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SEISMIC RESPONSE OF R/C FRAMES CONSIDERING DYNAMIC SOIL-STRUCTURE INTERACTION

M. Nasser

Graduiertenkolleg 1462, Bauhaus-University Weimar
99425 Weimar, Germany
E-mail: mourad.nasser@uni-weimar.de

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Abstract. *In spite of the extensive research in dynamic soil-structure interaction (SSI), there still exist misconceptions concerning the role of SSI in the seismic performance of structures, especially the ones founded on soft soil. This is due to the fact that current analytical SSI models that are used to evaluate the influence of soil on the overall structural behavior are approximate models and may involve creeds and practices that are not always precise. This is especially true in the codified approaches which include substantial approximations to provide simple frameworks for the design. As the direct numerical analysis requires a high computational effort, performing an analysis considering SSI is computationally uneconomical for regular design applications.*
This paper outlines the set up some milestones for evaluating SSI models. This will be achieved by investigating the different assumptions and involved factors, as well as varying the configurations of R/C moment-resisting frame structures supported by single footings which are subject to seismic excitations.

It is noted that the scope of this paper is to highlight, rather than fully resolve, the above subject. A rough draft of the proposed approach is presented in this paper, whereas a thorough illustration will be carried out throughout the presentation in the course of the conference.

1 INTRODUCTION

1.1 Statement of the problem

When considering the structure alone, the actual behavior of the structure under seismic load may significantly differ from what the analysis provides since the response of a structure during an earthquake depends not only on the structure itself, but also on the characteristics of the ground motion and the subsoil conditions. Particularly for soft soils, the foundation input motion during the earthquake differs from the so-called free-field ground motion that may exist in the absence of the structure. The assumption of fixed supporting for a structure upheld on soft soil ignores the interaction effects that result from the scattering of waves when reaching the foundation surface and the energy radiated from the structure during its vibration. These interaction effects lead to dynamic responses that may differ considerably in amplitude and frequency content from that what is obtained when a fixed supporting is assumed.

The main focus of this paper is to propose a methodology for evaluating soil-structure interaction (SSI) models, and also to exhibit the conditions under which the assumption of fixed-base supporting (no SSI effect) will lead to critical errors in the evaluation of the structural response. In addition, the required complexity level and SSI models, when SSI effect is taken into account, will also be examined. This is to be done for different configurations of R/C moment-resisting frame structures supported by single footings and subjected to seismic excitation. A unified and sequential methodology is used, in which, an investigation of the different assumptions and involved factors is performed with the utilization of the structural response characteristics. The final objective is to eventually draw some conclusion on the sensitivity of the calculated response to the complexity of the analysis, and to assign threshold values for the parameters related to soil, foundation, structure and earthquake. This will serve to highlighting and compare the robustness and suitability of the adopted SSI models for solving practical engineering problems with a desired accuracy.

It is noted that the scope of this paper is to highlight, rather than fully resolve, the above subject. A rough draft of the proposed approach is presented in this paper, whereas a thorough illustration will be carried out throughout the presentation in the course of the conference

1.2 Overview of soil-structure interaction models

Numerous books and research papers have been written on soil-structure interaction. Procedures that take into account soil–structure interaction in the seismic analysis of buildings are introduced in [1], whereas a comprehensive review of the literature can be found in [2]. Widely used methods on dynamic analysis of foundations have been initiated in [3, 4] and extended in [5, 6] where the emphasis is placed on rigid foundations represented by set of ‘‘mass-spring-dashpots’’ oscillating with either frequency-dependent or frequency independent stiffness and damping coefficients. The significant papers that deal with the impedance functions approach are [7, 8, 9]. Lumped-parameter models are used in many contributions, e.g. [10, 11, 12].

In [13], for example, the direct approach was presented whereas the substructure approach is used in [14]. Moreover, in [15, 16] the so-called hybrid method finite element– boundary element technique (FE–BE) is employed, and the coupled finite–infinite element method was used in [17, 18].

The concept macro-element provides an alternative simplifying approach to deal with SSI problem. This approach is based on the concept of generalized stress and strain variables [36, 38]. Several applications of the macro-element were presented in [39], whereas a similar simplifying and practical approach that also incorporates the capacity spectrum method can be found in [40, 41]. Figure 1 gives an overview about the commonly used approaches for soil-structure interaction problem.

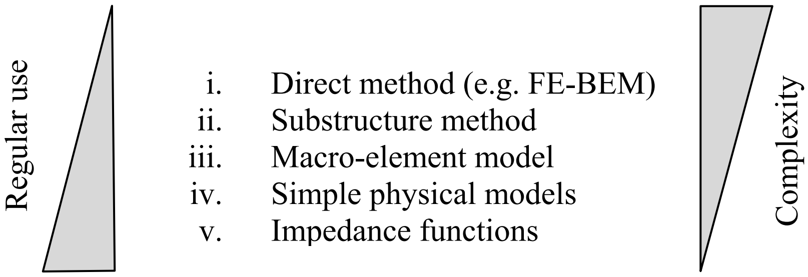

Fig. 1: Commonly used approaches for soil-structure interaction problem.

Regarding practical application, direct method allow the consideration of a lot of important factors, such as kinematic interaction and foundation flexibility, but it needs a huge analysis effort. On the other hand, impedance functions (spring-damper representation) provide the simplest way to consider SSI, but maybe with critical simplifications. Thus, a reasonable selection of the model depending on the given task is necessary.

2. DIRECT AND SUBSTRUCTURE METHODS

The two classical methods for modeling the problem of soil-structure interactions are referred to as the direct and substructure approaches. In the former, the computational model consists of the whole structure including foundations and soil media. The system in this approach is excited by a complex and incoherent wave field. From a computational point of view this problem is difficult to solve, particularly when the system contains significant nonlinearities, and hence the direct approach is rarely used in practice.

The substructure approach is computationally more efficient. Here the system is divided into two subsystems; a superstructure that may include a portion of non-linear soil around the foundation (near-field) and a substructure that includes the unbounded soil around the superstructure (far-field). The subsystems are connected by a general soil-structure interface.

The analysis of foundation input motion is required when using the substructure approach, which is normally referred to as kinematic interaction analysis. In the second step, the stiffness and damping characteristics of the soil are characterized using either relatively simple impedance function models for rigid foundations or a series of springs and dashpots distributed around the foundation. Distributed springs are needed when accounting for foundation flexibility.

Powerful computers can be very helpful in the research of soil-structure interaction since the application of numerical methods is significantly broader than that of analytical methods. Foundation flexibility, non-homogeneity, nonlinearity, kinematic interaction, and possible partial uplift of foundation are now included in the examination of the soil–structure phenomena thanks to computers.

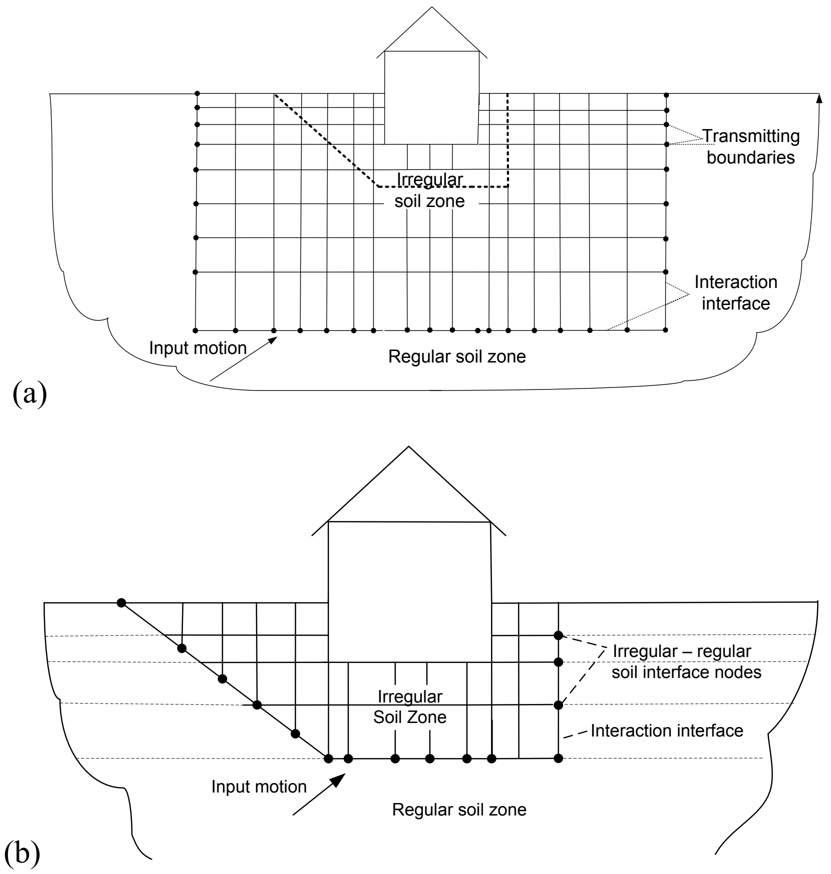

Fig. 2: Soil-structure system (a) direct method (b) substructure method.

The finite element method (FEM) has been one of the most widely used methods to solve soil–structure interaction problems. FEM is so general that it is possible to model, with a high degree of realism, many complex conditions such as nonlinear stress–strain behavior and material non-homogeneity. The difficulty in applying this method lies in selecting the proper transmitting boundaries, as stated in the pioneering works [20, 21, 22]. The problem of wave reflection and radiation on the boundaries of the soil domain has also been tackled by many authors [23, 24, 25] and energy absorbing boundaries have been used in FEM. Whereas in [26], Green's half-space functions has been used for the soil medium coupled with the finite element method in a technique to avoid the use of transmitting boundaries.

As an alternative to the FEM, the boundary element method (BEM) and the so-called hybrid FE–BE method have also been applied in SSI to determine the response of both rigid and flexible foundations subjected to either static or dynamic loads. BEM reduces the dimensions of the problem by one, and consequently saves substantial modeling effort and processing time. As the BEM automatically satisfies the ''far-field'' boundary conditions for the semi-infinite supporting media, which is an advantage of BEM over FEM, it is utilized to model the media under the structure, whereas the structure itself is modeled using the FEM.

2.1 Formulation of the direct and substructure methods

Despite the differences between the direct and substructure methods illustrated in Fig. 2 regarding the size of soil zone and definition of boundary conditions along interaction interface, a common formulation for both methods is possible as represented in [31]. Starting with the substructure formulation of the system shown in Fig. 3:

$$\left\{ \underbrace{\overbrace{\left[\begin{array}{cc:cc} \overline{K}_{ss} & \overline{K}_{sb} & 0 & 0 \\ \overline{K}_{bs} & (\overline{K}^{s}_{bb} + \overline{K}^{i}_{bb}) & \overline{K}_{bi} & 0 \\ \hdashline 0 & \overline{K}_{ib} & \overline{K}_{ii} & \overline{K}_{ih} \\ 0 & 0 & \overline{K}_{hi} & \overline{K}^{i}_{hh} \end{array}\right]}^{\text{structure}}}_{\text{in-homogeneous nonlinear soil}} + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \overline{S}^{r}_{hh} \end{bmatrix}}_{\text{homogeneous half-space}} \right\} \cdot \begin{Bmatrix} \overline{r}^{t}_{s} \\ \overline{r}^{t}_{b} \\ \overline{r}^{t}_{i} \\ \overline{r}^{t}_{h} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ \overline{P}_{h} \end{Bmatrix} \qquad (1)$$

Sub- and superscripts (s, b, i, h and r) refer to the structure, its base, irregular soil zone, interaction interface and regular soil zone, respectively.

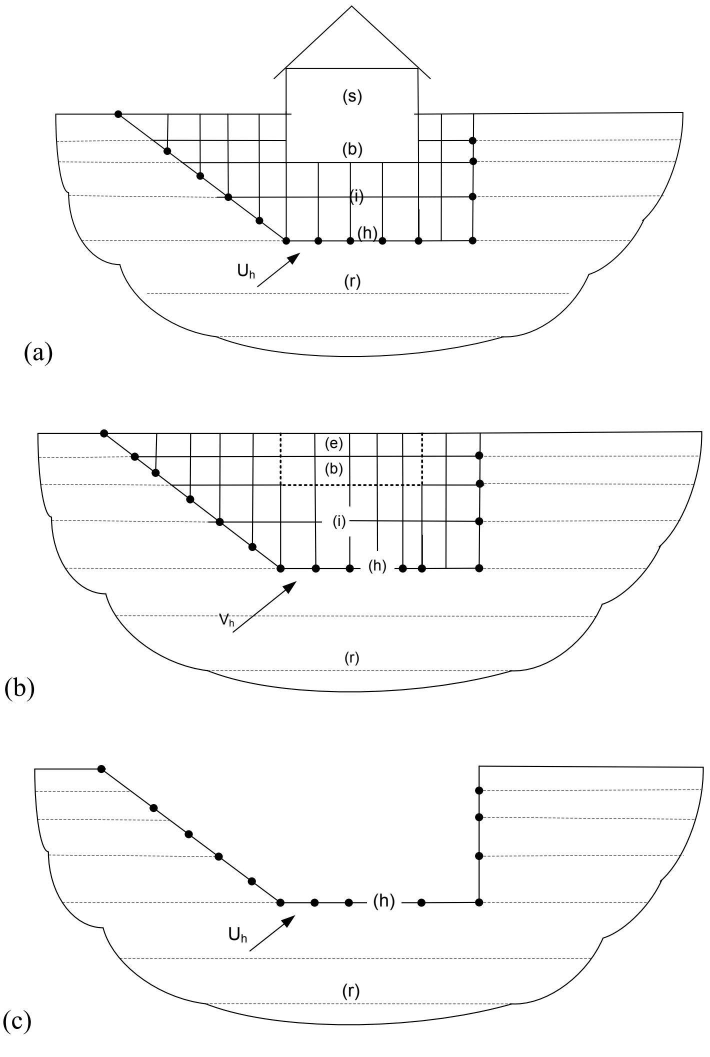

Fig. 3: (a) Coupled soil-structure system (b) soil system S1 (c) soil system S2 (after [31]).

The dynamic stiffness sub-matrices are expressed, in general, either as

$$\overline{\mathrm{K}} = K + i\omega C - \omega^2 M \qquad (2)$$

or $$\overline{\mathrm{K}} = K(1+2i\beta) - \omega^2 M \tag{3}$$

Overbars in Eq.1 refer to a frequency domain formulation. Sub-matrix $\overline{S}_{hh}^{r}$ is the dynamic stiffness matrix of unbounded regular soil zone; K, C, M represent the dynamic property matrices; ω is the frequency of excitation; β indicates the hysteretic damping ratio and the superscript t in the response vector represent the total displacement. The nonzero effective force vector component on the right-hand side of Eq.1 depends on the choice of soil system S that is used to define the free-field response [27].

In Fig. 3b and Fig. 3c two soil systems are shown. The first system S1 represents the soil in its original status whereas in the second one S2 the soil is excavated down to the interaction interface. Based on S2 the nonzero effective force vector component of Eq.1 can be expressed as:

$$\overline{P}_h = \overline{S}_{hh}^{r} \cdot \overline{u}_h \tag{4}$$

where $\overline{u}_h$ represents the free-field motion for S2. In order to state this motion in S1 structural degrees of freedom in Eq.1 are replaced with those of soil zone to be excavated for embedment and denoted by e in the following equation

$$\begin{bmatrix} \overline{K}_{ee} & \overline{K}_{eb} & 0 & 0 \\ \overline{K}_{be} & (\overline{K}_{bb}^{e} + \overline{K}_{bb}^{i}) & \overline{K}_{bi} & 0 \\ 0 & \overline{K}_{ib} & \overline{K}_{ii} & \overline{K}_{ih} \\ 0 & 0 & \overline{K}_{hi} & (\overline{K}_{hh}^{i} + \overline{S}_{hh}^{r}) \end{bmatrix} \begin{Bmatrix} \overline{v}_e \\ \overline{v}_b \\ \overline{v}_i \\ \overline{v}_h \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ \overline{P}_h \end{Bmatrix} \tag{5}$$

in which response vector components now represent the free-field motion for S1. One possibility to relate Eq.5 to Eq.1 in order to express the effective force vector of Eq.1 in terms of free-field response is directly to extract the last row of Eq.5 to define the effective force vector component as used in [27],

$$\overline{P}_h = \overline{S}_{hh}^{r} \cdot \overline{v}_h + (\overline{K}_{hh}^{i} \cdot \overline{v}_h + \overline{K}_{hi} \cdot \overline{v}_i) \tag{6}$$

The first term at the right-hand side represents the reaction forces acting along the outer face of interaction interface in case of S1 while the second term in parenthesis corresponds to the forces along the inner face. Except for the nodes immediately inside the interaction interface, the expression of Eq.6 is valid for linear as well as for nonlinear free-field response of irregular soil zone. Substituting load vector component given in Eq.6 into Eq.1 results in a formulation that is applicable for both substructure and direct methods. This formulation can be simplified by writing the total response component related to interaction interface as relative to the free-field response in S1:

$$\overline{r}_h^{t} = \overline{v}_h + \overline{r}_h^{\Delta} \tag{7}$$

in which the second term refers to the relative response. The superposition principle as applied in Eq.7 is valid, since the nodes on the interaction interface are linear by definition. By Substituting Eq.7 into Eq.1:

$$\begin{bmatrix} \overline{K}_{ss} & \overline{K}_{sb} & 0 & 0 \\ \overline{K}_{bs} & (\overline{K}^{s}_{bb}+\overline{K}^{i}_{bb}) & \overline{K_{bi}} & 0 \\ 0 & \overline{K}_{ib} & \overline{K}_{ii} & \overline{K}_{ih} \\ 0 & 0 & \overline{K}_{hi} & (\overline{K}^{i}_{hh}+\overline{S}^{r}_{hh}) \end{bmatrix} \begin{Bmatrix} \overline{r}^{t}_{s} \\ \overline{r}^{t}_{b} \\ \overline{r}^{t}_{i} \\ \overline{r}^{\Delta}_{h} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ -\overline{K}_{ih}\overline{v}_{h} \\ \overline{K}_{hi}\overline{v}_{i} \end{Bmatrix} \tag{8}$$

Eq.8 represents a common formulation of direct and substructure methods in the frequency domain. One can imagine that the irregular soil zone is expanding until interaction interface supposedly reaches the infinity. The first three rows of Eq.8 yield to traditional formulation of direct method [27, 28]. Also material nonlinearity within the irregular soil zone is considered regarding nonlinear response of the free-field. This can be also done in time domain by deriving following equations of motion from Eq.8,

$$\begin{bmatrix} M_{ss} & M_{sb} & 0 & 0 \\ M_{bs} & (M^{s}_{bb}+M^{i}_{bb}) & M_{bi} & 0 \\ 0 & M_{ib} & M_{ii} & M_{ih} \\ 0 & 0 & M_{hi} & M^{i}_{hh} \end{bmatrix} \begin{Bmatrix} \overline{r}^{t}_{s}(t) \\ \overline{r}^{t}_{b}(t) \\ \overline{r}^{t}_{i}(t) \\ \overline{r}^{\Delta}_{h}(t) \end{Bmatrix} + \begin{Bmatrix} Q_{s}(t) \\ Q_{b}(t) \\ Q^{i}_{i}(t) \\ 0 \end{Bmatrix} + \begin{Bmatrix} 0 \\ 0 \\ Q^{h}_{i}(t) \\ Q^{h}_{h}(t)+R_{h}(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ P_{i}(t) \\ P_{h}(t) \end{Bmatrix} \tag{9}$$

where the first term and the second term on the left-hand side refer to the inertial forces and nonlinear internal forces, respectively, except the nodes inside the interaction interface. Linear internal forces acting on the nodes along the interaction interface and directly inside of it are represented by $Q^{h}_{h}(t)$ and $Q^{h}_{i}(t)$, respectively:

$$Q^{h}_{i}(t)=K_{ih}r^{\Delta}_{h}(t)+C_{ih}t^{\Delta}_{h}(t) \tag{10}$$

$$Q^{h}_{h}(t)=K_{hi}r^{t}_{i}(t)+C_{hi}t^{t}_{i}(t)+K^{i}_{hh}r^{\Delta}_{h}(t)+C^{i}_{hh}t^{\Delta}_{h}(t) \tag{11}$$

In substructure method, the interaction forces, with the use of relative displacements along the interaction interface, can be expressed as

$$R_{h}(t)=\int_{0}^{t}S^{r}_{hh}(t-\tau)\cdot r^{\Delta}_{h}(\tau)\,d\tau \tag{12}$$

In the direct method, the expression of interaction forces depends on how the artificial transmitting boundaries are defined. In case of masses, springs and dashpots assigned for each node on interaction interface, the uncoupled interaction force for each node j can be written as

$$R^{j}_{h}(t)=K^{j}_{hh}r^{\Delta j}_{h}\left(t\right)+C^{j}_{hh}\dot{r}^{\Delta j}_{h}\left(t\right)+M^{j}_{hh}\ddot{r}^{\Delta j}_{h}\left(t\right) \tag{13}$$

Finally effective force vector components on the right-hand side of Eq.9 can be given as,

$$P_{i}\ (t)=-K_{ih}v_{h}(t)-C_{h}\dot{v}_{h}\left(t\right)-M_{ih}\ddot{v}_{h}\left(t\right) \tag{14}$$

$$P_{h}\ (t)=K_{hi}v_{i}(t)-C_{hi}\dot{v}\left(t\right)-M_{hi}\ddot{v}\left(t\right) \tag{15}$$

Eqs.9 through 15 represent a common formulation of direct and substructure methods in the time domain.

2.2 Simulation of the nonlinear material behavior

The simulation of the material behavior in soil-structure interaction analyses covers a wide range of soil behavior. Already in the static analysis of interaction problems the range of required material description covers the elasto-plastic range more than the elastic range. In the case of a dynamic soil-structure interaction analysis the complicated soil behavior under cyclic and dynamic loads have to be considered. One can distinguish between implicit and explicit models for application under seismic loads. Due to the limited number of load cycles under earthquake time histories also an implicit model can be adopted. The resulting numerical error from these models should be small for the given limited number of seismic loading cycles. At present, the most commonly used cyclic models are those based on strain. Practical formulations of different models are given in [32, 33]. The main advantages of these models are the well defined initial parameter as well as the validity of the Masing rule shown in the Software *FLAC 5.0* [34].

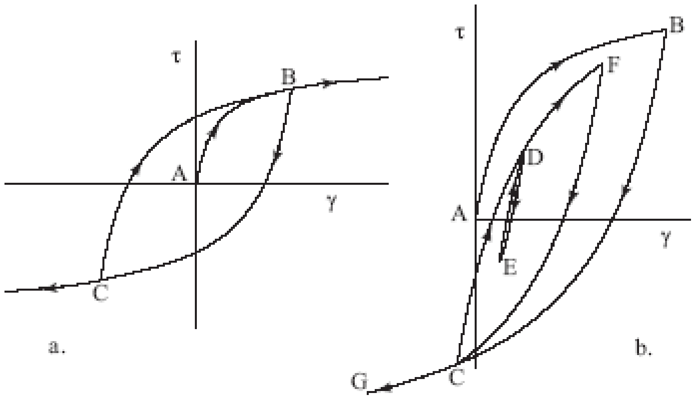

Fig. 4: Masing rule for stress-strain response (after [34]).

3 SIMPLIFIED DYNAMIC SOIL-STRUCTURE INTERACTION MODELS

Representative models for analyzing the dynamic soil–structure interaction range from the lumped parameter models (spring-dashpot-mass representations) and approximate simple physical models to the FE-BE models. The simplest soil-structure interaction models are those in which the building is supported by a rigid foundation because only six additional degrees-of-freedom (three translations and three rotations) are required. Numerical models take into account the effects of foundation flexibility.

The mechanical behavior of subsoil during an earthquake appears to be quite erratic and complex. It would seem impossible to describe this behavior by any mathematical law that would conform to actual observations. For this reason, simple models are preferred and used in most cases since the results obtained would appear reasonable

Many attempts have been made to improve these models by some suitable modifications to simulate the physical behavior of soil more closely. Along this line, John Wolf extended the concept of the truncated cones and developed lumped-parameter models to simulate the behavior of shallow and embedded foundations. A brief overview of these models follows.

3.1 Macro-element approach

The macro-element approach is based on the concept of generalized stress and strain variables and was primarily introduced in [36] .The concept has significant advantages since it simplifies the problem SSI without releasing the important response characteristics of the system.

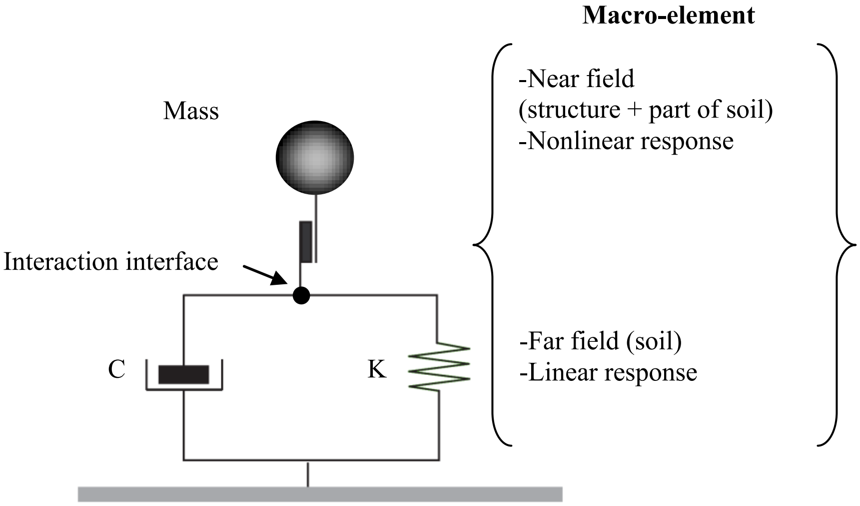

Fig. 5: Structure of the macro-element.

A generic description of the macro-element is introduced in [37] for a lumped mass supported by a circular rigid foundation as illustrated in Fig. 6. The system (soil-foundation-superstructure) is subject to seismic excitation. The macro-element can be introduced as a change in the scale of the considered system, in which the foundation and the near field soil is replaced with a plastic hinge and expressed by a macro-element. The motion of this representative point describes the motion of the rigid foundation as shown in Fig. 7.

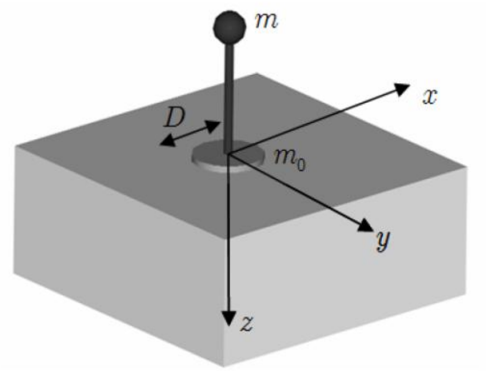

Fig. 6: Examined configuration for the development of the macro-element (after [37]).

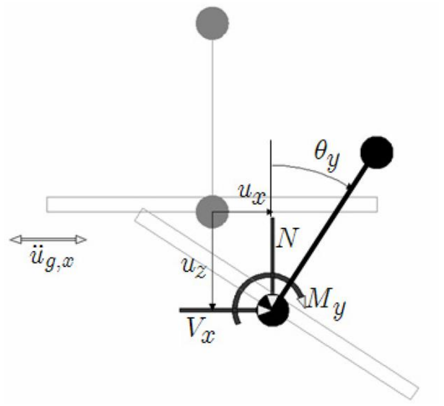

Fig. 7: Generalized forces and displacements in the macro-element (after [37]).

3.2 Simple physical models

For surface foundations on homogeneous soil, simple cone models are developed by Wolf [19]. In these models, the soil is modeled as homogeneous, linear elastic and infinite half space with the density ρ. For each of the six degrees-of-freedom an appropriate cone is assumed, in which different systems for translation and rotation are considered.

The basic concept of the cone model is the simulation of dynamic behavior of the semi-infinite halfspace by a suitable soil cone, whereas this cone gives information about the strain required to develop appropriate impedance functions. The basic mathematical assumption is the given partial differential equation (wave equation) for a rod with increasing diameter. This equation leads to fundamental solution which requires much less mathematical effort contains than the original three-dimensional wave equation.

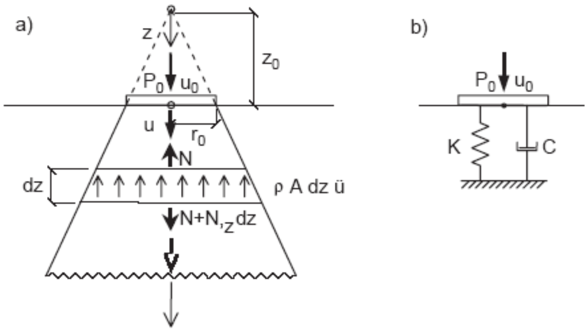

Fig. 8: Principal cone model and impedance function (after [19]).

Simple physical models consist of the following representations (Fig. 9):

1. Cones: Translational and rotational truncated semi-infinite cones are based on bar theory (plane sections remain plane) with the corresponding one-dimensional displacement.

2. Spring–Dashpot–Mass Models with frequency-independent coefficients. The unbounded soil is represented by the same type of dynamic model as the structure, enabling the same structural dynamics program to be applied.

3. Prescribed wave patterns in the horizontal plane: These are one-dimensional body and surface waves on the free surface and cylindrical waves.

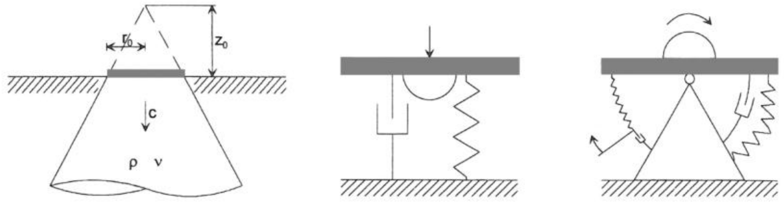

Fig. 9: Cone models and discrete models for translation and rotation (after [19]).

Simple physical models have significant advantages such as conceptual clarity and simplicity in physical description and application.

3.3 Impedance functions

Impedance functions are used in the analysis of foundation vibrations and/or in general for SSI problem. In comparison to the cone model, impedance functions are, in general, based on the solution of the three-dimensional or two-dimensional wave equation in the unbounded half-space. The analysis of dynamic SSI effect is done by separating the whole system into two parts; a lumped parameter system and a spring-dashpot combination which substitutes the soil media. The spring represents the stiffness of soil whereas the dashpot encloses the radiation damping of soil. In order to consider material damping D of soil, the analysis is done by using complex velocities $c_S^* = c_S(1 + 2iD)$ in a hysteretic assumption of the damping behavior.

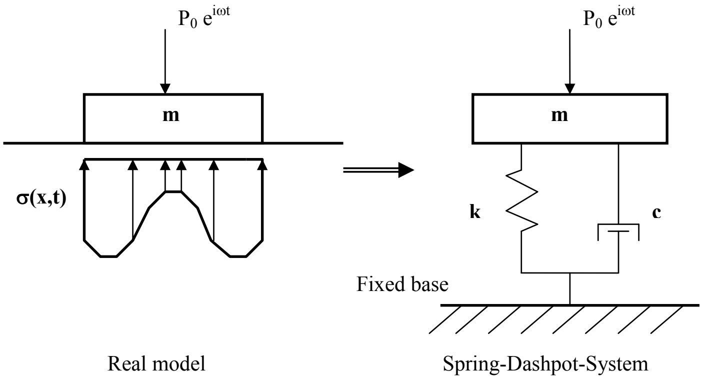

Fig. 10: Principal figure of the impedance function (after [35]).

Following the definition for impedance functions, the displacement function due to a specified excitation is given by

$$u(x,t) = \frac{P_0}{G}\left[f_1\left(\frac{\omega^2 \rho}{G}, \nu, x\right) + i f_2\left(\frac{\omega^2 \rho}{G}, \nu, x\right)\right] e^{i\omega t} \tag{16}$$

If Eq. (16) is reformulated under the consideration of the force equilibrium at the foundation level the impedance function can be defined as

$$\left(i\,\omega c+k\right)u-m\,\omega^{2}u=P_{0}\quad\rightarrow\quad\underbrace{\left[Gr_{0}\left(F_{1}-iF_{2}\right)-m\,\omega^{2}\right]}_{Complex\ \ impedance\,function}u=P_{0}\tag{17}$$

where the real part F1 describes the soil stiffness and the imaginary part F2 describes the radiation damping spread out from the foundation.

4. EVALUATION OF ADOPTED SSI MODELS

Structural engineering has reasonable concerns and criticisms regarding the involvement of dynamic soil-structure interaction effects on the structural analysis. The increasing complexity of analysis procedures using extreme refinement in the mathematical model requires a high computational effort. This in return, makes an analysis which considers SSI computationally uneconomical for regular design applications; moreover, the complexity of analysis is not consistent with the simplified assumptions that have to be made regarding material properties and dynamic response mechanism. On the other hand, analytical SSI models that are used to evaluate the influence of soil on the overall structural behavior are approximate models and may involve creeds and practices that are not always precise. This is especially true in the codified approaches which include substantial approximations to provide simple frameworks for the design.

Motivated by the above issues, a methodology is proposed in this paper that handles the several issues involving the problem of SSI in a unified and sequential approach. As mentioned before, a rough draft of the proposed approach is presented in this paper, whereas a detailed illustration will be carried out by the presentation in the course of the conference.

4.1 Considered substructures – frame and foundation

The study is to be carried out for 12 R/C frame structures in order to examine the effect of structural type, foundation shape and geometry, subsoil conditions, and the excitation characteristics on the calculated structural response, when using different SSI models. Only one parameter at a time is modified, so that the relative importance of each parameter can be considered. The alternative configurations of the structure are described as following:

- reference structure: a 5 story R/C moment-resisting frame structure, regular and symmetric, supported with a shallow rectangular foundation, on stiff soil
- 8 story structure (more flexible; has higher fundamental period)
- 3 story structure (stiffer; has lower fundamental period)
- irregular (its stiffness varies in the vertical direction)
- asymmetric (its stiffness varies in the horizontal direction)
- with slender columns
- with larger mass and dimensions
- supported by foundations that have altered geometry
- supported by circular foundations, in order to consider the effect of foundation shape
- supported by embedded foundations
- supported on soft soil
- subjected to modified earthquake frequency content

4.2 Essential Issues (IS) – analysis methods, parameters and assumptions

The quality of SSI models is affected by the analysis assumptions regarding soil, foundation and the structure, as well as by the consideration of possible involved factors. For that reason it is necessary to assign the above mentioned issues and to investigate their effects on the dynamic response of structures. This will allow identifying the conditions, if any, under which neglecting some of the factors or simplifying of assumptions, consistently leads towards conservative or tentative seismic design. Consequently, the assessment of SSI models will be possible, since they are based on different considerations. The significant issues are represented in (table 1):

Considerations		
Interaction	inertial	kinematic
Soil damping	radiation damping	material damping
Assumptions		
Foundation	rigid	flexible
Soil	homogeneous	inhomogeneous or layered
	linear behavior	nonlinear behavior
Analysis Methods		
2D ESDoF model: nonlinear static analysis (capacity spectrum method CSM)	2D ESDoF model: nonlinear dynamic analysis in time domain (time history TH records)	3D FE-BE model: nonlinear dynamic analysis in time domain (time history TH records)

Increased complexity →

Table 1: Considered issues in the evaluation of SSI models.

4.3 Key parameters of structural response

The structural response characteristics may differ from one model to another; therefore it is essential to adjust scenarios in such a way that they provide at least one common response criteria as an output of the analysis. Possible response characteristics of the structure are:

- f - eigenfrequency
- d - top displacement (global level)
- IDR - inter-story drift ratio (story level)
- M-θ - moment-curvature relationship (section level)
- translations and rotations at the (foundation level)

The analysis of several response parameters allows determining the consistency of the results; by investigating if the beneficial or detrimental effect resulted from different scenarios is the same for all response parameters.

4.4 Scenarios (SC)

Appropriate scenarios are to be established, in such a way that they involve all the above issues in different levels of analysis complexity, in order to investigate the sensitivity of the analyzed response of all 12 structures to SSI effect when different factors are either included or ignored in various combinations. This is done by the mean of different models which involve different assumptions, factors and analysis methods but still applicable for the same case study.

The investigation of structures with varied configurations serves in examining the validity of the resulted.

Scenarios	SC1	SC2	SC3	SC4	SC5	SC6	…
IS1	x		x				
IS2			x	x		x	
IS3		x					
IS4						x	
…	x	x		x	x		
f	x		x				
ζ						x	
d		x		x			
IDR	x		x		x		
V				x	x	x	

Table 2: The proposed analysis procedure for every studied structure ST, (The positions of "x" notations in the table is still not defined, this is just for illustration).

4.5 Damage and serviceability indices (DSI)

The structural response should be expressed quantitatively in terms of damage grades and ultimate deformations. The latter is important when taking into account the serviceability of the structures. There are different damage indices available; they may be based on plastic deformation or hysteretic energy, or a combination of maximum deformation response and hysteretic energy.

The main purpose of using damage indices is to express the structural damage by a normalized quantity between 0 and 1, in order to investigate the sensitivity of the potential structural damage and to make the comparison possible between different models. The damage index will be zero if the structure remains elastic, and will be one if there is a potential of structural collapse. Other structural performance states (such as minor, moderate and major damages) fall in between zero and one.

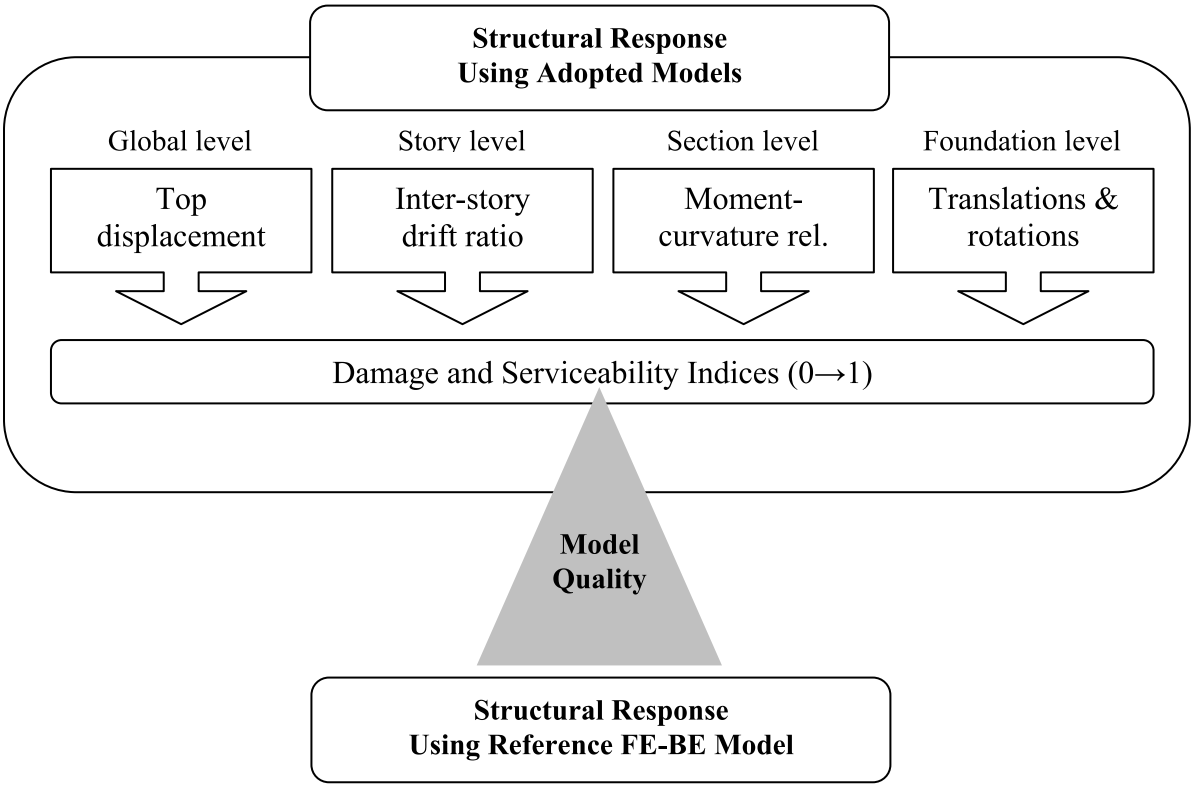

Fig. 11: Proposed approach for model evaluation.

4.6 Evaluation report – analysis of results and final recommendations

As a result of the proposed procedure, some conclusions can be made on the sensitivity of the calculated response to the analysis complexity and threshold values for the parameters related to soil, foundation, structure, and earthquake. This will serve in determining which model pairs up with its respective case.

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