11 WCEE

Paper No. 774. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

RESPONSE IDENTIFICATION OF PACOIMA DAM FOR THE 1994 NORTHRIDGE EARTHQUAKE

D.K.BELL & B.J.DAVIDSON

Department of Civil and Resource Engineering, School of Engineering, University of Auckland
Private Bag 92019, Auckland, New Zealand

ABSTRACT

A research programme is underway at the University of Auckland to determine the response characteristics and input conditions for Pacoima Dam during the 1994 Northridge earthquake. A network of strong motion recorders at the dam site have provided unique data on the behaviour of an arch dam system in a large earthquake. This paper reports on a frequency domain study of the dam acceleration records. The study shows the presence of nonlinear behaviour of the dam structure during the earthquake, and discusses topographic amplification and structure-foundation interaction effects around the dam structure. The study identifies principal modal frequencies, which indicate significant changes in the stiffness of the dam system.

KEYWORDS

Pacoima Dam; Northridge earthquake; Response identification; Modal identification

INTRODUCTION

The seismic behaviour of an arch dam in a large earthquake involves complex three-dimensional nonlinear action and interaction of the dam structure, the reservoir, and the foundation. In recent years a number of sophisticated arch dam analysis tools have been developed, however the development and application of these tools has been impeded by a shortage of observational data. Significant data has recently become available from the behaviour of Pacoima Dam in the 1994 Northridge earthquake. A number of strong motion recorders at the dam site have provided records of the motion of the dam structure and the surrounds during the earthquake.

A research programme is underway at the University of Auckland to determine the response characteristics of Pacoima Dam using the Northridge strong motion records. This response identification programme aims to provide information on arch dam seismic behaviour which may be utilised in the calibration of analysis tools, and in the identification of mechanical parameters and damage of dam systems. The focus of the research programme is on the identification of resonance features of the dam system, such as modal frequencies, and the detection of nonlinearity in the dam system. Also of interest is the form of the exciting ground motion, in particular, any variation in motion around the dam structure and any structure-foundation interaction effects.

This paper reports on frequency domain response identification studies using Fourier transforms of the dam acceleration records. Frequency domain procedures limit the order of the problem and provide some resilience to measurement noise and input uncertainty. Initially time-varying frequency spectra were calculated to identify the general response characteristics. By calculating frequency spectra of progressive segments of the time records, it is possible to identify nonstationary trends in resonance features, and to make comparisons between resonance features of nonstationary processes at different measurement locations. Following this general identification an attempt was made to identify specific modal parameters with a system identification procedure which uses the frequency domain equation of motion. The procedure involved a least squares best fit of a transformed segment of response record with the Fourier amplitude calculated for a dam system which has multi-component ground excitation.

RESPONSE IDENTIFICATION PROCESS

Time Varying Fourier Spectra

The frequency response of a dynamic system may be obtained via the Fourier transform. A discrete Fourier transform of a time record produces a complex spectrum comprising of the time-averaged response components of discrete frequencies. For a nonstationary system the frequency spectrum derived from a full response record can be viewed as the spectrum of an equivalent stationary system. Such a spectrum tends to be dominated by system characteristics during the peak amplitude portion of the time record. Fourier transforms of a series of segments over the length of a nonstationary time record yield a series of frequency amplitude spectra which follow variations of the record vibration properties with time. For a series of narrow overlapped time segments these spectra effectively represent a time-varying frequency spectrum (Safak 1986), where response amplitudes are given as a function of both frequency and time. This effectively gives a frequency spectrum for a nonstationary process.

In a time-varying frequency spectrum the spectral values at a time ordinate are not instantaneous values, rather they are average values for the time segment centred on the time ordinate. A time segment must be of sufficient length and contain a sufficient number of data points to capture the vibration characteristics of a system, so there is a limit on the time resolution of a spectrum that may be achieved. There is also a limit to the frequency resolution of the record due to the time segment length. The Fourier transform of a finite record is effectively a convolution of the full record transform with a transform 'window' of finite length. This can result in a smearing of the spectrum along the frequency axis. Time and frequency resolution can be improved by using a non-rectangular segment window. This places more importance on the data at the centre of the segment, and removes the discontinuities from the end of the records.

The resolution of a time-varying spectrum is in part dependant on the nature of the application. Earthquakes are typically highly nonstationary events of short duration, therefore small record segments must be used to track changes in system properties. For high rise buildings, which are low frequency systems, this can lead to frequency resolution problems. For arch dams, however, reasonable frequency resolution can obtained due to the relatively high fundamental frequencies of these systems (in the order of 5Hz). Time-varying spectra are therefore likely to be a useful tool for the analysis of arch dam systems. For the study of the Pacoima dam response, spectra were produced from 2.56 second segments at 0.64 second centres using a Hanning 'bell shaped' window. This effectively provides a time resolution of approximately 1.5 seconds and a frequency discretization of 0.4 Hz.

Modal Identification

An arch dam response record typically contains significant contributions from a number of closely spaced modes, and may be a function of all three components of ground motion. Arch dam modes can generally be categorised as symmetric, excited by upstream and vertical motion, and antisymmetric, excited by cross-stream motion. Both types of modes make contributions to upstream and cross-stream motion throughout the dam structure. Often two or more modes may have very similar frequencies, and their order may be sensitive to the relative flexibility of the foundation and structure. The frequencies of the first antisymmetric and first symmetric modes in particular tend to be very close.

The complexity of an arch dam response means that traditional methods cannot be used to identify modal parameters. Instead some form of system identification process involving the optimisation of a system model must be used. Frequency domain system identification may be performed using the standard frequency domain form of the modal equation of motion as the system model. Equation 1 gives the frequency response spectrum of a system, $Q(\omega)$, as a product of the frequency input spectrum, $Z(\omega)$, and a complex function of the system modal properties, the frequency transform function $H(\omega)$. The frequency transfer function is a summation of modal components, each component a function the mode frequency, ω_i, damping, ζ_i, and participation factor, c_i, corresponding to the specified input form.

$$Q(\omega) = H(\omega).Z(\omega) \tag{1}$$

The frequency domain equation may be extended to nonstationary systems by applying it to a series of time segments and making allowance for non-zero end conditions. This then represents the nonstationary system as a series of equivalent stationary systems. The modal identification procedure of McVerry (1980) uses this approach with the end condition effects calculated directly by the Fourier transform of the time-domain equation, and described by residual velocity, $V(\omega)$, and displacement, $D(\omega)$, terms. The response of each time segment is then given by equation 2.

$$Q(\omega) = H(\omega).Z(\omega) + V(\omega) + D(\omega) \tag{2}$$

The velocity and displacement terms are functions of the modal parameters and the differences between the modal velocities, v, and displacements, d, at beginning and end of the time segment. With this form of equation McVerry identified the modal parameters of two-dimensional systems for seismic loading through a least squares fit of the frequency response spectrum.

For an arch dam system the frequency response equation must be extended to account for the three-dimensional nature of the system. The response of the dam system is a function of three orthogonal components of input motion, $Z_X(\omega)$, $Z_Y(\omega)$, $Z_Z(\omega)$, and three transfer functions, $H_X(\omega)$, $H_Y(\omega)$, $H_Z(\omega)$, each a function of some or all of the system modes.

$$Q(\omega) = H_X(\omega).Z_X(\omega) + H_Y(\omega).Z_Y(\omega) + H_Z(\omega).Z_Z(\omega) + V(\omega) + D(\omega) \tag{3}$$

With this equation, modal participation factors are required for each component of input motion for each mode, therefore additional degrees of freedom are introduced to the system model. This form of the equation was used in the Pacoima study modal identification process. The identification process amounted to a least squares optimisation problem which was solved using the Levenderg-Marquadt, Gauss Newton method. The identification algorithm is described in detail in Bell & Davidson (1996).

The modal identification process was tested on a low degree of freedom arch dam model. The process was found to be reasonably resilient to noise in both the input and the response data. Modal frequencies showed little sensitivity to noise. Damping and participation factors showed some sensitivity, a result of the high coupling between these factors for a given mode. Phase bias in the response records, brought about by a time lag between input and response records, was found to introduce significant errors in damping and participation factor values. These errors were eliminated when the identification algorithm was amended to a fit of the frequency response amplitude (rather than the complex form of the response spectra).

PACOIMA DAM RESPONSE

Pacoima Dam Data

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 (Norton et al, 1994). Contraction joint opening and some cracking and block offset in parts of the dam were reported (Fenves & Motjahedi, 1995).

Northridge Records. Northridge earthquake accelerations were recorded by strong motion recorders at three stations at the Pacoima site (CSMIP, 94a). The 'Pacoima Dam - Downstream' station provided records of downstream, cross stream, and vertical components of motion at the base of the canyon approximately 130m downstream from the base of the dam. The 'Pacoima Dam - Upper Left Abutment' station provided records of three components of motion on a rock out-crop near the dam abutment. The 'Pacoima Reservoir - Pacoima Dam' station provided a number of records on and around the dam structure. The sensor locations for this station are shown in Fig. 1. The Pacoima reservoir station records are incomplete. All of these records were terminated after 11 seconds when the instrument system failed. Additionally the traces of a number of channels became interwoven during the period of peak acceleration (3.5 -4.5 sec.), and therefore could not be digitised in this region. Full, processed records are available for channels 9,10,11 (dam base), and channel 8 (dam left 1/4 point: 80% height) (CSMIP, 94b). Partially processed records with some portion of the period of peak acceleration missing are available for channels 1-6, 12, 13, 15-17 (CSMIP, 95). The channel 12 record is almost complete, with a break of only 0.05 seconds.

Modal Data. Tests carried out on Pacoima Dam have identified the frequencies of the first symmetric and antisymmetric modes as 5.45 & 5.60 Hz (Hall, 1988). Past analyses of the dam have calculated these principal frequencies to be 3.54 & 4.06 (IEC, 1983), 5.20 & 5.25 Hz (Dowling, 1987), and 4.3 & 4.4 Hz (Fenves and Mojtahedi, 1994), and calculated there to be up to 10 modes with frequencies less than 10 Hz.

Characteristics of the Pacoima Northridge Acceleration Records

Fourier spectra. Fourier spectra were calculated for all of the available Pacoima records. Plots of the time-varying spectra for the dam base, the upper left abutment, channel 8, and channel 12 are shown in Fig. 2. Comparisons of the Fourier spectra of dam records for selected time segments are shown in Fig. 3. The spectra for channels 1-6, 12, 13 & 15-17 were calculated from the partially processed records.

Ground Acceleration. The time records of the downstream and dam base motion are very similar. A comparison of the time-varying Fourier spectra at the two sites show the frequency content of the motion to be very similar also. Comparison of these spectra with those of the structure records, and prior knowledge of the dam structural response range, indicate that there is limited structural frequency information in the ground records. This difference, along with the similarity of the base and downstream records, suggest that structure-foundation interaction effects at the base of the canyon are small. The base records may therefore be a reasonable approximation of the base free-field motion at the dam site.

There is a significant amplification of the earthquake ground motion from the canyon base to the dam abutments. A comparison of the abutment spectra with base and dam spectra suggests that for the downstream abutment motion there is significant structure-foundation interaction on top of a broad range topographical amplification (Fig. 3 a-d), while the cross-stream motion amplification is principally due to topographical effects (Fig. 3 e). Differences between abutment and crest cross-stream motion suggests that the abutment cross-stream motion did not fully excite the dam antisymmetric. The acceleration records of the Pacoima upper left abutment site show a further amplification from the dam abutment records. Fourier spectra of the site motion indicate that the resonance of the site was heavily influenced by the local topography, and consequently that the upper left abutment records are not indicative of the input motion to the dam system (Fig. 2 a).

Dam Acceleration: The dam radial acceleration spectra show a principal response peak at about 4 Hz, with other significant peaks at 6, 7.5, and 10 Hz. These values agree well with the values from the 1994 Fenves study, which suggests that some of these peaks contain contributions from two or more modes. Inspection of the Fourier spectra over the length of the records show change in the frequency characteristics over the length of the earthquake (Fig. 2 f). Prior to the period of high acceleration with the first arrival of the S-wave, the first three response peaks are located at somewhat higher frequencies than the typical values, approximately 5, 6.5 & 8 Hz. During a second period of high acceleration the principal peak appears to temporarily split in to two peaks, at 2.5 and 4.5 Hz (Fig 3 a,b).

The shift of the dam frequency response peaks suggests significant reduction in the dam system stiffness due to nonlinearities such as joint opening and abutment movement. While the the response prior the to the first arrival of the S-wave is not directly comparable with the later response (records and spectra indicate that during this period the horizontal dam and abutment motion was induced by the vertical P-wave motion - Fig 3 f), it does appear that there is a permanent reduction in the principal response frequencies of the structure during the first period of strong horizontal acceleration. This would be consistent with a softening of the structure due to the damage at the left abutment and the first opening of joints. The splitting of the principal frequency response spectra peak during the second period of strong acceleration suggests a second, temporary reduction in the structure stiffness. Inspection of the dam time records during this period (Fig. 4) indicates that this feature is a result of the opening of dam joints. A cycle of the fundamental symmetric mode contains two phases, a compression phase at the frequency of the intact dam, and a tension phase at a lower frequency during which opening of the joints occur. The frequency of a full cycle is shown by the first spectrum peak at 2.5 Hz, while the frequency of the compression phase is shown by the second peak at 4.5 Hz.

Pacoima Dam Modal Parameters

The identification of modal parameters using the Northridge records is a difficult task due to the complexity and uncertainty of the input conditions, and the incomplete nature of the dam site records. These factors place severe limitations on the ability to identify the parameters of closely spaced modes. To limit the effects of input uncertainty the identification frequency range was limited to the principal structural response range, 2 - 9 Hz. The Pacoima downstream records were chosen to represent structure-foundation interaction free input.

Modal identification was carried out using the channel 1,2,5 & 8 records as response measures. Preliminary studies of these records with a number of models indicated the presence of symmetric and antisymmetric modes in the 4 Hz region, a symmetric mode in the 6 Hz region, and antisymmetric modes in the 7 - 8 Hz region. Two models, a three mode model [symmetric, symmetric, antisymmetric] with initial frequencies of 4, 6 & 7.5 Hz, and a four mode model [symmetric, antisymmetric, symmetric, antisymmetric] with initial frequencies of 4, 4.5, 6 & 7.5 Hz, were selected as most suitable for the modal system identification analysis.

The modal identification analysis provided approximations of the model modal frequencies and confirmed the observations made on system nonlinearities made from the spectra study, but the input uncertainty prevented the clear identification of the other modal parameters which would allow for verification of the assumed models. The modal frequencies were relatively stable, but the identified damping and participation factors showed high sensitivity. The two identification models gave reasonably consistent frequencies for the common modes, with the four mode model providing a better response fit. The four mode model analysis 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. The first symmetric mode temporarily dropped further during the second shear pulse to an average frequency of approximately 3.0 Hz. Modal damping was found to be typically in the 6 to 9 percent range.

To identify the dam system modal parameters with greater reliability, it would appear necessary to develop a more complex system identification accounting for the input uncertainty. It would also be beneficial to decrease the number of unknowns in the model by specifying values, or relative values, of modal participation factors. This would require the parallel development of a finite element model of the dam system.

CONCLUSIONS

Time-varying Fourier spectra were found to be useful tools for studying the seismic behaviour of an arch dam system. Application to Pacoima Dam Northridge earthquake records revealed a number of important features. Acceleration records at the base of the dam were found to be a reasonable approximation of the free-field motion on the canyon floor. There was significant amplification of ground motion over the height of the dam due to a combination of topographic and structure-foundation interaction effects. Records on the upper left abutment were found to be heavily influenced by local topography and not indicative of the dam input motion. Spectra of dam structure records displayed the principal resonance frequencies of the dam system and indicated the presence of significant nonlinear behaviour. There was a permanent reduction in dam stiffness of the duration of the earthquake, and a temporary reduction in stiffness during periods of high excitation. A proposed frequency domain system identification method identified the frequencies of the principal dam modes during the earthquake, confirming the reduction in structure stiffness. The modal identification study was restricted by the uncertainty and the complexity of the input conditions, and the incomplete nature of the acceleration records.

ACKNOWLEDGMENTS

Support for this study provided by the Electricity Corporation of New Zealand is gratefully acknowledged.

REFERENCES

Bell, D.K. & Davidson B.J. (1996). Frequency Domain Identification of an Arch Dam, *NZNSEE Technical Conference 1996 Proceedings*, New Zealand National Society for Earthquake Engineering.

CSMIP. (1994a). CSMIP Strong-Motion Records for the Northridge, California Earthquake of January 1994. *Report OSMS 94-07*, CSMIP, California Dept. of Conservation, Sacramento.

CSMIP. (1994b). Processed Data for Pacoima Dam - Channels 8 through 11 from the Northridge Earthquake of 17 January 1994. *Report OSMS 94-15a*, CSMIP, California Dept. of Conservation, Sacramento.

CSMIP. (1995). Phase 1 Data for Pacoima Dam - Channels 1-6,12,13,&15-17 from the Northridge Earthquake of 17 Jan. 1994. *Report OSMS 95-05*, CSMIP, California Dept. of Conservation, Sacramento.

Dowling, M.J. & Hall J.F. (1989). Nonlinear Seismic Analysis of Arch Dams. *Journel of Engineering Mechanics*, 115

Fenves, G.L. & Motjahedi S. (1995). Effect of Contraction Joint Opening on Pacoima Dam in the 1994 Northridge Earthquake. *SMIP95 Proceedings*, 57-68, San Francisco, California.

Hall, J.F. (1988). The dynamic and earthquake behaviour of concrete dams: review of experimental behaviour and observational evidence. *Soil Dynamics and Earthquake Engineering*, 7, 58-121.

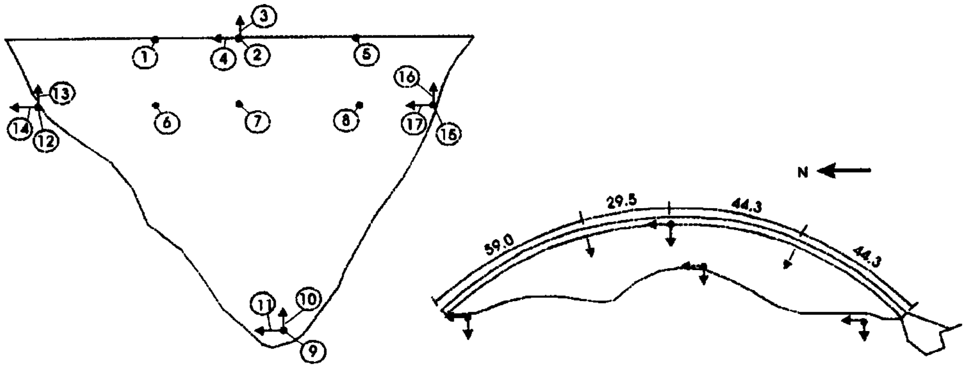
International Engineering Company Inc (1972). *Pacoima Arch Dam, Investigation and evaluation of effects of San Fernando earthquake*. San Francisco, California.

International Engineering Company Inc (1983). *Stability Reanalysis of Pacoima Dam, Final Report*. San Francisco, California.

McVerry, G.H. (1980). Structural Identification in the Frequency Domain from Earthquake Records. *Earthquake Engineering and Structural Dynamics*, 8, 161-180.

Norton, J.A. et al (1994). Northridge Earthquake Reconnaissance Report. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 27, 235-347.

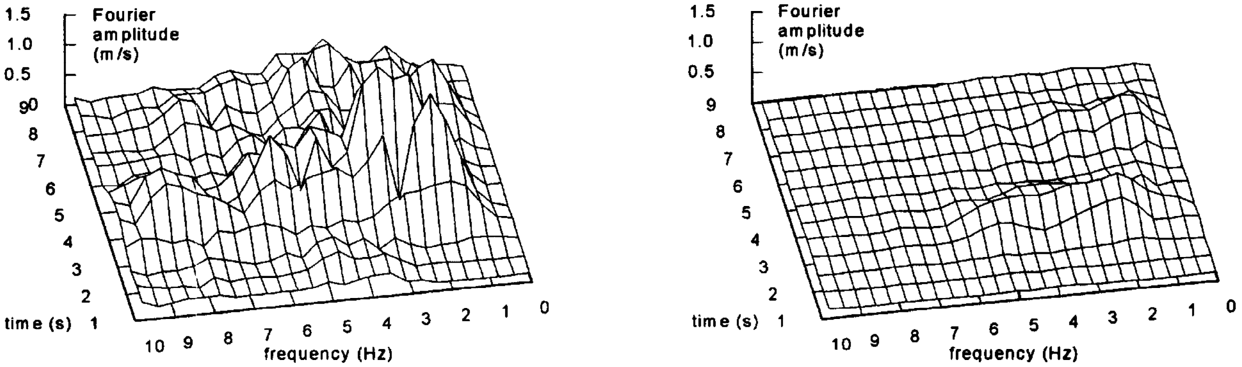
Sakak, E. (1986). Time Varying Characteristics Strong Ground Motion: The Imperial Valley, California Earthquake of October 15, 1979. *Open-File Report 86-443*, U.S. Department of Interior Geological Survey.



Elevation - Downstream face

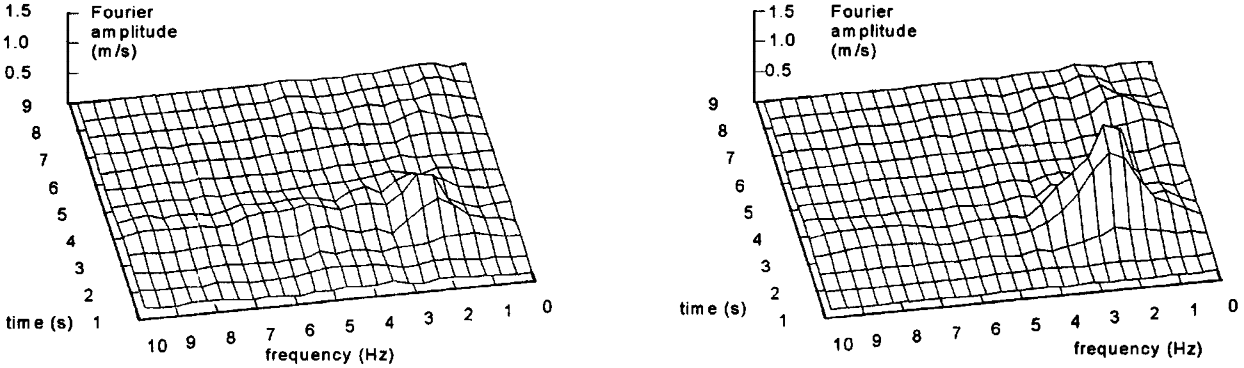
Plan

Fig. 1. Pacoima Dam Strong Motion Recorder Sensor Locations



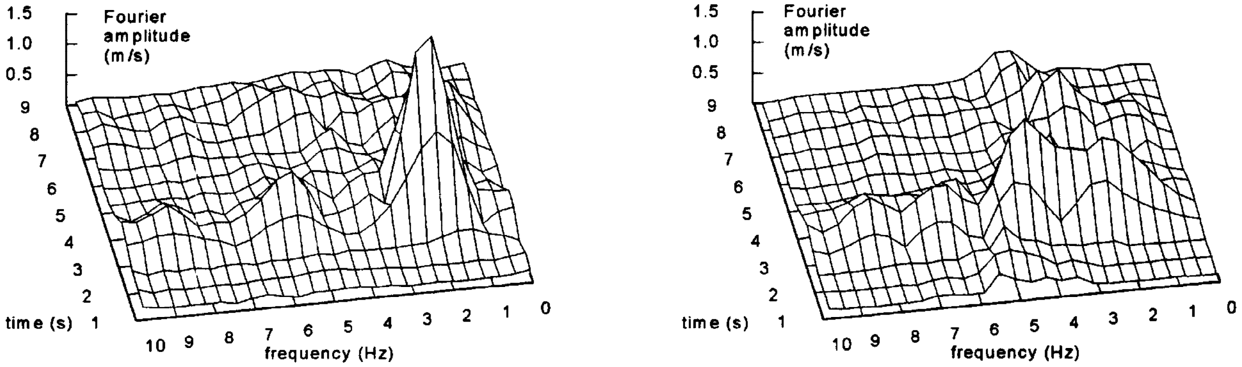
(a) Pacoima Upper Left Abutment - 115 deg.

(b) Pacoima Base - Channel 9 (270 deg.)



(c) Pacoima Base - Channel 10 (vertical)

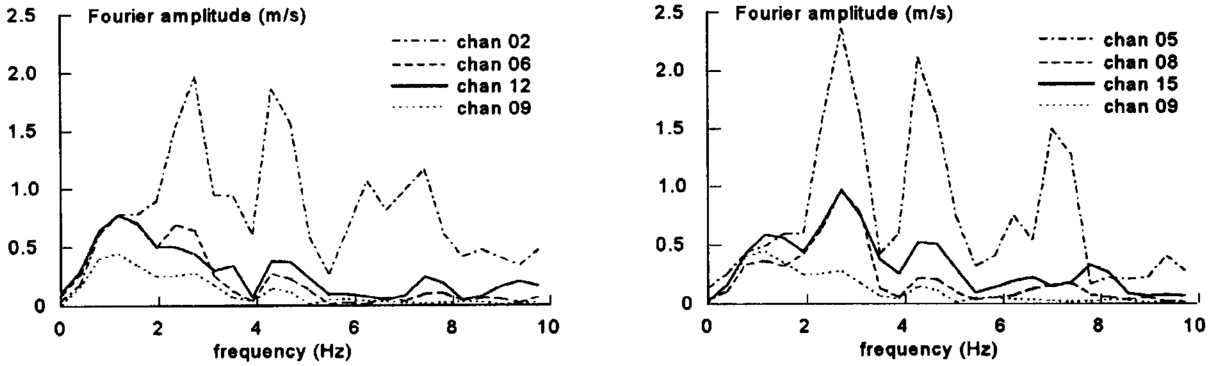
(d) Pacoima Base - Channel 11 (0 deg.)



(e) Pacoima abutment Abutment - Channel 12 (270 deg.)

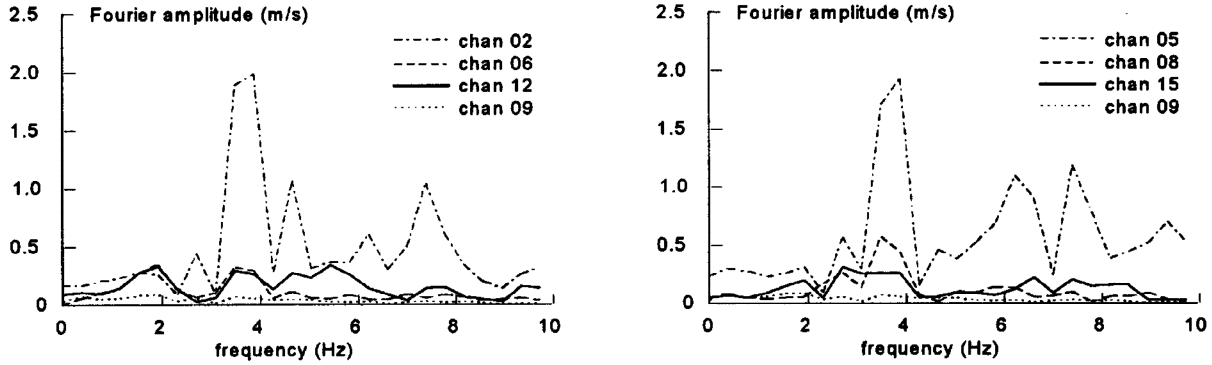
(f) Pacoima Dam - Channel 8 (Radial)

Fig. 2. Time-varying Fourier amplitude spectra of Pacoima Dam Northridge earthquake records



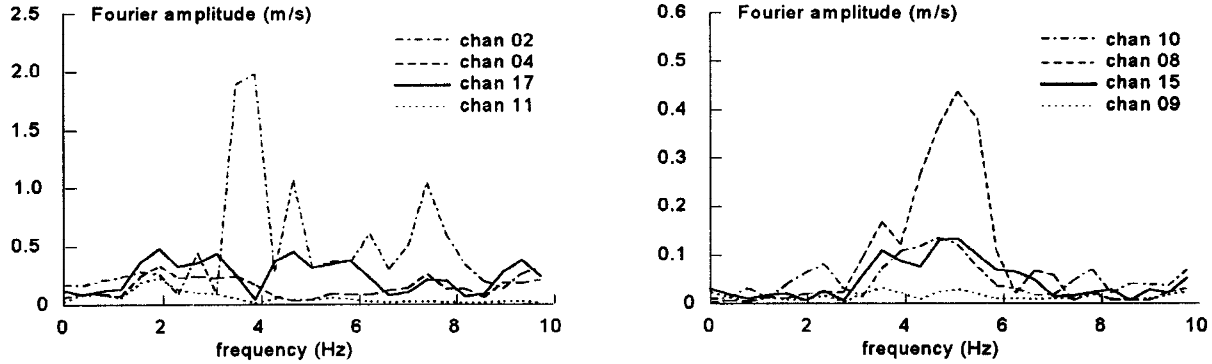
(a) Channels 2, 6, 9 & 12: t = 7.0 sec

(b) Channels 5, 8, 9 & 15: t = 7.0 sec



(c) Channels 2, 6, 9 & 12: t = 8.3sec

(d) Channels 5, 8, 9 & 15: t = 8.3sec



(e) Channels 2, 4, 11 & 17: t = 8.3sec

(f) Channels 8, 9, 10 & 15: t = 1.9sec

Fig. 3. Fourier amplitudes plots of Pacoima Dam acceleration record segments

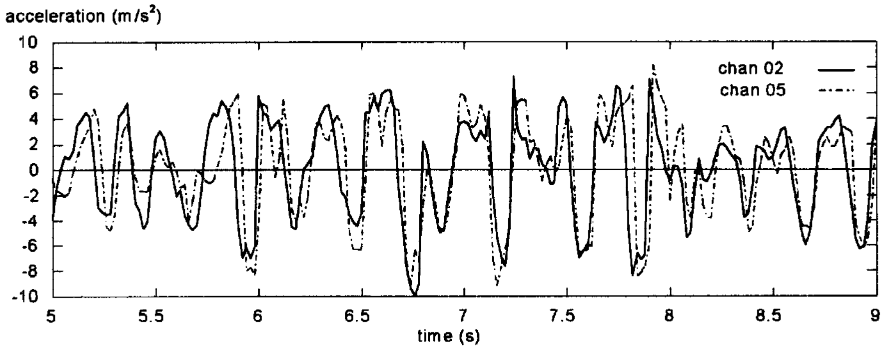


Fig. 4. Pacoima Dam Northridge earthquake acceleration records: Channels 2 & 5