An Efficiency Substructure Method for Nonlinear SSI Analysis of Large-scale Concrete Structures in Time Domain on the ANSYS Platform

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SUMMARY:
To take the structural nonlinear mechanical properties into consideration, time-domain analysis of dynamic Soil-Structure Interaction (SSI) based on the substructure method maybe more suitable for practical applications in engineering, such as high concrete dam, nuclear power plant. However, for dynamic analysis of the large-scale engineering structures, personal programming shows insufficient in many effects, such as the algorithmic efficiency, evaluation precision and engineering practicability. To overcome these difficulties, this paper presents an efficiency substructure method for the dynamic SSI analysis of large engineering structures on the ANSYS platform, in which the dynamic properties of the unbounded soil are simulated by the numerical implementation of the damping solvent extraction method (DSEM) on the basis of UPFs. The one-dimensional analytical expression on the effects of artificial damping in DSEM is put forward to determine the main parameters in analysis. The complex iterative analysis flow chart is also described in detail to consider the structural nonlinear properties. Certainly in this analysis procedure, the rich nonlinear element library and the powerful numerical solvers in ANSYS can be utilized directly. In the framework of finite element method, DSEM can avoid convolution integrals as in other common time-domain analysis of SSI. in DSEM, no singular integrals need be evaluated, and a better stability can be achieved. Taking the improved ANSYS as the analysis tools, the nonlinear dynamic response analysis of high concrete dam under the earthquake excitation is presented in final. The results show that the present method has good validity in simulation engineering.

Keywords: SSI, substructure method, damping solvent extraction method, ANSYS

1. INTRODUCTION

To some extent, high dams maybe present obvious nonlinear behaviour under the excitation of strong earthquake, therefore full time-domain modelling of the dynamic interaction among dam, reservoir and rock foundation has been of long-standing interest in engineering academic area. More efficiency and more accuracy of the time-domain numerical model of the infinite foundation has also become the main ultimate goal.

Numerical simulation of the radiation condition and evaluation of the interaction force on the interface between structure and soil are the two key issues in the dynamic interaction analysis. Among the recently numerous time-domain numerical models for infinite foundation, the Damping Solvent Extraction Method (DSEM, Wolf JP, Song C. (1996)) can be wholly implemented in the framework of traditional FEM, which is useful to establish the uniform analysis model for multi-physics coupling problems, and maybe leads to a good prospect in engineering application of DSEM. To consider the effects of radiation condition of infinite soil region, DSEM takes the similarity of the artificial material damping and the radiation damping in vibration reduction as the starting point, in which high artificial material damping is firstly introduced in the soil finite region adjacent to the soil-structure interface, and then the frequency shifting technique is utilized to extract the influence of artificial damping on the dynamic stiffness of soil region. The significant convolution operations as in other time-domain dynamic models of infinite soil are fully avoided in DSEM, and the numerical accuracy of DSEM is not affected by the type and direction of the incident earthquake excitation wave.

To obtain better application effect, the computation size of soil region and the artificial material damping take important roles in the implementation of DSEM, and have a certain degree of uncertainty (Basu U, Chopra AK. (2002)). On the one hand, artificial damping and the size of the computation soil region should be defined as big as possible to reduce the influence of reflection wave on the outer boundary of soil region; on the other hand, they should be chosen as small as possible to meet the requirement of Taylor expansion operation and to control the calculation amount. Thus, the selection of optimization parameters is a key factor. In addition, based on the substructure method of DSEM, the calculation of interaction force on the interface need twice dynamic analysis of soil region, which is difficult to numerically realize for the global analysis of structure and soil on the general finite element software platform.

To solve the above problems, Numerical implementation of DSEM on ANSYS is detailed described in this paper, in which UPFs feature of ANSYS is taken as the main tools (ANSYS Incorporated, (2007)). This paper is organized as follows. Firstly, an interface-coupling element with four nodes and twelve degrees of freedom is derived and introduced into ANSYS to simulate the influence of soil region on the structural stiffness. Secondly, the dynamic interaction force on the interface is advised to solve by FORTRAN plug-in program with the acceleration implicit algorithm. This is followed by a complete description of the implementation algorithm of DSEM in the universal finite element software of ANSYS, in which the rich element models and strong nonlinear solving ability in ANSYS can be used to simulate the structural dynamic behaviours. Finally, the performance of the proposed ANSYS model is assessed in detail and a three-dimensional large-scale dynamic dam-foundation interaction problem is analyzed.

2. FUNDAMENTAL EQUATIONS OF DSEM BASED WITH THE ACCELERATION IMPLICIT SOLUTION ALGORITHM

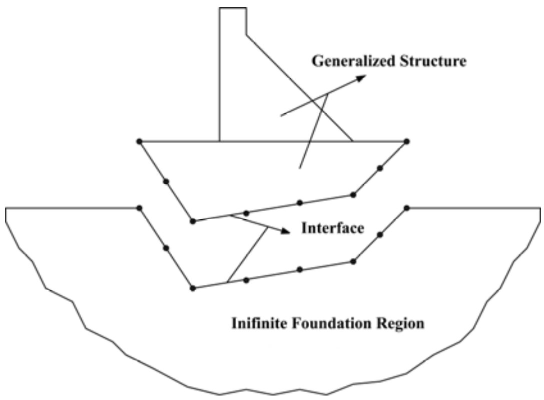


Figure 2.1 Modelling of soil-structure interaction system based on DSEM

The sub-structure solution pattern is usually used to implement the DSEM dynamic interaction analysis, in which the interaction force on the interface is firstly solved in soil region, and then the interaction force will be loaded on the structure region as a reaction force. For the interaction system only subjected to earthquake excitation shown in Figure 2.1, the equation of motion of structure in the time domain is expressed in the partitioned form as follows:

$$\begin{bmatrix} M_{ss}^s & 0 \\ 0 & M_{bb}^s \end{bmatrix} \begin{Bmatrix} \ddot{u}_s^t \\ \ddot{u}_b^t \end{Bmatrix} + \begin{bmatrix} C_{ss}^s & C_{sb}^s \\ C_{bs}^s & C_{bb}^s \end{bmatrix} \begin{Bmatrix} \dot{u}_s^t \\ \dot{u}_b^t \end{Bmatrix} + \begin{bmatrix} K_{ss}^s & K_{sb}^s \\ K_{bs}^s & K_{bb}^s \end{bmatrix} \begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ -R_b(\ddot{u}_b^t - \ddot{u}_b^f) \end{Bmatrix} \tag{2.1}$$

Where the superscript s refers to the structure; the subscripts b and s denote the nodes on the structure-foundation interface and the remaining nodes of the structure, respectively. The $\{u^t\}$ is the displacement vector in total motion; according to the secondary wave scattering motion $\{u_b\}=\{u_b^t - u_b^f\}$ on the interface of soil region, $\{R_b(u_b)\}$ is the interaction force vector between the structure and the unbounded foundation. Under the seismic excitation of $\{u_b^f\}$ on the interface nodes, the motion vector of $\{u_s^t \quad u_b^t\}^T$ is unknown in Eqn.(1). The key step to solve Eqn. 2.1 is how to numerically evaluate the interaction force $\{R_b(u_b)\}$.

On the basis of DSEM, the interaction force $\{R_b(u_b)\}$ can be determined by the twice dynamic calculation of the foundation, to avoid the complicated convolution operation. It is worth noting that the foundation region contains the artificial damping used to eliminate the reflected wave on the outer boundary of foundation.

If ζ is the nodal artificial damping coefficient, the mass matrix, damping matrix and stiffness matrix of the high artificial damping foundation region can be equivalently defined as follows,

$$[\hat{M}]=[M]^f \qquad [\hat{C}]=[C]^f+2\zeta[M]^f \qquad [\hat{K}]=[K]^f+\zeta^2[M]^f \tag{2.2}$$

Based on the formulation derivation of DSEM, the dynamic interaction force of $R_b(u_b)$ can be finally expressed as

$$\{R_b(u_b)\}=[\hat{M}]_{bb}\{\ddot{u}_b\}+([\hat{C}]_{bb}-2\zeta[\hat{M}]_{bb})\{\dot{u}_b\}+([\hat{K}]_{bb}-\zeta[\hat{C}]_{bb})\{u_b\}+[\hat{K}]_{bm}\{u_m\}+\zeta[\hat{K}]_{bm}\{v_m\} \tag{2.3}$$

Where the subscript m denotes the inside nodes of the bounded soil region. Corresponding to the excitation motion of $\{u_b\}$ on the interface, $\{u_m\}$ and $\{v_m\}$ are the basic and additional nodal displacements inside the bounded medium, respectively, which can be directly solved by the following equations.

$$[\hat{M}]_{mm}\{\ddot{u}_m\}+[\hat{C}]_{mm}\{\dot{u}_m\}+[\hat{K}]_{mm}\{u_m\}=-[\hat{K}]_{mb}\{u_b\}-[\hat{C}]_{mb}\{\dot{u}_b\} \tag{2.4a}$$

$$[\hat{M}]_{mm}\{\ddot{v}_m\}+[\hat{C}]_{mm}\{\dot{v}_m\}+[\hat{K}]_{mm}\{v_m\}=2[\hat{M}]_{mm}\{\dot{u}_m\}+[\hat{C}]_{mm}\{u_m\}+[\hat{C}]_{mb}\{u_b\} \tag{2.4b}$$

Engineers are used to taking the seismic acceleration records as the input motion for structural dynamic equations, and also the direct integration of acceleration may cause unrealistic drifts in displacement and velocity (Yang J., Li J.B., Lin G. (2006)). Use of the drifted displacement and velocity as input motions may have significant effect on the soil-structure interaction analysis, especially for the solution of Eqns. 2.4a and 2.4b. Therefore through the trial calculations, if the acceleration implicit solution algorithm is applied to solve the Eqns. 2.4a and 2.4b, relatively better solution stability can be obtained, and the integration time step can also be enlarged to 0.01s or 0.02s, which is more favorable in engineering application than the displacement direct solution mode with small integration time step. Thus, the structure and soil regions can utilize the integration schedules with same time step to improve the solution stability and efficiency of calculation, and during each time step does the Newmark-β integral assumption be also satisfied.

Substituting the Eqn. 2.3 into Eqn. 2.1 leads to the final solving formula of the whole dynamic interaction system, as the following

$$\begin{bmatrix} M_{ss}^s & 0 \\ 0 & M_{bb}^s+M^* \end{bmatrix}\begin{Bmatrix} \ddot{u}_s^t \\ \ddot{u}_b^t \end{Bmatrix}+\begin{bmatrix} C_{ss}^s & C_{sb}^s \\ C_{bs}^s & C_{bb}^s+C^* \end{bmatrix}\begin{Bmatrix} \dot{u}_s^t \\ \dot{u}_b^t \end{Bmatrix}+\begin{bmatrix} K_{ss}^s & K_{sb}^s \\ K_{bs}^s & K_{bb}^s+K^* \end{bmatrix}\begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix}=$$

$$\begin{Bmatrix} 0 \\ [M^*]\ddot{u}_b^f+[C^*]\dot{u}_b^f+[K^*]u_b^f \end{Bmatrix}-\begin{Bmatrix} 0 \\ [\hat{K}_{bm}](u_m+\zeta v_m) \end{Bmatrix} \tag{2.5a}$$

where,

$$[M^*] = [\hat{M}]_{bb} \qquad [C^*] = [\hat{C}]_{bb} - 2\zeta[\hat{M}]_{bb} \qquad [K^*] = [\hat{K}]_{bb} - \zeta[\hat{C}]_{bb} \tag{2.5b}$$

The detail numerical solution schedule for the Eqn. 2.5 can be founded in the reference literatures (Li J.B., Yang J., Lin G. (2008), Zhong H, Lin G, Li J.B, Chen J.Y. (2008)). Through the above descriptions, in order to implement DSEM on the ANSYS platform, key steps can be summarized as: a) Taking the substructure method as the basic solution procedure; b) Computing the added stiffness and damping matrix in soil region due to the nodal artificial damping; c) Twice dynamic analysis in soil region to calculate the interaction force on the interface.

3. USER-DEFINED 3D INTERFACE-COUPLING ELEMENT IN ANSYS AND ITS APPLICATION IN DSEM

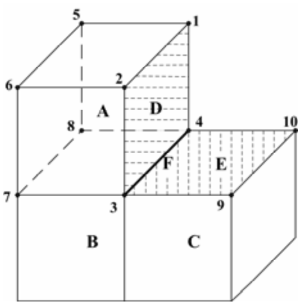


Figure 3.1 Establish sketch of three-dimensional coupling element

As shown in Eqn. 2.5a and Figure 3.1, a special kind of 3D coupling element on the interface should be defined to reflect the added matrix contributions ($[M^*]$, $[C^*]$, and $[K^*]$) of the high artificial damping soil region on the structural interface nodes. On the platform of ANSYS, such user-defined 3D interface-coupling element is to some extent inheritance and extraction of the traditional iso-parametric element, which is similar to the space plane element with three translational degrees of freedom at each node.

Firstly, geometrical topology analysis is performed only at one layer of soil elements adjacent to the structure to distinguish the interface nodes and the soil internal nodes. And then, based on the traditional FEM, the entity matrix of the layer of soil elements without artificial damping is expressed in the form of partition matrices as

$$\begin{bmatrix} K^e_{bb} & K^e_{bm} \\ K^e_{mb} & K^e_{mm} \end{bmatrix} \qquad \begin{bmatrix} C^e_{bb} & C^e_{bm} \\ C^e_{mb} & C^e_{mm} \end{bmatrix} \qquad \begin{bmatrix} M^e_{bb} & 0 \\ 0 & M^e_{mm} \end{bmatrix} \tag{3.1}$$

Taking the stiffness matrix $[K^e]_{bb}$ for example, the aimed stiffness $[K^e]^*_{bb}$ of the interface-coupling element can be obtained by introducing the influence of artificial damping, as the following

$$[K^e]^*_{bb} = [K^e]_{bb} + \zeta^2[M^e]_{bb} - \zeta([C^e]_{bb} + 2\zeta[M^e]_{bb}) = [K^e]_{bb} - \zeta^2[M^e]_{bb} - \zeta[C^e]_{bb} \tag{3.2}$$

The corresponding damping matrix and mass matrix of the interface-coupling element are

$$[C^e]^*_{bb} = [C^e]_{bb} + 2\zeta[M^e]_{bb} \qquad [M^e]^*_{bb} = [M^e]_{bb} \tag{3.3}$$

It is obvious that, the interface-coupling element matrix is only related to the soil elemental layer adjacent to the structure. The evaluation of such elemental matrices can be easily implemented on the basis of UserElem.f in ANSYS UPFs, in which no additional degrees of freedom is needed, and the number of elemental nodes can feasibly vary to better capture the location characteristics of the interface nodes. Furthermore, according to the Eqn. 2.4, a separate Fortran subroutine named Interload() is programmed to realize the dynamic analysis of the artificial damping soil region, And then, custom user function of User01.f in ANSYS UPFs is used to call the subroutine of Interload() to calculation the interface force in soil region.

As the remote infinite soil region is generally assumed as linear elastic, so many numerical discrete matrices during the solution to Eqn. 2.4 only need to be formed once, which improve the computational efficiency.

4. NUMERICAL IMPLEMENTAION OF DSEM DYNAMIC INTERACTION ANALYSIS ON THE PLATFORM OF ANSYS

The basic process is still the traditional dynamic analysis of structure, which can feasibly consider the non-linear properties of structure. The nonlinear mechanical characteristics of the near-site soil region can also be taken into consider by defining a generalized structure.

As described above, the key links to implement DSEM are the subroutine programming of the interface-coupling element and the solution to interaction force. Certainly, it is also significant that these subroutines are correctly connected with the standard ANSYS program, in which the interface-coupling element can be cited in APDL by the UserElem type, and the custom function of User02 can also be directly cited in APDL to solve the interaction force.

The detailed flowchart of the numerical implementation of DSEM dynamic interaction analysis on the ANSYS platform is as follows.

Step 1. Through topology analyzing the ANSYS model, gets the finite element meshing datas of strcuture and soil region, respectively.

Step 2. Build the 3d interface-coupling element to add the effects of soil region on the structure side.

Step 3. Code the Fortran subroutine of Interload() to calculate the interaction force, and coding the UPFs function User01.f to build the calling APDL command.

Step 4. As required in the UPFs, rebuild ANSYS in a new customer version.

Step 5. stepwise dynamic interaction analysis basing on the substructure method

a) Activate the APDL command of User01 to call the subroutine of Interload() to complete the twice dynamic analysis of soil region and to calculate the interaction force, which is corresponding to the seismic excitation at the current time;

b) By taking the interaction force as the extern structural load, dynamic analyze the structural response.

c) Update the interface motion $\{u_b\}$

d) Go to the sub-step of a) to calculate the interaction force at next time step, in which the motion of soil region is automatic updated.

Step 6. End program and exit.

5. NUMERICAL EXMPLES AND VALIADATION

Some engineering practices are used in this section to evaluate the validity and accuracy of the above model.

5.1. Solution of the interaction force and selection of the nodal artificial damping coefficient

A 1/4 square prism foundation embedded in a homogeneous half-space, is taken as an example to study the effects on the interaction forces for the nodal artificial damping coefficient and the size of the soil computation region.

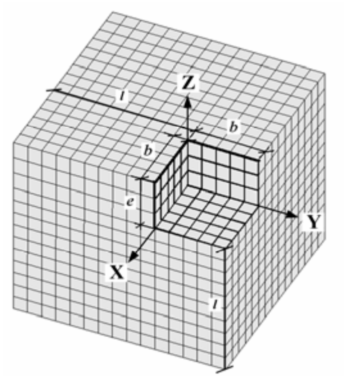
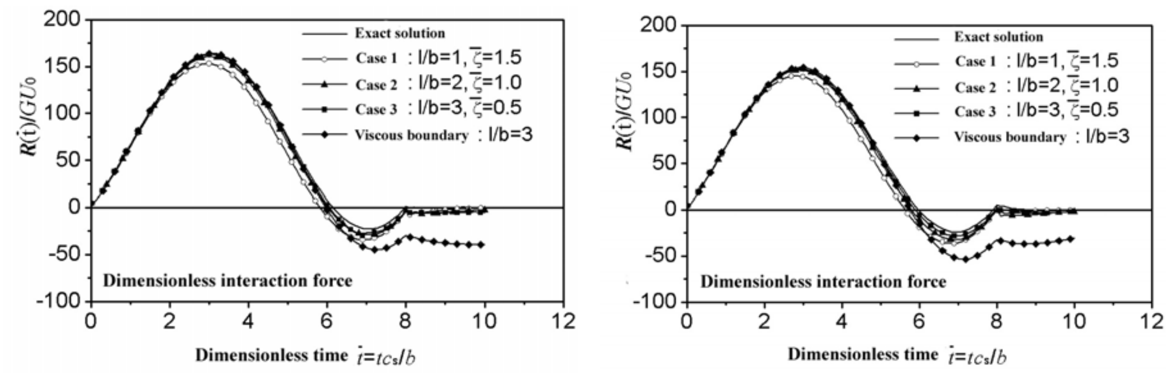


Figure 5.1 Finite-element modeling of a 1/4 square prism foundation

Referring to Figure 5.1, the soil interface is defined at the boundary of strip foundation, with the depth of $e = 2b/3$, where b is the characteristic length. The soil computation region is meshed by 3D 8-node solid element. The dimensionless artificial nodal damping is expressed as $\bar{\zeta} = \zeta b / C_s$. Harmonic displacement time-history at the centre of the rigid base is taken as the transient excitation in the horizontal and vertical direction respectively, with the period of $T = 8b / C_s$.



(a) Horizontal direction (b) Vertical direction

Figure 5.2 Computed time history of interaction force at the interface of unbounded foundation region

The computed time histories of the interaction force are shown in Figure 5.2 for three cases of artificial damping. The accuracy of the presented model is obvious higher than the traditional viscoelastic boundary model. Variation of the artificial damping has some effects on the results. Through many tri calculations, advising parameters of the artificial nodal damping are shown in Table 5.1.

Table 5.1 Advising Values For The Artificial Nodal Damping

Computed soil region *l*/*b*		1	2	3
Dimensionless artificial nodal damping coefficient $\bar{\zeta}$	Advising variation range	1.2~1.8	0.8~1.2	0.2~0.8
	Advising value	1.5	1.0	0.5

5.2. Dynamic interaction analysis of arch dam

In this example, the dynamic interaction of Dagangshan arch dam in the southwest of China under the strong earthquake is analyzed by using the DSEM on the ANSYS platform, in which the nonlinear behavior of dam body is simulated by ANSYS own element model, such as the solid element of Solid65 and the contact element of Contac52. The dam has a height of 210 m, a base width of 52 m, a crest length of 557 m, and a water level of 205 m in front of dam. There are about 108443 finite elements and 113113 nodes in the whole interaction system. Seismic excitation is taken into account in three directions, with the amplitude of 0.5575g in the horizontal direction, 0.3717g in the vertical direction.

The martial parameters of the dam concrete are as follows: elastic modulus $E = 2.4e10Pa$, Poisson's ratio $v = 0.17$, density $\rho = 2400kg/m^3$; the corresponding parameters of the rock foundation are $1.45e10Pa$, 0.25 and $2650kg/m^3$. The dimensionless artificial damping coefficient used in the soil region is $\bar{\zeta} = 1.5$.

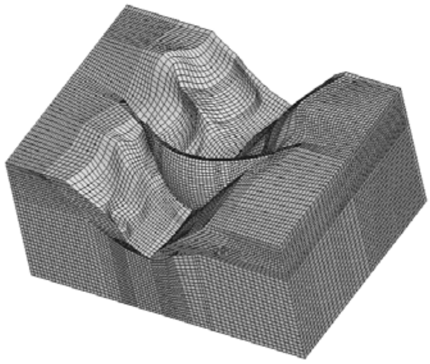
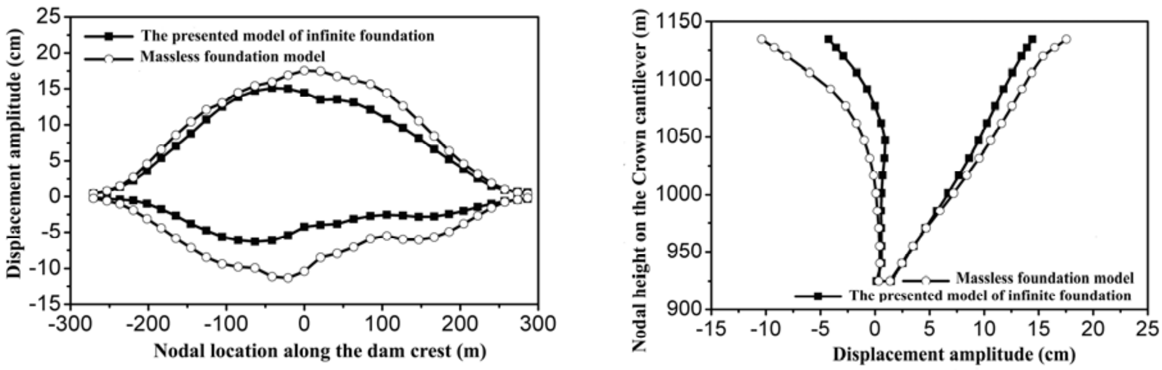


Figure 5.3 Finite element model of the dam-foundation dynamic system of Dagangshan Arch Dam

Two model cases of the arch dam with and without transverse joints are studies respectively. The dynamic responses of the dam without the transverse joints are shown in Figure 5.4 and Figure 5.5, in which the results are compared to the massless foundation model.

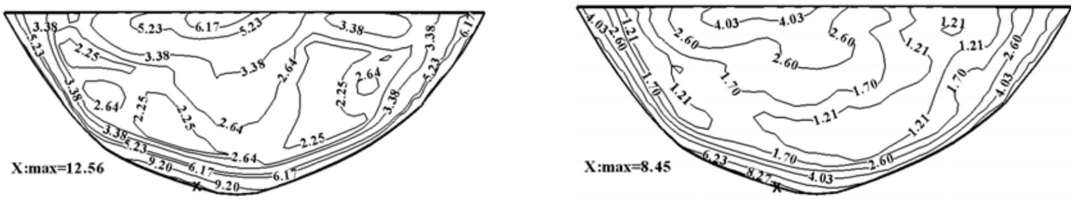


(a) Dam crest (b) Crown cantilever

Figure 5.4 Envelope curves of nodal displacement response along the river flow direction without the dam transverse joints

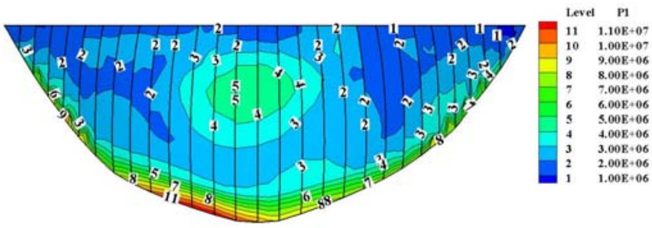
It is obvious that the radiation damping of infinite foundation has played a very significant weakening role on the displacement response of dam. When compared to the massless foundation model, a similar variation rule is found between the displacement along river flow direction on the top arch and the crown cantilever, in which just the amplitude evidently decreases, about 40%. The stress results show a similar effect, reduced about 33% for the principle tensile stress on the dam upstream face, when the infinite radiation damping is taken into consider. That is to say, the effects of the radiation condition should be appropriate and reasonable consideration in the evaluation of seismic safety.

Furthermore, directly using the ANSYS contact element of Contac52 to simulate the dynamic contact ion of the 27 transverse joints, the results are shown in Figure 5.6. Compared with the results of entire dam model, the principle tensile stress on the dam upstream face is more concentrated near the dam foundation surface, and the tensile stress shows a sight increase in the amplitude. The openings of the transverse joints are also in a reasonable range, less than 1cm. All these results show that the ANSYS own element models work well with the presented DSEM on the ANSYS platform.

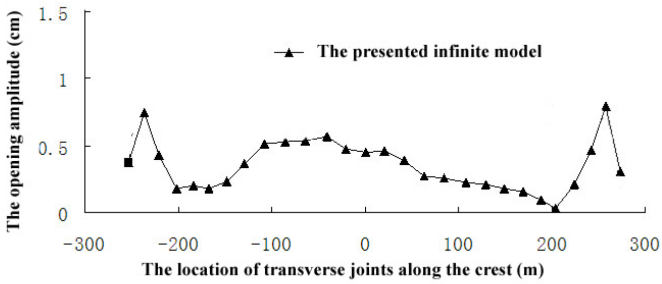


(a) Massless foundation model (MPa) (b) The presented infinite foundation model (MPa)

Figure 5.5 Distribution of the principle tensile stress on the dam upstream face without the transverse joints



(a) The principle tensile stress on the dam upstream face with the transverse joints (MPa)



(b) The opening amplitude of dam transverse joints

Figure 5.6 Dynamic responses of the arch dam with the transverse joints base on the DSEM

6 CONCLUSIONS

The damping solvent extraction method (DSEM) affords an effective approach to simulate the dynamic properties of infinite soil medium, in which the convolution calculation as in other traditional time-domain dynamic interaction analysis is wholly avoided. The availability and detailed implementation of DSEM on the ANSYS platform is demonstrated in this paper, by taking the APDL with UPFs joint model as main development tools. Finally, the ability of the presented model in analyzing complex structure-foundation dynamic interaction problem is validated by the numerical example of arch dam.

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