SIMULATION OF THE NON-LINEAR SEISMIC RESPONSE OF AN ARCH DAM

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SUMMARY

This paper reports on a study of the behaviour of arch dams in large earthquakes through an analytical simulation of the recorded response of a dam in a recent earthquake. The Pacoima Dam was chosen for the simulation study as unique records are available of the motion of the dam structure and the surrounds during the Northridge Earthquake.

The analytical simulation of the Pacoima Dam response was carried out using a finite element model of the dam, the reservoir, and the surrounding foundation. The non-linearity of the contraction joints was modelled using discrete joint elements. The near field foundation region was modelled with mass to account for variation in ground motion around the base of the structure. The model was calibrated using system identification techniques developed for the study.

The study achieved a good match between the analytical and recorded response. The developed system procedure identification proved to be a good practical means of calibrating an arch dam model.

INTRODUCTION

The evaluation of the behaviour of an arch dam in a large earthquake is a challenging engineering problem. The seismic behaviour involves the three-dimensional non-linear action and interaction of the dam structure, the reservoir, and the foundation. There has been a good deal of research in the field of arch dam seismic behaviour and analysis, however there are still short-comings in a number of areas. A major area where work is still required is in the verification and application of analysis methods. This process has been impeded by a shortage of observational data. Few arch dams have been subjected to strong earthquakes, and few records are available.

Perhaps the best data available for the seismic behaviour of an arch dam are records for the Pacoima Dam in the 1994 Northridge Earthquake. An earlier study at the University of Auckland looked at the response of Pacoima Dam during the Northridge Earthquake (Bell & Davidson 1996). This response identification study indicated that non-linear behaviour took place during the earthquake, and that complex excitation conditions existed, including non-uniform base excitation and structure-foundation interaction effects. This study was a prelude to a simulation of the dam behaviour through non-linear finite element analysis.

The aim of the simulation study was to identify a practical, accurate, seismic analysis method for arch dams. Originally it was envisaged that this would principally involve the development of a suitable system identification method which may be used to calibrate existing analysis procedures. However from the earlier response identification study and preliminary analysis investigations, it became apparent that the problem could not be treated with a formalised system identification procedure as a consequence of the uncertainties in the data and dam analysis methods. The level of uncertainty was such that the precise identification of system parameters could be meaningless. Ultimately the principal focus of the study was on the selection of the most appropriate analysis methods and data, based on the findings of the response identification study. Given these factors, a simple system identification method was developed and applied to refine the analysis process.

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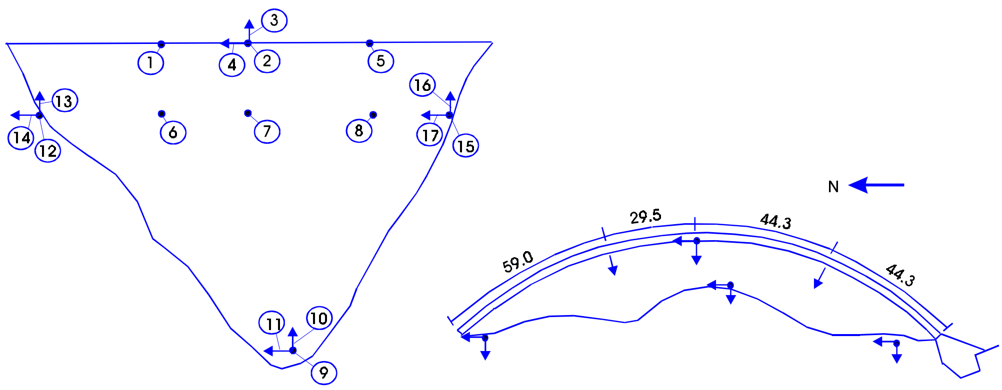
PACOIMA DAM

Pacoima Dam Data

The Pacoima Dam is a 113m high concrete arch dam located in the San Gabriel mountains in Los Angeles County. The dam was 19km from the Northridge earthquake epicentre. The dam experienced intense excitation and sustained some damage to its left abutment during the earthquake. Contraction joint opening and some cracking and block offset in parts of the dam were reported (MKC 1994). Northridge earthquake accelerations were recorded by strong motion recorders at three stations at the Pacoima site (CSMIP, 94a,94b,95); 'Pacoima Dam - Downstream' (the base of the canyon approximately 130m downstream from the dam), 'Pacoima Dam - Upper Left Abutment' (a rock out-crop near the dam abutment), and 'Pacoima Reservoir - Pacoima Dam' (the dam structure and dam interface). The sensor locations for this station are shown in Fig. 1. The majority of the Pacoima reservoir station records could not be fully processed as the traces of the channels became interwoven during the period of peak acceleration.



Elevation - Downstream face Plan

Figure 1. Pacoima Dam Strong Motion Recorder Sensor Locations

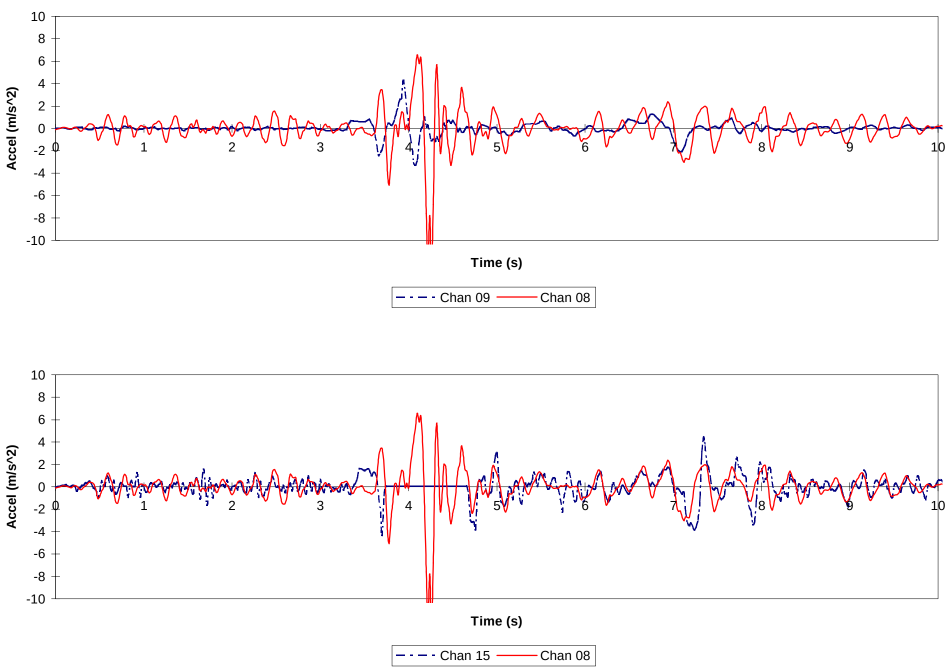


Figure 2. Comparison of base, upper abutment, and dam acceleration records

Characteristics of the Pacoima Northridge Response

The earthquake ground motion was found to vary significantly around the dam site. A peak ground acceleration of 0.44g was recorded at the base of the dam, while a peak acceleration of 1.5g was recorded on the upper left abutment. In general there was a significant amplification of the ground motion from the canyon base to the dam abutments. The motion recorded on the body of the dam down from the crest (channels 6 and 8) was very similar to that recorded at adjacent abutments, as shown in figure 2. At the dam crest the motion was amplified with accelerations of over 2g recorded. The dam crest motion had similar frequency characteristics to the abutment motion. The comparison of abutment and dam motion dam indicated that there was significant structure-foundation interaction in these areas. The ground motion at the dam base was found to be similar to the motion at the downstream site. The base records therefore provide a reasonable approximation of the base free-field motion at the dam site.

The earlier response identification study (Bell & Davidson 1996) indicated that there was a reduction in the dam system stiffness during the earthquake. This was consistent with the observations of joint opening and damage at the left abutment. The first four effective principal modes were identified at frequencies of 4, 4.5, 6 & 7.5 Hz. A detailed study of record segments identified the modal frequencies prior to the first arrival of the S-wave as approximately 4.8, 5.4, 6.8, and 8.0 Hz, and the typical modal frequencies following the pulse as 3.8, 4.7, 6.3, and 7.5 Hz. Modal damping was found to be typically in the 6 to 9 percent range.

ANALYSIS PROCEDURE

The non-linear behaviour of the dam structure was likely to be the result of opening of the vertical contraction joints. This form of discrete non-linearity can be modelled efficiently with local non-linear joint elements. Non-linear behaviour of the foundation region is likely to be more complex and could be distributed throughout the region. To model this non-linearity precisely would require an involved model and extensive calibration. Further, the analysis effort would be greatly increased. An alternative approach that was adopted, was to use an equivalent linear-elastic model that could be fitted with the response data.

There are a number of ways to model the structure-foundation interaction and site response. In general analysis methods fall into two categories. The first involves the application of the varying site free-field motion to the base of the structure, with an idealised foundation model accounting for stiffness and possibly damping effects. The second approach involves a rigorous model of the near and far field foundation including travelling wave effects. With this structure-foundation and site response effects are accounted for explicitly in the analysis.

The application of non-uniform motion to the base of the dam structure at first appeared to be the most attractive approach. However such a approach requires a reasonable knowledge of the site ground motion. At the Pacoima Dam site there were a number of major shortcomings in the measured response data. The records at the abutments could not be processed with accuracy due to gaps during the period of peak response, and there was no information on cross-stream motion on the left abutment. Further, the Pacoima response study (Bell & Davidson 1996) indicated that structure-foundation interaction rather than local site response effects were likely to be the dominant feature in the motion of the ground around the dam abutments. Therefore the recorded motion was likely to vary greatly from the free-field motion.

Given the number of potential shortcomings of an analysis of Pacoima Dam using generated non-uniform input motion, the alternative analysis approach of using a rigorous foundation model was investigated. Preliminary analyses of the Pacoima Dam system indicated that abutment motion similar to that recorded could be produced if the foundation adjacent to the dam was modelled with a relatively low stiffness. This suggested that more realistic modelling of the abutment topography and material properties, along with some model calibration could produce the desired abutment motion. A practical means of modelling the foundation system with conventional finite element programs would be to model near-field and far-field finite element regions. The near field region would model the major structure-foundation interaction features, while the use of the far-field model would avoid errors which can occur when the travelling wave effects at model boundaries are not modelled.

The Pacoima Dam simulation analyses were carried out using SAP2000(CSI 1998), a general purpose structural analysis finite element computer program. SAP2000 provides for a efficient non-linear analysis of systems with discrete non-linearites. Further SAP2000 allows for the analysis of structure foundation effects, either through the application of non-uniform motion, or through the application of a dynamic load to the structure. SAP2000 has an advantage over customised research programs in its pre- and post- processing capabilities. This is an important factor in an arch study given the complex structural form and the great volume of data involved.

Pacoima Dam Modelling and Analysis

The dam structure was modelled as a series of cantilever blocks connected by non-linear joint elements. Each cantilever block was modelled with a single layer of 3-D eight-node solid elements that include nine incompatible bending modes. The foundation was modelled as an idealised nominally semi-spherical region centred on the dam structure. The shape of the foundation model represents the general topography in the region of Pacoima Damand solid elements were used with incompatible bending modes suppressed. The region of the foundation adjacent to the dam was modelled with mass, while the remainder of the foundation was modelled as massless. The dam and foundation models are shown in figure 3. These models were formed using enhanced versions of the mesh generators of the ‘ADAP-88’ finite element program (Fenves et al 1989). Hydrodynamic action was accounted for through the inclusion of added mass on the dam face. This was calculated using the ‘Resvor’ finite element program (Fenves et al 1989).

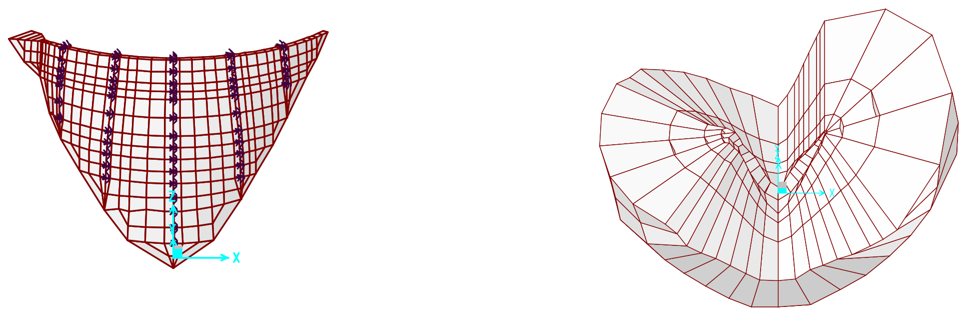


Figure 3 Pacoima Dam Structure & Foundation Finite Element Model

The Pacoima response study (Bell & Davidson 1996) indicated that satisfactory modelling of the structure foundation interaction could be the key to simulation of the dam response. Therefore for the purpose of the present study, the foundation model was divided into five arbitrary regions: the ‘far-field’ region, modelling stiffness only, three ‘near-field regions; the upper left abutment, the upper right abutment, and the lower abutments. The upper abutments were modelled separately as earlier site studies (MKC 1994) and post-earthquake inspections indicated that there was likely to be significant reductions in stiffness and strength in these regions. Further, the dam response records suggested that motion at the abutments may have been the result of low stiffness in these regions.

The Pacoima Dam model was subject to hydrostatic and seismic loading. The hydrostatic load was applied as pressure loading on the upstream face of the dam solid elements. The seismic loading was applied as an acceleration of the system mass. Three components of ground motion were applied. The records of the ‘Pacoima Downstream’ site were used, representing far field free-field motion.

The Pacoima Dam model was refined through a series of system identification analyses in an attempt to simulate the recorded response. Parameters selected for identification were the elastic modulus of the three near-field foundation regions, the equivalent viscous damping, and the elastic modulus of an equivalent linear dam. An equivalent linear dam was used during the identification stage as preliminary analyses indicated that the additional effort in modelling joint non-linearity was not warranted. The joint non-linearity was introduced following the identification of the other parameters.

The selected model parameters were adjusted so as to provide a best fit of the model response with recorded motion at chosen locations on the dam and the dam abutments. Those chosen were the upstream components of motion on the right and left abutments, channels 12 and 15 respectively, and the radial components of the dam motion on the right and left sides, channels 06 and 08 respectively. These records were chosen so as to reproduce the amplified motion of the abutments and relative motion of the dam in these areas. The selection of these records also had the advantage of being less influenced by the dam non-linearity. Due to the gaps in the acceleration records, only a portion of the records was considered. Comparisons were made of the smoothed Fourier amplitudes of 5.12 seconds segments, centred on 7.0seconds. A Hanning 'bell shaped' window was used in the calculation of the spectra. The system identification procedure developed for the Pacoima study is summarised below and described fully in Bell (2000).

INDENTIFICATION PROCEDURE

The identification procedure developed works interactively with the finite element analysis program used to model the dam system. The key aspects of the procedure are the methods used to calculate the system response and gradient values which are used in the identified parameter update process. Ideally these values are obtained directly from finite element analyses. This however is generally impractical due to the enormous computational effort involved in the non-linear seismic analysis of an arch dam. As it would be necessary to calculate the parameter gradients numerically from FEM analyses response values, each step in an iterative identification process would require at least n+1 full time-history analyses (gradients calculated using forward differences), where n is the number of parameters to be identified. Given the processing time for each FEM analysis, the total time required for one full identification analyses would be prohibitive.

To make the FEM model identification practical, it is necessary to minimise the number of full FEM analyses performed. The identification scheme used in this work achieves this by carrying out a series of local parameter identification analyses with response and gradient values calculated numerically from previous FEM analysis responses. This is equivalent to performing identification analyses on a series of numerical or quasi-equivalent models of the dam system. Each model is formed by fitting a numerical series (for this study a Taylor's series) to the FEM model in the region of the current parameter estimates. The model is used to estimate the optimum parameter values in the region. A new local model is then formed around the new solution, and the procedure is repeated until satisfactory convergence. The procedure increases efficiency by effectively increasing the number of identification iterations for each series of FEM analyses.

Procedure Algorithm

1. Initialise identification process
   - a) Select initial solution estimate and parameter bounds
   - b) Select Taylor's series model order and cross-parameters terms
   - c) Select data points for formation of initial Taylor's series model
   - d) Carry out finite element analyses for initial data sets
   - e) Calculate error measure each initial data set
2. Form model with weighted least squares best fit to initial data points
3. Carry out finite element analyses for new solution estimate
4. Calculate error measure for new solution estimate
5. Test for completion
6. repeat 2 to 6 until completion

ANALYSIS RESULTS

The model identification procedure was produced the following estimates of the model parameters.

Lower Abutment Elastic Modulus:	17 GPa
Upper Left Abutment Elastic Modulus:	0.5 GPa
Upper Right Abutment Elastic Modulus:	1.0 GPa
Dam Equivalent Linear Elastic Modulus:	22 GPa
Equivalent Viscous Damping:	8 %

A comparison of the model and recorded responses using these parameter values was remarkably good given the simplified foundation model used. Figures 4 shows the comparison for the four records chosen for the identification process. Figure 5 shows a comparison for the motion of the crest at the crown of the dam. As the motion of the dam crest was not included in the identification process, these records provided an independent check on the behaviour of the model. The motion of the dam and the abutments varied significantly from the input motion. This would appear to support the analysis approach of considering the combined dam and foundation system, rather than the dam structure alone.

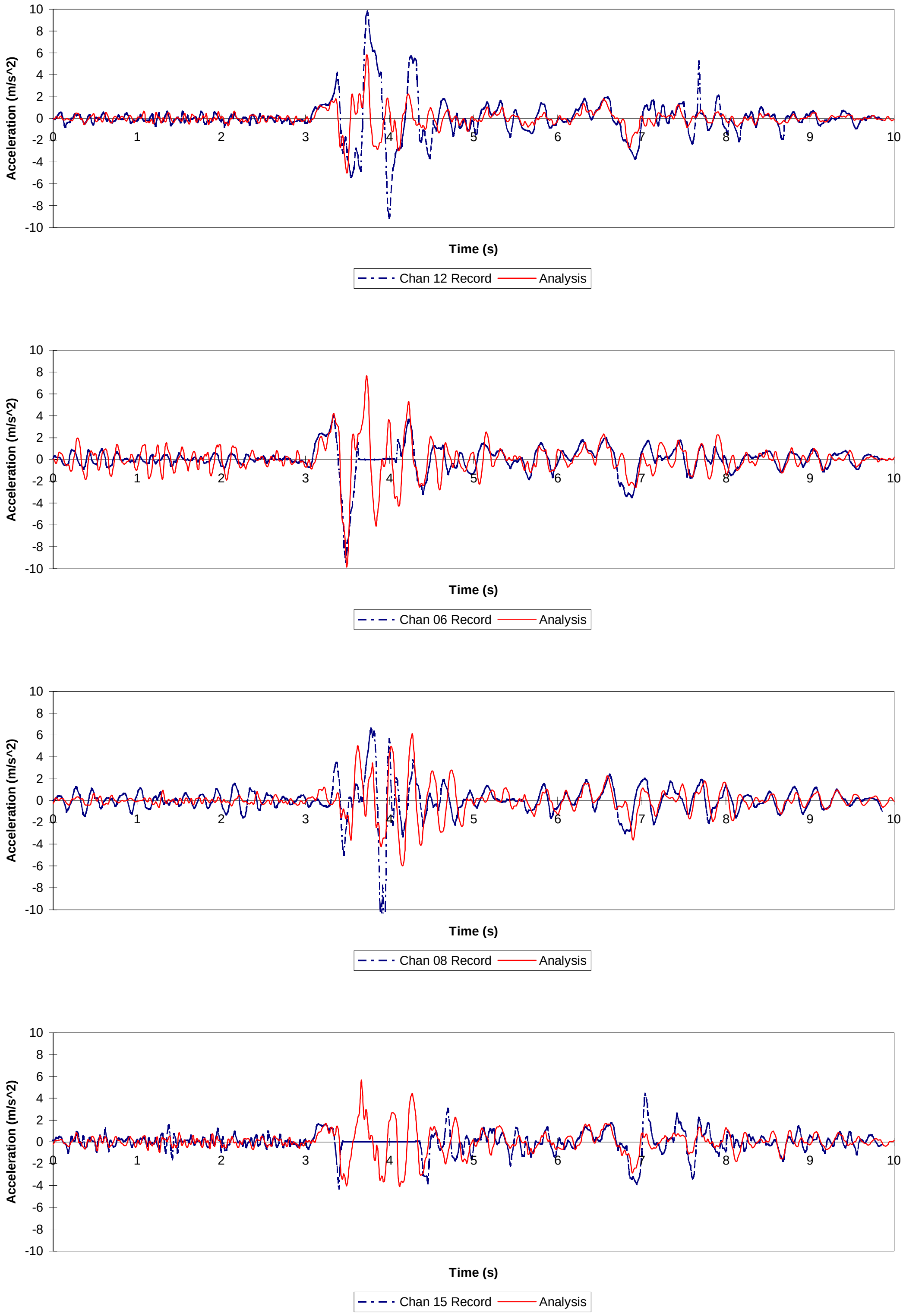


Figure 4. Comparison of acceleration records with results of equivalent linear analysis

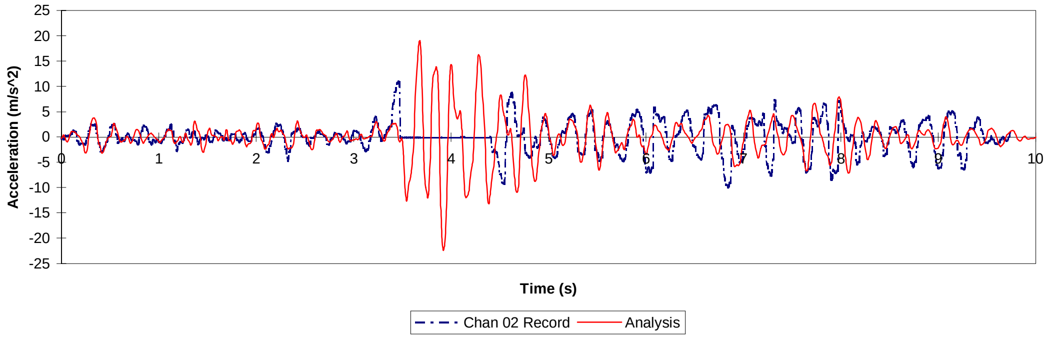


Figure 5 Comparison of crest acceleration record with results of equivalent linear analysis

The elastic modulus values of the upper abutments identified in these analyses are very low. There is evidence to support a low modulus for the left abutment (MKC 1994). Earlier site tests indicated values in the range of 0.5 to 5.0 Gpa (WLA 1971). Further, post-earthquake inspection of the dam site indicated that damage occurred in the region. The elastic modulus used may therefore be seen as an effective linear modulus. For the upper right abutment, it might be expected that the elastic modulus would be somewhat higher. However it needs to be considered that the value was identified for a simplified model and may account for topographic and jointing effects not considered explicitly.

It should be noted that the values of the model parameters and analysis model used are applicable to the damaged dam system under large motion. For this state, a characteristic vibration frequency of the system was in the order of 4 Hz. For the initial stages of the earthquake event, a characteristic vibration frequency of approximately 5 Hz was apparent. The 5 Hz frequency is in agreement with those determined from vibration testing (Hall, 1988). This would apply to low levels of vibration, and may be applicable to the dam structure rather than the dam-foundation system. A fundamental frequency in the order of 5Hz was obtained by analysis for the dam model with a moderately stiff foundation.

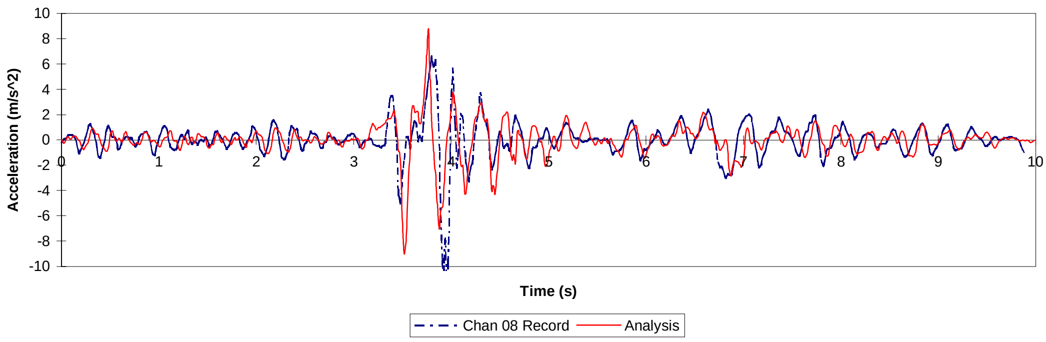


Figure 6 Comparison of channel 8 record with results of non-linear analysis

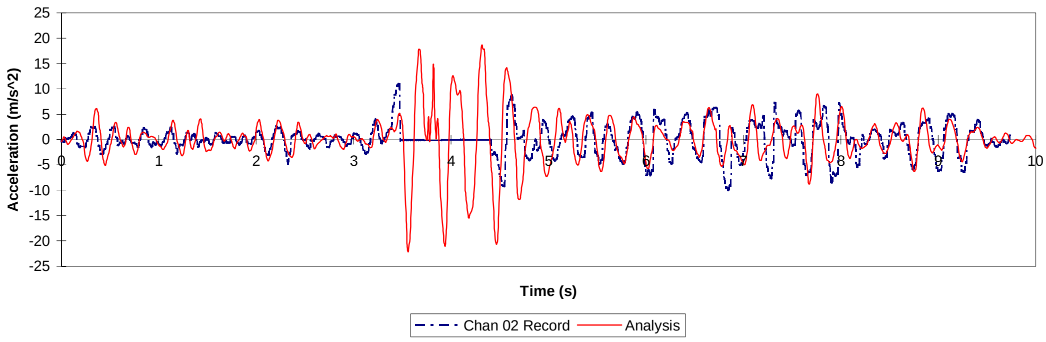


Figure 7 Comparison of crest acceleration record with results of non-linear analysis

Non-linear analyses modelling dam contraction joint opening typically produced a better of fit of high amplitude response. For the channels used to fit the equivalent linear model, the non-linear analyses produced similar motion to the linear analyses, except during the period of peak response (3.5 - 4.5 seconds) where a better fit was observed. A comparison of the recorded and non-linear analysis response for channel 8 is shown in figure 6. The most significant difference between linear and non-linear analysis results was apparent at the dam crest. The non-linear analysis produced a better fit with the recorded motion for throughout the period of strong motion, as shown in figure 7.

CONCLUSIONS

The principal response features of Pacoima Dam in the Northridge Earthquake were successfully reproduced through relatively simple modelling of structure-foundation interaction and dam non-linearity. The analysis model was calibrated using a general purpose system identification procedure. The study indicated that the key to achieving a good match of analytical and recorded response for Pacoima Dam was the modelling a flexible upper abutment foundation region

The study demonstrates a practical means of performing accurate seismic analysis of an arch dam, and shows the importance of modelling structure-foundation interaction. The study also provides a base for the more detailed study of aspects of arch dam behaviour.

ACKNOWLEDGEMENTS

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