AN IMPROVED NUMERICAL TIME-DOMAIN APPROACH FOR THE DYNAMIC DAM-FOUNDATION-RESERVOIR INTERACTION ANALYSIS BASED ON THE DAMPING SOLVENT EXTRACTION METHOD

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ABSTRACT :

Based on the damping solvent extraction method (DSEM), a new sub-regional explicit-implicit reciprocal solution method with integral strategy of mixed time step-size in time domain is proposed in this paper, to cope with the numerical analysis of dynamic soil-structure interaction. In the approach, an implicit integral arithmetic with big time step is applied in the computation of structure region, as explicit integral solution with small time step is used in the soil region. This method is convenient to combine the numerical advantages of big calculated time steps in implicit integration and wide applicability of explicit numerical integration. Furthermore, according to the similarity in the numerical expression between dynamic differential equations for structure and fluid mechanics, the above proposed solution methods on DSEM is extended to cope with the dynamic dam-reservoir interaction, in which the hydro dynamic pressure of unbounded water can be presented by explicit boundary interaction forces. Finally, some practical examples are presented to demonstrate that the evaluation efficiency can be efficiently improved in the condition of satisfying good engineering accuracy.

KEYWORDS: Dynamic structure-foundation interaction analysis, Time-domain numerical method, Infinite soil, Damping solvent extraction method

1. INTRODUCTION

Time-domain analysis of dynamic soil-structure interaction plays an increasing role in practical applications as compared with the frequency-domain analysis. Efficient and accurate modeling of the unbounded soil or rock medium has been a key issue in such an analysis. Among those time-domain numerical models of unbounded soil, on the basis of the Damping Solvent Extraction Method (DSEM)[1], a directly time-domain stepwise solution method to compute the interface dynamic force, can be feasibly deduced in the formwork of Finite Element Method, which can avoids the complicated convolution integrals as in other time-domain models, and brings great convenience for the interaction numerical analysis. However, facing the large-scale interaction analysis, some advanced numerical measures or procedures are still needed to be studied and investigated to improve the evaluation efficiency above the earlier proposed time-domain interaction analysis method based on DSEM[2,3], mainly due to the fact that the analysis of the finite soil region adjacent to the local structure interface will cause relatively larger calculation amount.

This paper presents some advanced numerical solution measures in time-domain, which mainly include the implemented formulation in the direct method analyzing the entire soil-structure system in a single step (DME), and a new sub-regional explicit-implicit reciprocal solution method with mixed time-step-size strategy (SRM). Particularly in the SRM, the deformational compatibility on the interface between structure and soil region can be naturally guaranteed, according to the same displacemental interpolation simulation in single time step for the explicit prediction-correction and implicit newmark-β integral arithmetic.

Furthermore, according to the similarity in expression between structural dynamic differential equation and the displacemental wave equation for fluid mechanics, the above proposed solution methods on DSEM can also be easily extended to cope with the dynamic dam-reservoir interaction, in which the hydro dynamic pressure of unbounded water can be expressed by explicit boundary interaction forces. Finally, some practical examples are presented to demonstrate that the proposed procedures are of good accuracy and feasibility.

Researches in this paper can give strong technique supports for the deeper investigation of the time-domain dynamic interaction analysis on DSEM, and also enlarge its application scope.

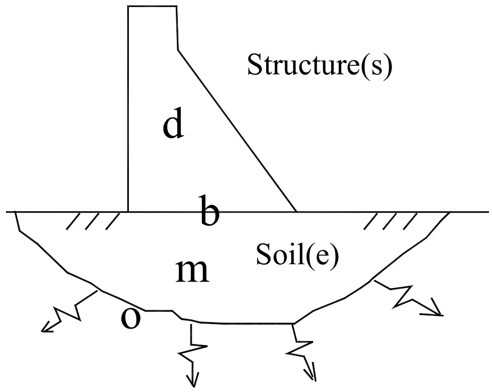


Figure1 Dynamic interaction system (g)

2. THEORETICAL COMPARISON AMAONG THE TIME-DOMAIN METHODS FOR DYNAMIC INTERACTION

As is well known, the substructure and direct method are the general two major analysis patterns for the dynamic soil-structure interaction problem (see Figure 1). On the other hand, distinguished by the seismic input models, there mainly are three different kinds of basic solution equations[4].

2.1 The Substructure Method

Under the conditions of force equilibrium and deformational compatibility at the interface nodes, the first kind of time-domain solution equations can be numerically induced in total motion as the following in the framework of the substructure method.

$$\begin{bmatrix} M_{dd}^s & M_{db}^s \\ M_{bd}^s & M_{bb}^s \end{bmatrix}\begin{Bmatrix} \ddot{u}_d^s \\ \ddot{u}_b^s \end{Bmatrix}+\begin{bmatrix} C_{dd}^s & C_{db}^s \\ C_{bd}^s & C_{bb}^s \end{bmatrix}\begin{Bmatrix} \dot{u}_d^s \\ \dot{u}_b^s \end{Bmatrix}+\begin{bmatrix} K_{dd}^s & K_{db}^s \\ K_{bd}^s & K_{bb}^s \end{bmatrix}\begin{Bmatrix} u_d^s \\ u_b^s \end{Bmatrix}=\begin{Bmatrix} 0 \\ -R^\infty(u_b^s-u_{bf}^e) \end{Bmatrix} \tag{1}$$

in which, the superscripts s and e denote the nodes on the generalized structure and the infinite soil, respectively. The subscripts b and d denote the nodes on the soil-structure interface and the nodes inside the generalized structure. $\{R^\infty(u_b^s-u_{bf}^e)\}$ means the interaction force of the undamped unbounded medium. u_{bf}^e denotes the input free-field motion at the interface. Under the dynamic load of relative deformation $u_b^s-u_{bf}^e$ on the soil-structure interface, Eq.(1) expresses that the structural nodal forces keep dynamic equivalence to the interaction force in the soil side.

2.2 The Direct Method

There mainly are two different kinds of basic moving equations in the framework of the direct method: the seismic load input at the outer boundary of soil (see Eq.(2)), and the structural inertia load (alternatively, structural quasi-static load, see Eq.(6)).

$$M_{II}\ddot{u}_I+C_{II}\dot{u}_I+K_{II}u_I=-C_{Io}\dot{u}_o^e-K_{Io}u_o^e \tag{2}$$

In which,

$$M_{II}=\begin{bmatrix} M_{dd}^s & M_{db}^s & 0 \\ M_{bd}^s & M_{bb}^s+M_{bb}^e & M_{bm}^e \\ 0 & M_{mb}^e & M_{mm}^e \end{bmatrix},\quad M_{Io}=\begin{bmatrix} 0 \\ 0 \\ M_{mo}^e \end{bmatrix},\quad u_I=\begin{Bmatrix} u_d^s \\ u_b \\ u_m^e \end{Bmatrix} \tag{3}$$

In the above equations of (2) and (3), the subscripts m and o denotes the nodes inside and located on the outer boundary of the bounded soil region. $\{u_o^e\}$ is the seismic input motion in free field. Eq.(2) is presented on the assumption that the structural deformation does few effects on the input free-field motion u_o^e at the outer boundary of soil region. If eliminating the quantities of the nodes m from Eq.(2), an alternative expression similar to Eq.(1) will be achieved.

In the next step, by defining the unknown quantities of u_b^s in Eq.(1) as the input free-field motion adding an unknown relative displacement,

$$u_b^s = u_{bf}^e + u_{bl} = u_{bf}^e + (u_b^s - u_{bf}^e) \tag{4}$$

Eq(1) results in

$$\begin{bmatrix} M_{dd}^s & M_{db}^s \\ M_{bd}^s & M_{bb}^s \end{bmatrix} \begin{Bmatrix} \ddot{u}_d^s \\ \ddot{u}_{bL} + \ddot{u}_{bf}^e \end{Bmatrix} + \begin{bmatrix} C_{dd}^s & C_{db}^s \\ C_{bd}^s & C_{bb}^s \end{bmatrix} \begin{Bmatrix} \dot{u}_d^s \\ \dot{u}_{bL} + \dot{u}_{bf}^e \end{Bmatrix} + \begin{bmatrix} K_{dd}^s & K_{db}^s \\ K_{bd}^s & K_{bb}^s \end{bmatrix} \begin{Bmatrix} u_d^s \\ u_{bL} + u_{bf}^e \end{Bmatrix} = \begin{Bmatrix} 0 \\ -R(u_{bL}) \end{Bmatrix} \tag{5}$$

Also, Eq.(5) could be readily rewritten into a greatly simplified expression as

$$\begin{bmatrix} M_{dd}^s & M_{db}^s \\ M_{bd}^s & M_{bb}^s + M_b^\infty \end{bmatrix} \begin{Bmatrix} \ddot{u}_d^s \\ \ddot{u}_{bL} \end{Bmatrix} + \begin{bmatrix} C_{dd}^s & C_{db}^s \\ C_{bd}^s & C_{bb}^s + C_b^\infty \end{bmatrix} \begin{Bmatrix} \dot{u}_d^s \\ \dot{u}_{bL} \end{Bmatrix} + \begin{bmatrix} K_{dd}^s & K_{db}^s \\ K_{bd}^s & K_{bb}^s + K_b^\infty \end{bmatrix} \begin{Bmatrix} u_d^s \\ u_{bL} \end{Bmatrix}$$
$$= -\begin{bmatrix} M_{db}^s \\ M_{bb}^s \end{bmatrix} \ddot{u}_{bf}^e - \begin{bmatrix} C_{db}^s \\ C_{bb}^s \end{bmatrix} \dot{u}_{bf}^e - \begin{bmatrix} K_{db}^s \\ K_{bb}^s \end{bmatrix} u_{bf}^e \tag{6}$$

Where $[M_b^\infty]$, $[C_b^\infty]$, $[K_b^\infty]$ denote the condensation mass, damping and stiffness matrices of the infinite soil, respectively. Obviously, according to the input free-filed motion of u_{bf}^e, the enforced external seismic loads, defined in the right side of Eq.(6), is given in the expression of the structural inertia loads.

3. SUB-REGIONAL STEPWISE IMPLEMENTATION IN TIME-DOMAIN FOR DSEM

To eliminate the absolute time variable t and the convolution integrals involved in the time-domain basic equations of DSEM, an assumption is made in Paper[5] for the nodal displacements inside of the bounded soil medium, $\{u_{rm}(t)\}$, such that

$$\{u_{rm}\} = t\{u_m\} - \{v_m\} \tag{7}$$

Accordingly, the time derivatives of $\{u_{rm}\}$ can be given as

$$\{\dot{u}_{rm}\} = t\{\dot{u}_m\} + \{u_m\} - \{\dot{v}_m\} \quad , \qquad \{\ddot{u}_{rm}\} = 2\{\dot{u}_m\} + t\{\ddot{u}_m\} - \{\ddot{v}_m\} \tag{8}$$

And thus yields the final expression of the interaction force in the infinite soil

$$\{R^\infty(t)\} = [\overline{M}_{bb}]\{\ddot{u}_b\} + ([\overline{C}_{bb}] - 2\zeta[\overline{M}_{bb}])\{\dot{u}_b\} + ([\overline{K}_{bb}] - \zeta[\overline{C}_{bb}])\{u_b\} + [\overline{K}_{bm}]\{u_m\} + \zeta[\overline{K}_{bm}]\{v_m\} \tag{9}$$

And

$$[\overline{M}_{mm}]\{\ddot{u}_m\} + [\overline{C}_{mm}]\{\dot{u}_m\} + [\overline{K}_{mm}]\{u_m\} = -[\overline{K}_{mb}]\{u_b\} - [\overline{C}_{mb}]\{\dot{u}_b\} \tag{10}$$

$$[\overline{M}_{mm}]\{\ddot{v}_m\} + [\overline{C}_{mm}]\{\dot{v}_m\} + [\overline{K}_{mm}]\{v_m\} = 2[\overline{M}_{mm}]\{\ddot{u}_m\} + [\overline{C}_{mm}]\{\dot{u}_m\} \tag{11}$$

Where $[\overline{M}] = [M]$, $[\overline{C}] = 2\zeta[M]$, $[\overline{K}] = [K] + \zeta^2[M]$ are the mass, damping and stiffness matrices, respectively, and $\{R\}$ is the load vector, ζ is the linear artificial nodal damping

Note the interaction force $\{R^\infty(t)\}$ in Eq.(9) can be conveniently computed by employing a step-by-step integration algorithm. Also, note that $\{u_m\}$ and $\{v_m\}$ can be computed based on the partition forms of Eqs.(10) and (11), while $\{u_b\}$ can be solved by combining Eq.(9) with the equation of motion of the generalized structure (See Eq.(1)). Introducing Eq.(9) into Eq.(1) will yields the following equation of motion for the whole generalized dynamic system.

$$\begin{bmatrix} M_{dd}^s & 0 \\ 0 & M_{bb}^* \end{bmatrix} \begin{Bmatrix} \ddot{u}_d^s \\ \ddot{u}_b^s \end{Bmatrix} + \begin{bmatrix} C_{dd}^s & C_{db}^s \\ C_{bd}^s & C_{bb}^* \end{bmatrix} \begin{Bmatrix} \dot{u}_d^s \\ \dot{u}_b^s \end{Bmatrix} + \begin{bmatrix} K_{dd}^s & K_{db}^s \\ K_{bd}^s & K_{bb}^* \end{bmatrix} \begin{Bmatrix} u_d^s \\ u_b^s \end{Bmatrix} = \begin{Bmatrix} 0 \\ [\overline{M}_{bb}]\ddot{u}_{bg}^e \end{Bmatrix}$$
$$+ \begin{Bmatrix} 0 \\ ([\overline{C}_{bb}] - 2\zeta[\overline{M}_{bb}])\{\dot{u}_{bf}^e\} \end{Bmatrix} + \begin{Bmatrix} 0 \\ ([\overline{K}_{bb}] - \zeta[\overline{C}_{bb}])\{u_{bf}^e\} \end{Bmatrix} + \begin{Bmatrix} 0 \\ [\overline{K}_{bm}]\{u_m\} + \zeta[\overline{K}_{bm}]\{v_m\} \end{Bmatrix} \tag{12}$$

where

$$[M_{bb}^*] = [M_{bb}^s] + [\overline{M}_{bb}] \quad , \quad [C_{bb}^*] = [C_{bb}^s] + ([\overline{C}_{bb}] - 2\zeta[\overline{M}_{bb}]) \, , [K_{bb}^*] = [K_{bb}^s] + ([\overline{K}_{bb}] - \zeta[\overline{C}_{bb}]) \tag{13}$$

Thus, responses of the total dynamic system can be solved step by step from Eq.(12) under the prescribed seismic excitations $\{u_{bf}^{e}\}$, $\{\dot{u}_{bf}^{e}\}$ and $\{\ddot{u}_{bf}^{e}\}$. It should be mentioned that in some cases only the earthquake ground acceleration $\{\ddot{u}_{bf}^{e}\}$ is available for the analysis while the displacement and velocity excitations have to be obtained by integrating the acceleration. The direct integration of acceleration may cause unrealistic drifts in displacement and velocity [6]. To solve this problem, Paper [7] suggests a least-square curve fitting technique, which can be used to directly process the acceleration time series to derive reasonable displacement and velocity excitations. More simply, a seismic input model for DSEM is suggest by Chen[8] in the patterns of masss-proportional loads, in which only the seismic acceleration history is needed.

4. ADVANCED SUBREGIONAL EXPLICIT-IMPLICIT RECIPROCAL SOLUTION PROCEDURE WITH MIXED TIME STEP-SIZE STRATEGY

As is well known, to solve the common structural dynamic equations, implicit numerical integral algorithms (such as Newmark-β, Willson-θ numerical integration) and explicit numerical integral algorithms (such as prediction-correction explicit integration method) are the two usual basic approaches.

Implicit integration has such advantages as better numerical integral stability for the usual dynamic analysis, bigger integral time step (such as 0.02s) for the large-scale dynamic problem. However, application practices also show that the solution accuracy of the implicit integral algorithm is accidentally low for the special dynamic problem of infinite region. On the other hand, explicit integral algorithm avoids the computation of the inverse stiffness, which results in a smaller calculation amount in one time step. However, its integral time step (such as 0.0005s) must be small enough to meet the requirements of integration stability.

Therefore, A new coupling sub-regional explicit-implicit reciprocal solution method is presented in this paper to reconcile their respective merit, which involves a explicit solution algorithm in the soil side, and a implicit solution algorithm in the structural side. To further reduce the structural extra computation amount leading by the implicit integration with a same small time step to the soil side, different integral time-steps (SRM) are suggested to be separately adopted in each sub-region of structure and soil.

And thus, the procedure of solving the Eqs.(12), (10) and (11) can be divided into the following three main steps.

Firstly, $delt$ is defined as the bigger integral time step in the structural side, which is m times as the smaller one dt in the soil side. Obviously, applying the prediction-correction explicit integration method in the Eqs.(10) and (11) , will results in

$$u_m^{t+dt} = A_1(u_m^t) - B_1 M_{mm}^{-1}(K_{mb}u_b^{t+dt} + C_{mb}\dot{u}_b^{t+dt}) \tag{14}$$

$$v_m^{t+dt} = A_2(v_m^t) + 2B_2(\dot{u}_m^{t+dt} + M_{mm}^{-1}C_{mm}u_m^{t+dt}) + B_2 M_{mm}^{-1}C_{mb}u_b^{t+dt}) \tag{15}$$

Where, $A_1(u_m^t)$, $A_2(v_m^t)$ and B_1, B_2, are explicitly numerical matrix function of the previous integral time step.

Secondly, in one integral time step form t to $t+delt$, the nodal deformations on the soil-structure interface are assumed to satisfy the following interpolation relations,

$$u_b^{t+i\cdot dt} = u_b^t + (u_b^{t+delt} - u_b^t)\cdot i/m \quad , \quad \dot{u}_b^{t+i\cdot dt} = \dot{u}_b^t + (\dot{u}_b^{t+delt} - \dot{u}_b^t)\cdot i/m \tag{16}$$

Thirdly, by introducing the Eqs of (15) and (16) into the solution to the dynamic equation of (12), the structural dynamic response can be easily implicitly solved with the bigger integral time step $delt$.

Certainly, according to the same displacemental interpolation simulation in a single time step for the explicit prediction-correction in the soil side and implicit newmark-β integral arithmetic adopted in the structure side, the deformational compatibility on the soil-structure interface can be naturally guaranteed [9].

5. TIME-DOMAIN NUMERICAL ANALYSIS ON DSEM FOR THE DYNAMIC DAM-RESERVOIR INTERACTION

Compared with the basic dynamic differential equations of the elastic body as follows

$$\ddot{u}_i = \frac{3K_s}{2\rho_s(1+\mu)} u_{k,ki} + Gu_{i,kk} \tag{17}$$

in which, u_i is the nodal displacement components. K_s, G, μ and ρ_s denote the Bulk modulus, Shear modulus, Poisson ratio, and Density of the elastic material, respectively.

The basic dynamic differential equations for the fluid mechanics can be presented in the patterns of nodal displacement as

$$\ddot{u}_i = c^2 u_{k,ki} \tag{18}$$

Where, $c = \sqrt{K/\rho}$ is the wave velocity in the liquid field. K and ρ denote the Bulk modulus and Density of liquid.

Obviously, the above two equations are very similar in the expression forms, according to the coefficient matrix of c^2 in Eq.(18) and the one of $3K_s/2\rho_s/(1+\mu)$ in Eq.(17). Therefore, it can be easily assumed that the solution method to Eq.(17) is also suit for the solution to the dynamic responses of infinite liquid field (See Eq.(18)). In other words, the proposed DSEM can possibly analyze the dynamic interaction between infinite reservoir and dam.

To verify this assumption, the computation of dynamic hydraulic pressure, a key problem in the dynamic dam-reservoir interaction, is take as a study aim. Same to the proposed DSE time-domain method in the above section 3, the following notes are firstly defined,

$$[\overline{M}^L] = [M^L],\ [\overline{C}^L] = 2\zeta[M^L],\ [\overline{K}^L] = [K^L] + \zeta^2[M^L] \tag{19}$$

In which, $[K^L]$、 $[M^L]$、$[C^L]$ denote the stiffness, mass and damping matrices in water field, respectively. ζ is the artificially introduced nodal damping in water. The topscript of L means the reservoir.

Thus, Similar to the Eq.(9), the dynamic hydraulic pressure $\{R_L\}$ of reservoir water can be given as

$$\{R_L\} = [\overline{K}_{bL}](u_L + \zeta v_L) \tag{20}$$

Where, the subscripts of b and L denote the inside and interface nodes in reservoir. Excited by the deformation of $\{u_b\}$ predefined at the dam-reservoir interface nodes, $\{u_L\}$ and $\{v_L\}$ can be solved on the basis of the Eqs. of (21) and (22).

$$[\overline{M}_{LL}]\{\ddot{u}_L\} + [\overline{C}_{LL}]\{\dot{u}_L\} + [\overline{K}_{LL}]\{u_L\} = -[\overline{K}_{Lb}]\{u_b\} \tag{21}$$

$$[\overline{M}_{LL}]\{\ddot{v}_L\} + [\overline{C}_{LL}]\{\dot{v}_L\} + [\overline{K}_{LL}]\{v_L\} = 2[\overline{M}_{LL}]\{\dot{u}_L\} + [\overline{C}_{LL}]\{u_L\} \tag{22}$$

During the practical computation, it should be mentioned that,

(a) If utilizing the relations of Eq.(17) to solve the Eq.(18) in water field, the Shear modulus G of water should be zero, which reflects that water can not bear the shear stress. However, in the practical evaluation, G can be assumed as a very small positive number, to avoid the numerical oddity of stiffness matrix of water. Herein, such parameters are used as the Bulk modulus of K=2.067e^9 for water, and the Shear modulus G=K*10^{-9}, Poisson ratio μ=0.5.

(b) If presented in the forms of nodal displacement, the computation procedures of mass and stiffness matrix in liquid field are same to the structure analysis. Since the damping matrix mainly reflects the effects of medium viscous, the seismic analysis of liquid field can be relatively conservative by ignoring the viscous properties of water.

(c) To deal with the dynamic dam-reservoir interaction analysis, the described computation method of dynamic hydraulic pressures can be combined with the structural dynamic equation of dam, similar to the Eq.(12).

6. NUMERCIAL EXAMPLES

In this section, accuracy and efficiency of the proposed schemes are evaluated using several examples.

6.1 Dynamic Interaction Analysis of Dam and Soil Region

Figure 2 shows a concrete gravity dam supported by unbounded medium. The dam has a height of 103m, a crest width of 13.8m and a base width of 70.1m. The material properties of the concrete dam are given as follows: Young's modulus $E = 30GPa$, Poisson's ratio $\mu = 0.20$, Density $\rho = 2500kg/m^3$, while the ones of the unbounded medium are as the following: $E = 15GPa$, $\mu = 0.20$, and $\rho = 2500kg/m^3$. The transient displacement excitation as prescribed by Eqn.(23) is assumed to act on the soil-structure interface.

$$u_b(t) = \begin{cases} u_0(1-\cos(2\pi t/T)) & t \le 3.5T \\ 0 & t > 3.5T \end{cases} \qquad (23)$$

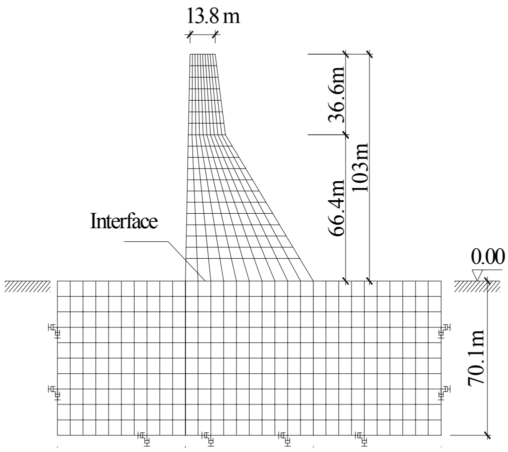
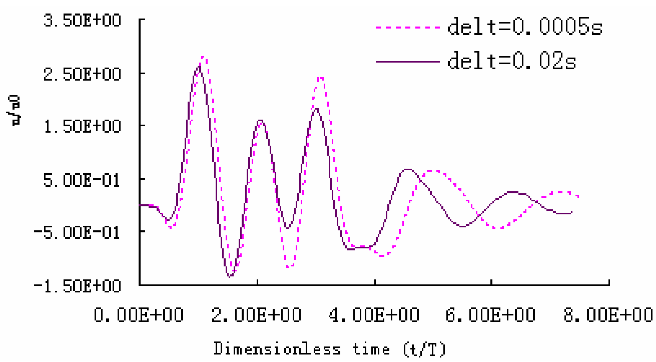
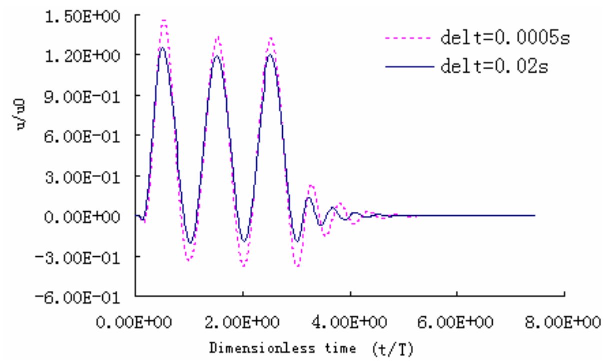


Figure2 Dynamic dam-soil interaction

Where, the amplitude u_0 is assumed to be 0.1m. Two different excitation periods, i.e, T=0.2s and 0.8s are investigated to show the various effects on the dynamic responses of dam for the relatively low-frequency and high-frequency components in seismic wave. During numerical computation in this subsection, a constant explicit integral time step is used as $dt = 0.0005s$ in the soil region, while various implicit integral time steps of $delt = 0.0005s$ and $delt = 0.02s$ are compared in the structure region. That means, the proposed SRM-DSE method will be utilized when $delt = 0.02s = 40dt$.



(a) excitation period of T=0.2s



(b) excitation period of T=0.8s

Figure3 Displacemental responses at the dam crest

Figure 3 presents the computed displacement response at dam crest for the two cases of excitation period. One may note that, during the forced vibration stage for both excitation periods of T=0.2s and 0.8s, compared with the basic case of $delt = 0.0005s$ (as a same time-step used for implicit and explicit integration), no obvious changes appear in the phase at the SRM case of $delt = 0.02s$, but only peak responses at the dam crest decrease for about 10%. In other words, the adoption of SRM method has a similar effect on the dynamic responses of dam as a certain of the computational damping increase. In views of practical applications, such a computational accuracy is yet permitted, which approves that the application of SRM method indeed yields a great decrease in computational amount without unreasonable loss in accuracy.

6.2 Numerical Computation of Dynamic Hydraulic Pressure

Figure 4 shows a grid gravity dam with a vertical upstream face. The dam has a height of 130m, with a water level of H0=100m in front of the dam. The material properties of the reservoir water are given as follows: Bulk modulus $K = 2.067GPa$, Poisson's ratio $\mu = 0.20$, and Density $\rho = 1000kg/m^3$. In order to investigate the dynamic effects of the reservoir water, a transient acceleration excitation acting on the dam-reservoir interface in the horizontal direction, as prescribed by Eqn.(24), is assumed to compute the dynamic hydraulic pressure.

$$a_b(t) = \begin{cases} a_0(1-\cos(2\pi t/T)) & t \le 8T \\ 0 & t > 8T \end{cases} \tag{24}$$

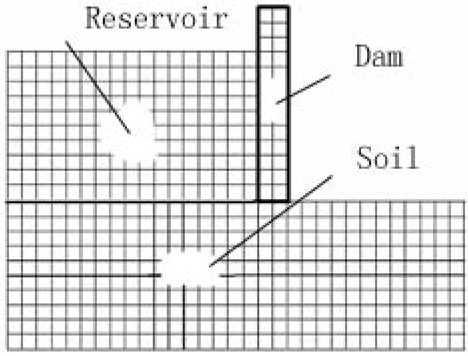


Figure4 Dynamic dam-reservoir interaction

Where, the amplitude a_0 is assumed to be 0.1m/s^2, and the excitation period T=0.6s. The computation procedure for dynamic hydraulic pressure in Eqn.(20) is similar to the dynamic interaction force in unbounded soil region in the Eqn.(9).

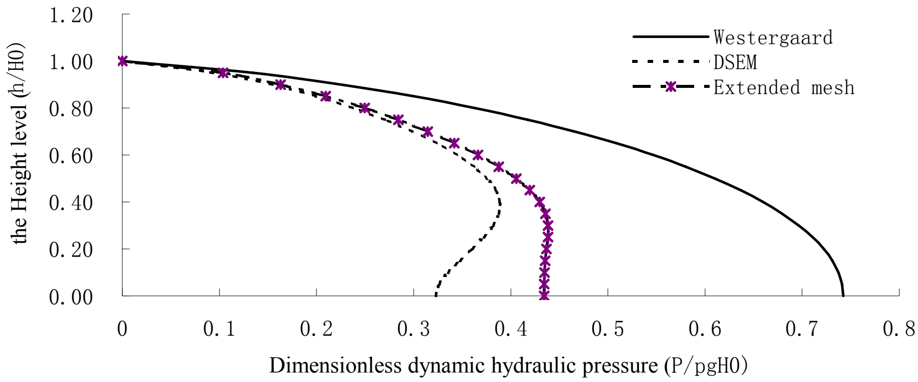
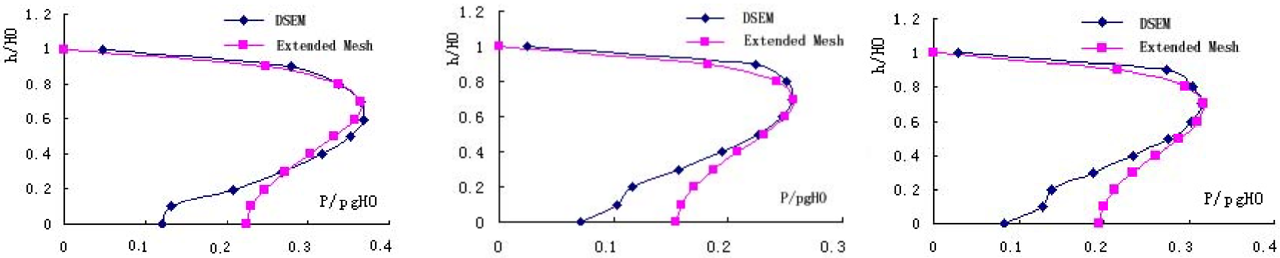


Figure5 Amplitude distribution of dynamic hydraulic pressure



(a) t=1.5s (b) t=3.3s (c) t=4.5s

Figure6 distribution of dynamic hydraulic pressure at various time step

Compared with the results by using the extended mesh model, and the Westergaard model, Fig.5 presents the amplitude distribution of dynamic hydraulic pressure along the height level. It is obvious that, by using the proposed DSE method in this paper, the computational results are identical to the accurate results of the extended mesh model at the middle and upper parts of dam, while the results of Westergaard model give an great exaggeration. Furthermore, Fig.6 presents the comparison of the computated dynamic hydraulic pressure at various time steps, giving a similar change trend as shown in the Fig.5.

It should be mentioned that, the introduced artificial nodal damping can not distinguish the effects along various coordinate axes (such as X and Y in this numerical example). In other words, the computed dynamic hydraulic pressure in the horizontal direction possibly be unreasonably affected by the introduced artificial nodal damping in the vertical direction. That is also the main reason for the evident difference of the results of the proposed DSE method existing at the bottom part of the dam, as compared to the extended mesh model. To overcome this problem, an advanced DSE method, with different artificial damping introduced in various coordinate axes, is offered to cope with the computation of dynamic hydraulic pressure only in the horizontal X direction. However, it is positively recognized that, gross of the dynamic hydraulic pressure can still be exactly determined, even only by using the proposed cursory DSE model in this paper for the liquid mechanics.

7. CONCLUSIONS

A sub-regional stepwise DSE method with an integration strategy of mixed time step-size is firstly described in this paper to deal with the time-domain analysis for the dynamic soil-structure interaction problems. A detailed evaluation of the performance of the formulation has been carried out for a concrete gravity dam located on a half-space and subjected to a harmonic excitation. And then, the DSE method is extended to compute the dynamic hydraulic pressure. In views of practical accuracy, the comparison of the various responses of the results with those obtained using other models indicates that the proposed methods are feasible and efficient for solving practical dynamic interaction problems.

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