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DYNAMIC RESPONSE OF A DAM STRUCTURE TO INCIDENT SEISMIC WAVES

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ABSTRACT: In this paper, the dynamic response of a dam structure resting on elastic foundation soil that is bounded by a rock medium and subjected to incident seismic waves is obtained. The rock medium that is confining the foundation soil is assumed to extend at infinity. The numerical solution is obtained via a coupled Finite Element-Finite difference formulation. Although the finite element can capture the dynamic response of finite systems, it fails to represent infinite domain. As such, the current model truncates the infinite domain into a near field and a far field, where the boundary used in this study represents the far field efficiently. In order to illustrate the effects of the rock medium properties on the response of the system, numerical results are obtained for one cycle input for inclined seismic waves applied at different incidence angles. The wave input motion is represented by a harmonic acceleration applied at the model interface separating the near field and the far field. The numerical results are obtained for three cases: the first case is a model of a flat free surface, and the second case corresponds to a dam structure resting on elastic foundation soil having the same properties and the third case is similar to the second one except that the soil medium is bounded by rock medium. The time history response is measured as acceleration at free surface, base and crest of the dam structure. The dynamic response is dependent on the geometry of the system and the physical properties of the media. As a result, the effect of varying the properties of the far field on the overall dynamic response is obtained through the variation of the radiating damping coefficient. Numerical results are obtained to demonstrate the effect of inclined seismic waves to estimate the dynamic response of a dam structure including soil-structure interaction.

1. Introduction

1.1. Historical development

The dynamic response of large structures such as dams to incident seismic waves is significantly influenced by the soil-structure interaction (SSI) effect. There are many factors that influence the dynamic soil structure response. Among the most important factors are the material properties, the geometry of the dam, the foundation soil, the topography of the surrounding medium and the dynamic loading.

Due to the complexity of the wave propagation phenomenon during seismic motion, exact solutions are yet impossible and only numerical solutions can be obtained. The most popular techniques that have been widely used in SSI problems are the finite difference, the finite element and the boundary element methods. Bounded methods such as the finite element method (FEM) can not be applied directly to infinite problems without imposing limits to the domain. To apply the FEM is to truncate the domain into two parts, namely near field and far-field. At the limits of the finite region, special boundary conditions are applied to account for the part of the soil that extends to infinity. The imposed boundary conditions should be able to simulate the transmission of the reflected waves from the interior region (the near field) to the exterior region (the far field). The model of the finite zone comprising the structure and the foundation soil includes directly the SSI since it allows modelling the structure and the foundation soil as one domain that represents the near field.

Several numerical solutions have been reported during the last three decades to model the dynamic response of the SSI system. The first very popular boundary conditions are those developed by Lysmer and Kuhlemeyer (1969). These boundary conditions are local and are interpreted as dashpots that can be concentrated at the boundary of the near field. The superposition boundary developed by Smith (1974) uses the concept of elementary boundaries allowing the imposition of boundary conditions that act as perfect reflectors without transmission or absorption of the energy. This type of boundaries leads to a highly computational effort and are not applicable for problems with multiple reflexion. Other boundaries applied to wave propagation problems were introduced by Clayton and Engquist (1977), Liao and Wong (1984).

Sarma and Mahabadi (1994) used continuity conditions to formulate radiating boundary conditions for vertically incident shear *SV* waves. These boundary conditions were incorporated into a finite difference scheme to study the seismic behaviour of earth dam. Naimi et *al* (2001) developed new inclined radiating boundary conditions valid for frequency and time domain analyses. These boundary conditions are based on continuity conditions of stresses, displacements and velocities at the interface separating the near field and the far field. They are incorporated into a finite element formulation after discretizing the equations using a finite difference scheme. The input can be a compression or shear wave applied uniformly at the boundary as acceleration.

In calculating the dynamic response of a soil-structure system to seismic ground motion, it is usually assumed that the shear wave *SV* is propagating vertically towards the free surface. However, there have been no results showing the effect of inclined incident *SV* waves by considering the effect of the radiating damping on the dynamic response of the soil-structure-system. The radiating damping coefficient is expressed as:

$$r = \frac{\rho S}{\rho_1 S_1} \tag{1}$$

where ρ, and ρ_1 are the mass densities of the near field and the far field respectively. Similarly, S and S_1 are the shear wave velocities of the near field and the far field respectively.

This paper studies the dynamic response of an earth dam structure resting on an elastic half space subjected to incident inclined harmonic seismic shear *SV* waves. At some distance from the dam base, the soil properties may have different characteristics than the foundation soil located in the vicinity of the dam. The body waves generated at some depth in the half space propagate towards the surface where they are reflected back to the soil medium. The forms of the reflected body waves are well documented in the literature. For incident inclined *SV* waves, the energy input at the free surface is converted into two different types of waves, namely *SV* and *P* waves. For the case of a dam structure, the incident waves arriving at the sloped edges of the dam reflect back to the soil medium in a similar manner of that of the free surface. This time the reflections that occur are due to the wedged shape of the dam. The mathematical model for this situation cannot be obtained analytically due to the complexity of the wave pattern that can be generated at a boundary. Analytical solutions for this situation are difficult to obtain, and only numerical solutions can be obtained. The bounded method such as the finite element method (FEM) cannot be applied directly to model infinite domains without special treatment. The domain of interest has to be truncated into two parts, namely into near field and far field. The near field will comprise the structure and the surrounding soil medium and the far field will represent the infinite part of the half space.

In this paper, three models are used. The first model is a half space, without a structure, composed of a flexible soil limited by an inclined rock medium. The second model comprises a dam structure resting on a flexible soil extending beyond the limits of the near field. The third model comprises a dam structure resting on a flexible soil limited by an inclined rock medium. All models are subjected to inclined harmonic shear *SV* waves propagating towards the free surface.

At the surface, the incoming shear *SV* waves are converted into *SV* and *P* waves and are reflected back to the soil medium. Because of the complexity of this energy conversion, exact analytical solutions are yet difficult to obtain and only numerical solutions are possible.

2. Formulation

2.1. Dynamic equilibrium equations of motion

Figure 1 shows the cross-section of dam structure resting on elastic half space with plane strain condition. The numerical solution is obtained via the mixed formulation finite element-finite difference FE-FD after discretizing the dam and the foundation soil medium using quadrilateral and triangular finite elements including the boundaries. The far field is modelled using inclined radiating boundary conditions (Naimi et al., 2001).

The dynamic equilibrium equations of motion are obtained using Hamilton's principle. The formulation starts by applying the conventional FEM for the near field. The element equations are obtained by assuming a displacement field vector defined in terms of shape function vector and nodal displacement vector which includes the degrees of freedom as the unknown nodal values. For each element the nodal values are defined by two translational degrees of freedom at each node. The element dynamic equilibrium equations are obtained as:

$$\boldsymbol{m}\ddot{\boldsymbol{d}} + \boldsymbol{c}\dot{\boldsymbol{d}} + \boldsymbol{k}\boldsymbol{d} = \boldsymbol{f} \qquad (2)$$

in which ***m***, ***c***, ***k*** are the element masse, damping and stiffness matrices respectively. ***f*** is the element nodal force vector.

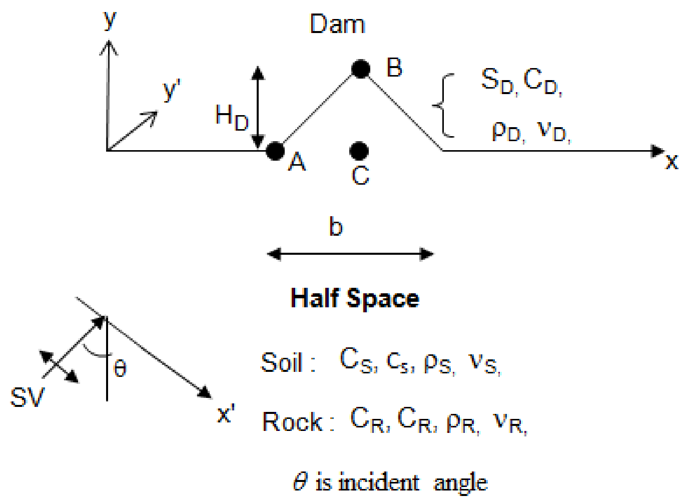


Fig. 1 – Dam cross section on half space

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 [Naimi et al 2001].

The loading vector at each boundary element expresses the earthquake excitation in the form of nodal accelerations acting on the near-field-far-field interface. With this approach, the inclined boundaries can simulate the transmission of the incident shear waves that are applied uniformly as well as the absorption of the reflected outgoing waves.

The element dynamic equilibrium equations are assembled to get the global dynamic equations as:

$$\boldsymbol{M}.\ddot{\boldsymbol{U}}' + \boldsymbol{C}.\dot{\boldsymbol{U}}' + \boldsymbol{K}.\boldsymbol{U}' = \boldsymbol{F} \qquad (2)$$

where ***M***, ***C*** and ***K*** are the global mass, damping and the stiffness matrices, and ***U'*** is the global displacement vector, the vector ***F*** represents the global force vector.

2.2. Dynamic response of earth dam to shear SV waves

The dam model considered in the present study is shown in Figure 1. The near field is represented by the foundation soil and the dam structure. The following symbols for the properties of the media are used :

S_D - Shear wave velocity of dam.
C_D - Compression wave velocity of dam.
ν_D - Poisson's ratio of dam.
ρ_D - Mass density of dam.
H_D - Height of dam.
b - Width of dam base.
S_s - Shear wave velocity of soil.
C_s - Compression wave velocity of soil.
v_s - Poisson's ratio of soil.
ρ_s - Mass density of soil.
S_1 - Shear wave velocity of soil that extends to infinity.
C_1 - Compression wave velocity of soil that extends to infinity.
ν_1 - Poisson's ratio of soil that extends to infinity.
ρ_1 - Mass density of soil that extends to infinity.

The input ground motion is an inclined shear *SV* wave represented by a harmonic acceleration of one cycle duration. The period of the loading *T=0.1* sec with amplitude of *1.0 g*, where *g* is the acceleration of gravity. The applied *SV* wave excitation, parallel to the *x'* axis and generated at the far field, propagates towards the ground surface.

The analyses are carried out assuming that the dam structure consists of a linearly elastic material and is resting on an elastic foundation soil medium.

3. Results and discussion

The time history analyses are performed for each model separately by varying the angle of incidence of the shear wave. Table 1 gives the material characteristics considered for the models.

It is assumed that the material damping of structural system is zero (ξ=0%) and only the radiating damping is present. In order to study the effect of radiation damping on the dynamic response of the dam structure, a finite element model with a mesh of 495 triangular and quadrilateral elements with a total number of 521 nodes is developed. The height of dam at crest is H_D =10 m and the base width b=100m.

Based on the combined soil-structure system represented by Figure 1, the effect of dynamic soil-structure interaction on the response of the dam is obtained.

Table 1 – Material characteristics for models.

Structure or medium	Compression wave velocity C m/s,	Shear wave velocity S m/s	Mass density ρ kg/m^3	Poisson's ratio ν
Dam	970	560	1841	0.25
Foundation soil	970	560	1841	0.25
Rock	1947	1125	2000	0.25

3.1. Free field response

It is of interest to examine first the effect of a flexible foundation soil having the properties of a dense soil as classified by the Canadian Highway Bridge Design Code 2014 (CHBDC), CAN/CSA-S6-14, bounded by rock medium. The harmonic acceleration is applied at the inclined boundaries as shear *SV* wave propagating towards the free surface. The near field and far field are represented by dense soil and rock medium respectively. The response amplification corresponds to a stiffness ratio r = 0.46. Three incident angles are considered, namely at 30, 35.5 and 60 degrees. The horizontal component of acceleration response is computed for a point located on the free surface as shown in Figure 2. The results show that maximum amplitude of acceleration for incident angles 30 and 35.5 degrees are higher compared to that of 60 degrees. The maximum accelerations are 0.97g, 0.71g and 0.66g for 30, 35.5 and 60 degrees with difference in phase. The delay time is attributed to the distance that is larger for higher incidence angle. As the angle increases the amplitude decreases and the wave takes more time to reach the free surface. This is the effect of spatial variability of the motion.

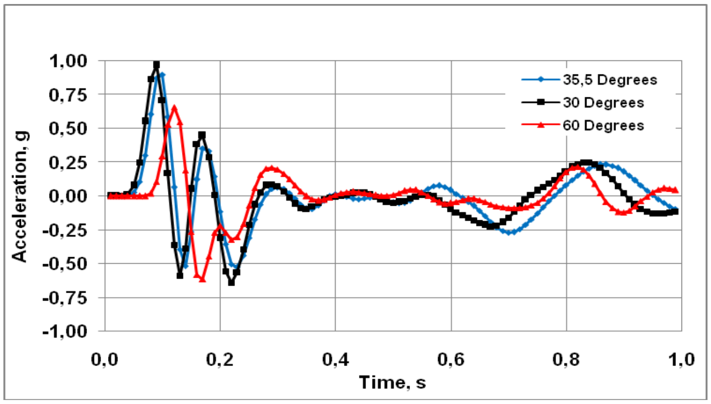


Fig. 2 – Free field response to inclined *SV* wave

3.2. Response of soil-structure system

3.2.1. Dam and foundation soil having identical properties

The second model is a dam structure resting on a foundation soil. For this case, identical material properties of dam and soil are considered as given by Table 1. In order to keep the radiating coefficient equal to one, the far field properties are assumed to be the same as the near field. Figure 3 shows the SSI response of point B located at the crest of the dam. The maximum amplitude of acceleration corresponding to incident angles 30, 35.5 and 60 degrees are of 0.44g, 0.35g and 0.52g respectively with delayed arrival time. Moreover, the response curves for 60 degrees incident show the presence of the wave reflection.

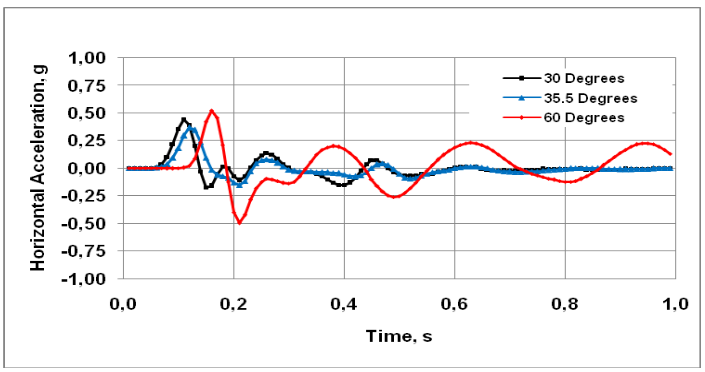


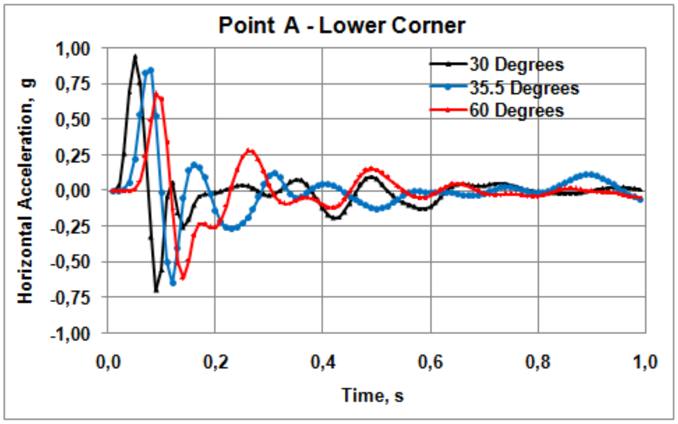
Fig. 3 – Response in soil-structure interaction to inclined *SV* wave a) Dam base, b) Dam crest

3.2.2. Dam and foundation soil limited by rock medium

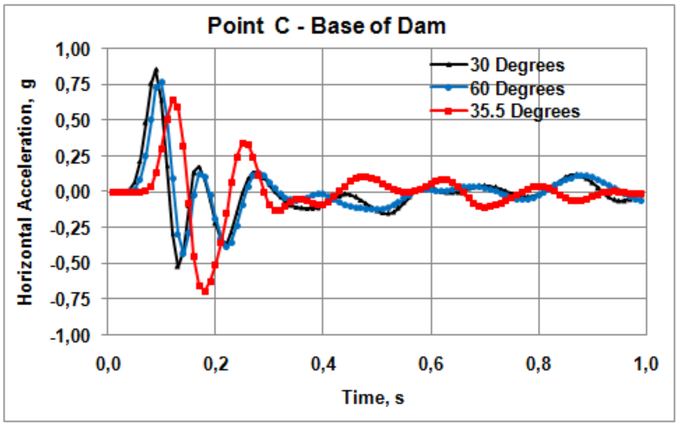
The third case concerns the response of a dam structure resting on a flexible soil type C, as classified by CHBDC, limited by rock medium. To investigate the effect of a hard boundary on the dynamic response of the dam, the relative stiffness conditions between soil medium and rock via their properties is considered. The relative rigidity between far field and near field depends on the radiating damping coefficient r. This coefficient is an important factor for estimating the dynamic response amplification. In this study, the maximum response amplification is obtained for r = 0.46 indicating the presence of a hard medium confining a flexible soil. The model studied referred to the dam structure resting on a foundation soil and limited by rock medium has the properties given by Table 1.

The time history of the horizontal component of accelerations measured at points A, B and C, corresponding to the left corner, the crest and the base of the dam respectively is shown in Figure 4. The results indicate an increase of the response compared to the previous case with identical properties of the dam, the near field and the far field are identical. The maximum response amplitude of acceleration for point C reaches the value of 0.77*g* for incident angle at 30 degrees. The increase in amplitude reaches

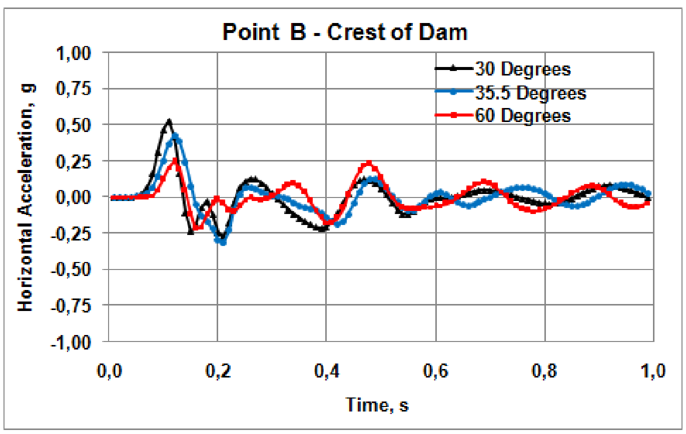
1.75 times the case of dam resting on a flexible foundation soil extending beyond the limits of the near field.



a)



b)



c)

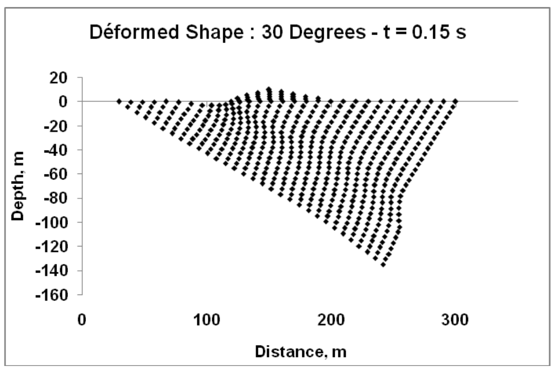
Fig. 4 – Response to inclined *SV* wave a) Left corner, b) Dam base, c) Dam crest

The SSI effect can be observed as shown by Figures 2 and 4a). A comparison is made between the values of maximum amplitude of acceleration for point A for the case of incident angle at 30 degrees. As shown in the plots, the amplitudes of maximum accelerations obtained for the free field and for the dam base reach the values of 0.97*g* and 0.86*g* respectively. It is therefore clear that the presence of the dam influences the free field response by reducing the value of the input acceleration to 13% for the case considered.

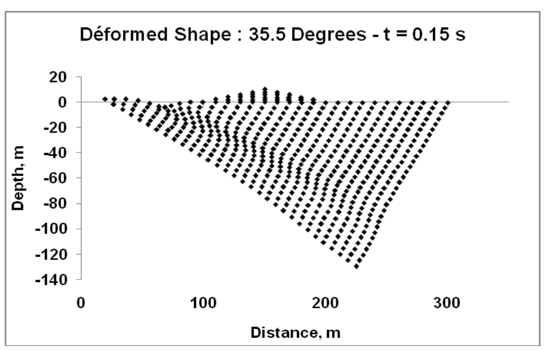
The responses measured at points A and B located at base and crest of the dam (Figure 1) respectively show that the maximum amplitude of acceleration (Figure 4) is influenced by the presence of the rock medium confining the near field. The increase in the response for both points signifies that more energy of the reflected waves remains longer inside the finite element region. This effect is due to the difference between the stiffness of the soil and the rock. As given by Table 1, the rock medium has properties that result in a stiffness greater than that of the foundation soil. Moreover, the response curves show that for both points there is no decrease in the response after completion of one cycle input of the shear wave. This means that the waves generated during one cycle continue to display until all reflections are transmitted away from the region by the radiating boundaries. Therefore, the wave reflections last longer because of the relative stiffness between exterior and interior region and this is known as site effect. This effect is magnified as the angle of incidence decreases. The results show also the effect of the wave passage that causes asynchronous motions along the base of the dam and this is observed at points A and C.

3.2.3. Dam and foundation soil limited by rock medium

The illustration of the deformed shapes of the dam on foundation soil confined by the rock medium are as shown in Figure 5 for all angles of incidence considered. The scale has been increased for purpose of illustration.



a)



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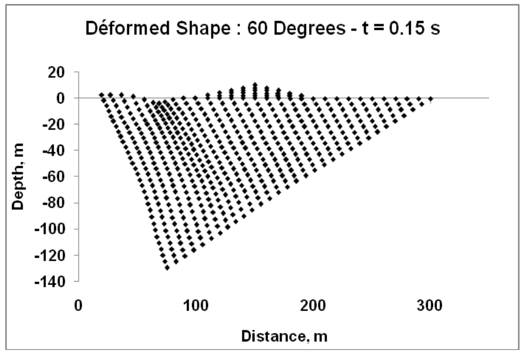

c)

Fig. 5 – Deformed shapes of dam on soil a) Angle at 30 degrees, b) Angle at 35.5 degrees, c) Angle at 60 degrees.

4. Conclusion

This study presented the effect of physical properties on the response in soil-structure interaction. The FEM was applied to model the response of a dam structure resting on a foundation soil. Three models were used, namely a flat free filed model without a structure, a model comprising an earth dam resting on a foundation soil medium extending beyond the limits of the near field, and a model of dearth am resting on a foundation soil limited by rock medium. The far field is represented by inclined radiating boundary conditions. The dynamic response of the dam-soil system is obtained by applying an inclined harmonic shear wave *SV* at different incidence angles. From these analyses, the effect of the wave propagation on the response is investigated. The conclusions derived from the parametric study are summarized as follows:

1. The measured response at the base of the dam is reduced compared to the free field response.
2. The response in soil-structure interaction is influenced by the angle of incidence. As the angle increases the response decreases.
3. The spatial variability of the ground acceleration across the dam base caused by the inclined incident *SV* wave leads to the delay of the maximum horizontal amplitude of acceleration and causes asynchronous motions along the base of the dam.
4. The presence of a rock medium limiting a near field influences the dynamic response in soil-structure interaction. If the near field is more flexible than the far field the waves are trapped inside the interior medium (near field) to cause amplification in the response.

5. References

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CHBDC CAN/CSA-S6-14, 2014, Canadian Highway Bridge Design Code, CSA Group.