Seismic Wave Propagation in Soil-Structures Systems

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Abstract

A discrete formulation of the seismic wave propagation in times domain is presented in order to calculate the seismic response of an idealized city. The buildings are modelled as being the prolongation of the continuous medium, and are subjected to the vertical shear wave propagation. The layers of the ground and the rock substratum under the base of the foundations are introduced in the formulation to take account of the effects of soil-structure interaction. The seismic response is expressed according to the travel time of the waves between the layers of the ground, the coefficients of reflexion and transmission and of the interfaces. In the developed equations one takes account of the effects of filtering dependent on the frequency which appear in the foundation and storey levels. The calculation of the response is thus reduced to a simple system of equations with finite elements for each layer, which can be solved starting from the rock substratum. Compared with the formulation generally used in the dynamics of structures which consists in using the concept of vibration, the formulation based on wave propagation provides several advantages, among which, simplified calculations, better representation of damping, the possibility of taking account of the effects of the stratification of the ground under the foundation, and better tools for identification and the detection of the damage in the case of seismic recordings. The examples presented in this article show the versatility of the method.

Keywords: Soil-structure interaction, Site-city effects, Shear wave propagation, Finite element approach.

1. Introduction

It is now a well established fact that vibrations produced by structures are transmitted to the ground by the so-called soil-structure interaction phenomenon, these vibrations can travel large distances and interact with other adjacent structures [1]. The effect of these interactions on the seismic response of structures, especially in dense populated cities resting on soft soils, was a subject poorly studied. Seismic risk in urban areas is an important subject of special interest given its impact on human losses and economic stakes.

Soil conditions at a given site may amplify the response of a given structure on a soil deposit. Not taking into account these structural response amplifications may lead to an under-designed structure resulting in a premature collapse during an earthquake.

The main idea behind this investigation is motivated by the fact that there is still great uncertainty into significance of seismic soil-structure interaction which takes into account site effects. There may be both beneficial and adverse effects into interaction. However, in many cases, soil-structure-interaction (SSI) is simply ignored in design without establishing whether it will increase or decrease the response of the structure. A second objective is that the probability of an earthquake of magnitude 7 or larger may occur in regions that have experienced strong earthquakes such as Chlef or Boumerdès or areas where new active faults are discovered (Annaba) following the second campaign of MARADJA [2]. Therefore, studies which include SSI effects will help for a better prediction of a performance of structures for future earthquakes [3].

State of the art knowledge and analytical approaches require that the structure-foundation system be represented by mathematical models that include the influence of the sub-foundation media.

Regarding the structural responses, the vibration and wave-propagation approaches represent two alternative solutions for the site-city problem. Vibration concept, such as the modal superposition of structure movements, has been the standard approach especially in code provisions. Wave-propagation concept developed by Iwan [4] is useful when the structure can be modelled as a continuous medium. This approach avoids the complex analysis of modal shapes, and it may be used for determining the inter-story drifts.

The structures are modelled as shear-beams with regular stiffness and mass. This allows considering the localized yielding, which produces softening in the affected stories. In this way, it is easy to see that localized yielding may lead to larger inter-story drifts. This method has the advantage to take account of the localized yielding at different stories and thus to determine the position of the collapsed story.

The objective of this study as reported herein focuses mainly on the numerical modelling of cities represented by structural groups of 5 storey reinforced concrete buildings incorporating special soft soil conditions, in order to assess the effects of SSI and site effects on the dynamic response of structures [5], [6].

2. Equations of wave propagation

A soil-structure system subjected to shear waves is given in “figure 1”. The waves can be represented by upward and downward parts as shown in the figure. The upward and downward waves are partly transmitted, and partly reflected when they hit an interface. The reflections and transmissions coefficients are denoted by R_u and T_x for the upward wave; and R_d and T_d reflection and transmission coefficients for the downward wave [7].

The upward wave $x_n(t)$ is the sum of the reflected part of the downward wave, and the transmitted part of the upward, that is

$x_n(t) = R_{d,n-1}\, d_n(t-\tau_n) + T_{x,n-1}\, x_{n-1}(t-\tau_n)$ (1)

where $R_{d,n-1}$ and $T_{x,n-1}$ represent the reflection coefficient for the downward waves and the transmission coefficient for the upward waves, respectively, at interface n-1. τ_n is the one-way travel time of the waves in layer n. Similarly, the downward wave $d_n(t)$ is made of the reflected portion of the upward wave, plus the transmitted portion of the downward wave, that is

$d_n(t) = R_{u,n}\, x_n(t-\tau_n) + T_{d,n}\, d_{n+1}(t-\tau_n)$ (2)

where $R_{u,n}$ and $T_{d,n}$ represent the reflection coefficient for the upward waves and the transmission coefficient for the downward waves, respectively, at interface n. Equations (1) and (2) are valid for all soil and building layers. For the first and the last layers, we introduce the boundary conditions and the equations become

$x_1(t) = R_{d,0}\, d_1(t-\tau_1) + T_{x,0}\, x_0(t-\tau_1)$ (3)

$d_1(t) = R_{u,1}\, x_1(t-\tau_1) + T_{d,1}\, d_2(t-\tau_1)$ (4)

and

$x_{m+N}(t) = R_{d,m+N-1}\, d_{m+N}(t-\tau_{m+N}) + T_{x,m+N-1}\, x_{m+N-1}(t-\tau_{m+N})$ (5)

$d_{m+N}(t) = R_{u,m+N}\, x_{m+N}(t-\tau_{m+N})$ (6)

where $x_0(t-\tau_1)$ is the incident wave at the bedrock–soil interface. We assumed that there are no reflections from the base of bedrock. Equations (1), (2), (3), (4), (5) and (6) give a complete description of wave propagation in an undamped soil-structure system. The motion, $y_n(t)$, of any layer in the building, or any soil interface, can be calculated by combining the upward and downward waves by using the following equation

$y_n(t) = x_{n+1}(t-\tau_{n+1}) + d_{n+1}(t)$ (7)

The incident wave $x_0(t-\tau_1)$ in equation (3) can be any of accelerations, displacements, or velocities. The calculated results are of the same type as the input.

For a given soil-structure system and base motion, they can be solved recursively starting from the base (i.e. with equation (3)) and continuing upward. The initial values of $x_n(t)$ and $d_n(t)$ are zero until the first arrival of the waves in layer n.

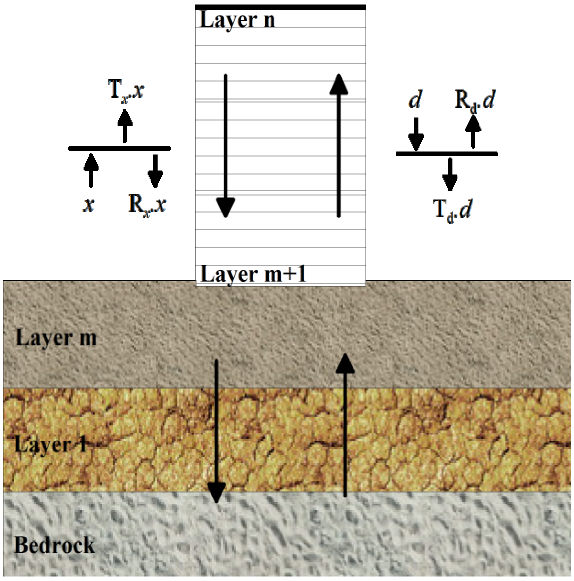


Fig. 1. Bedrock-soil-structure system showing layers, interfaces, upward and downward waves

3. Site-city effects

Site-city interaction was first studied by Guéguen [8] who modelled the effects of a group of buildings subjected to a realistic earthquake input motion. They addressed a fundamental question, that is, what is the effect of multiple soil-structure systems on the near-field ground motion and in on the response of individual structures as each one is affected by the presence of neighbouring ones and vice versa. Part of this subject is investigated in this paper.

Soil-structure interaction (SSI) effects represent a natural precursor to site-city interaction (SCI) problems. We follow a finite element approach, using Navier's equations we obtain the discretized equations by applying Galerkin ideas.

This leads to a system of ordinary differential equations of the form

$M\ddot{u} + C\dot{u} + Ku = f$ (8)

in which u is the vector of nodal displacements M, C, and K are the system's mass, damping, and stiffness matrices, and f is the vector of body forces that represent the earthquake source.

We are in a case of modelling large inventories of buildings considering soil-structure interaction systems in earthquake ground motion simulations, to study problems of site-city interaction. To this end we used simplified models of buildings in the finite-element simulation. We briefly explain the assumptions and approach to model large building inventories.

3.1 Building models

We model the soil-structure systems using plane-strain model of the buildings and layered soil as shown in "figure 1". In following this approach, the key issue is the appropriate selection of the material properties assigned to the building elements; that is, the material seismic velocity (V_s) and density (ρ) [9-10].

We select V_s so that, on average, the building models will reproduce the dynamic characteristics of the actual buildings (i.e., fundamental period estimated from the height and number of stories). For this, we follow two classical conceptual approximations in earthquake engineering. First, we assume that the buildings behaviour can be treated as shear beams whose natural period of vibration (T) may be approximated by the well-known expression

$$T = 4h/V_s \qquad (9)$$

where h is the thickness of the layer and V_s is its shear wave velocity. In a second assumption, the natural period of a building (T_B) may also be approximated as a fraction of the number of stories (N) as in

$$T_B = N/10 \qquad (10)$$

Combining these two expressions and taking the effective height of the first mode of vibration of the structure as $h = 0.7H$, where H is the total height of the building given by $H = Nh$, where h is the story height, one obtains

$$V_s = 28h \quad (11)$$

For typical story heights varying between 3 and 4 m, this yields Vs values for the building blocks between 84 and 112 m/s. Here, we use V_s = 100 m/s for the building blocks.

The buildings material density was generally set between 250 and 350 kg/m^3 (we choose a value of 300kg/m^3); and the critical damping ratio of 5%. These values are all in good agreement with others used in similar 2D studies [11], [12], [13], [14], and [15].

4. Evaluation of site effects in Annaba city

The city of Annaba situated in Northern Algeria is one of the areas of the Algerian territory where seismic risk is important. It is located on a sedimentary basin, overlooked by Edough's mountains.

The presence of saturated silty and plastic clayey formations on the upper 30 m thick layer "figure 2", suggests for seismic site effects. One-dimensional equivalent linear and one-dimensional nonlinear analyses are carried out to evaluate the dynamic site responses using DEEPSOIL computer program [16].

The average shear wave velocity of soil is given in "figure 2". The results of ground response analysis are presented in "figures 3 to 5" which indicate that the increase in maximum acceleration at the surface is as much as 3.21 times higher than at the bed rock. The results in the central basin show that the eigenmodes are mainly controlled by the upper unconsolidated formations present above the relatively sandy-clayey layer.

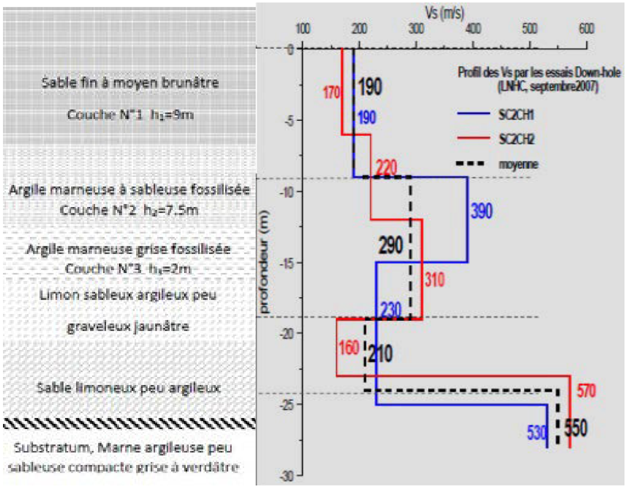
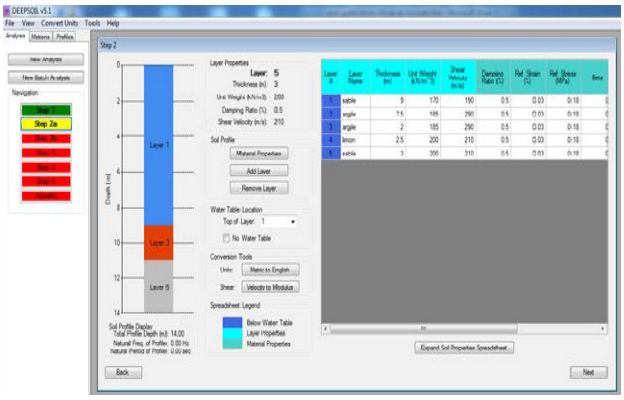


Fig. 2. Soil profile and shear wave velocity from down hole test.



Layer Properties

Layer: 5

Thickness (m): 3

Unit Weight (kN/m^3): 200

Damping Ratio (%): 0.5

Shear Velocity (m/s): 210

Soil Profile

Water Table Location

Top of Layer: 1

☐ No Water Table

Conversion Tools

Units: Metric to English

Shear: Velocity to Modulus

Spreadsheet Legend

🟦 Below Water Table

🟦 Layer Properties

🟩 Material Properties

Soil Profile Display

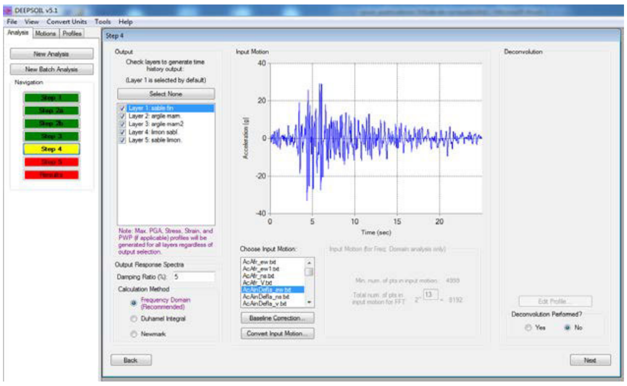
Total Profile Depth (m): 14.00

Natural Freq. of Profile: 0.00 Hz

Natural Period of Profile: 0.00 sec

Layer #	Layer Name	Thickness (m)	Unit Weight (kN/m^3)	Shear Velocity (m/s)	Damping Ratio (%)	Ref. Strain (%)	Ref. Stress (MPa)	Beta
1	sable	9	170	190	0.5	0.03	0.18	
2	argile	7.5	185	290	0.5	0.03	0.18	
3	argile	2	185	290	0.5	0.03	0.18	
4	limon	2.5	200	210	0.5	0.03	0.18	
5	sable	3	200	210	0.5	0.03	0.18	

Fig. 3. Characteristics of soil profile as introduced in DEEPSOIL.



Output

Check layers to generate time history output:

(Layer 1 is selected by default)

☑ Layer 1: sable fin

☑ Layer 2: argile marn

☑ Layer 3: argile marn2

☑ Layer 4: limon sabl

☑ Layer 5: sable limon

Note: Max. PGA, Stress, Strain, and PWP (if applicable) profiles will be generated for all layers regardless of output selection.

Output Response Spectra

Damping Ratio (%): 5

Calculation Method

● Frequency Domain (Recommended)

○ Duhamel Integral

○ Newmark

Choose Input Motion:

AcAfr_ew.txt
AcAfr_ew1.txt
AcAfr_ns.txt
AcAfr_V.txt
AcAinDefla_ew.txt
AcAinDefla_ns.txt
AcAinDefla_v.txt

Input Motion (for Freq. Domain analysis only)

Min. num. of pts in input motion: 4555

Total num. of pts in input motion for FFT: 2^13 = 8192

Deconvolution Performed?

○ Yes ● No

Fig. 4. Earthquake accelerograms used for calculation.

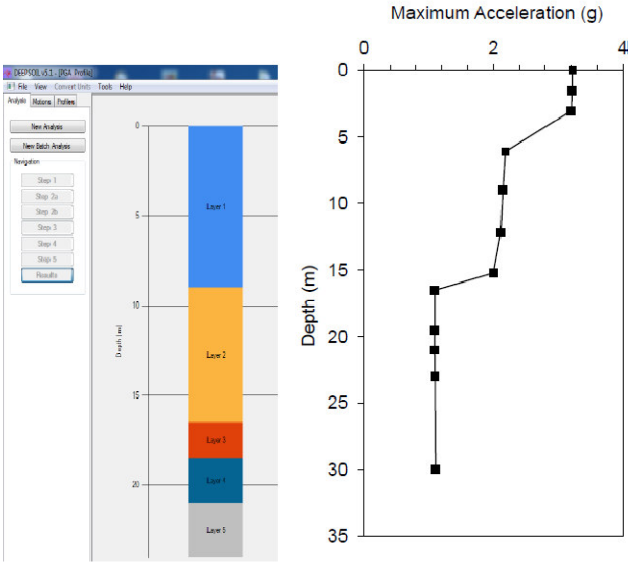


Fig. 5. Earth Maximum acceleration amplification through soil profile.

5. Evaluation of site-city effects of an idealized city

The proposed analysis model is applied to study the dynamic responses of ten five storey reinforced concrete buildings to earthquake excitation in time domain. The computational model employed in this section is shown in “figure 6”, where the numerical results are obtained using finite element method.

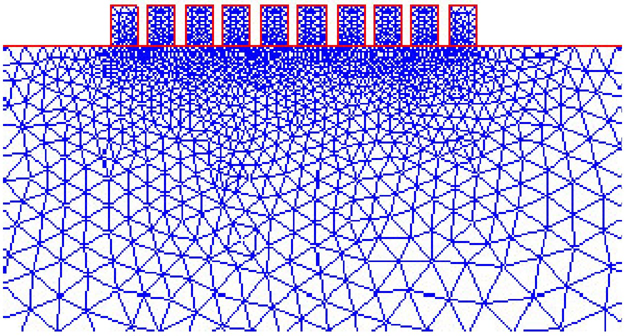


Fig. 6. Geometry of the sub domain 1500mx400m.

The model is submitted to 44 earthquake accelerograms 31 from Boumerdès earthquake and 13 from USGS office) (http://nsmp.wr.usgs.gov/docs/smcfmt.txt).
The ten buildings are of the same type (5 storeys). They are 3.0 m x 3 = 10.5m wide and their total height from ground level is 4.08m x 6 = 24.48m. The dead loads acting on each floor are up to 2.92 t/m and the live load up to 1.18 t/m.
The following material properties are used:
- Concrete: Young's modulus E = 33,300 x106 KPa, Poisson's ratio ν = 1/3 and Density ρ = 2500 kg/m^3
- Mohr-Coulomb Soil: Young's modulus E = 4,532 x10^4 KPa; Poisson's ratio ν = 0.2; cohesion c = 2 KPa; Friction angle =24°; Shear wave velocity and density as given in the soil column (Figure 2); soil layer depth = 30.0 m.

In this domain, we simulated an earthquake from Boumerdès scenario. We use a hypothetical realistic urban setting composed of 10 buildings having the same properties. All building blocks have Vs = 100 m/s.

6. Discussion of results and conclusions

A numerical model for the prediction of wave induced vibrations in buildings has been developed and used for analysis. The coupled soil-structure system takes account of the free field wave induced vibrations in buildings; the model is based on a direct formulation approach for dynamic SSI problems.
A study on the determining factors for wave induced vibrations in buildings has been performed; the response has been calculated for free field, one and ten buildings type cases. The importance of SSI for dynamic SSI problem has been investigated. The conclusions from the investigation of the modal characteristics of the structure and response in terms of displacement and acceleration in different points of the site-city system are summarized as follows:

1. There is an indication of rather large response not only in the buildings, but also on the ground level, and in the layer; this was also confirmed by some authors for periodic distribution of identical blocks [14]. The buildings constitute diffractors whereby seismic surface waves are locally generated, which then travel back and forth in between pairs of buildings, thus resulting in the coupling of the motions of the buildings via the soil so as the result will be a longer duration of the shaking inside the buildings which is longer than the one observed in the one-building case.

The time histories represented in “figures 7-8”, call for the following comments.

2. The peak amplitude response is larger at locations of the 10-buildings case than in the 1-building case.
3. The response of the buildings varies significantly from one building to another “figures 9-10”, corresponding to increased vulnerability for the 10-buildings case, which suggests that some of the buildings may suffer severe damage, while others will go unaffected, as a result of an earthquake in a city such as this one.
4. The effect of site to which one should expect the most spectacular lies in the upper layers, the amplification of the signal increases with the thickness of the sediments up to a factor of 3.2 “figure 5”.
5. Annaba geotechnical data are often limited to surface layers. Indeed, apart from these sites, particularly in the vicinity of the reliefs, it is difficult to predict the frequency or the frequencies that will lead to the greatest site effects.

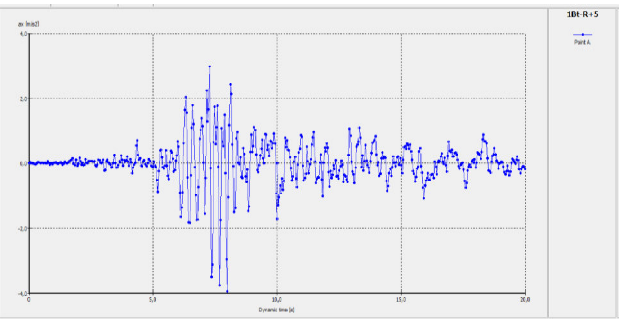


Fig. 7. Displacement time history curves at bottom, foundation and top level of the 1-building case model.

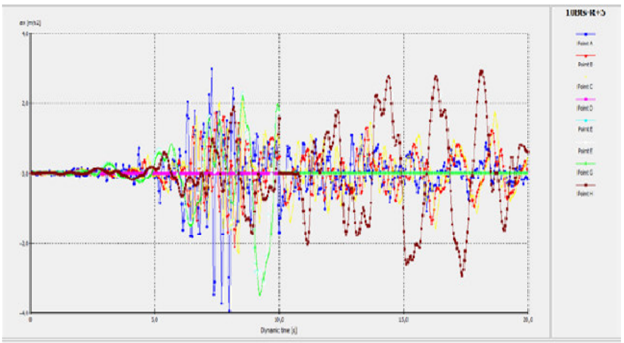


Fig. 8. Acceleration time history curves at bottom, foundation and top level of the 10-buildings case model.

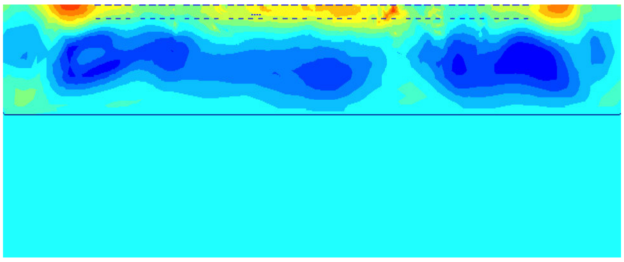


Fig. 9. Total displacement field in the absence of all blocks (free field); Red designates large displacement and blue small displacement.

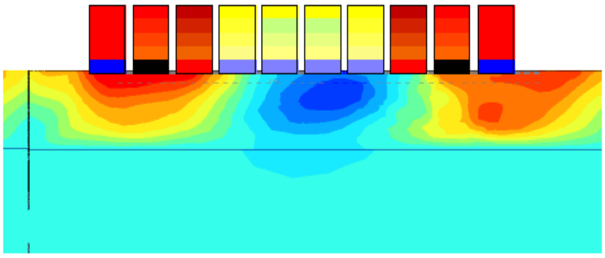


Fig. 10. Total displacement field of ten blocks; Red designates large displacement and blue small displacement

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