FIELD TEST OF FINITE ELEMENT CONCRETE DAM ANALYSIS

Ronald F. Scott[I] and J. Brent Hoerner[II]

SUMMARY

The finite element method is now commonly used in the dynamic analysis of dams. However, the resulting calculations have rarely been tested against prototype performance. With seismoscope records obtained in the 1971 San Fernando, California earthquake, the opportunity of testing the analysis of a concrete arch dam arose. The record of one seismoscope was processed to yield the abutment accelerations, which were applied to the finite element boundaries. Computed resulting crest accelerations were then employed in the calculation of an imitation crest seismoscope record, for comparison with the real trace. Correspondence was surprisingly good and gave confidence to this model.

INTRODUCTION

The Big Tujunga Dam is located in the San Gabriel mountains north of Los Angeles, U.S.A. The dam is a variable radius concrete arch which functions as a flood control and conservation facility. It is owned and operated by the Los Angeles County Flood Control District. Constructed during the years 1930 and 1931, the dam's crest height above its foundation measures 251 feet and the crest length of the arch portion is 400 feet. Thickness varies from 8 feet at the crest to 73 feet at the base. This mass concrete structure was poured in five foot lifts between full height vertical contractive joints approximately 50 feet apart. A concrete triangular abutment block, affixed to the south end of the arch, distributes arch thrust into a highly fractured south ridge, while an open ogee weir spillway borders the arch on the north (Fig. 1).

Following the San Fernando earthquake of 1971, a systematic program of re-evaluating the earthquake safety of dam structures in California was undertaken. As part of this program the Flood Control District employed Lindvall, Richter and Associates to select design earthquakes for the Big Tujunga Dam, sample the dam and foundation material, construct a three-dimensional finite element model of the dam and foundation, and examine and interpret the response of the dam to the imposed design earthquakes under various reservoir loading conditions [ ]. The properties of the finite element bricks were obtained in the usual way from field and laboratory tests of dam and foundation samples, but there is always the question: how well does the numerical model actually simulate the real structure, especially when the amount of foundation rock to be included in the model is selected arbitrarily?

[I] Professor of Civil Engineering, California Institute of Technology, Pasadena, California, U.S.A.

[II] Associate Professor, School of Engineering and Computer Science, California State University, Northridge, California, U.S.A.

Generally there is no way of testing the modeling, because of the absence of records of the full-scale structural response to earthquake shaking. In this case, however, two seismoscopes, one on the abutment rock and one on the crest, had recorded the movements of the site and structure during the San Fernando earthquake, with local horizontal accelerations of about 0.25g. It was decided to use a technique which had been developed previously [4] to generate two horizontal components of acceleration from the abutment seismoscope, and to apply them as input to the finite element model. The acceleration response of a model node corresponding closely to the crest seismoscope location was then applied to a computer representation of seismoscope behavior to calculate a pseudo-seismoscope crest response. This was compared to the actual seismoscope record obtained on the crest. Although other techniques, such as ambient and forced vibration studies, were also used to check the validity of the finite element dam model, the amplitude of the vibrations was much lower than that caused by the 1971 earthquake, and these investigations will not be described here.

FINITE ELEMENT MODEL

A linearly elastic finite element program was used to analyse Big Tujunga Dam and a 150-foot thick layer of the surrounding foundation. The material properties used in the analysis were based upon laboratory investigations and ambient vibration surveys [3]. The outer boundaries of the model's foundation were assumed completely fixed against translation and rotation. The linearly elastic assumptions permitted the normal mode method of analysis to be used in determining the time-dependent responses of the dam during dynamic load conditions. The computer program ADAP [1] (NISEE, University of California, Berkeley) was used to determine displacement and stress distributions in the dam for both static and dynamic load conditions. In addition, ADAP was upgraded to include added masses due to the dynamic effects of water and silt on the dam's upstream face in a manner suggested by Westergaard [5].

The arch portion of the dam was modeled with nine eight-node thick-shell elements, one sixteen-node 3-D shell element and six eight-node brick elements. The abutments and foundation were modeled with 27 and 131 brick elements respectively. The modeled dam and its foundation are illustrated in plan and profile views (Fig. 2). For comparison with the conditions prevailing during the February 9, 1971 earthquake, the dam was analyzed with water and silt levels respectively 96 feet and 162 feet below the dam's crest. Silt, represented in the analysis as a dense liquid, was assigned a specific gravity of 1.6. Some of the periods and mode shapes obtained for the arch portion of the dam by the finite element model are illustrated in Figure 3.

SEISMOSCOPE RECORD OF FEBRUARY 9, 1971

Two seismoscopes were present at the Big Tujunga dam site during the 1971 San Fernando earthquake, one on the south (left) abutment and one on the crest of the dam. Acceptable records (Figs. 4 and 5) of the earthquake motions were obtained on both seismoscopes, although the abutment trace was much clearer than the crest record. The abutment record indicated the greatest amplitude of movement in a north-west by south-east direction. The trace obtained on the crest was intermittent, indicating some skipping of the recording needle, and was also smudged, probably as a result of the technique of smoking the watch glass. The dominant direction of the crest record was approximately east-west, at right angles to the dam axis at the seismoscope location. Although portions of the record are missing, the crest seismoscope clearly indicated slightly larger motions than are shown on the abutment record; the relative spectral displacements, S_d, have been given as 2.17 and 2.78 cm respectively for abutment and crest records [2]. The actual maximum peak-to-peak excursions measured on the records are 1.6 and 2.3 cm, for abutment and crest records, respectively. It can be seen that the base motions of the two instruments were substantially different.

Both records contain the high frequency component which has been noted previously in seismoscope traces [4]. However, the clearer nature of the abutment record renders the high frequency oscillation more apparent, and the record offers only moderate difficulty for disentangling and analysis. The discontinuities in the in the crest trace make analysis impossible.

The abutment record was analysed to develop the horizontal acceleration components generated at the dam site during the 1971 earthquake. The procedure described by Scott [4] was followed. A 20 to 1 enlargement of the original seismoscope watch glass record was prepared, overlaid with transparent plastic, and a trace of the development of the needle track with time worked out. When this had been done, all the major swings of the instrument were accounted for. The result was a second or two of smaller motions followed by an uncertain connecting portion and then 7 or 8 seconds of unambiguous large motion. This was connected dubiously with a second or two of final smaller motions. There are so many intersections, particularly in the central portion of the watch glass, that it is difficult to obtain an entire connected trace without uncertainty.

When the record had been disentangled, it was digitized. The resulting plot was smoothed by hand, and the intersections of the timing oscillations identified. These intersections were then digitized again to give a complete time history of the seismoscope's movements in x-, y- and t-coordinates. A computer program had been written previously to convert these data into two components (North, East) of an acceleration history at the seismoscope site, filtered to exclude excitations at frequencies higher than 10 Hertz.

The two computed components are shown in Figure 6 and peak accelerations in this frequency range of about 25%g are indicated, with peak velocity and dipslacement of about 0.1 m/s and 3 cm, respectively. At 2% damping, spectral relative velocities had maximum values in the range of 0.4 to 0.5 m/s.

ANALYSIS, COMPARISON, AND CONCLUSION

These calculated accelerations of the abutment rock were employed as input to the dam finite element model and two horizontal components of acceleration at the dam crest (node No. 461) were computed. The node location is within a few feet of the crest seismoscope location. A vertical acceleration record at the crest, with peaks of the order of 0.2g was also computed as a result of the horizontal input but was not used in these calculations. The acceleration histories which had peak accelerations as high as 3g, were used as input to a computer program which calculates the response of an hypothetical seismoscope with essentially the same characteristics as the real one. The major difference is that the seismoscope model does not include the high-frequency mode of response which is exhibited by the real seismoscope and which is used in the analysis of the abutment seismoscope record reported above.

The measured crest seismoscope record, reproduced in Figure 5, is to be compared with Figure 7 which shows the computed response of the hypothetical crest seismoscope to very closely the same scale (the difference is due only to the difficulty of reproducing a photograph to an exact scale). Both figures are oriented in the correct direction. It should also be noted that, because of the torsional freedom of the seimsoscope, and because its orientation is obtained usually by compass, the directions shown on Figure 5 are probably good only to about $\pm 10^{o}$. The first and most obvious point to be noted in comparing Figures 5 and 7 is that they are quite remarkably similar, even down to the details of the motion. This is even more apparent if the measured seismoscope record is rotated clockwise a few degrees so that the orientations of the two records match more closely. In detail, the computed N-S and E-W trace dimensions are slightly smaller than the dimensions of the real record in the same directions. Holding other variables constant, this might indicate that slightly too great damping has been employed in the computer model of the dam. However, for practical purposes, the differences are negligible.

Since there may be questions about the response of the seismoscope to the high accelerations indicated for short durations by the calculated histories, the computed acceleration records were modified by truncating all the peaks greater than +1g or less than -1g. The modified records (with peak accelerations limited to ±1g) were then used to calculate another seismoscope response.

It was found that the putative seismoscope response was substantially changed by the modified acceleration input, and was no longer as similar to the recorded response as is Figure 7. It is apparent, therefore, that, at this level, the seismoscope is responsive to peak accelerations of the amplitude and duration of those in the computed histories. The results of this analysis give confidence in the original acceleration calculations based on the abutment seismoscope San Fernando earthquake record and in the modeling of, and properties assigned to the dam and foundation rock structures.

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5. Westergaard, H. M., "Water Pressures on Earth Dams During Earthquakes," Trans. ASCE, 98, 418-433, and discussion, 1933.

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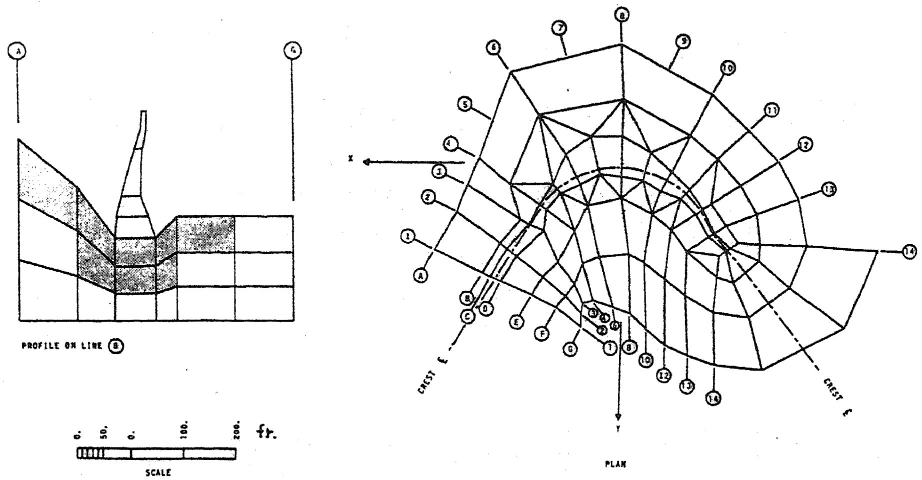


Figure 2. Computer model of dam and foundation

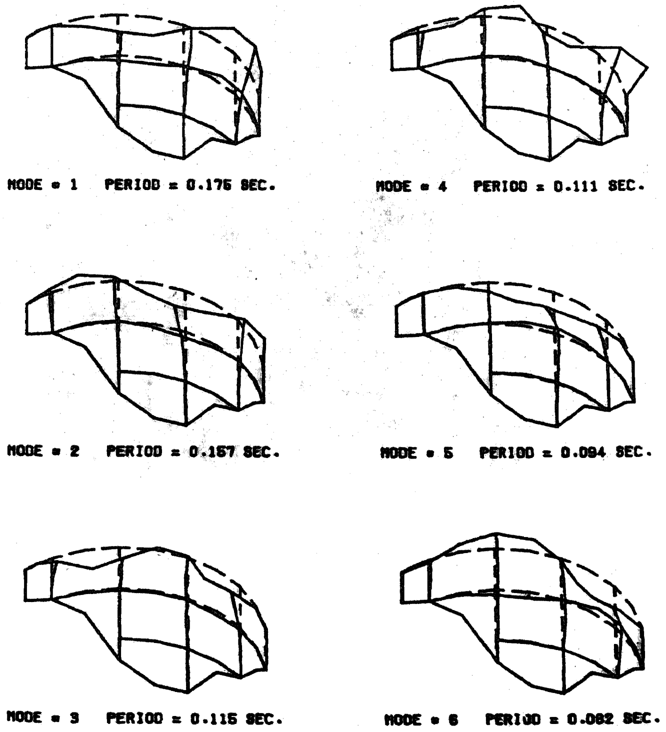


Figure 3. First 6 mode shapes of dam.

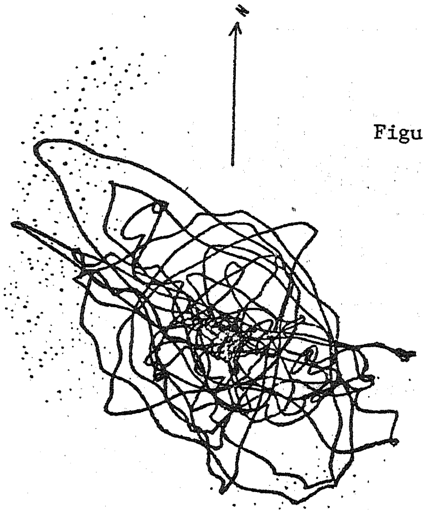
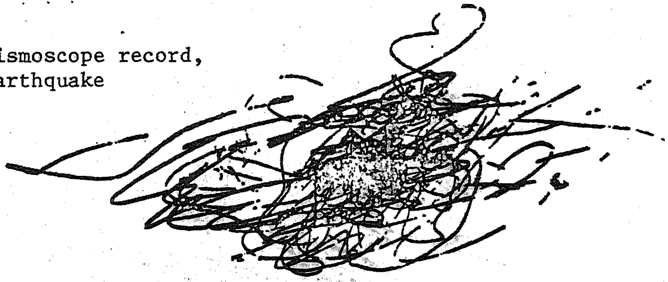


Figure 4. Abutment seismoscope record, 1971 San Fernando earthquake

Figure 5. Crest seismoscope record, 1971 San Fernando earthquake



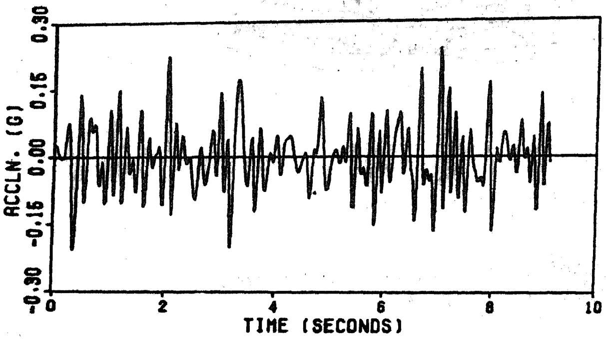


Figure 6. **Computed abutment acceleration components (a) NS**

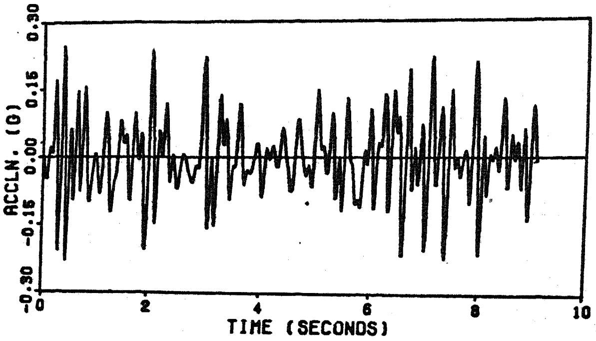


Figure 6. Computed abutment acceleration components (b) EW

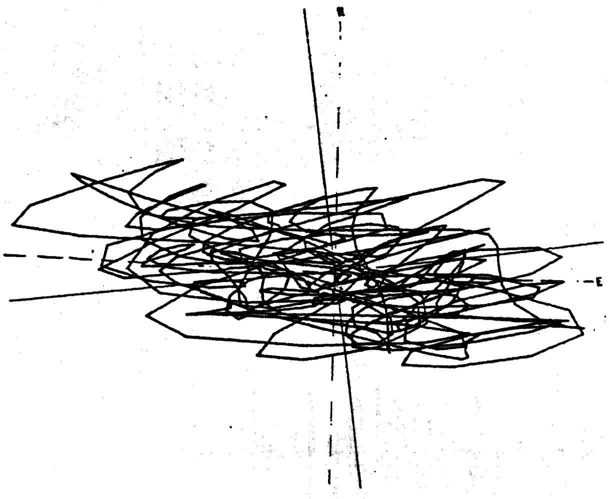


Figure 7. Computed crest "seismoscope" record (compare with Fig. 4)