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KNOWLEDGE - BASED EXPERT SYSTEM FOR CONSIDERING SOIL - STRUCTURE INTERACTION EFFECTS IN THE DESIGN OF R/C BUILDINGS

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Abstract. *It is generally accepted that foundation soil conditions may modify the dynamic characteristics and the subsequent seismic response of structures. Extensive research performed in this field has revealed that, depending on the earthquake and soil characteristics, as well as on the relative structure-foundation-soil flexibility, neglecting the role played by the foundation subsoil may lead to unconservative design under certain circumstances, despite the common perception that Soil-Structure-Interaction (SSI) has a beneficial effect on the structural response. This paper is therefore concerned with the description of a Knowledge-Based Expert System (KBES) aiming to assist both the qualitative and the quantitative assessment of the significance of SSI effects during the seismic design process. Based on expert judgment, state-of-the-art scientific publications and seismic code provisions the modular System interacts with the user and decides whether SSI effects should be accounted for in the design, while it provides the appropriate dynamic stiffness matrices required for the finite element representation of the problem.*

1 INTRODUCTION

In engineering practice, during seismic design of R/C buildings, Soil-Structure-Interaction (SSI) effects are often treated as a beneficial phenomenon on the basis of the perception that amount of seismic forces that the structure will be subjected to, will be eventually reduced due to both the anticipated period elongation of the building and the energy dissipation that results from the wave radiation and hysteretic damping at the soil-foundation interface. As a result, with the exception of structures of particular importance, buildings are most commonly considered and designed as fully fixed at their base, hence still ignoring what is nowadays widely accepted after decades of extensive research: that the foundation is flexible, dissipates energy and interacts with the surrounding soil and the superstructure, in such a way that it filters seismic motion (kinematic interaction) while it is subjected to inertial forces generated by the vibration of the superstructure (inertial interaction). This phenomenon is indeed complex and its beneficial or detrimental effect on the dynamic response of the bridge is dependent on a series of parameters such as ([1], [2], [3]) the intensity of ground motion, the dominant wavelengths, the angle of incidence of the seismic waves, the stromatography, the stiffness and damping of soil, as well as the size, geometry, stiffness, slenderness and dynamic characteristics of the structure.

Apart from the perception that ignoring the interaction of the building with its foundation and the surrounding soil is a conservative approach, the lack of detailed seismic code provisions and ready-to-use, widely accepted methodologies impose an additional restriction even for cases that to the foundation compliance effects are indeed deemed important. This fact is further stressed by the difficulty and fuzziness, that the engineers encounter in practice when attempting to quantify the material characteristics of the foundation subsoil, as well as by the inherent uncertainty related to the prediction of the anticipated earthquake characteristics and their subsequent effect on the (frequency dependent) soil-foundation-building system interaction. As a result, it is rather unlikely that the design engineers will be able to deal with concepts and requirements which have an extensive theoretical background without the aid of an expert external consultant.

Along these lines, a Knowledge-based Expert System (KBES) has been developed and presented herein that assembles expert experience and engineering judgement, latest research results, experimental data and international seismic code advances in order to provide a structured, computer-based decision making procedure that: a) predicts *a-priori* the necessity to consider SSI effects in design, and if the latter are indeed important, b) suggests methods and dynamic stiffness matrix coefficients to be used directly in the finite element formulation by the user. It is believed that the particular Expert System whose background and architecture are described in the following sections, is a handy tool for both researchers and professionals.

2 KKNOWLEDGE BASED EXPERT SYSTEMS FOR CIVIL AND EARTHQUAKE ENGINEERING PROBLEM SOLVING

During the last decades, various Artificial Intelligence (AI) techniques have been used to develop solutions for the design of problems where conventional computer-based approaches have been proved inadequate. Three are the main, widely used AI techniques applied to solve design problems: Case-Based Reasoning (CBR), Artificial Neural Networks (ANN) and Knowledge-Based Expert System (KBES). Although the ability to learn from existing cases and training processes have made both CBR and ANN especially appropriate for dealing with complex situations or solving new kinds of problems, a KBES approach is still considered an effective means for the explicit representation of both the knowledge base and the heuristic rule bases related to common civil engineering problems. Moreover, the explanation facility component that is inherently embedded in KB expert systems, additionally allows for the gradual training of the user (instead of the system itself), a fact that is of primary importance for the particular problem, given the lack of insight that most engineers have towards the understanding of SSI effects.

A number of KBES have been developed during the last years to solve various civil engineering problems. The most recent involve Expert Systems for the analysis and design of liquid-retaining structures [4], optimal selection of retaining walls [5], management of underground pipelines [6] and maintenance planning of highway concrete bridges [7], [8], [9] among others. The implementation of fuzzy logic into such civil engineering expert systems has quantified the uncertainty of various subjective factors as a part of the decision process

[10], [11]. Nevertheless, relatively few Knowledge-Based Expert Systems have been developed purely for Earthquake Engineering applications (i.e. [12], [13]), the most recent primarily dealing with reinforced concrete design for seismic loading [14], or the assessment of earthquake induced building damage [15] and pre-earthquake assessment of buildings [16]. As a result, the potential of developing a specialised tool for managing the decisions related to the consideration of SSI effects was deemed indeed challenging. However, in order to provide an insight of the importance of soil-foundation-superstructure interaction on the dynamic response of buildings, both the SSI concept and the corresponding assessment methodology adopted herein has to be briefly described.

3 METHODOLOGY TO ASSESS DYNAMIC SOIL-FOUNDATION-STRUCTURE INTERACTION EFFECTS

The main reasons, which render the consideration of the foundation-soil system compliance and damping an important parameter of the seismic design process currently recognised by most modern seismic codes worldwide, although no detailed provisions are provided with the exception of Eurocode 8-Part 5 [17] which provides an informative annex of simple equations for the case of pile groups. According to EC8:

- the foundation motion of the flexibly-supported structure will differ from the free-field motion and may include an important rocking component of the fixed-base structure
- the overall damping of the flexibly-supported structure will include both the radiation and the internal damping generated at the soil-foundation interface, in addition to the damping associated with the superstructure.
- the fundamental period of vibration of the flexibly-supported structure will be longer than that of the fixed-base structure.
- the natural periods, mode shapes and modal participation factors of the flexibly supported structure will be different from those of the fixed-base structure, while rocking around the three axes of the foundation is also anticipated.

The basic methods to deal with in the analysis of Soil-Structure Interaction effects by implementing Finite Element Discretization are the Complete Finite Element approach and the Substructure Method. The KBES presented herein is developed based on the latter, and particularly on the decoupling and superposition of kinematic and inertial interaction concept as proposed by Kausel and Roesset [18], Makris and Gazetas [19] and Mylonakis et al. [20]. According to this approach, the dynamic stiffness matrix of the superstructure is coupled with an additional impedance matrix representing the underlying unbounded soil-foundation region. The superstructure is then excited by the response history (denoted as Foundation Input Motion – F.I.M.) of a hypothetical soil-foundation sub-system lacking the superstructure mass (Figure 1) but supported on appropriate 6-DOF, frequency dependent, dynamic impedance elements (i.e. “springs” and “dashpots”) that are associated with all the swaying (R_x, R_y and R_z), rocking (R_{rx}, R_{ry} and R_{rz}) and cross-swaying-rocking motion of the foundation. Especially for the rotational stiffness of those foundations support columns which have a potential to develop plastic hinge at their base, a non-linear moment-rotation relationship is adopted [21] combining the rotational compliance of the foundation with a lumped plasticity model for the R/C section. The implementation of the particular concept in the Expert System developed herein is presented and described in more detail in section 4.3.

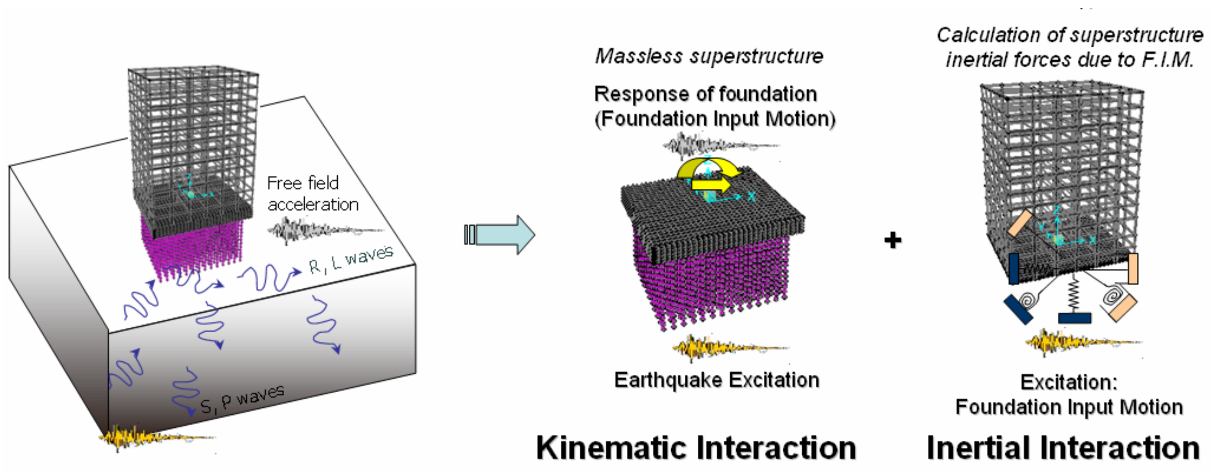

Figure 1: Decoupling of Kinematic and Inertial interaction effects

4 DEVELOPMENT OF A KBES FOR THE ASSESSMENT OF SSI EFFECTS

4.1 Principles and scope

The proposed Knowledge Based Expert System for SSI (EXSYS-SSI) is an interactive environment that has been that has been designed in order to:

- transform the knowledge of “human experts” regarding the potential impact of SSI effects into a structured knowledge base so that, depending on the information that is each time provided by the user, it can essentially act as a single computer-based consultant that provides advice for the particular building.
- assess, based on qualitative criteria the necessity of considering S.S.I. phenomena in the design of the building which is located on specific soil and seismotectonic conditions.
- estimate the fundamental period of the fixed-base and flexibly supported building.
- validate the initial estimation about the necessity of considering S.S.I. effects depending on two quantitative criteria and data asked to (and provided by) the user.
- in case that the system itself decides that SSI effects have to be accounted in design, calculate the appropriate static/dynamic stiffness matrices (the latter in terms of spring and dashpot coefficients) for the particular foundation (surface or deep) and for different types of structural analysis (i.e. equivalent static load, response spectrum, pushover, elastic and inelastic analysis in the time domain).

The present system was developed using Visual Basic & Visual Basic.NET programming languages involving approximately 160 different variables that are incorporated into three main modules and numerous submodules as can be seen in Figure 2:

- Module 1: Check for the necessity of considering the D.S.S.I. phenomena. It consists of three different levels check implemented in the subsequent submodules.
- Module 2: Calculation of the dynamic stiffness matrix for the case of surface foundations.
- Module 3: Calculation of the dynamic stiffness matrix for the case of deep foundations.

Data are imported by the user at all the above stages while the estimated parameters are exported directly to the widely used commercial Finite Element code ANSYS [22] using the built-in APDL scripting language. The complete flowchart of the Expert System module structure and the internal rules associated, are illustrated in Figure 3, while the overall System architecture is described in the following.

4.2 Expert system's architecture

The structure of EXSYS-SSI consists of a number of different components, that are typical for an Expert System ([23], [24], [25]), which are classified as follows:

Knowledge Base: The expert system's core stores knowledge derived from the seismic code provisions (i.e. EC8 [17], FEMA 273 [26], FEMA440 [27], ATC-40 [28]), state-of-the-art research findings and data, expert knowledge and engineering judgment. The available knowledge has been assembled into a logical flowchart connecting the case study data (as interactively defined by the user) with the final qualitative decisions and quantitative results using the ***Inference Engine*** (i.e. specific calculations, "if … then" statements and other conditions). Depending on the decision made on the importance of SSI effects in the first place (i.e. Module 1), the ***Calculation engine*** is activated through Modules 2 and 3, where the calculation of springs and dashpots are implemented either for the surface foundation (footings) or for the single pile or pile group. The calculation engine is also activated during the second level check in order to compute the fundamental period of the fixed-based and flexibly supported building, as well as in order to calculate various structural performance characteristics according to FEMA provisions.

User interface: The graphical environment developed assists the used to browse easily between the different system modules and calculation scenarios, thus creating an interactive and effective channel of contact between the software's core calculation modules and the user. This interactivity is further enhanced through the ***Explanation subsystem*** which provides messages, references as well as reasoning and handling explanations at all stages of the decision making process up to the final calculation. The rules and logic flow is therefore easily traced by the user and it continuously improves his/her understanding towards SSI effects, while most importantly, increases the designers' acceptance of the system's output.

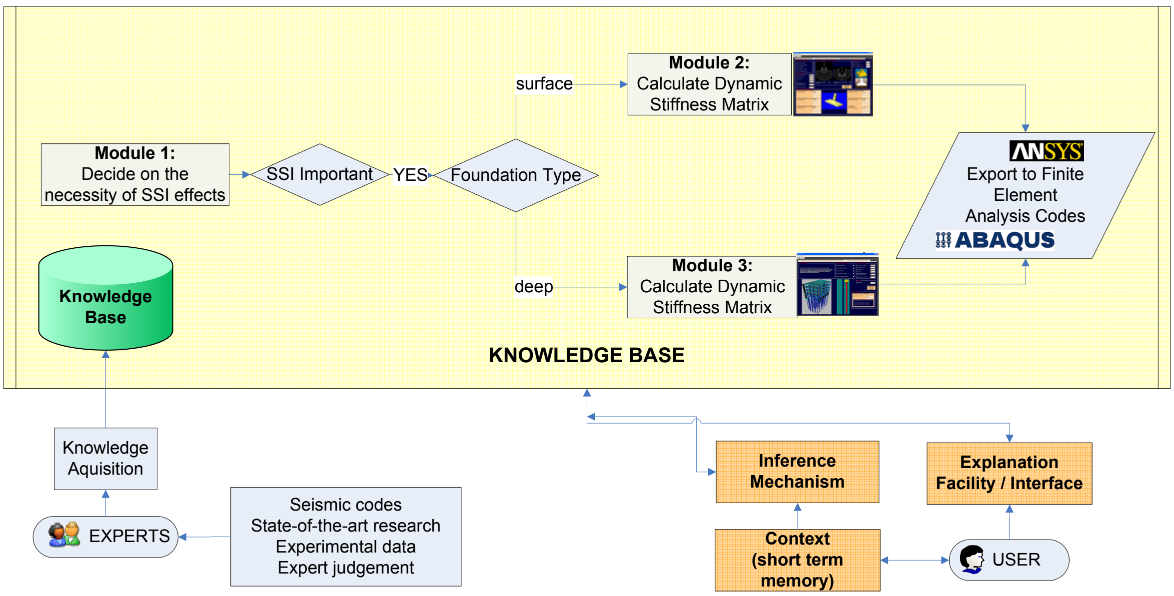

Figure 2: EXSYS-SSI architecture

4.3 Module description

Module 1: Decide on the importance of SSI effects

As mentioned previously, the first module of the Expert System is dedicated to conclude on the necessity of considering Soil-Structure-Interaction effects in the design of the particular building. It comprises of three individual decision levels, depending on the data provided by the user for each building's case. The three checks performed, which correspond to three internal submodules, are broken down as follows:

First Level Check submodule

As a ***First Level Check***, EXSYS-SSI requires general information about the soil-building system in order to perform an initial qualitative estimation about the necessity of considering S.S.I. phenomena. The information provided is related to the importance of the structure, the foundation soil category, the foundation type, the existence of high level water table, the existence of basement, potential exposure to near field earthquake motions, the regularity of the structure in height and plan (i.e. setbacks and pilotis), any torsional sensitivity of the structure and information regarding previously observed excessive settlements in adjacent structures. In the case that the above general conditions are deemed to form a case where soil-structure-interaction has a high probability of being of secondary importance, the user is guided to terminate the process. The conditions of such 'immediate exit' are summarised in Table 1. However, it is noted that, even in this case, the engineer is not prevented from performing a more refined SSI analysis, hence he is practically allowed (although practically discouraged) to proceed to Modules 2 or 3 directly.

Second Level Check submodule

In case that based on the abovementioned conditions the system cannot judge whether SSI effects are negligible or not for the particular building, the user is forwarded to the ***Second Level Check.*** The particular check point is based on FEMA 440 provisions for accounting for soil-foundation compliance and essentially requires a number of specific data (i.e. concrete class, number of storeys, complete geometry & loads of typical storeys, complete geometry of building shear walls, soil material properties, anticipated peak ground acceleration of seismic excitation, complete geometry of footings) in order to compute the fundamental periods of both the fully-fixed and the flexibly supported building (Figure 4). It is noted that the procedure proposed by FEMA 440 has been improved and modified in order to comply with European standards and design practice; details regarding the necessary adaptations made can be found elsewhere [29].

Depending on the computed relative elongation of the (translational) fundamental period the system provides a first quantitative estimate on the importance of SSI effects according to the following threshold value of an acceptable 30% increase:

$$\bar{T}/T \leq 1.30 \Rightarrow S.S.I.\ not\ important \quad (1)$$

In case that SSI effects are deemed indeed important, the system proceeds to Modules 2 to calculate the soil-foundation stiffness matrix for the building shallow foundation. It is also noted that, judging SSI effects as rather of limited importance according to equation 1, does *not* allow the user to neglect SSI phenomena before a final decision is made based on a combined criterion involving both the second and the third level quantitative check (as also illustrated in Figure 3. Apparently, the computation performed is inevitably an approximation that has to be verified by structural analysis, especially for complex, irregular or high-rise buildings. For this reason, the Expert system skips the particular ***Second Level Check*** for:

a) buildings with insufficient number and dimensions of shear walls along their two principal directions, or,
b) buildings founded on pile or micropile foundation.

For the above cases that the particular criteria are not fulfilled, the user is passed directly to the ***Third Level Check***.

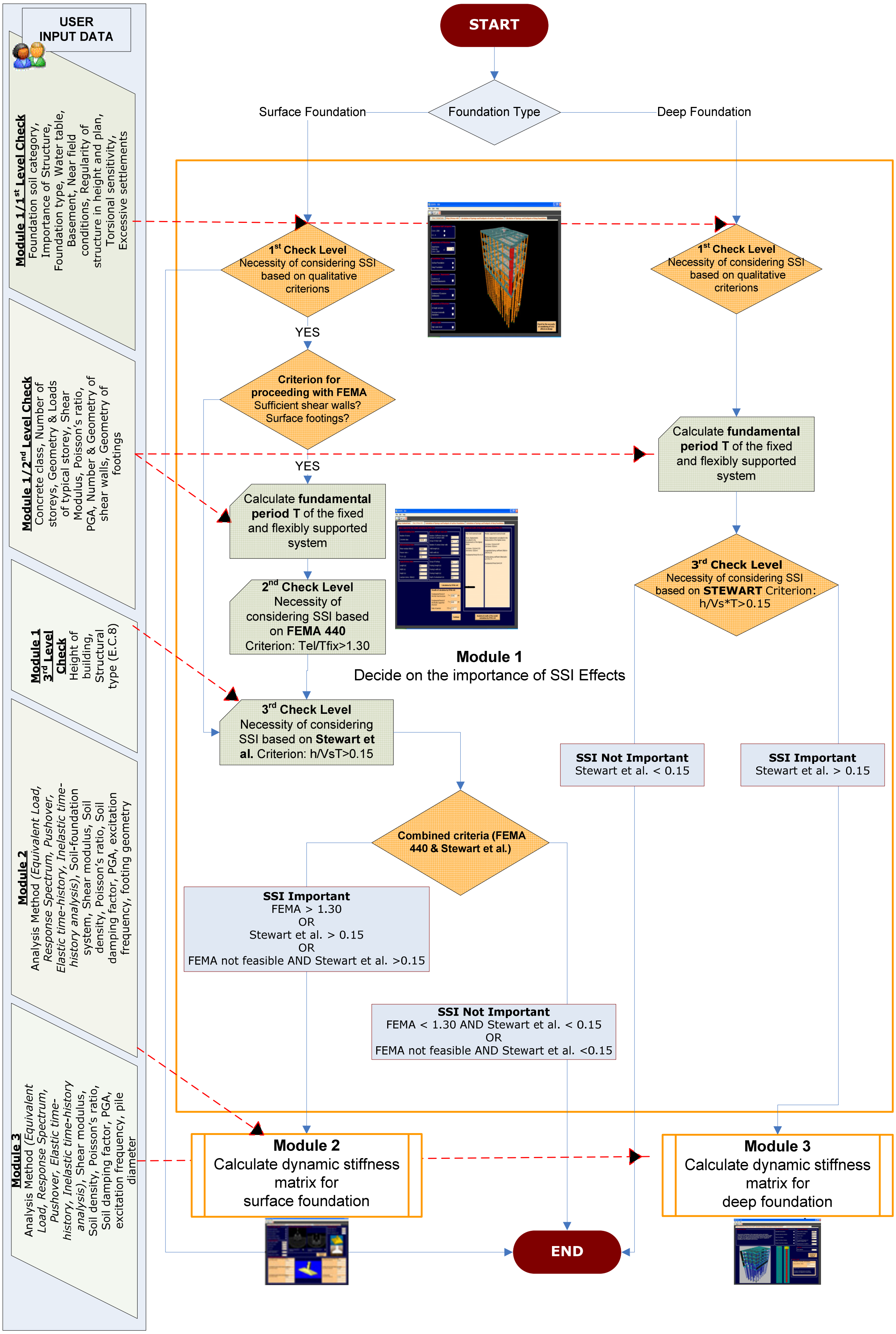

Figure 3: Flowchart of the Expert System for SSI (EXSYS-SSI) module structure and internal rules

Third Level Check submodule

Having estimated the fundamental period of the building, an additional criterion is applied based on the following expression:

$$\begin{cases} \dfrac{1}{\sigma} = \dfrac{H}{V_s \cdot T} \leq 0.15 \Rightarrow S.S.I.\ are\ Not\ Important \\ \dfrac{1}{\sigma} = \dfrac{H}{V_s \cdot T} > 0.15 \Rightarrow S.S.I.\ are\ Important \end{cases} \tag{2}$$

where H is the total height of the building, V_s is the shear wave velocity of the foundation subsoil and T is the fundamental period of the structure (as computed in the previous stage or derived according to FEMA 273 approximate expressions). The particular criterion has been proposed by Stewart et al. (1999) [30], [31] and it is based on measured data of numerous California buildings of various structural configurations. It is also adopted by EC8 commentary (Fardis et al., 2005) [32].

In order the system to conclude on the necessity of considering the S.S.I. phenomena, the results of the different check levels are weighed by the inference engine of the system. The final decision depends on the results of both the ***Second*** and ***Third Level Check*** as it is summarised in Table 2. It is noted the overall judgment on the basis of the particular combined criterion is purely heuristic and is proposed by the authors as a conservative rule of thumb.

Modules 2 & 3: Calculation of springs and dashpots of surface and deep foundations

Based on the final assessment of the potential importance of SSI effects on the dynamic response of buildings and the subsequent necessity to numerically simulate the dynamic properties of the soil-foundation-superstructure system, the Expert System proceeds to the calculation of the appropriate static or dynamic stiffness matrices depending on the type of analysis foreseen (i.e. equivalent static load, response spectrum, pushover, elastic and inelastic analysis in the time domain), soil material data, earthquake characteristics (in terms of dominant frequency and PGA) and the foundation type (shallow or deep). In particular, Module 2 is activated for the case of embedded footings on a homogeneous half space based on the solution proposed by Mylonakis et al. (2002) [3] and Module 3 is utilised for pile foundations according to Makris and Gazetas (1991) [33]. A snapshot of the particular modules is presented in Figure 5. It is noted that in case of deep foundations, the solution currently implemented in EXSYS-SSI does not account for the dynamic pile group effect.

5 CONCLUSIONS

This paper is concerned with the description of a Knowledge-Based Expert System, EXSYS-SSI. This system is an electronic tool, which facilitates the quantitative and qualitative assessment of soil-structure interaction effects on reinforced concrete buildings. Based on expert knowledge, state-of-the-art research and seismic code provisions, EXSYS-SSI a) assesses the necessity of considering the dynamic soil-structure interaction effects during the design of buildings and if this is indeed important, b) performs the proper calculations of the soil-foundation superstructure system dynamic stiffness matrices for direct implementation into finite element codes. It is believed that the particular system, which is evidently under further development, may reduce the uncertainty related to proper handling of the particularly complex phenomenon of Soil-Structure-Interaction by the designer, thus enhancing the reliability of structural analysis and improving seismic design reliability.

	Conditions of immediate exit (no demand for considering the S.S.I. effects)					
	EXIT 1	**EXIT 2**	**EXIT 3**	**EXIT 4**	**EXIT 5**	**EXIT 6**
Foundation soil category	**A (EC8)**	**-**	**B (EC8)**	**B (EC8)**	**C (EC8)**	**B (EC8)**
Importance of structure	**-**	**low**	**ordinary**	**ordinary**	**ordinary**	**ordinary**
Foundation type	**-**	**-**	**Surface**	**-**	**Surface**	**Deep**
High water level	**-**	**-**	**-**	**-**	**-**	**-**
Basement	**-**	**-**	**-**	**YES**	**-**	**-**
Near field condition	**NO**	**-**	**NO**	**NO**	**NO**	**NO**
Regularity in height & plan	**-**	**-**	**YES**	**-**	**YES**	**YES**
Torsionally insensitive	**-**	**-**	**YES**	**-**	**YES**	**YES**
Excessive Settlements	N/E	**-**	N/E	N/E	**NO**	N/E

N/E = Not expected to occur under the particular conditions

Table 1: Conditions of “immediate exit” from the EXSYS-SSI

Case ID	**Qualitative Assessment (1st Level Check)**	**Quantitative Assessment**		**Final decision on the necessity to consider S.S.I.**
		2nd Level Check	**3rd Level Check**	
		FEMA 440 [27]	**Stewart et al. [30], [31]**	
1	SSI Important	N/F	$\frac{H}{V_s \cdot T} \le 0.15$	SSI not Important
2	SSI Important	N/F	$\frac{H}{V_s \cdot T} > 0.15$	SSI Important
3	SSI not Important	skipped	skipped	SSI not Important
4	SSI Important	$\bar{T}/T \le 1.30$	$\frac{H}{V_s \cdot T} \le 0.15$	SSI not Important
5	SSI Important	$\bar{T}/T > 1.30$	$\frac{H}{V_s \cdot T} \le 0.15$	SSI Important
6	SSI Important	$\bar{T}/T \le 1.30$	$\frac{H}{V_s \cdot T} > 0.15$	SSI Important
7	SSI Important	$\bar{T}/T > 1.30$	$\frac{H}{V_s \cdot T} > 0.15$	SSI Important

N/F: Not feasible to be performed (the user does not have adequate data to perform the particular quantitative check).

Table 2: Final assessment of SSI importance based on the three check levels

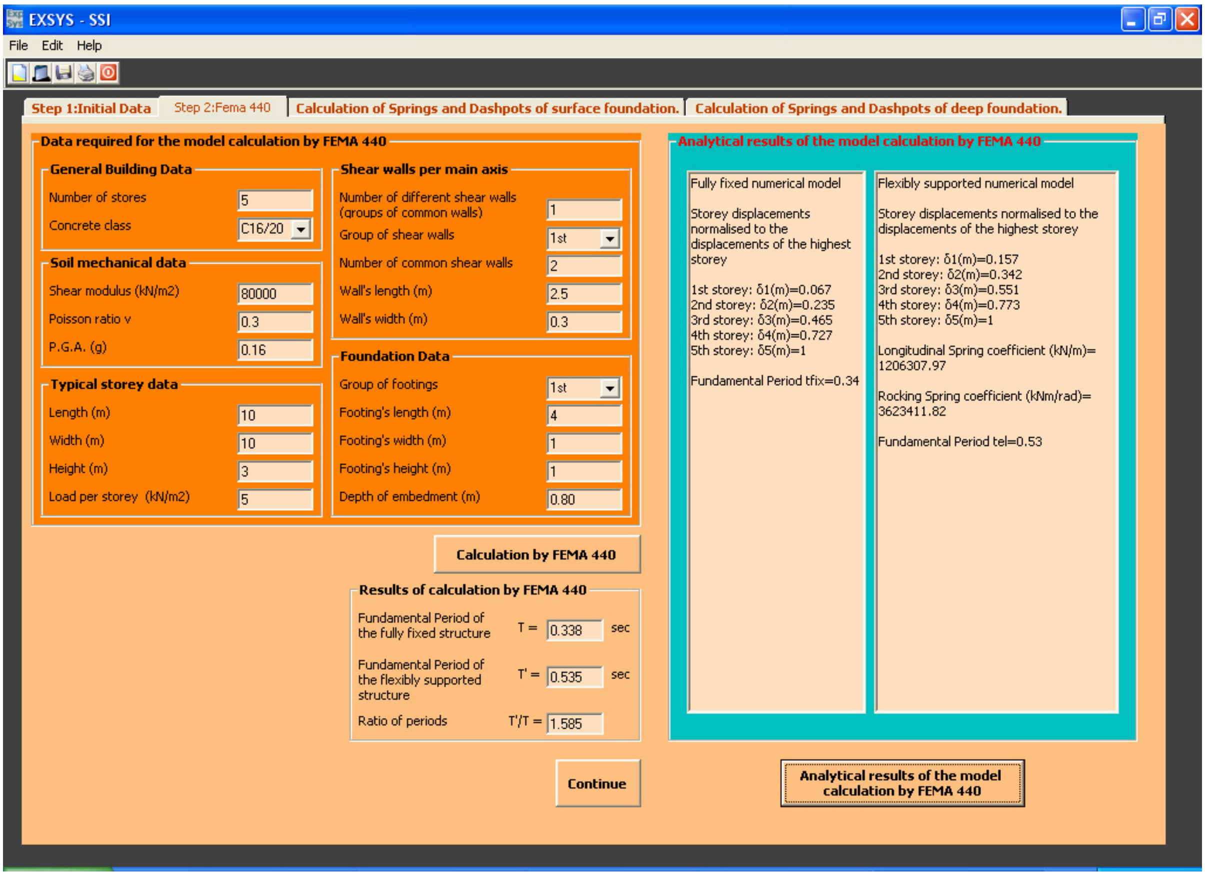

Figure 4: Quantitative estimate of the building's period elongation due to soil compliance

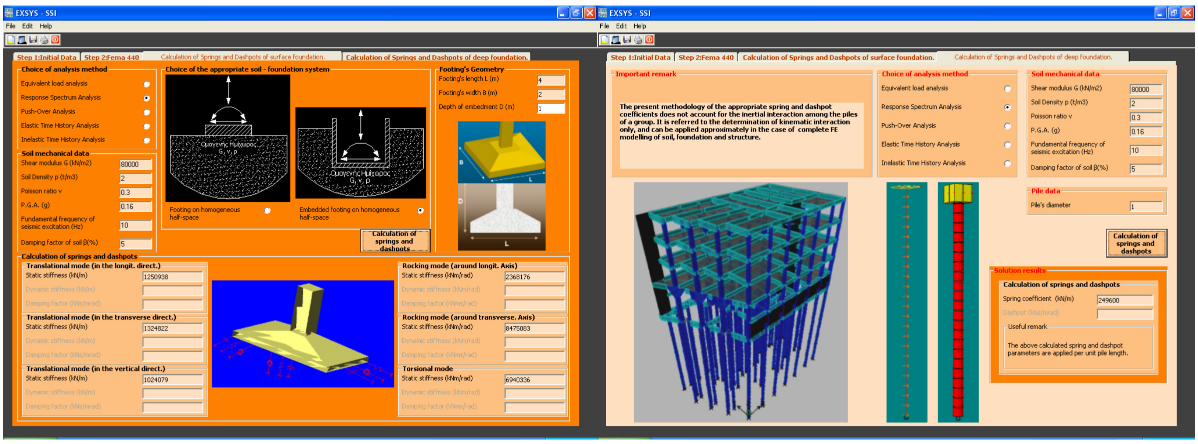

Figure 5: Display of Module 2 (left) and Module 3 (right) for the calculation of the soil-foundation static and dynamic stiffness matrices

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