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EFFECT OF SOIL-STRUCTURE INTERACTION ON THE SEISMIC RESPONSE OF AN INSTRUMENTED BUILDING DURING THE CEPHALONIA, GREECE EARTHQUAKE OF 26-1-2014

Christos Karakostas[1], George Kontogiannis[2], Konstantinos Morfidis[1], Emmanouil Rovithis[1], George Manolis[3] and Nikolaos Theodoulidis[1]

[1] Institute of Engineering Seismology & Earthquake Engineering (EPPO-ITSAK)
Dasiliou Str., Eleones, Pylaia, GR55535, Thessaloniki, Greece
e-mail: {christos, kmorfidis, rovithis, ntheo}@itsak.gr

[2] Civil Engineer A.U.Th., BETA CAE Systems SA,
Kato Scholari - Thessaloniki, GR-57500 Epanomi, Greece
geokonto92@gmail.com

[3] Civil Engineering Dpt., Aristotle University
GR54124 Thessaloniki, Greece
gdm@civil.auth.gr

Keywords: Soil-Structure Interaction, seismic response, Cephalonia earthquake, Lefkas island, seismic hazard estimation.

Abstract. *An investigation of SSI effects on the seismic response of the Prefecture building in the island of Lefkas is conducted, based on recordings of an earthquake excitation at its base and at a nearby free-field station. Detailed F.E. models of the building are developed and used as a basis for the development of simpler, yet reliable models for the numerical investigation of SSI effects. Both kinematic and inertial interaction are taken into account, using the substructure approach. The comparison of the predicted response with the actual one recorded at the basement of the building is presented and discussed, as well as the various repercussions due to the potential underestimation of the seismic hazard from recording stations housed at the basement of buildings.*

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1 INTRODUCTION

The present research effort deals with the investigation of the Soil-Structure-Interaction (SSI) effects on the seismic response of a R/C building housing the Prefecture of the island of Lefkas, Greece, under a strong earthquake that occurred on 26/1/2014 at the neighboring island of Cephalonia. In the early months of 2014, two major events took place in the southwestern end of the island of Cephalonia, the first (M6.1) on January 1, 2014 followed by a M6.0 one on February 3, 2014. Both events are related to the Cephalonia Transform Fault, a right-hand strike-slip fault with reverse thrust [1]. In the town of Lefkas (capital of the namesake island), around 80km NE of the earthquake epicenters, and at the basement of the aforementioned Prefecture building (Figure 1, yellow dot), the excitations were recorded by a high-resolution accelerograph that had been installed by the Institute of Engineering Seismology & Earthquake Engineering (EPPO-ITSAK) as part of the Hellenic National Strong-Motion Network. In the framework of a research program and at a distance of approximately 70m from the building (Figure 1, green dot), a similar accelerograph was installed in free-field conditions in 2012, and also recorded the event [2].

Figure 1: Location of the accelerographs in the town of Lefkas

A comparison between the two recordings of the 26-1-2014 event (Figure 2) shows that at the free-field location the recorded acceleration amplitudes are larger than those at the basement of the building, and it is also observed that the frequency content is richer.

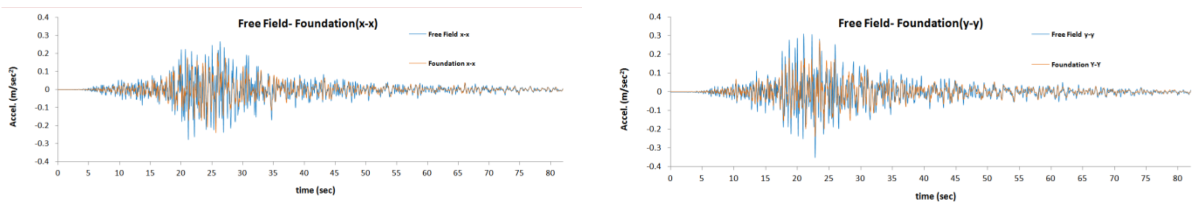

Figure 2: Recordings of the 26-1-2014 event at the free-field (blue) and the basement of the Lefkas Prefecture building (orange)

This comparison clearly shows the effect of SSI on the recordings, a phenomenon still open to research, even though the first investigations on the subject are dated from the 1950s. By definition, SSI leads to a differentiation of the seismic response of a structure primarily due to rigid body motions of the foundation in translation and rotation and mobilization of energy dissipation in the soil in the form of radiation and hysteretic damping with no counterpart in the corresponding fixed-base structure. SSI effects have been shown to be more pronounced for stiff buildings founded on soft soils, as is the case herein examined. For the analytical investigation of the phenomenon, two main methodologies have been developed, namely direct and substructure methods. In direct methods, a single numerical model (using finite elements, sometimes in combination with boundary elements) comprises the structure, its foundation and the surrounding soil, allowing for the analytical investigation of non-linear effects ([3], [4], [5]). Substructure methods are suitable for only linear response (or linearised assumptions), and, being less computationally demanding, have been adopted by the current seismic codes. In these methodologies the coupled SSI system is decomposed into a kinematic and an inertial part ([6], [7]). The latter is accounted for through appropriate generalized springs and dashpots attached at the structure base. Kinematic interaction refers to the stiffness of the (massless) foundation, which may modify the free-field excitation. The main parameters affecting kinematic interaction are the dimensions of the foundation and its embedment depth. Taking into account the kinematic interaction effects leads to the computation of the modified free-field motion which is to be introduced as excitation at the base of the foundation (foundation input motion –FIM). On the other hand, inertial interaction is due to the mass and stiffness of the foundation and the structure and also affects the structural response for a given FIM. In the present paper we present an analytical estimation of SSI effects on the seismic response of the Prefecture building in the town of Lefkas (using the free-field recordings as the basis of the computations) and we compare the analytical predictions with the actual recordings at the building's basement.

2 THE PREFECTURE BUILDING AT LEFKAS – DESCRIPTION AND ANALYTICAL F.E. MODELS

In the following, a description of the Prefecture Building at Lefkas town is presented, together with analytical finite element (F.E.) models that were developed in order to investigate its dynamic behaviour.

The building under investigation is a statically independent part (Figure 3 right, shaded part III) of a complex of buildings that house the administrative agencies (Prefecture and Municipality) of the island of Lefkas.

Figure 3: The Prefecture Building at Lefkas (statically independent Part III, in yellow ellipse)

2.1 Load Bearing system

The R/C building was originally designed on July 1991, and a revision took place on August 2007, according to the provisions of the 2000 Greek Reinforced Concrete Code (EKOS2000) and Greek Seismic Code (EAK2000), and their later amendments. The building consists of a basement, ground floor and 1st floor, each with a surface of 761m^2. The height of the basement is 3m while the height of each one of the two floors 3.25m. The building also has an inner courtyard with a surface of 114.95m^2. The typical formwork of the basement and ground floors is presented in Figure 4, together with that of the strip foundation.

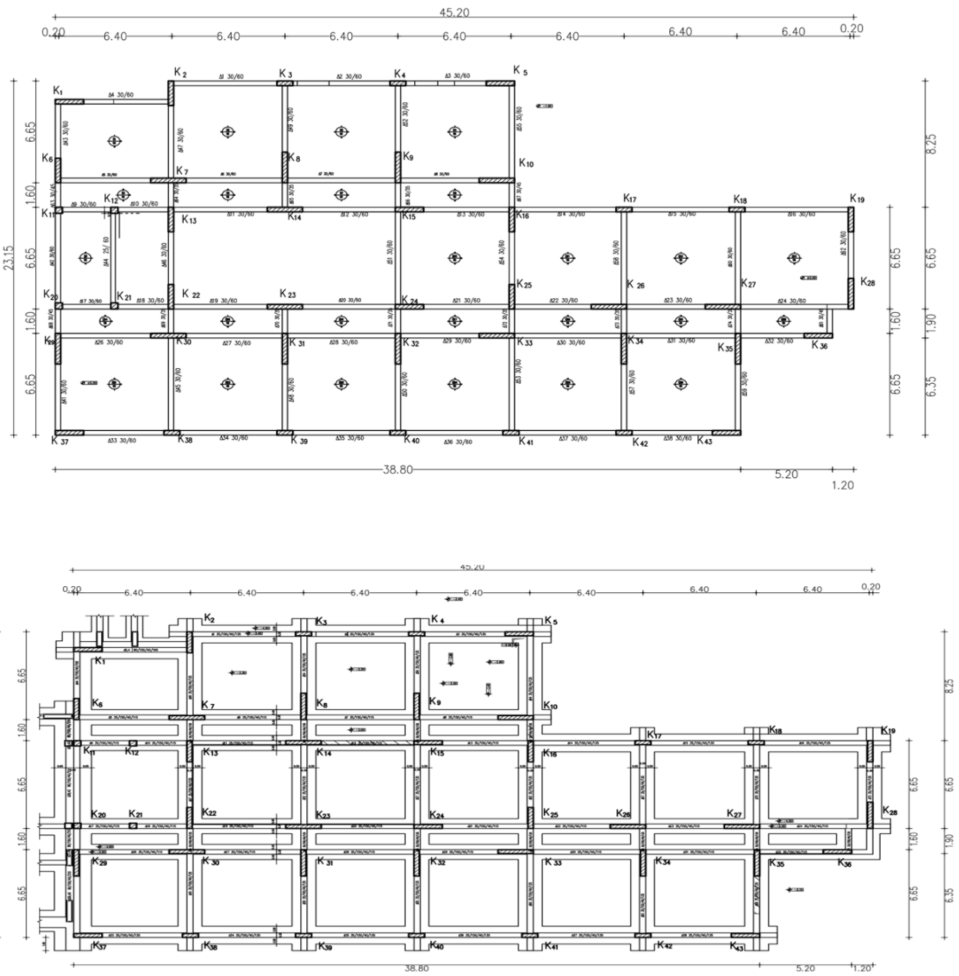

Figure 4: Formwork of the basement and ground floors (top) and of strip foundation (bottom)

2.2 Development of analytical F.E. Models

For the analytical investigation of the seismic response of the building several 3D F.E. models of various levels of complexity were developed using the SAP (2000) program. Given the elongated shape of the building and the inclusion of the inner courtyard, 3D models with full modeling of the floor slabs with plate elements were developed (Figure 5, left) which were used to validate simpler 3D models with the assumption of a diaphragmatic behaviour of the floor slabs (Figure 5, right). The comparisons under fixed-base conditions (Table 1) of the dynamic characteristics (eigenvalues, eigenmodes) showed that the simpler, "diaphragmatic" models can also reliably describe the dynamic behaviour of the building. In order to facilitate the subsequent analytical investigations which include consuming time-history computations, an equivalent "stick" model (i.e. with a lumped mass and one column for each floor – an extended version of the model is presented later in Figure 11) was developed, with dynamic properties similar to those of the exact 3D models (Table 1) and which was henceforward used as a basis for the analyses. A more detailed presentation of the developed F.E. models can be found in [8].

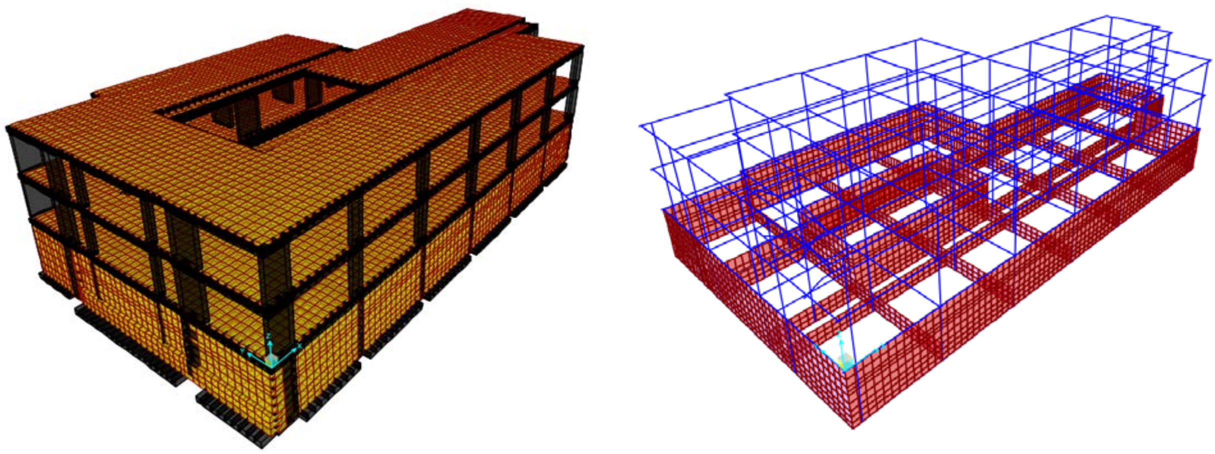

Figure 5: 3D F.E. models of the building with plate elements modeling the floor slabs (left), and with the assumption of diaphragmatic behaviour of the floor slabs (right).

Eigenvalue	Direction	Period (sec)		
		Model with plate elements for floor slabs	Model with diaphragmatic behaviour of floor slabs	"Stick" Model
1	Translational Y	0.144	0.158	0.173
2	Translational X	0.129	0.153	0.154
3	Torsional Z	0.118	0.120	-

Table 1: Main eigenvalues of the Prefecture building (3D models)

3 INVESTIGATION OF SSI EFFECTS ON THE SEISMIC BEHAVIOUR OF THE PREFECTURE BUILDING

The purpose of the investigation is to predict, based on the recorded free-field excitation, the Foundation Input Motion (FIM) in terms of translational and rotational motion of the foundation by means of available empirical and theoretical models in the literature. The computed FIM is then used as input to the "Stick" F.E. model of the building (suitably modified in order to take into account the dynamic properties of the soil), in order to predict the building's response at the basement, and compare it with the actual motion recorded by the accelerometric station.

3.1 Kinematic interaction analysis

The physical mechanism of kinematic SSI studied herein refers to rigid massless embedded foundation under vertically propagating shear waves (Figure 6).

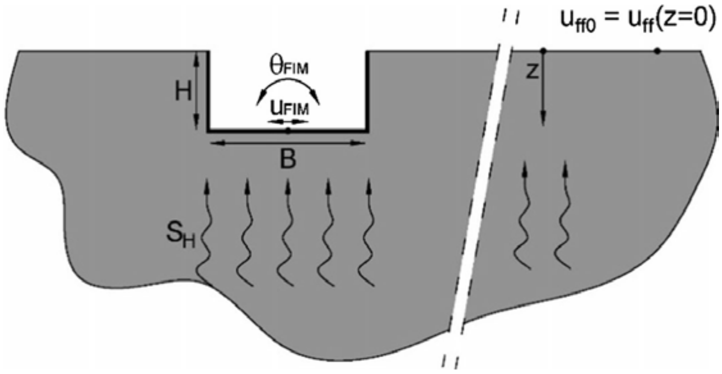

Figure 6: Schematic representation of the soil–foundation kinematic interaction in the case of embedded foundations and vertically propagating SH waves (from [9])

In this case, the translational component of the foundation input motion (U_{FIM}) may differ from the free-field motion (U_{ff0}) recorded at ground surface due to base slab averaging and embedment effects while it can also introduce a rotational component of motion (θ_{FIM}) as a result of differential displacements imposed upon the foundation over its embedded depth.

Among various proposals found in the literature, in the present effort we apply an approximation of the actual foundation response relative to ground surface proposed by Elsabee and Moray [10] based on the following equations for the two kinematic factors pertaining to the horizontal and rotational component of the foundation motion:

$$\mathrm{I_u} = \frac{U_{FIM}}{U_{ff0}} = \begin{cases} \cos(\frac{\omega H}{V_s}) & \frac{\omega H}{V_s} \leq 1.1 \\ 0.453 & \frac{\omega H}{V_s} > 1.1 \end{cases} \tag{1}$$

and

$$\mathrm{I}_\theta = \frac{\theta_{FIM}\mathrm{H}}{U_{ff0}} = \begin{cases} 0.257\frac{2H}{B}\left[1-\cos(\frac{\omega H}{V_s})\right] & \frac{\omega H}{V_s} \leq \frac{\pi}{2} \\ 0.257\frac{2H}{B} & \frac{\omega H}{V_s} > \frac{\pi}{2} \end{cases} \tag{2}$$

where V_s may be interpreted as an effective velocity $V_{s,avg}$, averaged over an effective depth z_p, according to the following expression ([11]):

$$\mathrm{V_{s,avg}} = \frac{z_p}{\sum_{i=1}^{n}\frac{\Delta z_i}{V_s(z)_i}} \tag{3}$$

Depending on the deformation mode of the foundation, the effective depth z_p (measured below the foundation bearing level) can be taken from:

$$z_p = \sqrt{BL} \quad \text{, for the translational mode} \tag{4}$$

$$z_p = \sqrt[4]{B^3 L} \quad \text{, for the rocking mode around x-x axis} \tag{5}$$

$$z_p = \sqrt[4]{BL^3} \quad \text{, for the rocking mode around y-y axis} \tag{6}$$

where B and L in Eqs. (4) – (6) refer to the half-dimension of the entire foundation plan.

In the case of the Lefkas Prefecture building, the dimensions of the plan and section views of the foundation are shown in Figure 7. According to these, a foundation width-to-embedment depth ratio of $(B/H)_{x\text{-}x}$=11.9 is computed along the X-axis and correspondingly $(B/H)_{y\text{-}y}$=6.1 along the Y-axis.

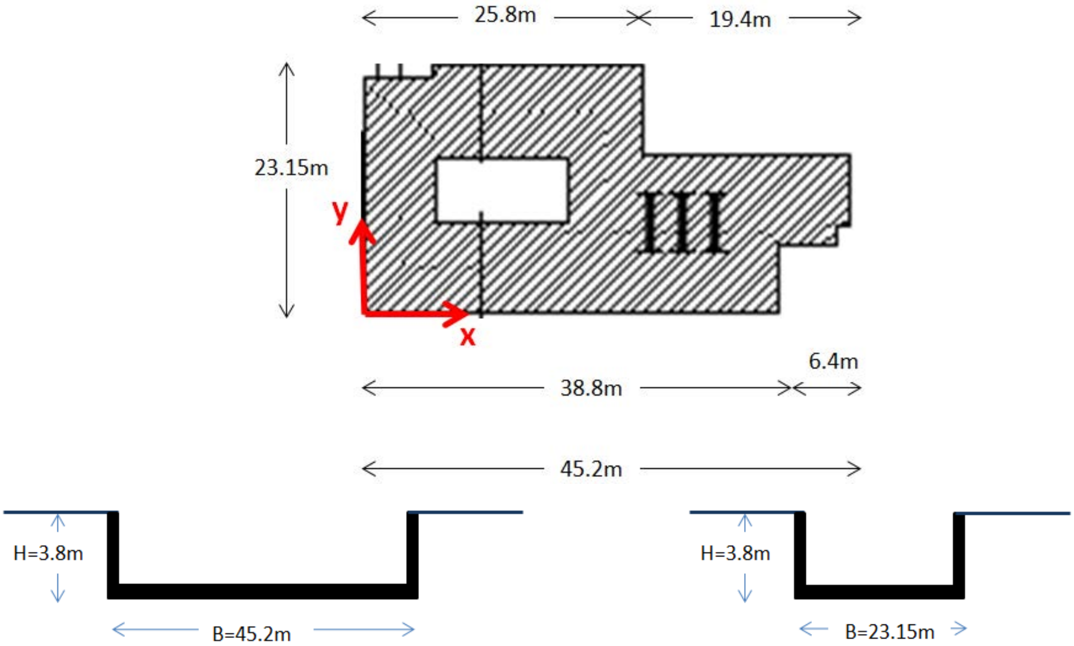

Figure 7: Foundation of Lefkas Prefecture building: Plan view (top), Section view along X-axis (bottom left) and Section view along Y-axis (bottom right)

Due to unavailability of the actual soil profile data at the building site, a two-layer V_s profile over half space at a nearby site was assumed based on previous works ([12],[13],[14], see Table 2).

	1st layer	**2nd layer**	**Half–space (bedrock)**
V_{so} (m/sec)	110	600	2000
Thickness h(m)	8	75	-
Qs	17	50	200
D (%) (=1/2Qs)	2.9	1	0.25
ρ (t/m^3)	1.9	2.2	2.5

Table 2: Soil profile parameters used for the analyses

According to EC8, non-linear soil response may be accounted for in an approximate manner by taking reduced shear modulus values depending on the acceleration at ground surface (EC8, § 4.2.3). Given the amplitude of peak acceleration (PGA=0.03g) recorded at the free-field station close to the Lefkada building for the 01/26/2014 Cephalonia earthquake, a slight reduction of V_s/V_{so}=0.95 was adopted to account for the above issue. Based on the above data, the average $V_{s,avg}$ was computed for two cases: Case 1 with V_s averaged over the depth (z_p+H), which led to an average value of V_s~160m/sec and Case 2 with V_s averaged over the embedment depth (H), leading to an average value of V_s~100m/sec.

Having computed the Kinematic Interaction Factors (KIF) according to eqs. (1) and (2) for the translational and rotational vibration mode of the foundation, a prediction of the foundation motion (FIM) in time domain is possible by means of the following procedure shown in Figure 8 (FFT and iFFT denote Fast Fourier and Inverse Fast Fourier Transformations). It is noted that the product of Fourier spectrum times the KIF is performed in the complex regime with soil material damping (ξ) incorporated in the solution of Eqs. (1) and (2) by using the standard substitution $V_s \rightarrow V_s^* \cong V_s\,(1 + i\xi)$

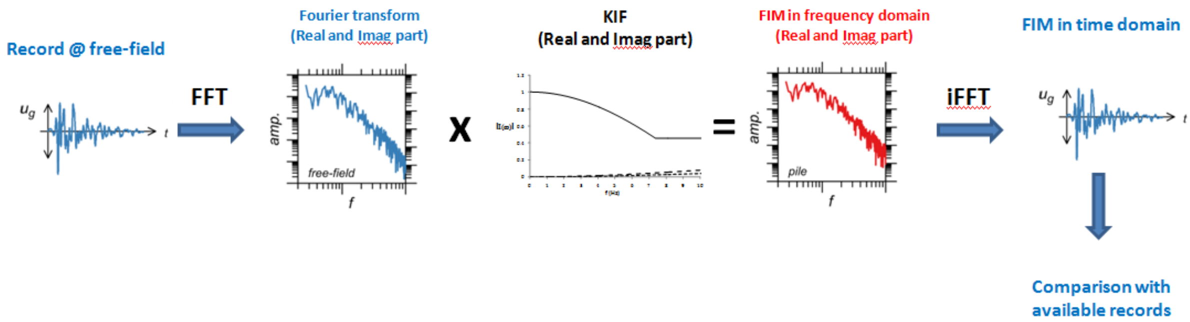

Figure 8: Schematic representation of the computation of FIM from free-field recordings (modified after [15])

The implementation of this procedure for the Lefkas Prefecture building showed that Case 2 (i.e. for V_s~100m/sec) yielded results that compare better (in terms of elastic response spectra) to the recorded response at the building basement, than that of Case 1, which is more compatible with the code provisions (eqs (3) to (6)), but nevertheless predicted more accentuated elastic response spectra in the lower (T<0.5sec) period range than that of the actual recordings (Figure 9).

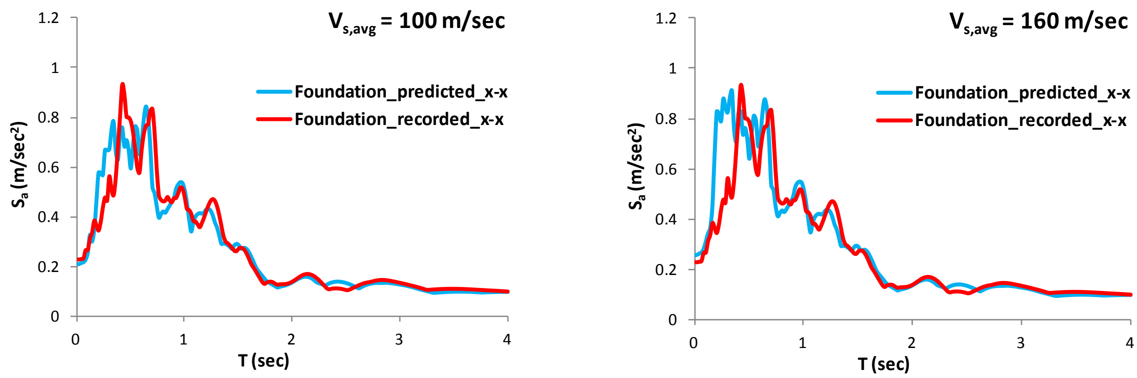

Figure 9: Elastic response spectra of predicted FIM (blue) and recorded response (red) for the two examined values for $V_{s,avg}$ (X-direction)

A possible explanation may be the fact that the actual soil profile at the building site is not exactly similar to the one adopted (see Table 2), and due to various reasons (e.g. different layer thickness, lower actual V_{so} values for each layer etc), an average value for V_s~100m/sec better represents the actual site conditions. For this reason, and also considering that the – still to be taken into account - inertial part of the SSI will most likely further accentuate the predicted response, an average value of value of V_s=100m/sec was adopted for the subsequent analyses.

3.2 Inertial interaction analysis

For the computation of the Inertial SSI part, proper impedance functions were used, which represent the frequency-dependent stiffness and damping characteristics of soil-foundation interaction, in the form:

$$\bar{K}_j = k_j + i\omega c_j \tag{7}$$

where $\bar{K}_j$ denotes the complex-valued impedance function; j is an index denoting modes of translational displacement or rotation; k_j and c_j denote the frequency dependent foundation stiffness and dashpot coefficients, respectively, for mode j; and ω is the circular frequency (rad/s). A dashpot with coefficient c_j represents the effects of damping associated with soil-foundation interaction. Pertinent formulas for embedded foundations ([5], [16]) were employed to derive springs and dashpots for the case of Lefkada building by assuming the whole foundation as fully embedded (embedment depth D=3.8m, see Figure 7). Some of the (in general frequency-dependent) results for the computed dynamic stiffness (springs) and damping (dashpots) are presented in Figure 10.

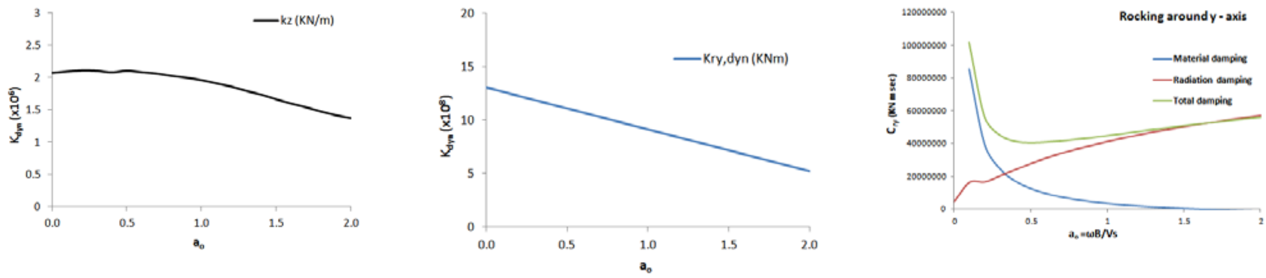

Figure 10: Indicative dynamic stiffness (left, center) and damping (right) values for the Lefkas Prefecture building

As already discussed, the computed dynamic stiffness and damping were introduced (through appropriate springs and dashpots) in an updated version of the developed “stick” model of the building (see §2.2), that was extended to also include the slab of the foundation (Figure 11). The implementation was done using the NLink elements of the SAP F.E. code. Since the dynamic stiffness and damping are frequency-dependent, and the code does not provide this possibility, their values were computed for a “representative” frequency, which corresponds to the mean period value of the FIM time-histories evaluated in §3.1. According to Rathje et al. [17] the mean period *(Tm)* is the best simplified frequency content characterization parameter, being estimated with the following equation, where C_i are the Fourier amplitudes, and f_i represent the discrete Fourier transform frequencies between 0.25 and 20 Hz.

$$T_m = \frac{\sum C_i^2 / f_i}{\sum C_i^2} \tag{8}$$

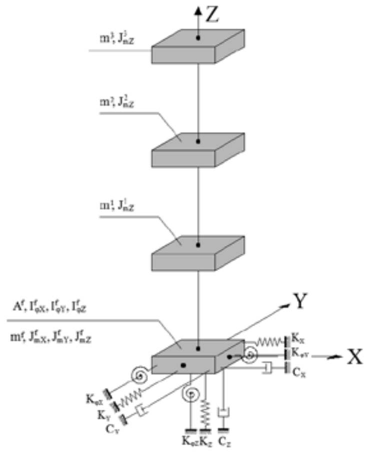

Figure 11: Extended "stick" model for the Lefkas Prefecture building

In Figure 12 the computed response at the foundation node of the model for the two horizontal directions and the corresponding input motion (FIM) are presented, together with their difference (in black), which essentially is the contribution inertial interaction of the response to the SSI effect, which cannot be deemed as insignificant.

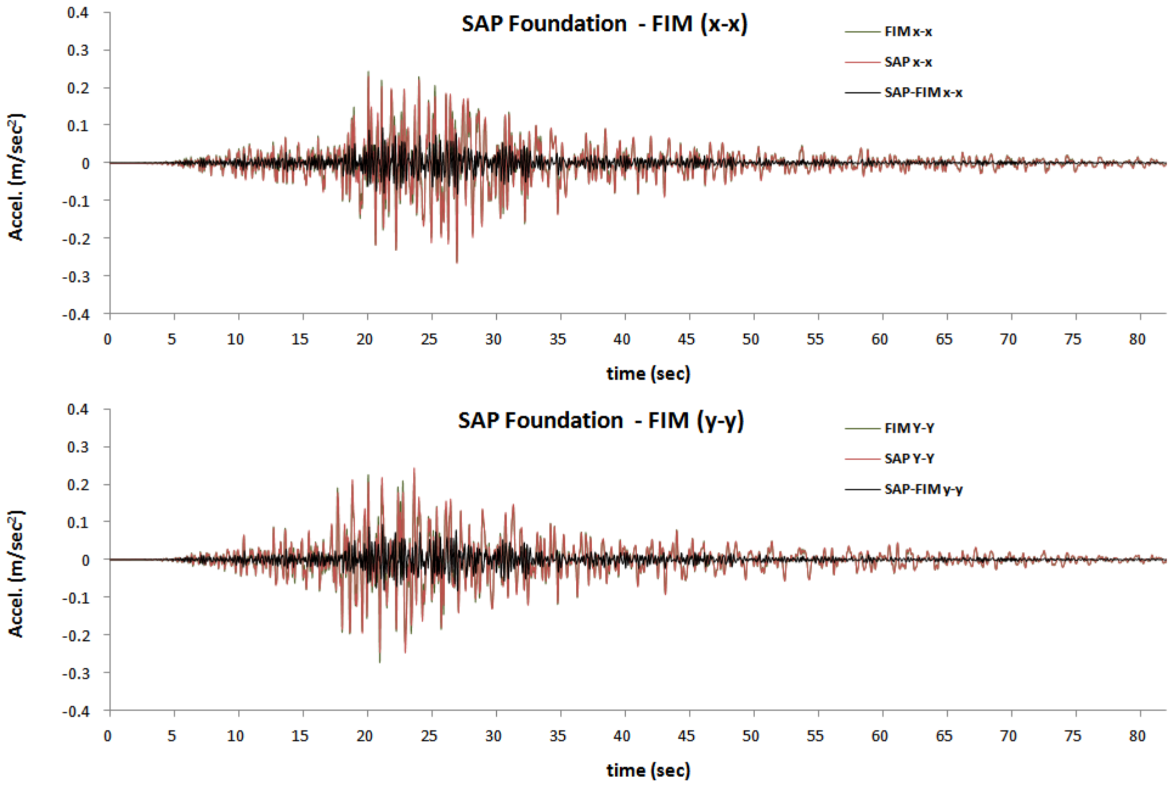

Figure 12: Computed response at the basement of the Lefkas Prefecture building (red), corresponding input motion (green) and contribution of inertial interaction (black)

In Figure 13 the computed response at the foundation node of the model (in red) is compared to the actual recording of the sensor at the building basement (in blue). It can be seen that the analytical prediction is in general satisfactory, from an engineering point of view, both in the time and frequency domain.

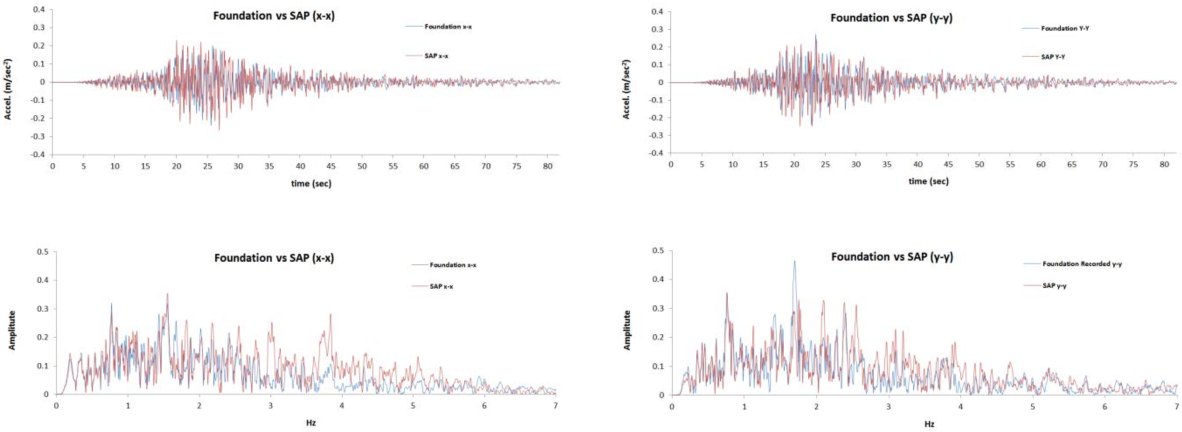

Figure 13: Computed (red) vs. recorded (blue) response at the basement of the Lefkas Prefecture building in time (top) and frequency (bottom) domain

A more quantitative way to confirm that the computed response is adequately equivalent to the recorded one, is to compare some ground motion parameters that are proposed in the literature (e.g. [18]) to represent the potential of an accelerograph regarding the expected structural damage (Table 3). In the same Table, the corresponding values of the recorded free-field response are also presented.

Ground Motion Parameter	Recorded response X-dir (Basement)	Predicted response X-dir (Basement)	Recorded response X-dir (Free-field)	Recorded response Y-dir (Basement)	Predicted response Y-dir (Basement)	Recorded response Y-dir (Free-field)
Max Acceleration (m/sec^2)	0.22507	0.25233	0.27724	0.27325	0.26908	0.33668
Arias Intensity (m/sec)	0.0173	0.02538	0.03047	0.02057	0.02405	0.03188
Acceleration Spectrum Intensity (m/sec)	0.2213	0.29218	0.33165	0.23656	0.29483	0.36266

Table 3: Ground motion parameters for recorded and computed response

From Table 3, we can deduct that the predicted response slightly overestimates the actual one, but within an acceptable degree, from an engineering point of view. Also, in general, the free-field recording has greater ground parameter values, and hence a higher potential for structural damage. This is mostly true for the max acceleration (PGA), which is the sole parameter currently adopted in the Seismic Codes to represent the intensity of the expected seismic excitation. Taking into account that, in several countries (including Greece), many recording stations of national strong-motion networks are housed, for practical reasons, at the basement of structures, we see that the recorded responses will in general yield lower than actual PGA values to be used for the seismic design of structures, the computation of Ground Motion Prediction Equations (GMPEs) etc. This is an issue that requires attention and further investigation in order to minimize all the undesirable repercussions of such an underestimation of the seismic hazard due to SSI effects.

4 CONCLUSIONS

- An investigation of SSI effects on the seismic response of the Prefecture building in the island of Lefkas has been conducted, based on recordings of an earthquake excitation at its base and at a nearby free-field station.
- Detailed 3D numerical F.E. models were developed and used as a basis for the development of simpler, yet reliable models for the numerical investigations.
- A substructure method was used for the investigation of the SSI effects. The kinematic interaction effects were first taken into account, yielding the predicted foundation input motion (FIM) from the free-field recording. The FIM was used as input in the simplified F.E. model of the building to predict its seismic response, also taking into account the inertial interaction effects.
- It was found that for the case we herein investigate, the kinematic interaction affects to a greater degree the seismic response of the building, however the contribution of the inertial interaction is also not negligible.
- The comparison of the finally predicted response agrees well, from an engineering point of view, with the actual one recorded at the building basement.
- Recording stations housed at the basement of structures in general may yield lower PGA and spectral values than at nearby free-field conditions. Further investigation and actions are required to minimize all undesirable repercussions stemming from such an underestimation of the seismic hazard due to SSI effects.

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