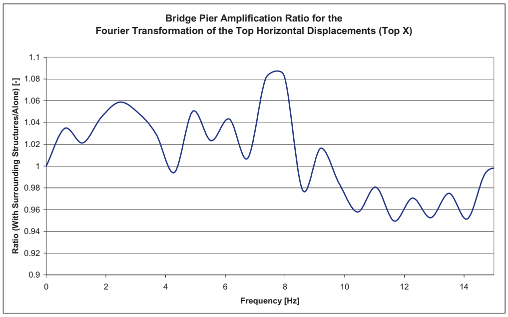

Figure 7. Influence of the surrounding structures on the bridge pier for a harmonic wave excitation

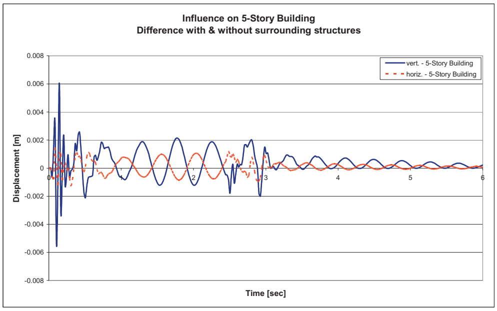

Figure 8. Influence of the surrounding structures on the response of the 5-storey structure for a harmonic wave excitation

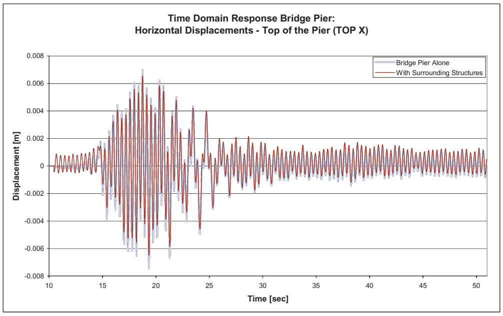

Figure 9. Time domain: influence of the surrounding structures on the bridge pier response in the horizontal direction

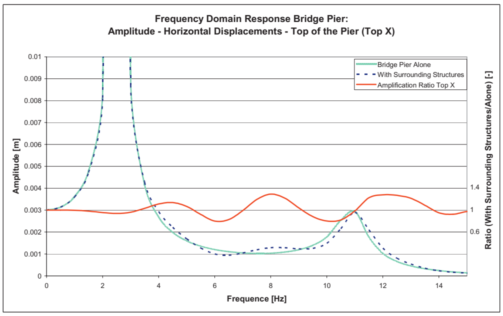

Figure 10. Frequency domain: Horizontal influence of the surrounding structures on the bridge pier

An investigation of the effects of the surrounding structures has also been performed on the basis of the actual recorded Arnea earthquake with the Magnitude 5.8 (4/05/1995, PGA = 0.35g, epicentral distance = 30km). Therefore the N-S and vertical component of the Arnea event have been applied to the subgrade. The results in the time and frequency domain analyses are presented in the following.

Figure 9 illustrates the influence of the surrounding structures on the bridge pier response in the horizontal direction which again is small but not negligible. This can be seen in more detail in Figure 10, which presents the horizontal response of the pier in the frequency domain for the two cases examined (i.e. with or without the effect of the nearby structures). The ratio of the amplitude of the motion in the two cases indicated by the solid line and measured at the right vertical axis shows that the increase in the response can be approximately 5-8% for frequencies of interest (2-3 Hz). Along these lines and in order to confirm the preliminary results presented herein, further analyses are required and additional parametric studies have to be carried out in order to identify the circumstances under which the influence may be more important.

6 CONCLUSIONS

It has been recognized that the presence of built environment may introduce noticeable changes both to the earthquake input motion as well as to the dynamic response of a structure of interest compared to the same structure standing alone. The present numerical simulation, studying this interaction problem, aims to examine numerically tools that can successfully be applied in order to deal with this coupled structure-soil-structure interaction system in a realistic and feasible way.

Having established a level of confidence on the tools utilized for the study of this complex phenomenon and because it is highly desirable to validate the findings of such a numerical investigation with in-situ observations it was decided to apply the present investigation to the built environment of the Volvi – Greece European Test Site for Earthquake Engineering. This offers the advantage that the site represents a controlled environment both in terms of the model structures built there as well as of the existing soil conditions.

The results drawn by the numerical analysis indicate that complex wave field developing at the foundation soil cannot be assessed using the widely used approaches. Moreover, the dynamic behavior of the structures in the presence of other buildings can differ compared to the response of the structure alone, but has to be studied in depth before drawing some more general conclusions in terms of potential design implications.

ACKNOWLEDGEMENT

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