

SIGNIFICANCE OF SOIL-STRUCTURE INTERACTION IN SEISMIC DESIGN

Zs. B. Pap⁽¹⁾, L. P. Kollár⁽²⁾

⁽¹⁾ MSc, PhD student, Dept. of Structural Engineering, Budapest University of Technology and Economics, pap.zsuzsa@mail.bme.hu ⁽²⁾ Professor, Dept. of Structural Engineering, Budapest University of Technology and Economics, Ikollar@eik.bme.hu

Abstract

Soil-structure interaction (SSI) fundamentally changes the behaviour of structures subjected to earthquakes. In case of static design, the foundation is usually assumed to be fixed, but in case of base excitation the neglect of the deformability of the soil leads to unacceptable errors.

The effect of the soil deformations can be considered in several ways.

- i. Fixed support is assumed, which neglects the influence of the soil, although this method is not recommended for earthquake design.
- ii. The deformation of the soil is taken into account by linear springs (indirect approach).
- iii. In case of the "substructure method" the soil and the structure are modelled independently, and the effect of soil is replaced by an impedance matrix, which is based on the 3D solution of the soil.
- iv. The "cone model" is a compromise between the above two methods, where the soil is replaced by a spring and a dashpot. Their characteristics are determined from the dynamic solution of an infinite bar with variable cross section that represents the soil.
- v. The most accurate method is the direct method, where the structure and a part of the soil are examined together with 3D finite element method. This requires time consuming calculation.

The accuracy of two simplified models (cone model and indirect approach) is investigated through several numerical examples. Model parameters are varied systematically: the effect of soil type, soil thickness, foundation embedment, structural stiffness are analysed. Time history analyses with different earthquake records are performed together with the response modal analyses. The results of different approximate methods are compared to the direct method. A relatively small number of soil-structure systems are analysed, therefore the results cannot be generalized. They only show that how much error can be made by using the different simplified models.

In accordance with the literature the assumption of *fixed support* in not acceptable, the error may exceed 100%.

In case of soil B (defined by Eurocode 8), the difference between the response of the structure supported by *springs* and the direct method is large: 20-90%. For softer soils this difference is even bigger, up to 150% for soil C, and up to 200% for soil D.

In most practical cases the *cone model* gives results with much better accuracy, the difference is only 5-10%. Note, however that for softer soil the reliability of the cone model may be lower.

Keywords: soil-structure interaction, cone model, direct approach



1. Introduction

In case of static design usually fixed foundations are assumed, but in case of seismic design the deformability of the soil should be considered. The goal of this paper is to analyse the differences between several modelling options for soil-structure interaction (SSI).

The influence of the soil can be taken into account with several models [1]. When a fixed support is assumed (Fig. 1a) the effect of the soil is neglected. This method is not recommended for seismic design. The deformability of the soil can be taken into account by supporting the structure with (swaying, translational, rocking and torsional) springs. Spring coefficients can be determined by explicit formulae of static soil-structure interaction [2] or from static finite element method (Fig. 1b). Another option is the substructure approach, where the dynamic effects (wave propagation in the soil) are also considered. In this model the soil is replaced by an impedance matrix (Fig. 1c). For the calculation of the impedance matrix the so called cone model [3] is investigated in details. The direct approach (Fig. 1d), where both the structure and soil are modelled with 3D finite elements is considered as the exact calculation. At this level the non-linear behaviour of the soil, soil-liquefaction and other special features of SSI can be considered.



Fig. 1 – Modelling levels of soil: a) fixed structure, b) elastic support, c) substructure approach, d) direct approach

The main advantage of the simplified models is that the calculation time is much shorter than in case of the direct method. That is why the simplified models are preferred for general design by practicing engineers. To explore the accuracy of the different simplified methods, numerical analyses are performed and evaluated for different structures and conditions. The goal of these analyses is to investigate the significance of soil-structure interaction through the comparison of different modelling levels, and to investigate the accuracy of the simplified approaches. The results will help the civil engineer decide which method to use in different design situations.

2. Modelling

2.1 The earthquake record for time-history analysis

In order to be able to compare the methods with each other the accelerograms are generated from Eurocode response spectra. The acceleration record is formulated according to the following function:

$$a = \sum_{i} \cos\left(\omega_{i}t + \varphi_{i} 2\pi\right) I , \qquad (1)$$

where φ_i are random numbers and *I* defines the shape and length of the accelerogram (Fig. 2). The length of acceleration records is 18 s for the analyses presented in this paper.





2.2 Direct approach

In the direct approach the structure and the soil have to be modelled together (Fig. 2) and analysed in a single step with a numerical method such as the Finite element method or the Finite Difference Method.

where ρ is the density of the soil, c_p is the P-wave velocity and c_s is the S-wave velocity [4].





A 3D finite element model is built in the 14.5. release of ANSYS Mechanical APDL to analyse the problem of SSI. SDOF and MDOF structures are built up from beam (BEAM188) and mass elements (MASS21). The foundation is circular and modelled by SOLID185 elements, and the soil is also modelled by SOLID185 elements. The radiation damping must be taken into account; energy dissipation is modelled by damping elements (COMBIN14). Damping on unit area is calculated as (Fig. 2):

$$C_n = \rho c_p , C_i = \rho c_s , \qquad (2)$$



Different models are built; the parameters of the geometry can be seen in Fig. 4. The ground acceleration, soil properties, embedment of the foundation, stiffness of the beam and the mass of the structure are varied in the analysis.



Fig. 4 - The axonometric view and middle section of the finite element model with embedded foundation

The soil is excited at all of its bottom points with an artificial earthquake record generated from the response spectrum for class A soil (i.e. rock) of Eurocode 8. A rigid rock layer is assumed under the softer (class B, C and D) soils, hence the whole rock mass moves together.

2.3 Substructure approach

In this approach the global system is separated into two subsystems and the responses are analysed independently.

This method requires much less computational resources than the direct method. However, its applicability is limited, because it provides sufficiently accurate results only for linear systems.

The method consists of three main steps (Fig. 5) [1]:

- Solution of the kinematic interaction (1)
- Calculation of the dynamic impedance matrix (2)
- Consideration of the inertial interaction while calculating the dynamic response (3)



Fig. 5 – Steps of the substructure approach



In the first step the kinematic interaction is solved by the calculation of the Foundation Input Motion (FIM). The Strata software [6] is used to calculate the response at the top of the soil layer. In Strata the soil is modelled as a 1D soil column.

In the second step the impedance matrix is determined through calculation of its vertical, horizontal swaying, rocking and torsional spring and damping elements. There are several formulae in the literature for the calculation of these coefficients; Hsieh [7] and Lysmer [4] developed solutions for circular foundations, Gazetas [8], [9], [10] for rectangular and general polygon shaped foundations. For our calculations the so-called cone model [3] is used. Assuming a circular foundation on the surface, the homogeneous half-space underneath can be modelled approximately with a semi-infinite bar with increasing cross section as illustrated in Fig. 6. The spring and dashpot elements are modelled with COMBIN14 elements in ANSYS if the foundation is on the soil. In case of embedded foundations, a cross-coupling horizontal-rocking stiffness has to be modelled as well, which means the MATRIX27 element needs to be used.

The third step is the solution of the dynamic interaction, where the structure is supported by the springs and dashpots calculated in the second step and excited by the FIM calculated in the first step.



Fig. 6 - Cone model

2.4 Indirect approach

A common design procedure is to only take the deformability of the soil into account. In this case the structure is supported by springs calculated by static analysis. The values of the coefficients are determined with formulae in the literature [2] or static FEM analysis. The structure is modelled in the same was as in case of the direct approach and it is supported by spring elements (COMBIN14). For the time-history analysis the earthquake record was generated from the response spectra corresponding to class B, C, or D soils in Eurocode 8.

2.5 Soil modelling

Despite the presence of artificial boundaries, a large volume of soil needs to be modelled around the structure in the direct approach. As a result, the number of degrees of freedom of the combined soil-structure system is very large. Furthermore, to capture the response of the soil and of the structure at relatively large frequencies, a very fine discretization of the system is needed.

In order to represent a travelling wave of a given frequency accurately, approximately 8-10 nodes per wavelength are required. Fewer than that can create numerical damping, because the discretization misses certain peaks of seismic wave. The minimum wavelength can be determined with the following formula [11]:

$$\lambda_{\min} = \frac{c_s}{f_{\max}} , \qquad (3)$$

where f_{max} is the highest relevant frequency of the input motion. Typically, for seismic analysis it can be assumed that f_{max} is 10 Hz. Accordingly, the minimum element size (h_e) in the soil [11]:



$$h_e \le \frac{c_s}{(8 \div 10) f_{\text{max}}} \,. \tag{4}$$

Several soil types are analysed; their properties are summarized in Table 1. The density of sands and clays is in the range of 1800-1900 kg/m³. The Poisson's ratio of sand and clay soils is approximately 0.3.

No	Soil type	v _s	ρ	G_{\max}	ξ	H	ω	Т	β	v	h_e
		[m/s]	[kg/m ³]	[N/m ²]	[-]	[m]	[1/s]	[s]	[s]	[-]	[m]
B1	В	600	1850	6.66E+08	0.05	40	23.5	0.26	0.0042	0.3	4
B2	В	360	1800	2.33E+08	0.05	40	14.1	0.44	0.0070	0.3	2
B3	В	800	1800	1.15E+09	0.05	40	31.4	0.20	0.0031	0.3	4
C1	С	270	1850	1.35E+08	0.05	80	5.30	1.19	0.0189	0.3	2
D1	D	150	1850	4.16E+07	0.05	70	3.36	1.86	0.0297	0.3	1

Table 1 – Properties of the analysed soil types

 v_s : shear wave velocity, ρ : density, G_{max} : shear modulus, ξ : damping ratio, H: thickness of soil layer, ω : first natural circular frequency of soil, T: fundamental period of soil layer, β : stiffness proportional Rayleigh damping, v: Poisson's ratio

3. Results

We compared the results of the direct approach with the motions of different structures supported by springs (indirect approach) and with the results of the substructure approach. First, the structure (which is an SDOF system) is placed on different soils of class B. Structures with different periods are analysed by changing the mass of the SDOF system. Result sensitivity to soil thickness, the stiffness of the structure and foundation embedment are analysed for class B soils. Structural response on softer soils (C and D) is also investigated. For the sake of simplicity, results of the direct approach are denoted by SSI while results of the structure supported by springs (indirect approach) are denoted by EC.

First the results of a structure on soil B1 are presented. The properties of the foundation and the structure are shown in Table 2. These values (mass, geometry, stiffness) can approximately represent a containment structure with 56 m diameter and 2 m wall thickness.

Structure					Foundation					Soil	
Mass	EI	h	v	r	tf	ρ	E	v	sx,sy	SZ	
(kg)	(Nm^2)	(m)	(-)	(m)	(m)	(kg/m^3)	(N/m^2)	(-)	(m)	(m)	
7.85E+07	4.78E+15	84	0.2	28	5	2500	3.4E+10	0.2	80	40	
EI: stiffness of the structure, h: height of the structure, v: Poissons's ratio, r: radius of the foundation, tf:											
thickness of the foundation, E: Young's modulus of foundation, sx, sy: horizontal dimensions of soil,											
sz: thickness of soil layer											

Table 2 – Properties of the structure, foundation, and geometry of the soil



The results of the direct and indirect approach in case of soil B1 (v_s =600m/s) are shown in Fig. 7. The relative displacements of the top point are denoted by *urel*, the displacement of the top point (in addition to the movement due to rocking) by *ux*, and the rocking of the foundation by *roty* (Fig. 8).





Fig. 9 – First mode of the system

The response of the structure in case of the SSI (direct) method is around 60% smaller than in case of the EC (indirect) method, 73% for *urel*, 58% for *ux* and 77% for *roty*. It can also be observed that the natural periods



of vibration of the two systems are almost the same ($T_{\text{spring-str}}=0.85$ s, $T_{\text{soil-str}}=0.81$ s). This suggests that the differences in the acceleration of the mass elements of the two systems are proportional to the differences in the relative displacements of their top points. The first mode of the system belongs to the rocking of the structure (Fig. 9). In Fig. 9 the response of the fixed structure is also presented. It shows an entirely different behaviour and response; the fundamental period of the fixed structure is also different, only 0.35 s.

Different structures on different B soils are examined in the following step; the results are presented in Fig. 10, and the curve B of EC8 is shown in the same figure. It can be seen that in case of small periods (T<0.4s) the calculated points are above the curve defined by EC8, in the middle range (0.4s<T<4s) the results from SSI are smaller than the accelerations according to the curve, and in case of large periods (T>4s) the points are almost on the curve. Pitilakis [12] recommended a more detailed division for the soil types, and he also suggested that the curves should be improved. He proposed improved spectral amplification factors for different site conditions based on an extensive theoretical and experimental study of the characteristics of seismic ground response. He analysed a large set of worldwide well-documented strong motion recordings and performed a large number of numerical analyses of various representative models with realistic site conditions. According to his results the curves for soil types B1 and B2 are shown in Fig. 10. It can be seen that in most cases our results of the direct approach are more suited to the curves suggested by Pitilakis, especially in the middle range of periods, where the EC curve gave much bigger results.



Fig. 10 - Curves suggested by Pitilakis [12], EC8 and the results of direct approach

The effect of softer soils is also investigated (Fig. 11). Both soil C and D are softer than soil B. The depth of the analysed soil C is 80 m, the thickness of the examined soil D is 70 m. The properties of the soils can be found in Table 1, they are denoted by C1 and D1. In these cases, the difference between the direct and indirect approach is even bigger (100-150%).



Fig. 11 – Comparison of the results calculated by the direct approach and the indirect approach in case of soil C1 and D1

Finally, the direct approach is compared with the substructure approach. The structure described in Table 2 is placed on top of, and (in a separate analysis) its foundation is embedded in soil B1. In the former case the foundation input motion (FIM) is calculated with Strata [6], because the foundation is placed on the top of the soil, and there are no disturbing effects such as scattering. The program calculates the vibration at the top of soil B1 due to the excitation described by the artificial record at the base rock (Fig. 12). In case of the embedded foundation the surface vibration is calculated with the finite element model instead of Strata.



In both cases the differences between the direct and substructure approach are small (1-10%), Fig. 13 illustrates the results of the two approaches.



Fig. 13 – Comparison of direct and substructure approach (soil B1, 5 m embedment)



4. Discussion

In the article first the soil-structure interaction is analysed with simplified methods (structure supported by springs, and substructure approach) and then the results of these models are compared with the results of the direct approach. The results of the direct approach (a 3D soil-structure system) are considered the exact solution; hence the simplified models were compared with a 3D finite element model. A summary of the results is presented in Table 3.

The difference between the fixed model and direct model is the most significant, the rigid support assumption may lead to very conservative design. The error in acceleration is up to 130 % on the safe side for soil B; up to 700% for soil C; and up to 1700% for soil D.

In case of stiff structures (T<0.3s), and class B soil, unconservative differences occur between the direct and indirect approach (~10%), which means that the displacements of the structure supported by springs are less than the corresponding response with the direct approach. For larger periods (T>0.4s) the results of the structure supported by springs are on the safe side, the differences are between 20-90%. The thickness of soil B is relatively small (max. 60 m), therefore it is better to calculate the spring stiffnesses with static FEM than with formulas that correspond to the static solution of the half-space. With this method the errors of the indirect approach can be reduced to 20-40%.

The effect of the embeddment of the foundation is also investigated. The motions of the embedded structure are smaller than the motions of the structure placed on the soil surface. This phenomenon is taken into account by different formulae in the literature [3], the difference between the direct and indirect approach is the same as in case of non-embedded structures (20-90%).

The effect of softer soils (C and D) is also examined. The differences between the responses of the structure supported by springs and the SSI direct approach are more significant; it is more than 100% in case of soil C and more than 150% in case of soil D. In these cases, the spring coefficients calculated according to the finite element method do not reduce the differences, because the thicknesses of the soil layers are bigger and the spring coefficients calculated according to the theoretical formulae are almost the same.

Finally, the substructure and the direct approach are compared. The values of the impedances (spring and damping coefficients) are calculated according to the cone model. The differences are analysed for two different cases. First, for the original structure placed on soil B, then the original structure embedded in soil B. Two embedment depths (5m and 10m) are examined. The differences between the substructure and direct approach are negligible, only 7% on average. This implies that in case of stiff soils the substructure approach is a good approximation of the 3D finite element model.



	Soil type	Simplified models						
3D soil-structure system is considered as the exact solution		Fixed		support	Substructure approach			
			Theoretical	FEM	Cone model			
	В	~130%	20-90%	20-40%	~7%			
Errors	C	~700%	~100%	~100%	-			
	D	~1700%	~150%	~150%	-			

Table 3 - Errors on the safe side of different simplified models

5. Acknowledgement

This work is being supported by the Hungarian Scientific Research Fund (OTKA, no. 115673), and we would like to express our gratitude to Prof. Tamás János Katona for his support, expertise and help.

6. References

- [1] Lai CG, Martinelli M (2013): Soil-Structure Interaction Under Earthquake Loading: Theoretical Framework. *ALERT Doctoral School Soil-Structure Interaction*.
- [2] Kausel E (2010): Early history of soil-structure interaction. *Soil Dynamics and Earthquake Engineering*, **30**, 822–832.
- [3] Wolf JP and Deeks AJ (2004): Foundation vibration analysis: a strength-of-materials approach. Elsevier, Oxford.
- [4] Lysmer J, Kuhlemeyer RL (1973): Finite Element Method Accuracy for Wave Propagation Problems. *Journal of Soil Mechanics and Foundation Division*, **99** (SM5), 421–427.
- [5] Ramadan OMO, Sanad AM, Al-Anany YMM (2012): Effects of Soil-Structure Interaction on Nonlinear Seismic Response of Buildings. 15th World Conference on Earthquake Engineering, Lisbon, Portugal.
- [6] Kottke AR, Rathje EM (2009): Technical Manual for Strata.
- [7] Braja MD (1992): Principles of soil dynamics. PWA-KENT Publishing Company.
- [8] ASCE 4-98 (1998): Seismic Analysis of Safety-Related Nuclear Structures and Commentary.
- [9] Arefi MJ (2008): Effects of Soil-Structure Interaction on the Seismic Response of Existing R.C. Frame Buildings. *Master Thesis*, University of Pavia.
- [10] Çelebi E, Firat S, Çankaya I (2006): The evaluation of impedance functions in the analysis of foundations vibrations using boundary element method. *Applied Mathematics and Computation*, **173**, 636–667.
- [11] Jeremic B, Jie G, Preisig M, Tafazzoli N (2009): Time domain simulation of soil foundation structure interaction in non-uniform soils. *Earthquake Engineering and Structural Dynamics*, **38**, 699–718.
- [12] Pitilakis K, Gazepis C, Anastasiadis A (2004): Design Response Spectra and Soil Classification for Seismic Code Provisions. 13th World Conference on Earthquake Engineering, Vancouver, Canada.