A time-domain coupled scaled boundary isogeometric approach for earthquake response analysis of dam-reservoir-foundation system

G. Lin, Y. Zhang, Y. Wang & Z.Q. Hu
School of Hydraulic Engineering, Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024,China

15 WCEE
LISBOA 2012

SUMMARY:
The proposed approach combines the advantages of isogeometric analysis (IGA) and scaled boundary finite element method (SBFEM). The IGA is employed for idealization of the dam structure, while SBIGA is developed for modeling the semi-infinite fluid domain of reservoir and unbounded elastic half-space of the dam foundation. Water compressibility, reservoir boundary wave absorption can be taken into consideration with relative ease. Numerical examples of dam-reservoir-foundation system demonstrate that the proposed approach is highly accurate and consumes less degrees-of-freedom than conventional widely used finite element method and boundary element method.

Keywords: Dam-Reservoir-Foundation System (DRFs);Isogemetric Analysis (IGA); Scaled Boundary Isogeometirc Analysis (SBIGA); Dynamic Interaction; earthquake response analysis.

1. INTRODUCTION

An approach based on isogeometric analysis (IGA) and scaled boundary isogeometric analysis (SBIGA) is proposed for the earthquake response analysis of dam-reservoir-foundation system. Isogeometric analysis has great potential to improve the efficiency and accuracy of numerical structural response analysis. IGA was proposed by Hughes *et al* [Hughes, 2005] with some features in common with finite element method (FEM) and meshless method. Taking inspiration from computer aided design (CAD) non-uniform rational B-splines (NURBS) are used as basis functions for interpolation. as a result, exact geometric model can be constructed even in rather coarse mesh. Refinement of meshes can be implemented at all mesh levels without the necessity of subsequent communication with CAD description. In this paper, IGA is employed for idealization of the dam structures.

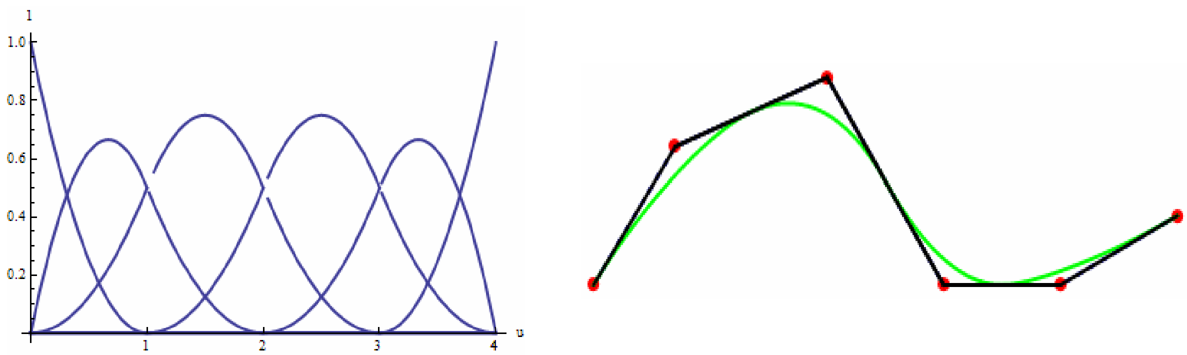
The scaled boundary finite element method (SBFEM) put forward by Wolf and Song [Wolf, 2000] offers more than combing the advantages of FEM and BEM. Only the boundary needs to be discretized which leads to the spatial dimension reduced by one, but no fundamental solution is required. As a result SBFEM has emerged as an attractive alterative for the numerical analysis. SBFEM has outstanding performance in solving unbounded domain problems, and it satisfies rigorously the radiation condition at infinity. In the present research, the SBIGA approach [Zhang, 2010], which couples SBFEM and IGA, is developed to model the semi-infinity fluid domain of reservoir and the unbounded elastic half space of dam foundation. SBIGA fully inherits the merits of IGA and SBFEM. Numerical example of a time-domain earthquake response analysis of gravity dam-reservoir-foundation system is presented. Effects of water compressibility, reservoir boundary wave absorption and structure-unbounded foundation interaction are taken into consideration. The computing and post-processing time for various cases of dam, reservoir and foundation modeling were compared to show the effectiveness of the proposed approach. Though the emphasis is placed on the two-dimensional dam-reservoir-foundation system, the presented formulation can be easily applied to three-dimensional system.

2. MODELING OF THE DAM STRUCTURE

The discretization model of the dam structure is constructed by IGA. The basis functions NURBS for IGA are generated from B-splines. Two spaces in B-spine have to be distinguished: the parametric space, specified by a knot vector defining the B-spline basis function and the physical space formulated by control points associated with basis functions. The B-spline parametric space corresponds to a patch in the physical space, consisting of multiple elements. Patch plays the role of subdomain within which element type and material models are assumed to be uniform.

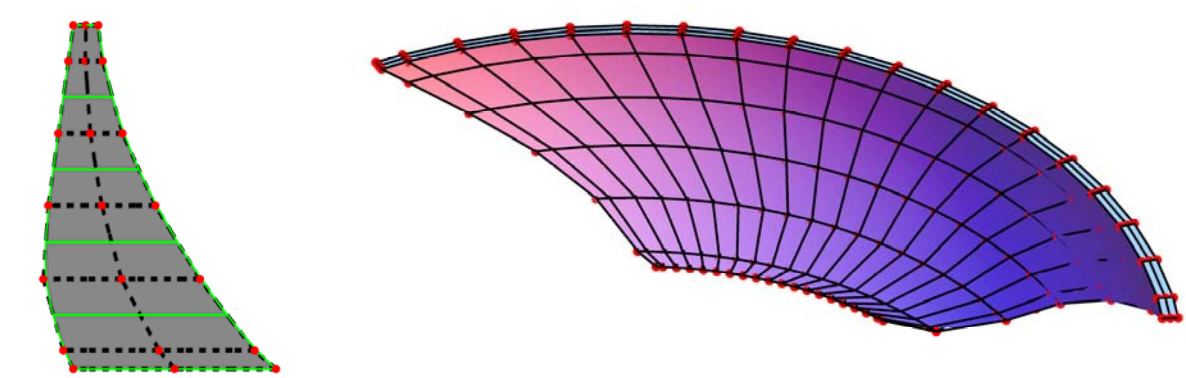
An analysis framework based on NURBS consists of the following features: (a) A mesh for a NURBS patch in two or three dimensions is defined by the product of knot vectors. (b) Based on isoparametric concept, the displacement and stress fields in structural dynamics are represented in terms of the same basis functions as the geometry. The coefficients of the basis functions are the degrees-of-freedom (DOFs) on control points. (c) Mesh refinement strategies are developed from a combination of knots insertion and order elevation techniques. (d) Arrays constructed from isoparametric NURBS patches can be assembled into global arrays in the same way as finite elements. (e) In general, control points are not interpolated by B-spline curves, except for the end control points for the open knot vectors.

Fig. 2.1 shows an example of one-dimensional quadratic NURBS basis functions with knot vector $\{0,0,0,1,2,3,4,4,4\}$ and the corresponding NURBS curve with control points denoted by red points. Fig. 2.2 shows 2D NURBS surface and 3D NURBS solid. And Fig. 2.3 demonstrates the mesh refinement for dam structure.



(a) quadratic NURBS basis functions (b) quadratic NURBS curve

Figure 2.1. quadratic NURBS basis function and NURBS curve



(a) quadratic NURBS surface (b) quadratic NURBS solid

Figure 2.2. quadratic NURBS basis function and NURBS curve

(continued)

(a) level 1 (b) level 2

Figure 2.3. mesh refinement

3. MODELING OF THE RESERVOIR

An efficient procedure based on SBFEM is developed by the authors [Lin, 2012] for hydrodynamic analysis of dam-reservoir system. Only part of the reservoir boundaries, which coincide with the upstream dam face, needs to be discretized. The effects of dam flexibility, the water compressibility and the reservoir bottom wave absorption can be conveniently taken into consideration. In case the reservoir is idealized to extend to infinity along the river direction with a uniform cross-section, in the IGA formulation the hydrodynamic pressure at the control points are expressed as follows

$$\left\{p(\omega)\right\} = -\left[S_w(\omega)\right]\left\{\ddot{u}(\omega)\right\} \tag{3.1}$$

$$\left[S_w(\omega)\right] = [\Phi_{12}][\Phi_{22}]^{-1}[M_1] + \left([\Phi_{12}][\Phi_{22}]^{-1}[B_1] - [B_2]\right)[M_2] \tag{3.2}$$

where $\left[S_w(\omega)\right]$ denotes the dynamic stiffness of hydrodynamic pressure in the frequency domain and $\left\{\ddot{u}(\omega)\right\}$ the exciting acceleration on control points of dam face. Coefficient matrices $[\Phi_{12}]$, $[\Phi_{22}]$, $[B_1]$, $[B_2]$, $[M_1]$ and $[M_2]$ are functions of the exciting frequency ω and related to the shape functions of the upstream dam face and the boundary absorption behavior of the reservoir.

For time domain analysis, performing inverse Fourier transform of $\left[S_w(\omega)\right]$ leads to the acceleration unit-impulse response matrix $\left[S_w(t)\right]$

$$\left[S_w(t)\right] = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left[S_w(\omega)\right]e^{i\omega t}\mathrm{d}\omega \tag{3.3}$$

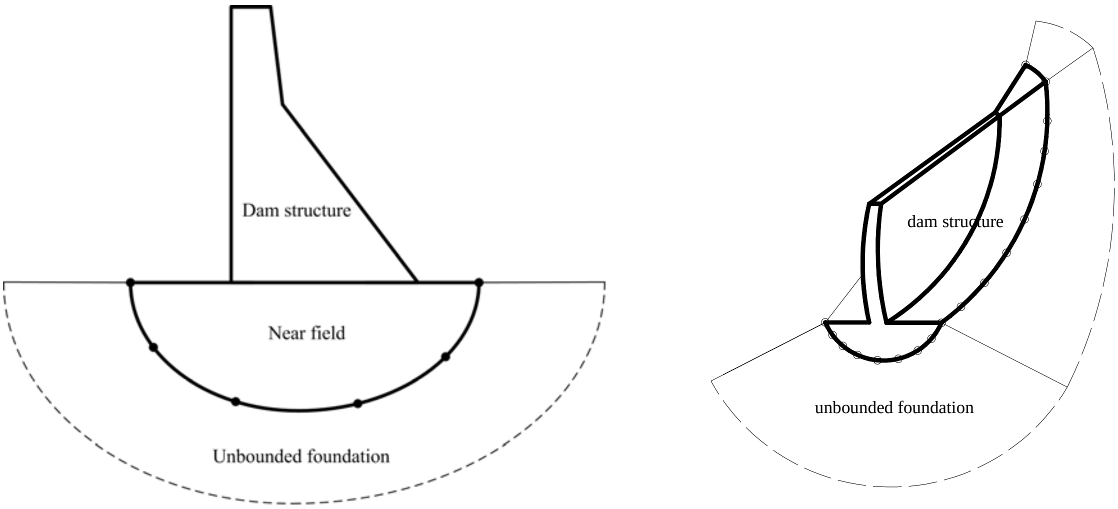
and

$$\left\{\mathrm{p}(t)\right\} = -\int_0^t\left[S_w(\tau)\right]\left\{\ddot{\mathrm{u}}(t-\tau)\right\}\mathrm{d}t \tag{3.4}$$

4. MODELING OF THE UNBOUNDED FOUNDATION

The SBFEM approach to simulate the unbounded dam foundation proposed by the authors [Lin, 2007] is applied. Only the dam-foundation interface needs to be discretized. Some cases of foundation inhomogeneity can be easily taken into consideration. For the case of arch dam, the dam structure and a finite bounded foundation region adjacent to the dam (near field) are idealized as a substructure, the surrounding unbounded half-space of the foundation is approximated by a truncated zone as shown in

Fig. 4.1.



(a) gravity dam (b) arch dam

Figure 4.1. Koyna earthquake record

5. GOVERNING EQUATIONS FOR THE EARTHQUAKE RESPONSE OF DAM-RESERVOIR-FOUNDATION SYSTEM

In order to formulate the governing equations for the general dam-reservoir-foundation system, the algorithm proposed by [Radmanovie, 2012] to solve dynamic soil-structure interaction problem is applied. They have derived an integration scheme for time domain evaluation of dam-foundation interaction force vector

$$\left\{r_{b,n}\right\}=\left\{r_b\left(t_n\right)\right\}=\int_0^{t_n}\left[M_b^{\infty}\left(\tau\right)\right]\left\{\ddot{u}_b\left(t_n-\tau\right)\right\}\mathrm{d}\tau=\left[K_{bb}^{g}\right]\left\{u_{b,n}\right\}+\left\{q_{b,n}\right\} \tag{5.1}$$

with

$$\left[K_{bb}^{g}\right]=\left(a_1-a_{10}\right)\left[M_0^{\infty}\right]+a_{10}\left[M_1^{\infty}\right] \tag{5.2}$$

where $\left[M_b^{\infty}\left(t\right)\right]$ denotes the acceleration unit impulse response matrix at the dam-foundation interface; $a_1=\gamma/\left(\beta\Delta t\right)$, $a_{10}=1/\left(N\Delta t\right)$, with β and γ being the parameters of Newmark- β scheme and $\left\{u_{b,n}\right\}$ the displacement vector at the dam-foundation interface and time instant t_n . $\left\{q_{b,n}\right\}$ depends solely on the values of the time steps before time t_n . It is worth to note, for late times $\left[M_b^{\infty}\left(t\right)\right]$ tends asymptotically toward linear curve, the evaluation of $\left\{q_{b,n}\right\}$ can be simplified.

When subjected to earthquake ground acceleration input $\left\{\ddot{u}_b^{g}\left(t\right)\right\}$, the interaction force vector becomes

$$\left\{r_{b,n}\right\}=\left\{r_b\left(t_n\right)\right\}=\int_0^{t_n}\left[M_b^{\infty}\left(\tau\right)\right]\left(\left\{\ddot{u}_b\left(t_n-\tau\right)\right\}-\left\{\ddot{u}_b^{g}\left(t_n-\tau\right)\right\}\right)\mathrm{d}\tau=\left[K_{bb}^{g}\right]\left(\left\{u_{b,n}\right\}-\left\{u_{b,n}^{g}\right\}\right)+\left\{q_{b,n}\right\} \tag{5.3}$$

Let $\left\{u_w\right\}$ represents the DOFs at the dam-reservoir interface, $\left\{u_b\right\}$ the DOFs at the dam-foundation interface and $\left\{u_s\right\}$ the DOFs of the dam structure excluding $\left\{u_w\right\}$ and $\left\{u_b\right\}$, dynamic equation of motion of the dam-reservoir-foundation system in the partitioned form for time-domain analysis is expressed as

$$
\begin{bmatrix} [M_{ss}^{s}] & [M_{sw}^{s}] & [M_{sb}^{s}] \\ [M_{ws}^{s}] & [\bar{M}_{ww}^{s}] & [M_{wb}^{s}] \\ [M_{bs}^{s}] & [M_{bw}^{s}] & [M_{bb}^{s}] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}_{s,n}\} \\ \{\ddot{u}_{w,n}\} \\ \{\ddot{u}_{b,n}\} \end{Bmatrix} + \begin{bmatrix} [C_{ss}^{s}] & [C_{sw}^{s}] & [C_{sb}^{s}] \\ [C_{ws}^{s}] & [C_{ww}^{s}] & [C_{wb}^{s}] \\ [C_{bs}^{s}] & [C_{bw}^{s}] & [C_{bb}^{s}] \end{bmatrix} \begin{Bmatrix} \{\dot{u}_{s,n}\} \\ \{\dot{u}_{w,n}\} \\ \{\dot{u}_{b,n}\} \end{Bmatrix}
$$
$$
+ \begin{bmatrix} [K_{ss}^{s}] & [K_{sw}^{s}] & [K_{sb}^{s}] \\ [K_{ws}^{s}] & [K_{ww}^{s}] & [K_{wb}^{s}] \\ [K_{bs}^{s}] & [K_{bw}^{s}] & [\bar{K}_{bb}^{s}] \end{bmatrix} \begin{Bmatrix} \{u_{s,n}\} \\ \{u_{w,n}\} \\ \{u_{b,n}\} \end{Bmatrix} = \begin{Bmatrix} \{p_{s,n}\} \\ -\{f_{w,n}\} \\ -\{q_{b,n}\} \end{Bmatrix} \tag{5.4}
$$

where $[\bar{M}_{ww}^{s}]$ and $[\bar{K}_{bb}^{s}]$ have been modified to take into consideration the effect of dam-reservoir interaction and dam-foundation interaction.

$$
[\bar{M}_{ww}^{s}] = [M_{ww}^{s}] + [T][S_{w,0}], \ [\bar{K}_{bb}^{s}] = [K_{bb}^{s}] + [K_{bb}^{g}] \tag{5.5}
$$

where $[S_{w,0}]$ represents hydrodynamic stiffness matrix at the initial time $t = 0$, matrix $[T]$ transforms hydrodynamic water pressure into force with x, y, z components, and

$$
\{f_{w,n}\} = [T]\sum_{j=1}^{n}[S_{w,j}]\{\ddot{u}_{w,n-j}\} \tag{5.6}
$$

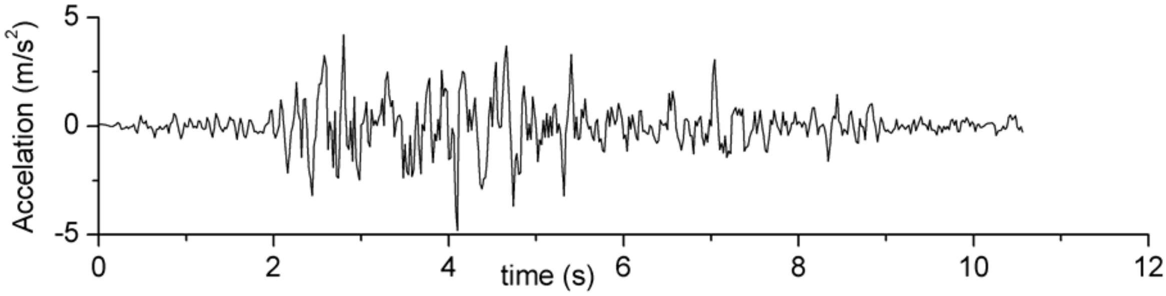
6. NUMERICAL EXAMPLES

The koyna gravity dam with a height of 103*m is* selected for this study (see Fig. 6.1). The koyna earthquake record is used for the ground motion input, the peak acceleration in the longitudinal as well as in the vertical direction is assigned as 0.49*g* and 0.34*g* respectively. The wave reflection coefficient at the reservoir boundary is assumed as 0.75. Six cases modelling the dam, reservoir and unbounded foundation as shown in Table 6.1 were considered. In the first three cases dam-reservoir-foundation interaction with various models was studied, while in the last three cases only dam-reservoir interaction was studied, and rigid foundation is assumed. The total number of nodes (or control points) for discretization, the CPU time and post-processing time were compared.

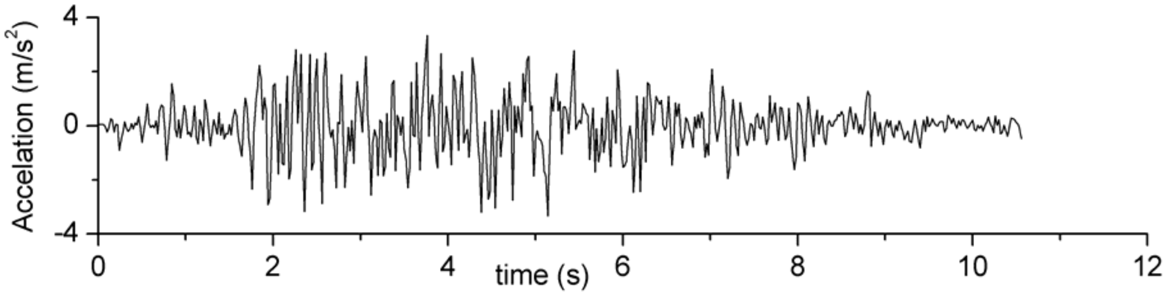
Table 6.1. Cases studied

model	Case1	Case 2	Case 3	Case 4	Case 5	Case 6
reservoir	Westergaard's added mass	SBFEM-FSI（39 nds[a]）	SBIGA-FSI（35 cps[b]）	Westergaard's added mass	SBFEM-FSI	SBIGA-FSI（35 cps）
Dam structure (near field included)	FEM（6179 nds）	FEM（6179 nds）	IGA（988 cps）	FEM（2459 nds）	FEM（2459 nds）	IGA（630 cps）
Unbounded foundation	massless	SBFEM- SSI (41 nds)	SBIGA - SSI（19 cps）	rigid	rigid	rigid
CPU time	40 min	30 min	10 min	10 min	25 min	8 min
Post processing time	10 min（Ansys[c]）	120 min	50 min	10 min（Ansys）	120 min	50 min

Annotation: [a] nds-nodes; [b] cps-control points; [c] processed by ANSYS software;
FSI- fluid structure interaction; SSI- soil structure interaction.

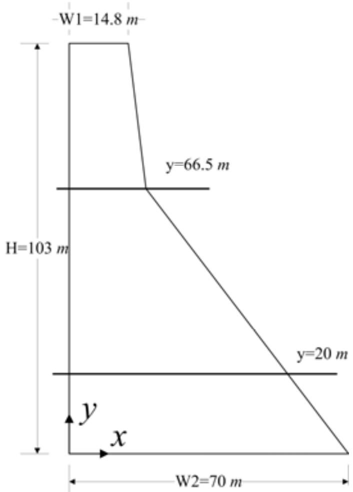


(a) Horizontal (peak 0.40*g*)

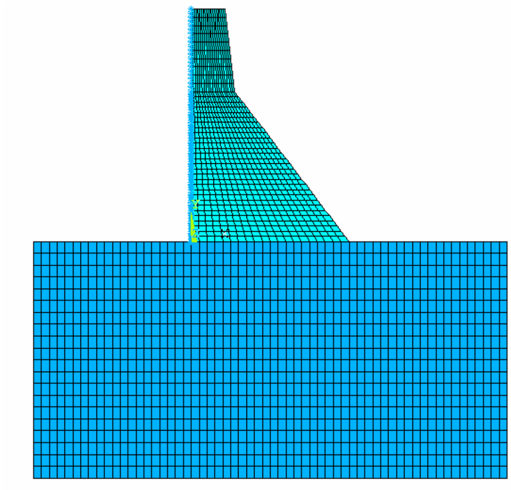


(b) Vertical (peak 0.34*g*)

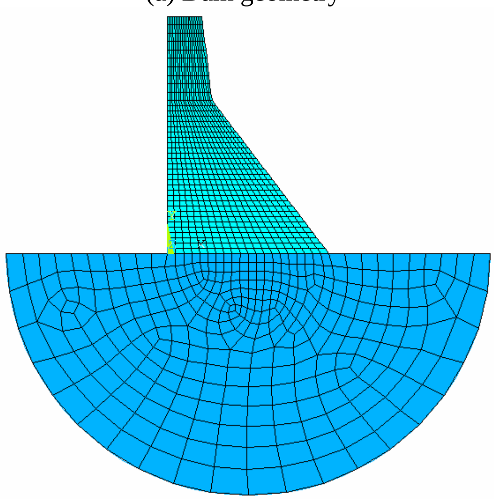
Figure 6.1. Koyna earthquake record



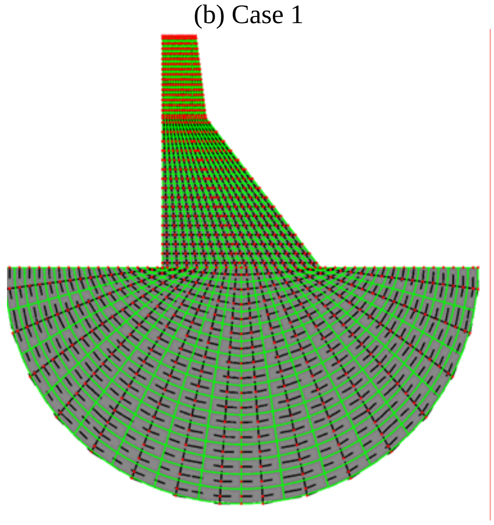
(a) Dam geometry



(b) Case 1

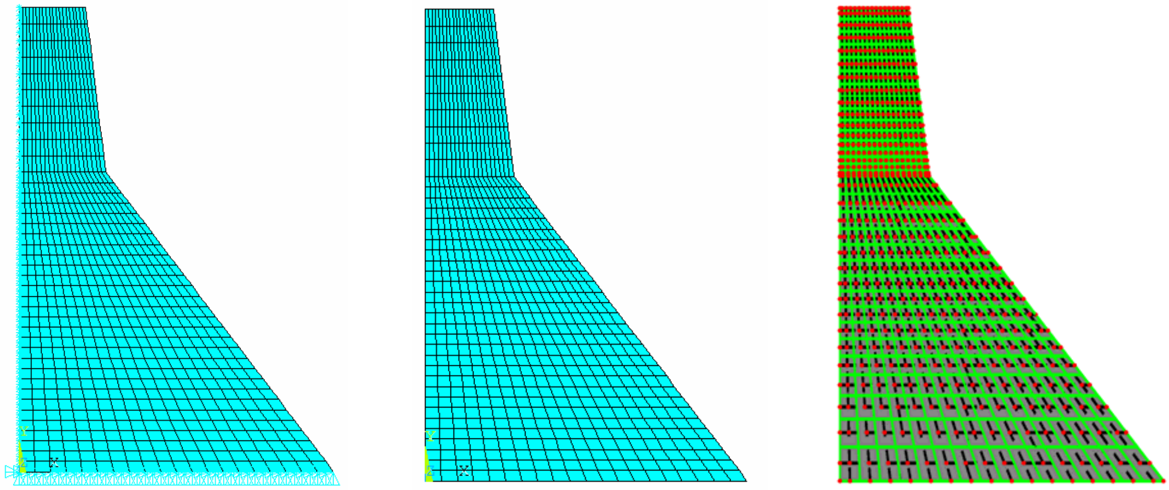


(c) Case 2



(d) Case 3

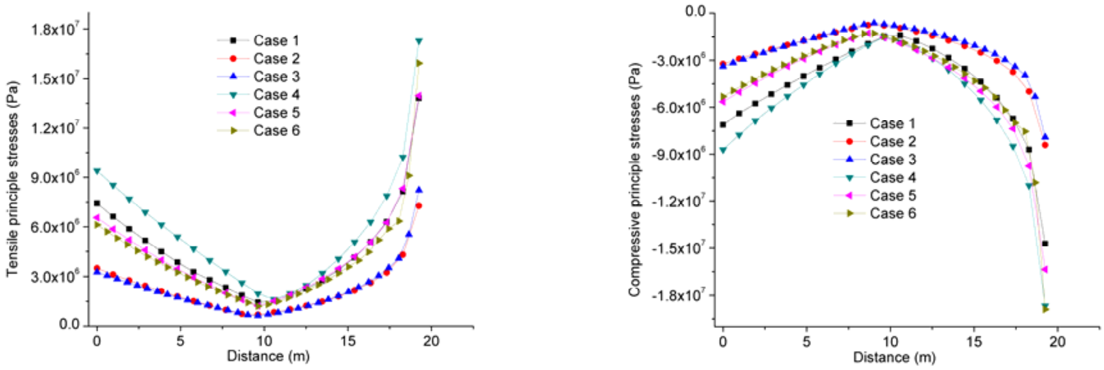
(continued)



(e) Case 4 (f) Case 5 (g) Case 6

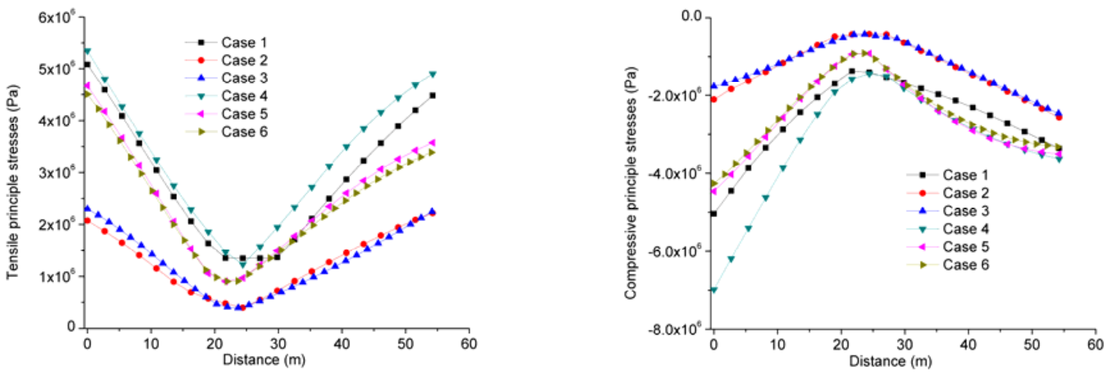
Figure 6.2. Koyna dam geometry and its mesh discretization

Stress induced by earthquake excitation only are examined. The stress distribution along the neck section and the section 20*m* above the base are plotted in Fig. 6.3 and Fig. 6.4. Envelope of principle stresses contours for first 3 cases is depicted in Fig. 6.5. As can be observed from Figs. 6.3 and 6.4 and Table 6.1, both dam-foundation interaction and reservoir-boundary absorption introduce additional damping to the system, which results in the reduction of the earthquake response of the dam structure.



(a) Tensile principle stresses (b) Compressive principle stresses

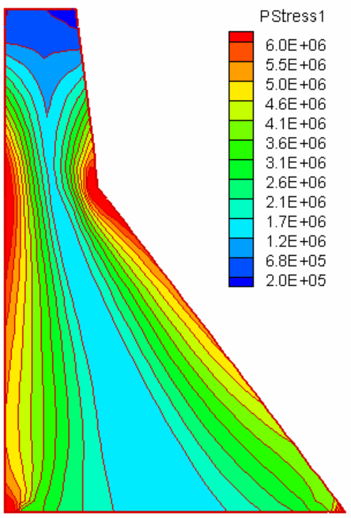
Figure 6.3. Stress distribution at the neck section of the Koyna dam



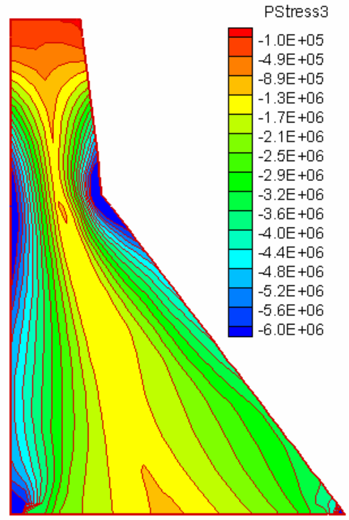
(a) Tensile principle stresses (b) Compressive principle stresses

Figure 6.4. Stress distribution at the section 20m above the base at the Koyna dam

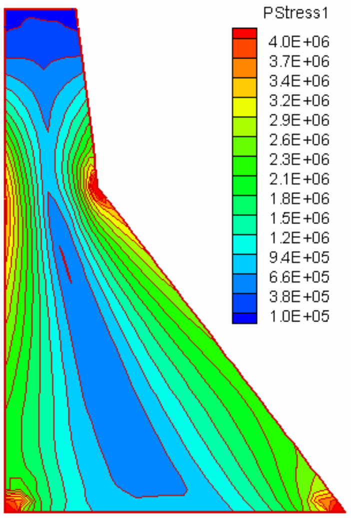
The IGA-SBIGA model and FEM-SBFEM model give the least stress amplitudes. The massless foundation and the Westergaard's added mass approach overestimate the earthquake response of the dam structure. Especially at the position of stress concentration, such as the point of slope change at the downstream face, the predicted stress amplitudes may be magnified considerably.



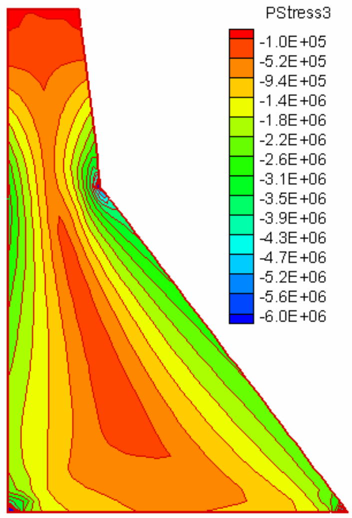
(a) Contour of tensile principle stress (case 1)



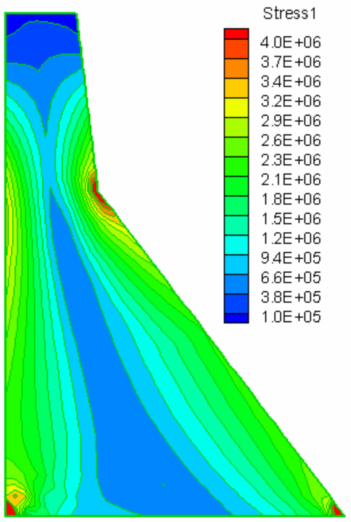
(b) Contour of compressive principle stress (case 1)



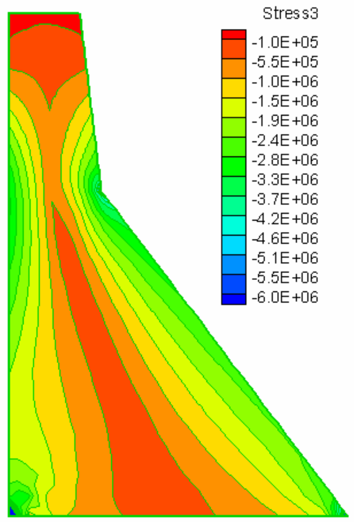
(a) Contour of tensile principle stress (case 2)



(b) Contour of compressive principle stress (case 2)



(a) Contour of tensile principle stress (case 3)



(b) Contour of compressive principle stress (case 3)

Figure 6.5. Envelope of dynamic strees contours of koyna dam subjected to the koyna earthquake

7. CONCLUSIONS

A coupled IGA and SBIGA approach for time-domain earthquake response analysis of dam-reservoir-foundation system is proposed. Numerical examples demonstrate that the proposed approach is computationally quite economical, while highly accurate results can be achieved.

AKCNOWLEDGEMENT
The research was supported by Grants 51138001 from the National Natural Science Foundation of China and the Grants GZ 566 from Sino-German Science Foundation, for which the authors are grateful.

REFERENCES

Hughes T.J.R., Cottrell J.A. and Bazilevs Y. (2005). Isogeometric analysis CAD, finite elements, NURBS, exact geometry and mesh refinement. *Comput. Methods Appl. Mech. Engrg.* **194: 39-41**, 4135-4195.

Lin G., Wang Y. and Hu Z.Q. (2012). An efficient approach for frequency-domain and time-domain hydrodynamic analysis of dam–reservoir systems. *Earthquake Engng Struct. Dyn.* DOI: 10.1002/eqe.2154.

Lin, G., Du J.G., and Hu Z.Q. (2007). Earthquake analysis of arch and gravity dams including the effects of foundation inhomogeneity. *Front. Archit. Civ. Eng. China*. **1-1**, 41-50.

Radmanovic B. and Katz C. (2012). Dynamic soil-structure interaction using an efficient scaled boundary finite element method in time domain with examples. *SECED, Newslettez*. **23-3**, 3-13.

Song C. and Wolf J.P. (2000). The scaled boundary finite-element method-a primer: solution procedures, *Comput. Struct.* **78**, 211-225.

Wolf J.P. and Song C. (2000). The scaled boundary finite-element method-a primer: derivations. *Comput. Struct.* **78**, 191-210.

Zhang Y., Lin G. and Hu Z.Q. (2010). Isogeometric analysis based on scaled boundary finite element method. *IOP Conf. Series: Materials Science and Engineering.* **10**,012237.