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Numerical simulation of spatial variability and kinematic effect of ground motion on the response of above ground structure

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ABSTRACT

The effect of the spatial variability and kinematic effect of ground motion during an earthquake is mainly attributable to the passage of the seismic wave as well as to local soil-structure interaction. This study introduces the relative importance of these effects on the seismic response of above ground structure. In addition, site effects, which can significantly modify the signal of seismic motion, constitute a kind of natural vulnerability that is explained by kinematic effect which are now implemented in seismic guidelines for buildings. However, its dynamic response is significantly influenced by the effect of wave passage and site conditions. In the presence of geological conditions with irregular configurations of the layers of the ground profile, the inconsistency of the seismic movement combined with the local site effects amplify the seismic effects on the foundations of the structure. Numerical results are obtained to demonstrate the spatial variability and kinematic effects of ground motion on the response of above ground structure considering soil-structure interaction.

Keywords: Spatial variability, Soil-Structure Interaction, kinematic, finite element, seismic.

INTRODUCTION

The seismic response of structures including the ground depends on dimensions, type of structure, type of foundation and soil profile. In the presence of geotechnical conditions, the dynamic response of above ground structures is significantly affected. The dynamic response of the soil-structure system to earthquake ground motion is very complex to evaluate. This complexity is due to the phenomenon of propagation of seismic waves and the multiple reflections and refractions that occur in the ground mass and at the foundation of the structure. There is no exact solution for this type of problem. The solution can only be obtained by using numerical models in soil-structure interaction (SSI) considering the presence of soil, the foundation of the structure and the superstructure.

In the past, several numerical solutions have been reported for the dynamic response in soil-structure interaction. The first popular numerical solution developed for SSI incorporates boundary conditions [1]. These are known as viscous boundary conditions and are interpreted as dashpots and springs concentrated at the boundary of the near field. Many other transmitting boundaries as well as fictitious boundaries can be found in many references. One of the most boundary conditions that are valid for time domain as well as frequency domain analyses includes formulation for inclined radiating boundary conditions for both P and SV waves [4]. Based on the latter, past study [3] has shown the importance of modelling soil-structure interaction using radiating boundaries for seismic P and SV waves.

When the structure undergoes multiple different effects due to the passage of the seismic wave its dynamic response is significantly influenced by this effect.

The determination of the seismic loading on the soil-structure system represents an important step for the assessment of the seismic response in SSI. Indeed, the earthquake ground motion will not necessarily be the same from one point to another at the foundation of the structure. This difference, known as variability, is due to the arrival time or time-shift of the seismic wave at the foundation of the structure. The effect of the spatial variability of the ground motion during an earthquake is mainly attributed to the wave passage, the loss of coherence and local ground conditions. These effects are mainly caused by seismic waves incident at an inclined angle. Moreover, past research shows that vertically propagating seismic waves are not dominant compared to inclined seismic waves because of the nature of the wave reflection and refraction at the surface.

It is commonly accepted that earthquake ground motion propagates vertically upwards towards. This assumption is not always true. Indeed, seismic waves propagate, in general, following an inclined direction [2-4]. This hypothesis represents the case of body waves which propagate in all directions with variable angles of incidence. This paper considers the ground motion as incident compression wave inclined at 45° from the vertical and studies the numerical simulation in SSI for variability and kinematic effects for above ground structure.

NUMERICAL SIMULATION OF SOIL-STRUCTURE INTERACTION, VARIABILITY OF GROUND MOTION AND KINEMATIC EFFECT

Description of the domain of analysis

The finite element (FE) model of the soil profile including the structure is shown in Figure 1. To apply the finite element method, the domain of analysis needs to be limited in dimensions by reducing its size by imposing boundaries. Therefore, the resulting truncated system will contain the near-field, interior region, and the far-field, exterior region, represented by the fictitious absorbing boundaries [4]. The application of the radiating boundary conditions to represent the far field is achieved by using a finite difference scheme applied to discretize the partial differential equations.

The numerical formulation starts by forming the finite element equations for individual elements. For each element the nodal values are defined by two translational degrees of freedom at each node. The global dynamic equations are obtained by assembling element equations by means of standard procedure. In this formulation, the FE is applied to the near field and the finite difference (FD) is applied to discretize the boundary conditions [4]. This mixed formulation allows the incorporation of the boundary conditions into the numerical FE-FD approach. A computer code was developed in C++ language to include the numerical formulation as well as the radiating boundaries.

The loading vector at each element located on the boundary expresses the earthquake excitation in the form of applied nodal accelerations acting on one side of the finite element with one side coincident with the near-field-far-field interface and a second side inside the core region. With this approach, the inclined boundaries can simulate the transmission of the incident waves that are applied uniformly and absorb the outgoing waves. The input ground motion can be an acceleration time history applied parallel to the axes x' and y' as shown in Figure 1.

The SSI consists in a structure resting at the surface of the soil medium and is assumed to be a symmetrical structure supported by a general raft foundation resting on ground. Figure 1 shows a two-dimensional model comprising a flexible structure resting on a foundation soil medium. The structure and the foundation soil are discretized using finite elements bounded by radiating boundaries that replace the missing soil extending to infinity. The boundary conditions can transmit both the incoming and the outgoing seismic waves. In Figure 1, C, S, ρ, ν and C_1, S_1, ρ_1, ν_1 are the compression wave velocity, shear wave velocity, unit mass and Poisson's ratio for interior and exterior soil media respectively. For the concrete structure and its foundation, the mechanical properties are the unit weight ρ_s, Young's modulus E_s and Poisson's ratio ν_s.

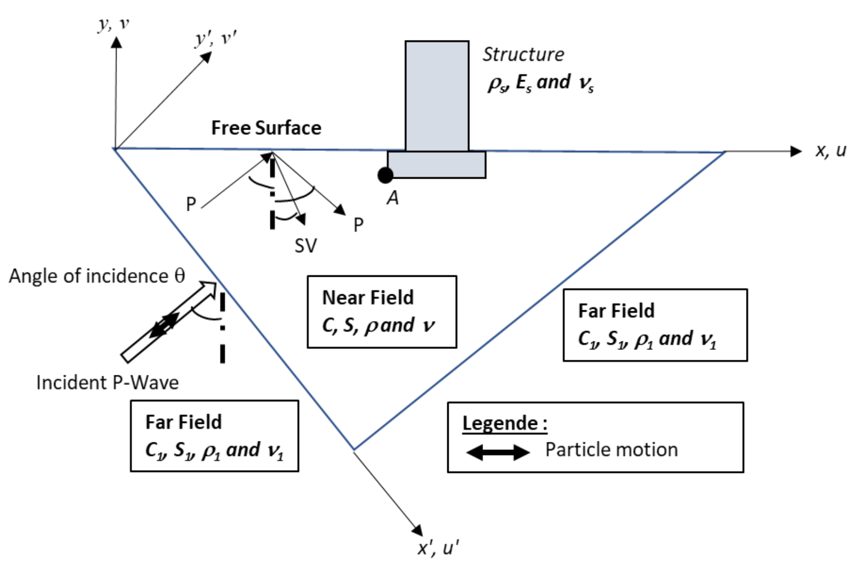

Figure 1. truncated semi-infinite space comprising the structure.

Soil-structure interaction (SSI)

The dynamic response is obtained for the SSI system for which the structure is resting on a flexible foundation homogeneous medium. The SSI model comprises two regions; the first region is the near-field, and the second region is the far-field. Both regions have the same mechanical properties. The SSI system is a linear flexible structure resting on a linear homogeneous elastic foundation soil medium. The analysis is carried out assuming that the structure consists of a linearly elastic material and is resting on an elastic foundation soil medium.

The excitation is generated at the boundary as an inclined P-wave uniformly distributed and propagating towards the ground surface at an angle of incidence θ to the vertical. The wave motion is described by a harmonic acceleration time history of period T, amplitude, and duration t. The wave motion can also be represented by an acceleration time history that can be collected from a seismic record.

At the free surface, the incident P-wave is converted into a reflected compression P-wave at the same angle as the incidence and a shear SV-wave at a different angle as shown in Figure 1. At the structure foundation, the same phenomenon occurs except that refracted waves into the structure will be present. The resulting SSI system is then analyzed by the so-called direct method that includes the soil and the structure together with the boundaries in one single system and the ground motion history is applied to the left inclined boundary as shown in Figure 1.

Description of soil profile properties

The properties of the foundation soil are as classified by the National Building Code of Canada [5], which include the types of soil profiles depending on the range of the average shear wave velocity Vs for the 30 first meters of the soil profile.

The properties of the soil media of the near-field and the far-field were chosen from reference [2]. The properties used for the analysis of the SSI system are based on the range of values as given by the NBCC and are represented by compression wave velocity C, shear wave velocity S, density ρ, and Poisson's ratio ν. Table 1 shows the soil profile and the data used for the SSI system. The properties for both the far field and the near field are identical since the soil profile is assumed to be homogeneous.

In this study, it is assumed that the material damping of the structure and the soil medium is zero (ξ=0%) and only the radiating damping is present in the system.

Table 1. Material properties.

Site	Compression Wave Velocity, C m\s	Shear Wave Velocity, S m/s	Unit Mass, ρ Kg/m^3	Poisson's Ratio ν
Interior region	560	270	1841	0.3
Exterior region	560	270	1841	0.3

The structure is a shear wall, with height H = 15 m and cross section 2.5mx1m is supported on a concrete foundation with plan dimensions 5mx5m and 2.5 m embedment. the mechanical properties are the unit weight ρ_s = 24 kN/m^3 Young's modulus E_s = 27040 MPa and Poisson's ratio ν_s = 0.2.

RESULTS AND DISCUSSION

The dynamic response of the SSI system is obtained for a harmonic incident compression P-wave at an angle of 45 degrees to the vertical. The period of the incident P-wave is equal to be 0.1s and correspond to the low period range. The time history results correspond to points located at the foundation of the structure and at the free surface.

The SSI system is discretized using finite elements. The near-field is discretized using a mesh of 312 triangular and quadrilateral finite elements with a total number of nodes of 351 using the material properties as shown in Table 1. Based on the combined soil-structure system represented by Figure 1, the effect of dynamic soil-structure interaction on the response of the structure is obtained.

The time history is as shown in Figure 2 for a harmonic inclined P-wave that propagates towards the surface of the soil medium of type D. The duration of the harmonic motion is 0,1s. The measured maximum acceleration response of the free field is 1.3g and that measured at the foundation corner is 1.0g, g is the acceleration of gravity. The increase of the acceleration of the free field is attributed to the wave reflection-refraction at this location. All the measured quantities shown by the curves dye-out after a time of 0.2s referring to the radiation of the waves that are transmitted by the boundaries.

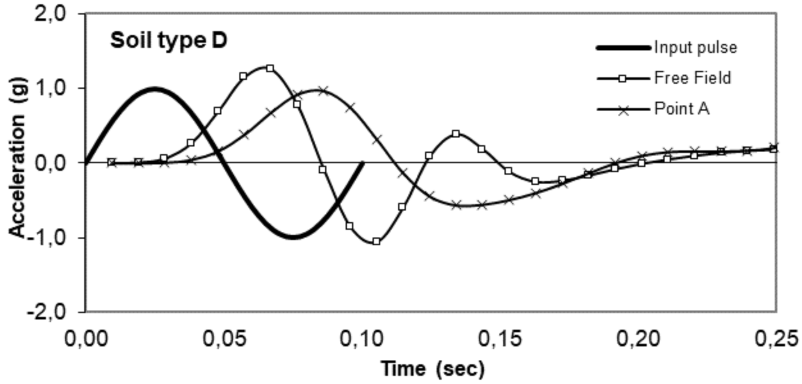

Figure 2. Response in soil-structure-interaction, T=0.1 sec, soil type D.

To quantify the variability of the ground motion, the variation of the acceleration is measured at different points near the surface. The nature of the incidence generates reflected and refracted waves at the free surface and at the foundation of the structure. This results in a modification of the ground motion that will have different response amplitudes. The results clearly show the time delay between the points located at the free surface and at the foundation of the structure. The effect of variability of the ground motion is attributed to the time delay for the seismic wave to travel from one point to another in the SSI system. The numerical model simulates this phenomenon since the incident waves propagate at inclined angle with a time delay and accounts implicitly for the complex phenomenon of reflection and refraction of the incidence since at the free surface an incident P wave is converted into a reflected P-wave and SV-wave at different reflection angles.

The kinematic effect is known as the modification of the effective input ground motion because of the depth and rigidity of the foundation system [6]. This modification is the result of the space variability of the ground motion that can be measured at the foundation of the structure [7]. When the structure is resting on a mat foundation then the so-called slab averaging occurs when the incident seismic wave is inclined. The effect of the slab averaging depends on the size of the mat and the wavelength of the seismic ground motion.

The numerical model of the present study predicts the variability of the ground motion over the base of the foundation of the structure as well as the free-field motion. The kinematic effect is obtained with the same system in SSI with a structural system without mass and only the stiffness is considered. The mechanical properties of the structure are accounted for in the element stiffness formulation. To quantity the kinematic effects, Eq. (1) gives the ratio of acceleration at the foundation and the free field:

$$Kin = \frac{Afo}{Aff} \tag{1}$$

Where Kin is the coefficient of the kinematic effect, Aff is the free-field acceleration and Afo is the acceleration at the foundation.

The kinematic effect is well simulated by the numerical model of the SSI system under the effect of harmonic seismic P-wave. The effect of the interaction phenomenon between the soil and the structure modifies the incident ground motion since reflection and refraction occur at different points along the base of the structure. This type of interaction affects the amplitude of the ground motion at the base of the structure because of the relative rigidity between structure and soil. Since the ground motion is inclined, the arrival time of the incidence is delayed from one point to another, and this variation affects the dynamic behavior of the structure as well as the amplitude of the ground motion.

The numerical results show clearly that the variability of the incident ground motion is influenced by the presence of above ground structure. The results show that for soil type D, the amplitude of acceleration response is reduced as shown in Figure 2 for point located at the base of the structure. This is mainly attributed to the presence of the structure and the relative stiffness effect between soil and structure.

To quantify the kinematic effect, the dynamic response of a point located at the base of the structure is obtained by measuring the maximum amplitude of acceleration and comparing it to that of the free field. The time history of the acceleration response parallel to the inclined y' axis is shown in Figure 2. The estimated kinematic effect is about 77% showing the modification of the amplitude of the incident wave for soil type D. this modification is attributed to the complex phenomenon of waves impinging at the foundation of the structure. In fact, the input energy of the seismic P-wave is converted to reflected and refracted waves. The reflected wave goes back to the soil medium, and the refracted wave propagate in the structures. This cyclic effect influences the ground motion as well as the structure. Since the phenomenon is complex in its nature, only numerical approach can predict and approximate the dynamic response and gives an estimation of the kinematic effect. The maximum acceleration response for the case of soil profile type D, as depicted in Figure 2, shows the ground motion modification for kinematic effect. Therefore, the kinematic coefficient is an important factor that can be used as a response spectral modification factor to account for SSI.

The results presented in this study are limited to the case of homogeneous soil profile of class D subjected to inclined harmonic P-wave. Further studies to include different angles of incident and shear wave velocity as well as different soil profiles are ongoing.

CONCLUSIONS

The effects of seismic ground motion variability on the response of soil profile type D were presented. These effects have an influence on the dynamic behavior of soil and therefore a direct effect on the dynamic response of above ground structure. The effect of variability is attributable to the passage time of the seismic wave to travel from one point to another for the free-filed and at the foundation of the structure. Consequently, different response amplitudes are measured due to the presence of the structure that influences the ground motion. The kinematic effect is quantified through the numerical simulation that accounts for the modification of the ground motion when SSI is considering. Further studies are ongoing to investigate the case of shear wave incidence under different angles of incidence and different soil profiles.

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