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Modelling the Effects of Sediment on the Seismic Behaviour of Kinta Roller Compacted Concrete Dam

Huda A.M.[1], M.S. Jaafar[1], J. Noorzaei[1*], Waleed A. Thanoon[2] and T. A. Mohammed[1]

[1]Department of Civil Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

[2]Faculty of Engineering, University of Nizwa, Oman

[*]E-mail:jamal@eng.upm.edu.my

ABSTRACT

An attempt was made in this investigation to trace the dynamic response of roller compacted concrete dam, which is subjected to horizontal ground motion by considering the interactions between flexible foundations, reservoir water, and bottom reservoir sediments. Two-dimensional finite-infinite element was used for the non-linear elasto-plastic dynamic analysis. In this analysis, special emphasis was given to the non-linear behaviour of discontinuities along RCC dam-bedding rock foundation which was modelled by thin layer interface. Analysis was first carried out under static loading (self-weight and hydrostatic pressure), and this this was followed by seismic analysis, with hydrodynamic pressure effect in a dam-reservoir system. Based on the numerical dynamic results, it is concluded that the bottom reservoir sediment has significant effect on the seismic response of the RCC gravity dam. Moreover, there is a redistribution of the stresses at thin layer interface with significant stresses reduction, which is resulted from the release of energy through different modes of deformation in this region.

Keywords: **Seismic analysis, roller compacted concrete dam, coupled finite-infinite elements, sediment, thin layer interface**

ABBREVIATIONS

2D	Two dimension
B	Strain-displacement matrix
c	Cohesion
$\overline{C_e}$	Local elastic matrix of thin layer interface
C_e	Global elastic matrix of thin layer interface
C_{ep}	Elasto-plastic matrix of thin layer interface
CVC	Conventional concrete
D_e	Elastic matrix of the material
D_{ep}	Elasto-plastic matrix of the material
E	Young's modulus
f	Yield function
FE	Finite element method
FFT	Fast Fourier Transform technique
f_t	Tensile strength
f_c	Compressive strength
hs	Height of sediment

[*]Corresponding Author

K	Stiffness matrix of the system
k_{nn}	Normal stiffness of thin layer interface
k_{ss}	Shear stiffness of thin layer interface
PGA	Peak ground acceleration
RCC	Roller compacted concrete dam
t	Thickness of thin layer interface
T	Transformation matrix of thin layer interface
v	Poisson ratio
α, β	Coefficient of Newmark method
ϕ	Friction angle
ρ	Mass density of material
σ_n	Normal stress
τ	Shear stress

INTRODUCTION

Reservoir sedimentation reduces storage capacity. This loss is considerable and reservoir sedimentation is one of the primary problems to be dealt with in the 21st century. The problem arises from geological sources, agricultural cultivation, destruction of forest, and other natural causes and hazards. Considerable efforts have also been devoted in the recent years to investigate the seismic response on the concrete dams. To obtain realistic results, the reservoir sedimentation must be taken in the analysis of the dam-reservoir-foundation interaction.

Dam-reservoir-foundation-sediment interaction has been investigated by many researchers. Among other, Fenves and Chopra (1984: 1985) presented a model which includes reservoir bottom absorption for the seismic analysis of gravity dam by the means of an absorbing boundary condition. The study concluded that the sediment could significantly reduce the hydrodynamic pressure effect on the seismic response of the dam. Meanwhile, Lotfi *et al*. (1987) modelled the sediments as linearly viscoelastic, which was included as hyper-elements in a finite element analysis. The water-sediment-foundation interaction was taken into account rigorously. A model based on the boundary-element method was presented by Medina *et al*. (1990). In their analysis, the sediment was considered as a viscoelastic material which could only transmit compressional waves. The effect of the two-phase poroelastic sediments on the seismic response of gravity dams was investigated by Bougacha and Tassoulas (1991). The sediment was considered as a uniform horizontal layer and included as a hyper-element in their finite element model.

An investigation into the effect of reservoir bottom sediment on the seismic response of concrete gravity dams was carried out by Zhao *et al*. (1995) using coupled finite-infinite elements and Fast Fourier Transform (FFT) technique. They suggested that (1) the finite and infinite element coupled method is more suitable for the seismic analysis of a concrete gravity dam, and (2) the reservoir bottom sediment has a significant effect on the seismic response of concrete gravity dam. More recently, Dominguez *et al*. (1997) presented a boundary-element approach for the dynamic analysis of concrete gravity dam. The dam was subjected to ground motions and it interacted with water, foundation, and bottom sediment.

Based on the review of some published papers, none of them has addressed the effects of sediment and its dynamic non-linear interaction with roller compacted concrete (RCC) dam in time history analysis, particularly when the RCC dam-reservoir-foundation-sediment interaction is considered with the coupled finite and infinite elements.

Attempting to fill the apparent gap, an RCC dam-reservoir-foundation-sediment interaction which is subjected to earthquake ground acceleration is modelled using finite-infinite elements. Elasto-plastic non-linear dynamic analysis was carried out in time domain using modified two dimensional finite element program to represent the unbounded domain in the foundation and interfacial behaviour along discontinuities. For more realistic analysis, the non-linear behaviour along discontinuities between RCC dam-bedding foundations was investigated for safety evaluation. Therefore, Kinta dam in Malaysia was selected to be used in this investigation.

MATERIALS AND METHODS

Finite Element Computer Code

An existing two-dimensional finite element code by Noorzaei *et al*. (1995) was modified for the purpose of this study. The modification was made by:

(i) Adding infinite elements and thin layer interface elements in the element library.

(ii) Strengthening the library of the yield with evolved elasto-plastic constitutive models of thin layer interface element to simulate failure mechanism of the discontinuity based on the modified Mohr-Coulomb criterion *(Fig. 1)*.

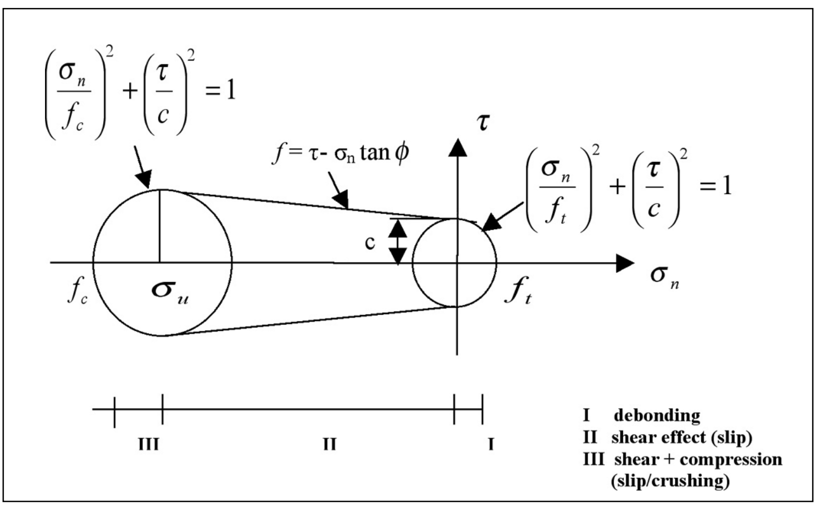


Fig. 1: Modified Mohr-Coulomb criterion (Linsbauer, 1999)

Details of the formulations and modification had been presented by Thanoon *et al*. (2006), and the generalized flowchart of this computer program is illustrated in *Fig. 2*. The program consists of the main sub-routines that execute the program processes and reads the various control parameters such as material properties, element type, element node connectivity number, nodal coordinates, and boundary conditions. Meanwhile, earthquake records and numbers of iterations for seismic analysis are executed in the main sub-routines. The software is of multi-element features, which is achieved by identifying each element of a particular code number. Based on their pre-assigned element code number, the number of nodes per element, order of integration, shape function, and

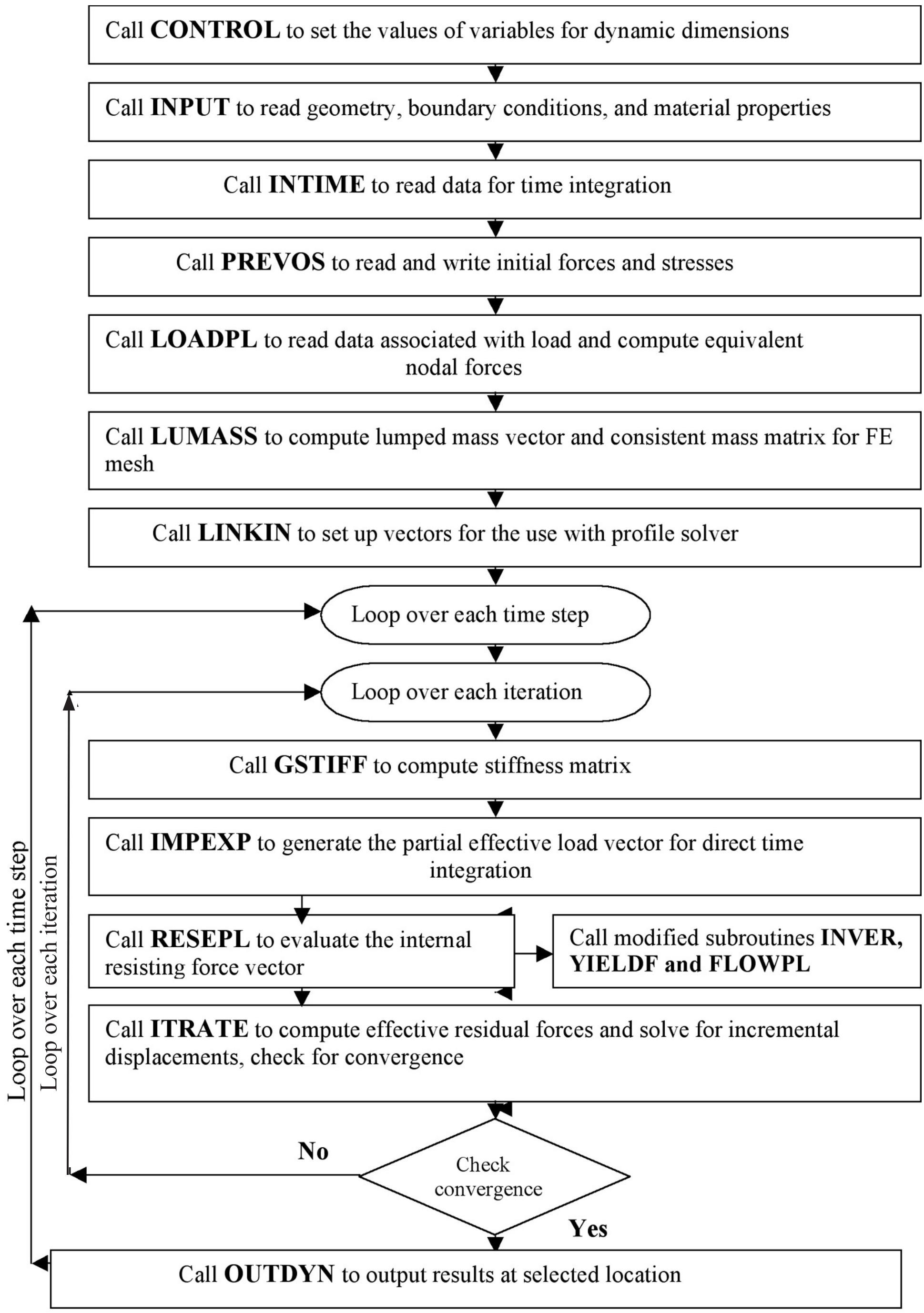


Fig. 2: General flow chart of 2D FE program

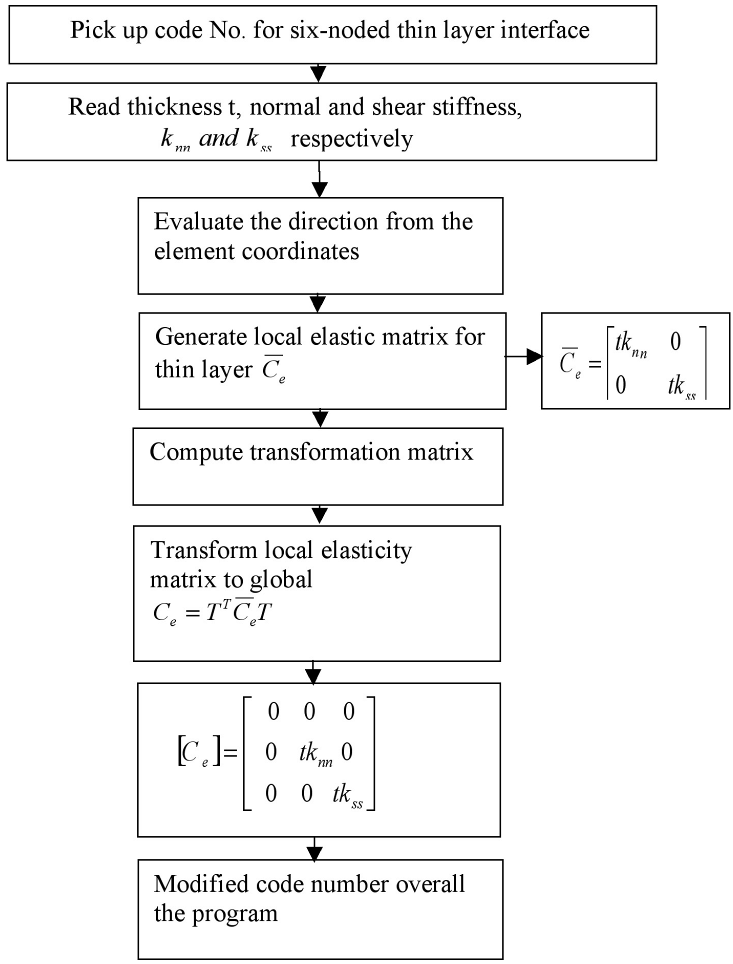


Fig. 3: Flowchart of the implementation of thin layer interface element

their derivations were picked up automatically.

The sub-routine MODPS was developed to account for the calculation of elasticity matrix for the thin layer interface element. The flowchart of the developed sub-routine is shown in *Fig. 3*. The implementation was carried out in such a way that the constitutive relations were codified and made compatible with the original program over all the sub-routines that are related to the use of elasticity matrix.

Based on the theory of plasticity, the finite element program was modified for modelling the different modes of deformation of the thin layer interface element. Sub-routines which were developed are INVAR, YIELDF, FLOWPL, GSTIFF, and RESEPL and they represent the elasto-plastic constitutive laws for debonding, slipping, and crushing behaviour of the thin layer interface. The stiffness matrix for each element was calculated in the GSTIFF sub-routine to account for any plastic deformation of the material and consequently the elasto-plastic matrix must be employed. The flowchart of the developed sub-routine GSTIFF is shown in *Fig. 4*.

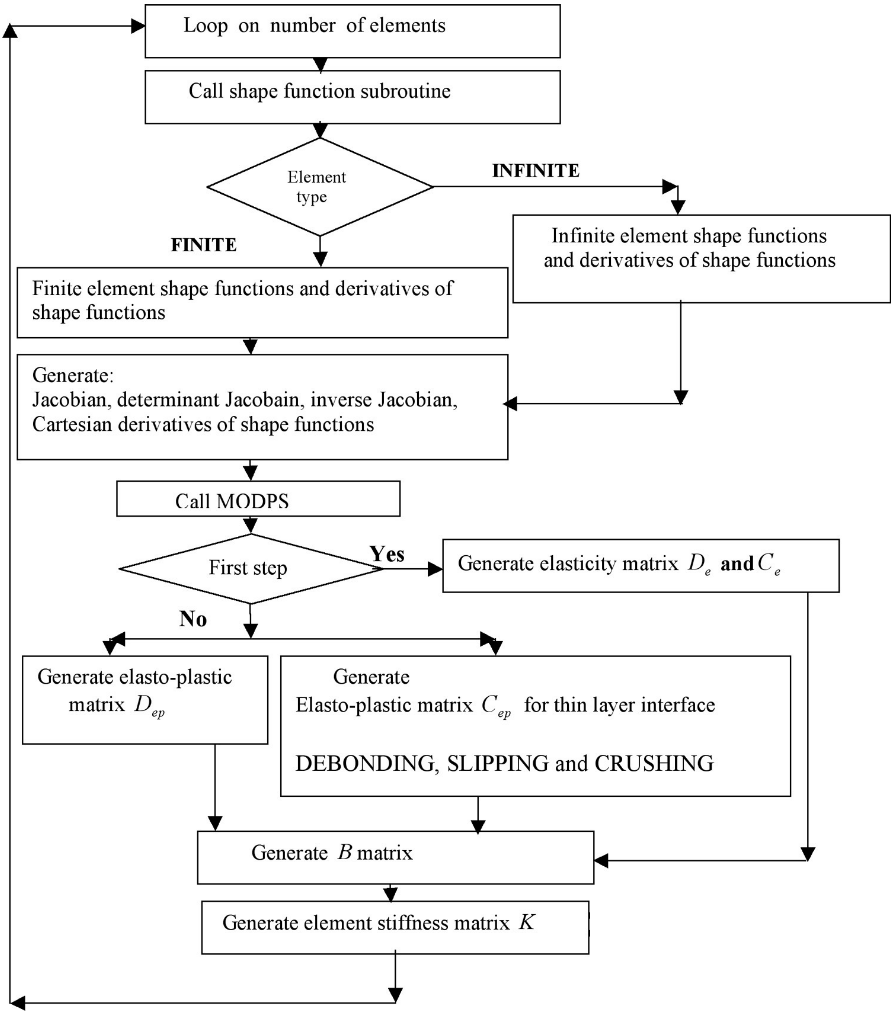


Fig. 4: Flowchart of the developed sub-routine GSTIFF

RCC Kinta Dam - Case Study

The Kinta Dam is a roller compacted concrete (RCC) gravity dam and is the first RCC dam in Malaysia. In the present study, the Kinta dam is selected to assess the response of an RCC dam under seismic excitation. The structural geometry of dam-foundation-sediment is illustrated in *Fig. 5*. Meanwhile, the finite-infinite and thin layer mesh of the dam-foundation-sediment is shown in *Fig. 6*. The following elements are used for discretization purposes:

(a) Eight noded isoparametric finite elements to represent RCC dam-sediment-bedding foundation for the near field (Zienkiewicz *et al*., 1972).

(b) Five noded infinite elements to represent the far field media of the foundation bedding system (Noorzaei, 1991).

(c) The interfacial behaviour between the RCC dam body-foundation bedding media is idealized using six noded thin layer interface elements (Sharma *et al*., 1992).

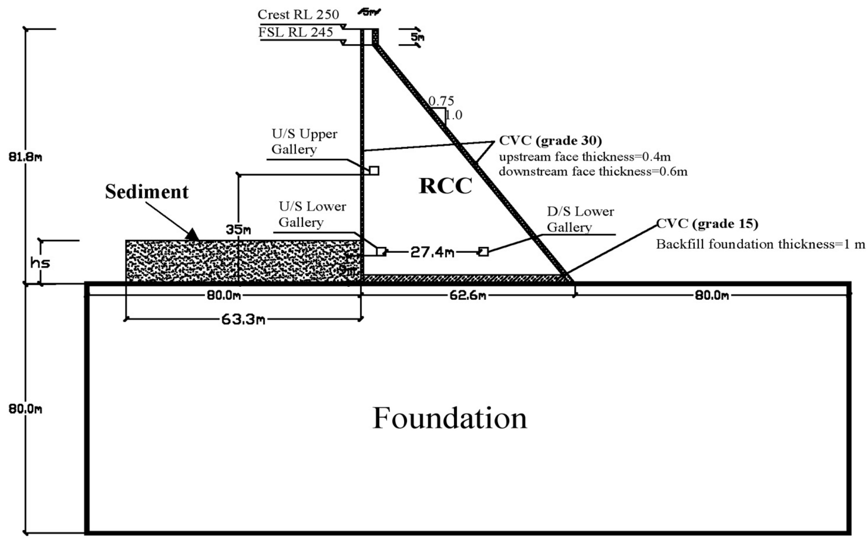


Fig. 5: Structural geometry of the RCC dam-sediment-foundation system at the deepest section

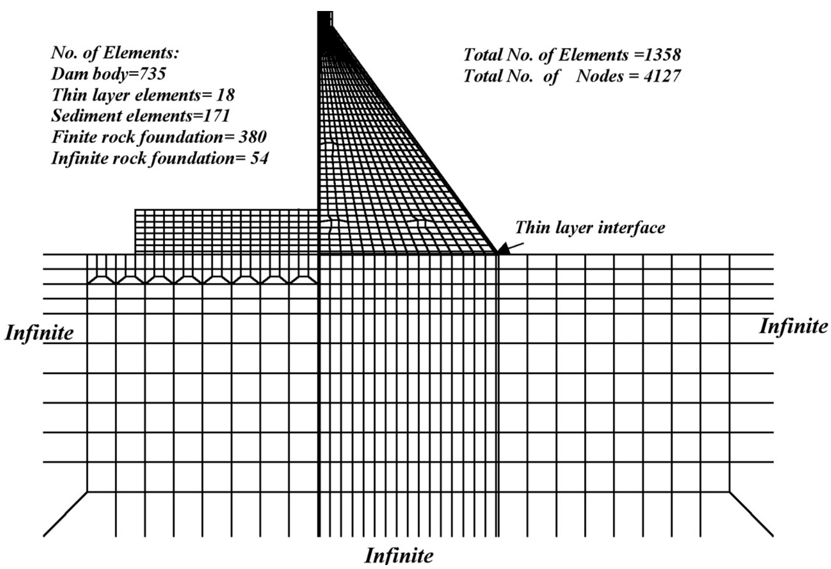


Fig. 6: Coupled finite-infinite idealization of Kinta RCC dam-foundation-sediment system

The dynamic material properties of the RCC dam-foundation-sediment system and selected grade of conventional concrete (CVC) are shown in Table 1. The dynamic properties were obtained by considering the static properties from the technical report by GHD 2002. Since specific information on the sediment behind the RCC dam is not available, the sediment properties are utilized on the basis of the available properties in the literature, similar to those used by Zhao (1995). The properties of the thin layer interface are shown in Table 2.

TABLE 1
Dynamic material properties of Kinta RCC dam-foundation-sediment system

Material parameters	RCC	CVC G30	CVC G15	Foundation	Sediment
Young's modulus E (N/m^2)	0.23E+11	0.32E+11	0.23E+11	0.30E+11	0.252E+9
Poisson ratio ν	0.2	0.2	0.2	0.2	0.3
Mass density ρ (kg/m^3)	2386	2352	2325	2650	2000
Compressive strength f_c (MPa)	20	40	20	18	-
Tensile strength f_t (MPa)	2.5	5.0	2.5	2.25	-

TABLE 2
Properties of the thin-layer interface

Material parameters	Thin layer
Mass density ρ (kg/m^3)	2325
Normal stiffness k_{nn} (N/m^3)	0.47E+12
Shear stiffness k_{ss} (N/m^3)	0.19E+12

TABLE 3
Mohr-Coulomb yield surface parameters

Material	f_c (MPa)	f_t (MPa)	c (MPa)	ϕ
Concrete (RCC and CVC G15)	20	2.5	3.535	51.06
Concrete facing (CVC G30)	40	5.0	7.06	51.06
Foundation	18	2.25	3.182	51.06
Sediment	-	-	0.098	29
Thin layer interface	18	1.0	0.7	30

The Mohr-Coulomb yield criterion was adopted for the RCC dam-foundation-sediment system. The modified Mohr-Coulomb criteria were used to simulate the different modes of deformations which could occur at the thin layer interface. Table 3 shows the parameters c and ϕ which are related to material tensile and compressive strength, and required to define yield the surface for the Mohr-Coulomb criterion.

Prior to the seismic excitation, the static stresses due to the gravity weight and hydrostatic load for full reservoir were calculated and stored separately. The hydrodynamic effect of the impounded reservoir water due to seismic loading was calculated by Westergaard added mass method (U.S., 2003) on the upstream face of the RCC dam. The horizontal ground motion, which was used for

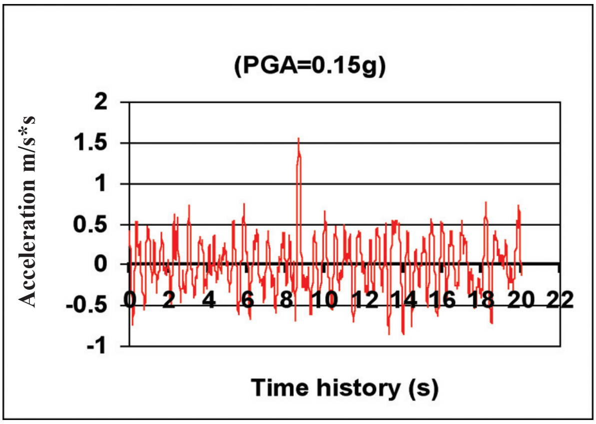


Fig. 7: Horizontal earthquake records excitation

the seismic analysis, was a Malaysian earthquake record, with a peak ground acceleration (PGA) of 0.15g, as shown in *Fig. 7*.

Dynamic Analysis

The non-linear dynamic analysis of the RCC dam-reservoir-foundation-sediment was carried out with a structural damping ratio of 5%. The integration of the dynamic equation of motion was done in the time domain using the Newmark method with $\alpha = 0.25$ and $\beta = 0.5$ and a time step of 0.02 sec. Massless foundation was considered in the analysis. Meanwhile, the time history response of the dam was carried out under plane stress condition. Therefore, the responses of the RCC dam, under seismic excitation with respect to the acceleration, displacement and stress, are presented and discussed.

RESULTS AND DISCUSSION

The absolute peak envelopes values of acceleration, displacement and stresses generally occur at different time steps during earthquake excitation; they serve to identify the critical values (U.S. army, 2003). In the next step, the time history of the nodal points or Gaussian points are plotted to evaluate the seismic response of the RCC dam.

The horizontal acceleration, with and without sediment effect along the height, is shown in *Fig. 8*. The top part of the dam experiences higher acceleration at the crest of about 1.02g and 1.1g for the two cases with and without sediment, respectively. The effect of sediment has lowered the magnitude of peak acceleration along the height, where the greatest influence is at the lower part of the dam. The lower part of the dam indicates about 30% reduction in the peak acceleration value.

The variation of peak absolute horizontal acceleration along section A-A at the foundation is shown in *Fig. 9*. The maximum value is about 0.30g and 0.41g for the two cases with and without sediment effect, respectively. As observed from these plots, the seismic response is affected by the sediment, where the peak acceleration is reduced at the foundation. This reduction is due to the absorption of the bottom reservoir sediment to the ground motion acceleration.

The envelopes of contour lines of the peak absolute displacement in the RCC dam body for both cases, i.e. with and without sediment effects, are shown in *Fig. 10*. As observed from these plots, the maximum value is located at the crest of the dam. The crest displacement is about 2.0 to

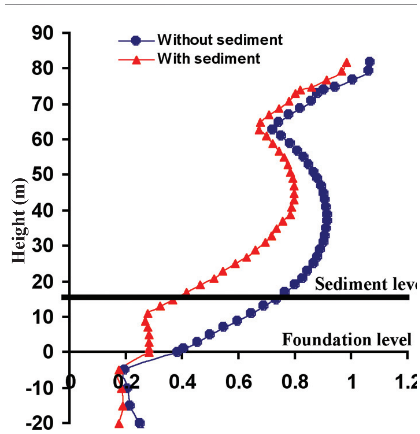


Fig. 8: Variation of the peak absolute horizontal acceleration along the height

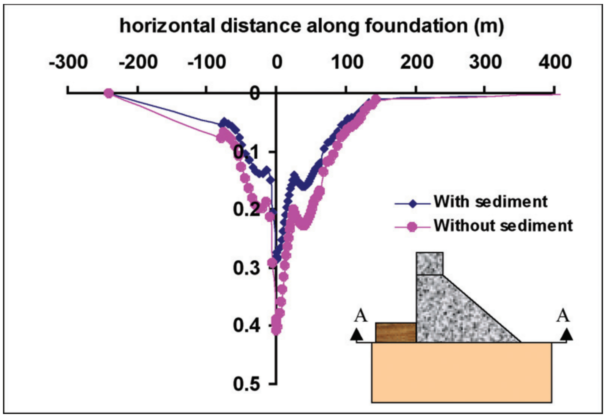
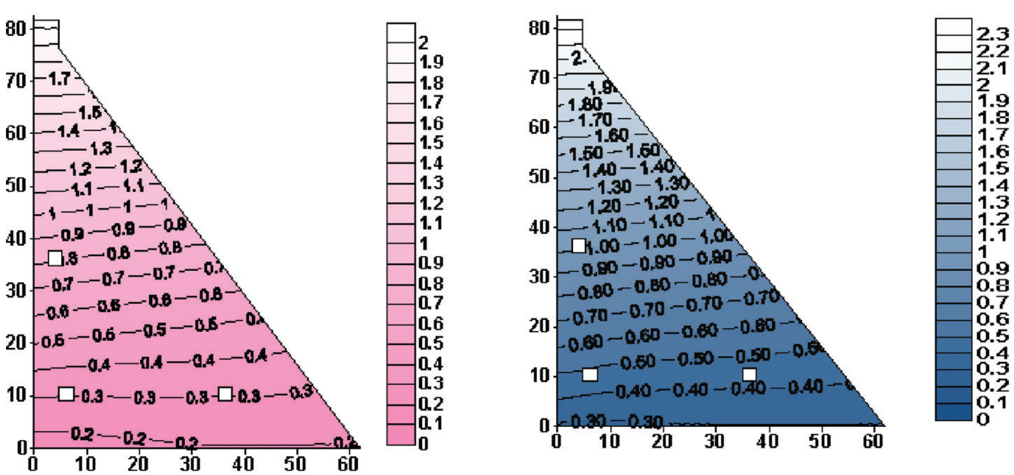


Fig. 9: Variation of the peak absolute horizontal acceleration along section A-A



(a) With sediment

(b) Without sediment

Fig. 10: Envelopes of the peak absolute horizontal displacement in the RCC dam

2.36 cm, indicating the reduction in peak displacement of about 15%. Since the highest value of horizontal displacement occurred at the crest, the horizontal displacement time history responses for both cases are plotted as in *Fig. 11*.

In this study, the level of stresses in the RCC dam body, the envelopes of contour lines in the peak tension and the compression stresses in dam body *(Figs. 12-13)* were respectively assessed for both cases. In general, these plots demonstrate that the maximum value of the tensile stress is observed at the base of the dam heel on the upstream face. The sediment reduces the seismic response of the hydrodynamic pressure, especially at the dam heel on the upstream face where the sediments are present.

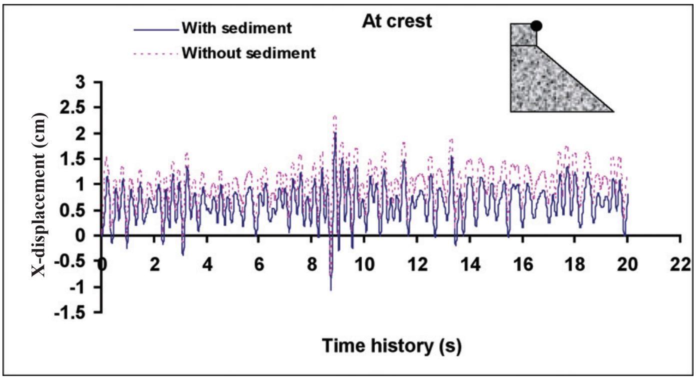
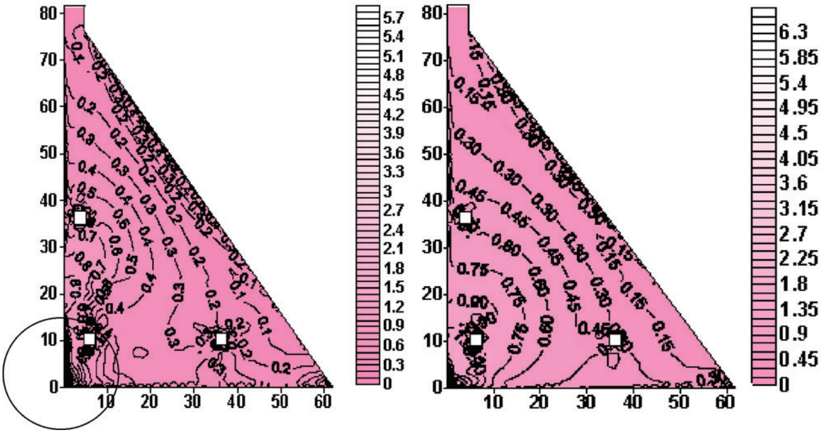
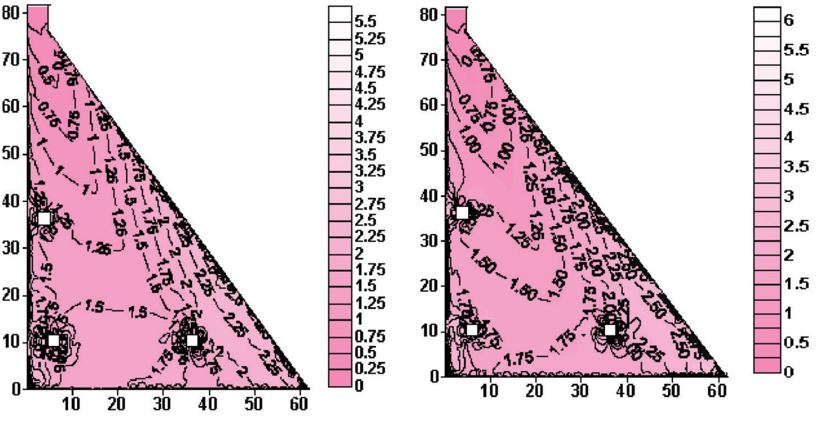


Fig. 11: Time history graphs of the horizontal displacement at crest



(a) With sediment *(b) Without sediment*

Fig. 12: Envelopes of the contour lines of peak maximum principal stress in the RCC dam



(a) With sediment *(b) Without sediment*

Fig. 13: Envelopes of the contour lines of peak minimum principal stresses in the RCC dam

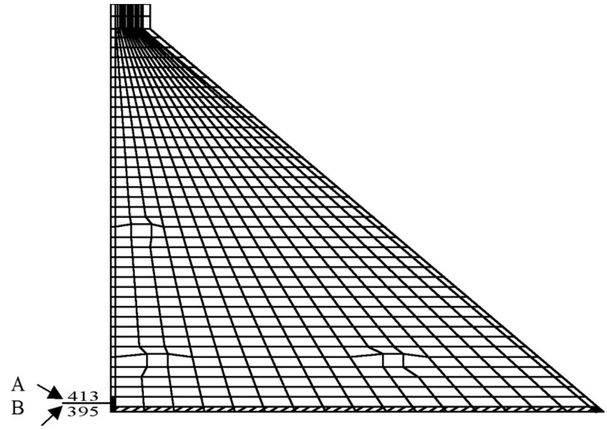
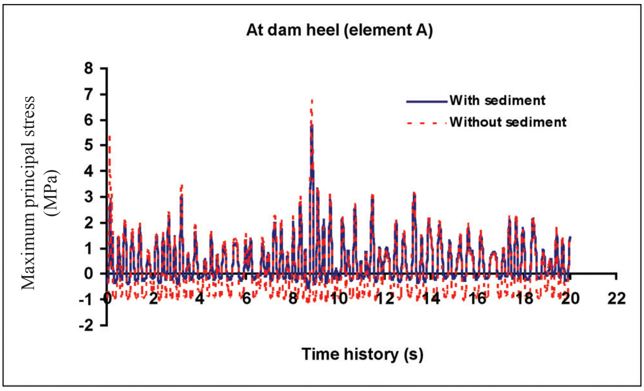
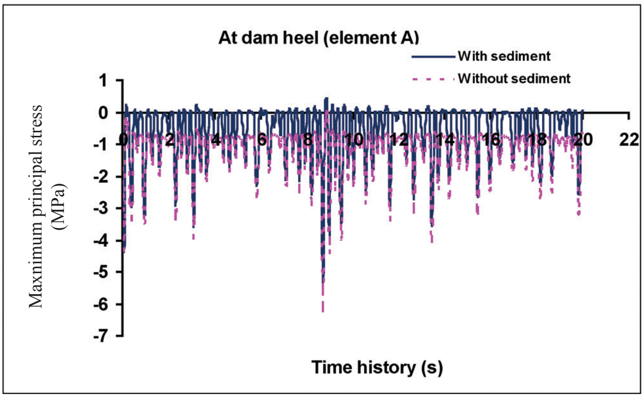


Fig. 14: Selected elements on the finite element mesh

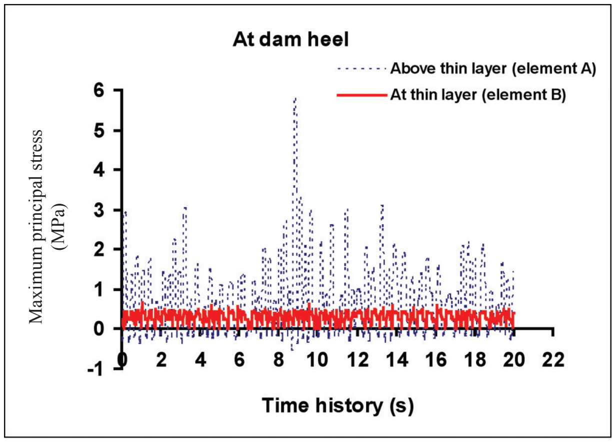


(a) Maximum

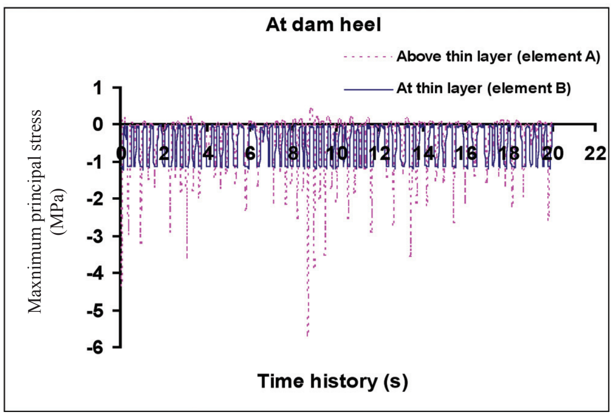


(b) Minimum

Fig. 15: Time history responses of the maximum and minimum principal stresses at the heel of the RCC dam, with and without sediment effect



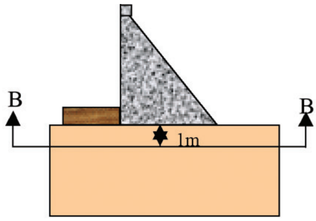
(a) Maximum



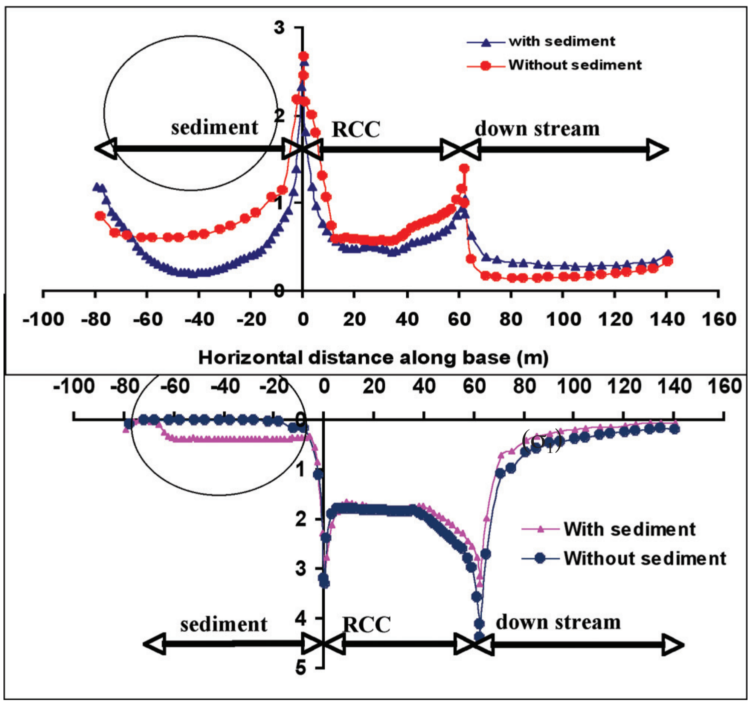
(b) Minimum

Fig. 16: Time history response of the principal stresses, above and within the thin layer interface with the effect of sediment

Based on this analysis, these elements were then selected together with the other elements at the thin layer interface element to plot the time history response graphs so as to trace the dam response at the dam heel. The location of those elements is marked on the mesh, as shown in *Fig. 14*. The responses of the maximum and minimum principal stresses occurred in these elements are presented in *Figs. 15-16*. The maximum peak tensile stress (σ_1) is represented in element 413, i.e. at the base of the dam at the upstream faces. This value reaches approximately 5.7 and 6.7 MPa for the two cases, indicating a reduction in the value of the peak tensile stress by about 15% due to the sediment effect. The analysis leads to a maximum peak compressive stresses of (σ_3) -5.6 and -6.2 MPa for the two cases. Similar to the tensile stress, the presence of the sediment has also reduced the compressive stress. The reduction in the compressive stress is about 10%. The seismic response in terms of stresses above and within the thin layer interface can be observed in the graph of the time history response with sediment effect *(Fig. 16)*. The stresses within the thin layer reflect the response when the modified Mohr-Coulomb failure criterion governs the



(a) Tensile



(b) Compressive

Fig. 17: Variation of the peak tensile and compressive principal stresses along section B-B on the dam foundation

behaviour of the thin layer between the RCC dam-bedding foundations. Meanwhile, the peak values of the tensile stress (σ_1) is 5.7 MPa and the compressive stress (σ_3) is 5.6 MPa, which are located at the dam heel. The distribution of the stresses in the thin layer interface during the plasticity is also shown in *Fig. 16*. The peak tensile and compressive principal stresses range between 0.7 to -1.2 MPa, respectively. A comparison of the seismic response above and within thin layer demonstrates that there is a redistribution of the stresses at the thin layer leading to stress reduction. This is due to the release of stresses during debonding and slipping deformations.

The predicted stresses at the rock foundation, with and without sediment effects, are summarized in *Fig. 17*. These plots are made at section B-B which is located 1 m below the foundation elevation. For the whole foundation response, the peak tensile value was located below

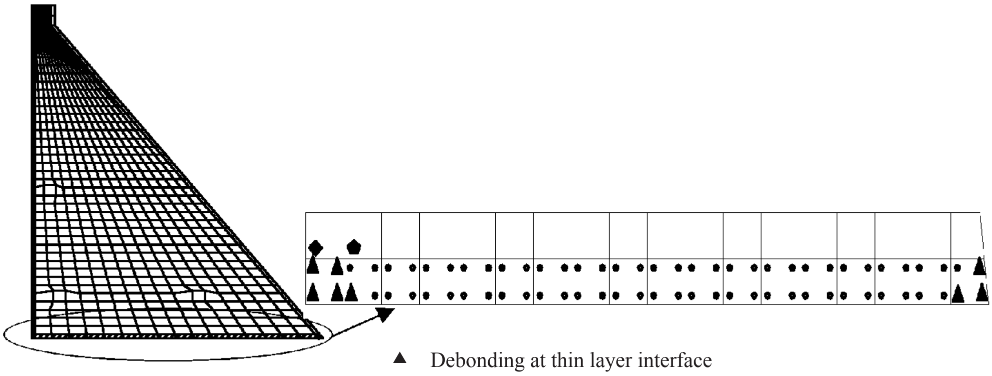


Fig. 18: Spread of plasticity at the base of the dam at 20.0 sec. of earthquake excitation

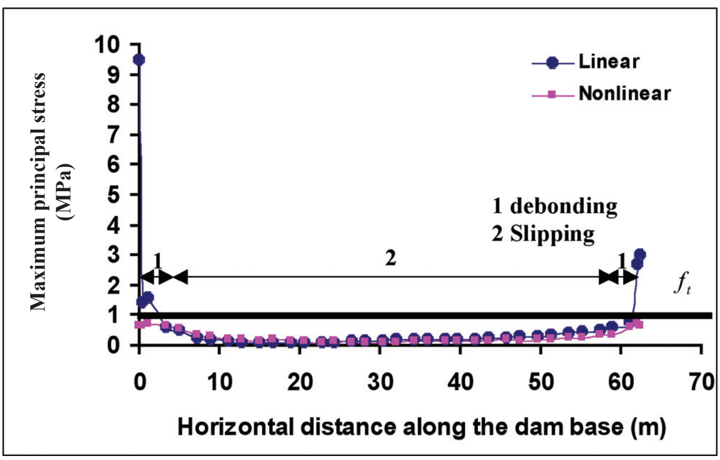


Fig. 19: Debonding and slipping deformation at the thin layer interface elements

the heel of the dam and the peak compressive value was located below the toe of the dam. The seismic response of the tensile and compressive stress is clearly affected by the presence of the sediment.

Fig. 18 summarizes the results gathered from the distribution of the plastic deformation at the lower part of the dam and at the end of the earthquake excitation (t=20 sec). The results of the non-linear elasto-plastic analysis carried out at the lower part of the dam show that the plasticity deformation occurred at about 74 Gauss points after 20 sec of seismic excitation. The locations of these points are presented in the CVC and RCC dam and in the thin layer interface at the base of the dam. The printed index refers to debonding and slipping deformation at the thin layer interface elements, as shown in *Fig. 19*.

Based on the results, the overall trend of the seismic response is found to be higher for the RCC dam without the reservoir bottom sediment as compared to the dam with the reservoir bottom sediment. This finding indicates that the reservoir bottom sediment has a certain effect on the dynamic analysis of the RCC dam-reservoir-sediment-foundation interaction. The results for the effect of the bottom reservoir sediment are generally in agreement with those obtained by Zhao (1995).

CONCLUSIONS

An investigation into the effect of reservoir bottom sediment on the seismic response of the RCC dam was carried out using the coupled finite-infinite elements. For this purpose, the non-linear elasto-plastic time history analysis was also applied to the dam-reservoir-sediment-foundation interaction, with special emphasis given to the non-linear behaviour of discontinuous along the dam-bedding foundation. A thin layer element was utilized to simulate the actual behaviour between the RCC dam and bedding foundation.

Therefore, the following conclusions can be made based on the findings of the present study:

1. Since the far field of the system was modelled using the infinite elements, the infinite extension of the foundation could be simulated more appropriately. Thus, the finite-infinite coupled method is more suitable for the seismic analysis of the RCC-sediment-foundation interaction.
2. The implementation of the failure mechanism of the thin layer interface element was carried out based on modified Mohr-Coulomb failure criterion. The major advantage of such formulation is that it permits computerized programming of the yield function which allows deformation modes such as debonding, slipping, and crushing.
3. The overall trend of the response of the RCC dam-bedding system is observed to have been affected by the bottom sediment. Thus, the reservoir bottom sediment has significant effect on the seismic response of the RCC dam-reservoir-sediment-foundation interaction.
4. The failure mode of the thin layer interface element is debonding and slipping mode of deformation. The results demonstrate that the deformation model is able to predict the non-linear behaviour of discontinuity.

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