THE MEANING OF SPECTRA OF EARTHQUAKE RECORDS OBTAINED IN OR NEAR STRUCTURES

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The response spectrum of a disturbance, for example the acceleration recorded in a particular location at a given time, is defined as the relation between the maximum response of a simple oscillator to the disturbance and the period or frequency of that oscillator. The oscillator may be undamped or may have a particular kind and magnitude of friction or damping. Different damping relations give different response spectra, of course. The response may be in terms of maximum displacement, deflection, velocity, acceleration.

Numerous earthquake response spectra have been constructed from accelerograms recorded during strong or moderate earthquakes. On account of the complexity of earthquake motions the spectrum has appeared to offer the simplest means of comparing earthquakes with respect to their engineering effects and of drawing general conclusions as to these effects.

All these spectra, especially those with zero damping, have contained a number of peaks and valleys, implying that small changes of oscillator frequency result in large changes in oscillator response. In about 1938 it was suggested verbally by Prof. Hugo Benioff of the California Institute of Technology that these peaks, or some of them at least, might not be really characteristic of the earthquake itself but rather contributions from the structures that house the recorders to the motion felt by the recorders. Partly for convenience and partly in the hope of correlating ground motions with the response of large buildings, accelerometers have frequently been placed in the basements of large, important structures. It is the suggestion that the motion recorded in such a place would be the combination of the motion of the earthquake together with the motion of the foundation relative to the earth. Presumably, this latter component, although small, would be nearly periodic and contain a number of cycles of period corresponding to the natural periods of the housing structure. The contribution to the total spectrum, especially undamped, might be important. These suggestions were contained in a report by the author that was prepared at the California Institute of Technology for the Department of Building and Safety of Los Angeles County, California in 1939.

To get evidence on this question some forced vibration tests were made at that time under the direction of Dr. D. S. Carder of the U. S. Coast and Geodetic Survey to determine the vibration characteristics of

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two Los Angeles buildings that housed USCGS accelerometers, the Subway Terminal Building and the Hollywood Storage Building. The former is a complicated structure with a large number of low order modes and frequencies corresponding to oscillations of different parts. The Hollywood Storage Building is a rectangular, nearly symmetrical structure 51 ft x 217 ft in plan and 141 ft (14 stories) high, with reinforced concrete walls and floors. It is an attractive structure for analysis.

The buildings were caused to oscillate in various modes by means of a mechanical vibrator capable of applying a periodic horizontal force of adjustable frequency and magnitude at a given point. The displacements so produced were small compared to those of a strong earthquake, the maximum being about 0.075 mm. In the test of the Hollywood Storage Building, motions were recorded at various points throughout the structure, including the basement where an accelerometer was permanently located, and outside the structure at distances up to several hundred feet. In the basement, the induced motion was found to have approximately 4.5 percent of the amplitude of the roof motion. There was a lag of about 65 in phase. At a distance of 100 feet the amplitude ratio was about 0.9 percent with a phase lag of about 108 degrees and at 500 - 750 feet the amplitude ratio was about 0.6 percent.

From these results it appears probable that the records obtained by the basement accelerometer in the Hollywood Storage Building contained not only components furnished by the motion of the building itself, but also may have received contributions from other large buildings in the vicinity. This would then be true for records obtained in other large buildings also. The question is what is the importance of this effect?

As a matter of interest, it should be mentioned that O'Hara has recently suggested that while the spectrum peaks are associated with the actual modes and frequencies of a complete system that are (a) excited, and (b) impose motion on the support of the recording device, the <u>valleys</u> of such a spectrum tend to occur at frequencies that would be found if that part of the system below the recorder (in this case the earth) were frozen (1). In other words, the structure acts as a damper, suppressing or reflecting ground energy at those frequencies equal to its own frequencies if rigidly supported. This correspondence between spectrum minima and fixed-support frequencies is not likely to be perfect on account of the probability of coincidence between a real frequency and a fixed-support frequency of different order.

Consider now the numerical results of the Hollywood Storage Building shaker tests and apply them to the accelerometer records obtained in basement and penthouse during the October 2, 1933 earthquake. It must be mentioned that the ratio of earthquake amplitude to shaker motion at the roof was of order 100 (7.5 mm compared to 0.075 mm.) in the fundamental E-W mode. This ratio is so large that one must be cautious in applying the shaker results blindly to predictions of earthquake response; however, it is believed that one can draw intelligent conclusions as to orders of magnitudes of effects found at the larger amplitudes. For example, the shaker indicated a fundamental E-W mode period of 0.5 seconds, while the corresponding period during the earthquake was about 0.6 seconds.

Figure 1 shows a sketch of the roof level accelerations in the E-W direction recorded during the October 2, 1933 shock. Note that the fundamental mode is prominent and contains some 15 - 20 oscillations with a maximum amplitude of order 60 cm/sec^2, lasting for about 10 seconds. Assuming that the foundation participation factor that was found by the shaker - 0.045 - holds for these much larger amplitudes, we would expect that the foundation accelerometer record would contain about 15 cycles of a maximum amplitude of about 2.7 cm/sec^2. These are too small to be evident in the record (not shown here). However, the contribution of this motion to the base acceleration spectrum can be easily estimated. For an acceleration j_o sin ωt that continues for n cycles the undamped acceleration spectrum A_s has at resonance an amplitude that is approximately

$$A_s = n \pi j_o$$

In the present case, let $n = 15$, $j_o = 2.7$ cm/sec^2, $\omega = 2\pi/0.6 = 10.5$. Then the acceleration spectrum amplitude due to this motion is 126 cm/sec^2 or 0.13 g.

An acceleration spectrum has been determined for the recorded E-W basement acceleration and is shown in Figure 2. It can be seen that there is a peak at the period of the fundamental building mode (0.6 seconds), with a value of about 0.2 g. In determining this peak the time of occurrence was found to be about 9 seconds, or 15 building periods after the motion began. The author believes that about half of this total value, or the amount by which the peak exceeds the spectrum for slightly shorter periods is due to coupling between building and foundation. It does not follow that all spectrum peaks have this explanation but the author recommends that caution be used in drawing conclusions from earthquake spectra until something more is known about this.

Bibliography

(1) "Effect upon Shock Spectra of the Dynamic Reaction of Structures," (NRL Report 5236) by George J. O'Hara, 16 Oct. 1958.

FIGURE 1

RECORDED E-W ACCELERATION
ROOF HOLLYWOOD STORAGE BUILDING

OCTOBER 2, 1933

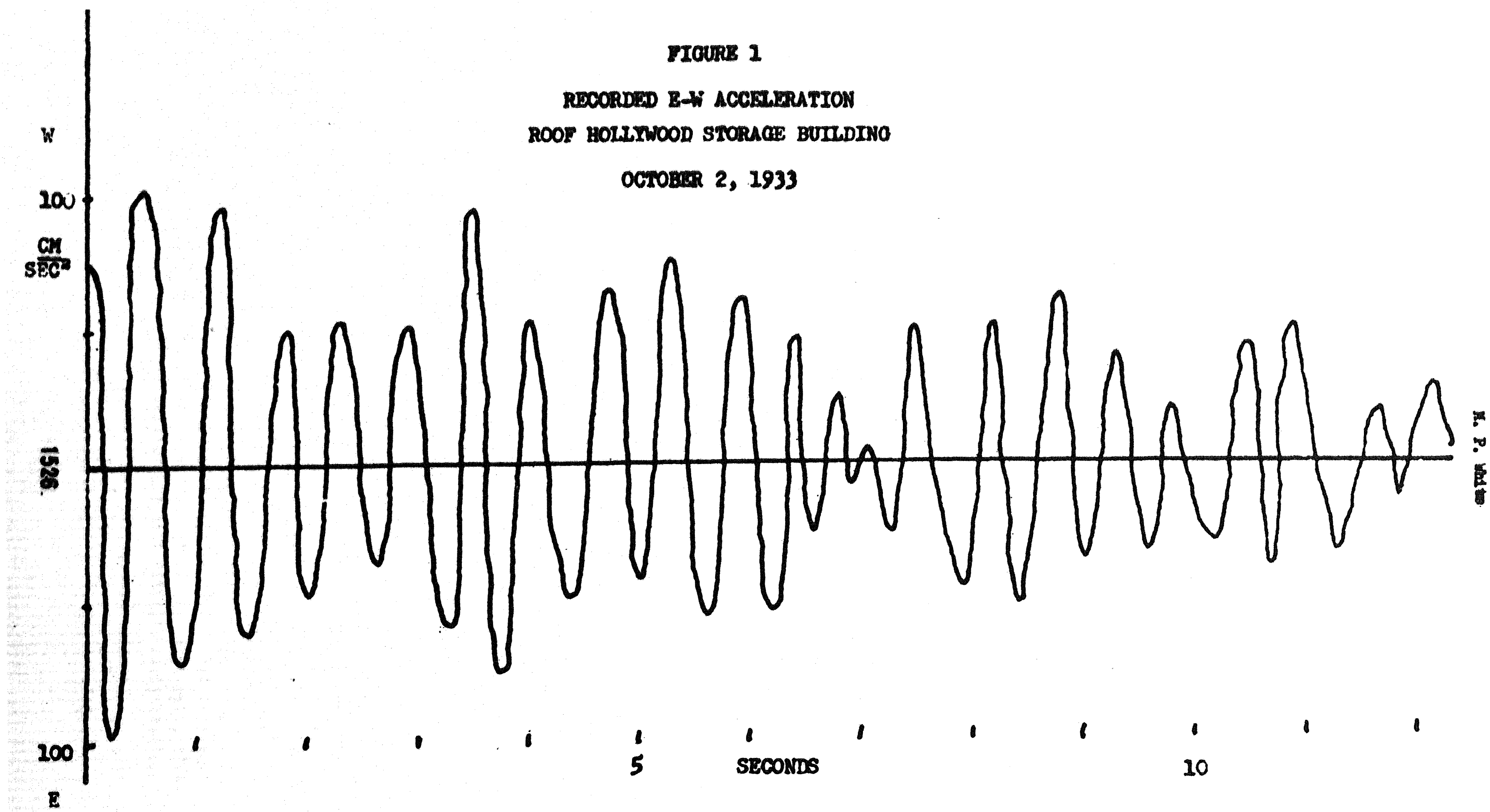


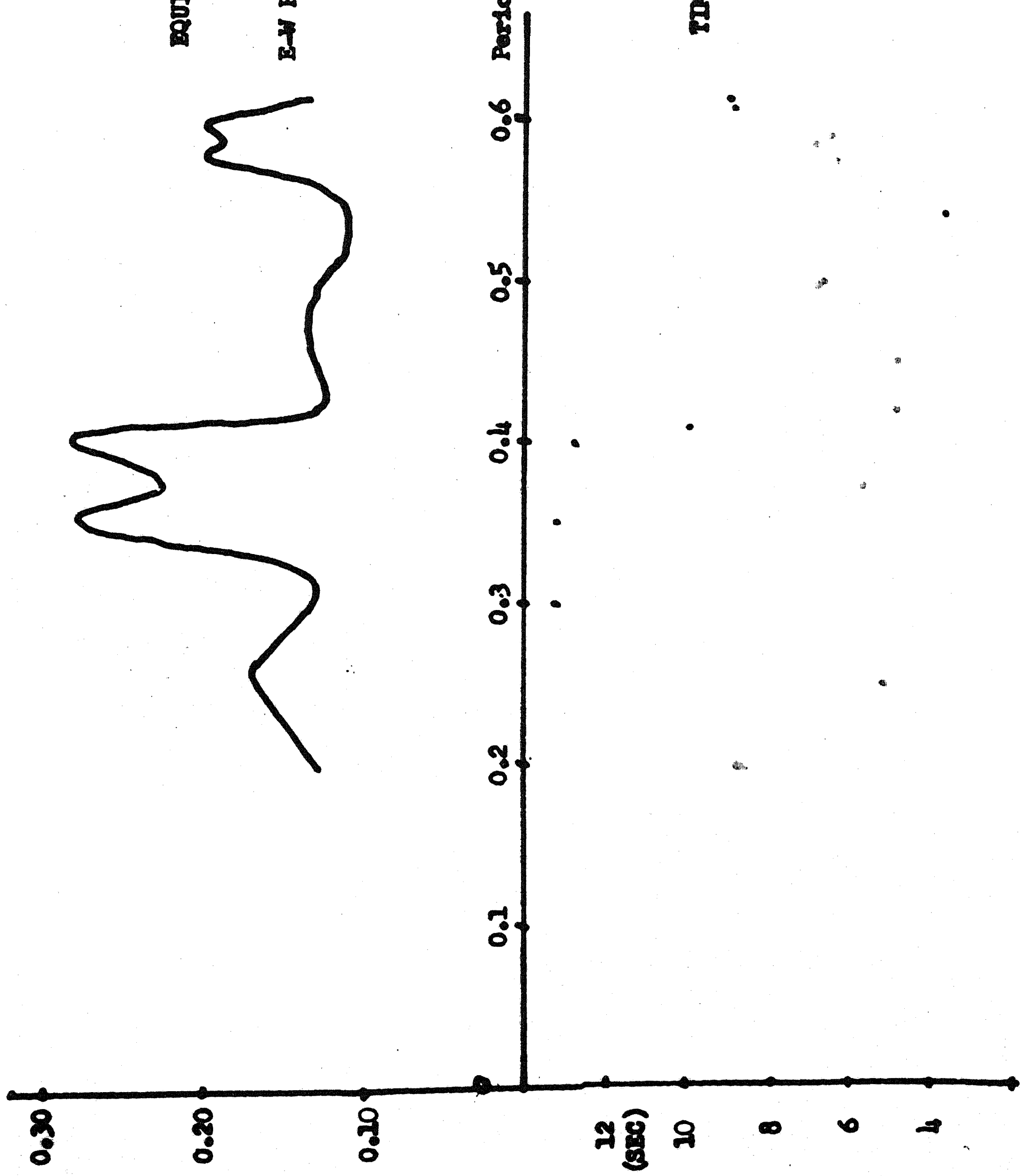
FIGURE 2

EQUIVALENT ACCELERATION IN g's

(ZERO DAMPING)

E-W HOLLYWOOD STORAGE BUILDING

OCTOBER 2, 1933



DISCUSSION

D. S. Carder, U.S. Coast & Geodetic Survey, U. S. A.:

Is the fundamental period from the earthquake (Oct. 1933) the same as that of normal vibrations set up by the wind?

M. P. White:

No, it is different. The fundamental period in the E.W. direction found in the October 1933 earthquake was 0.6^s, while the period observed in the shaker test was 0.5^s.