SANDIA REPORT

Printed January 1982

DE82011784
SAND-81-2214

Ground Motion From Earthquakes and Underground Nuclear Weapons Tests: A Comparison as it Relates to Siting a Nuclear Waste Storage Facility at NTS

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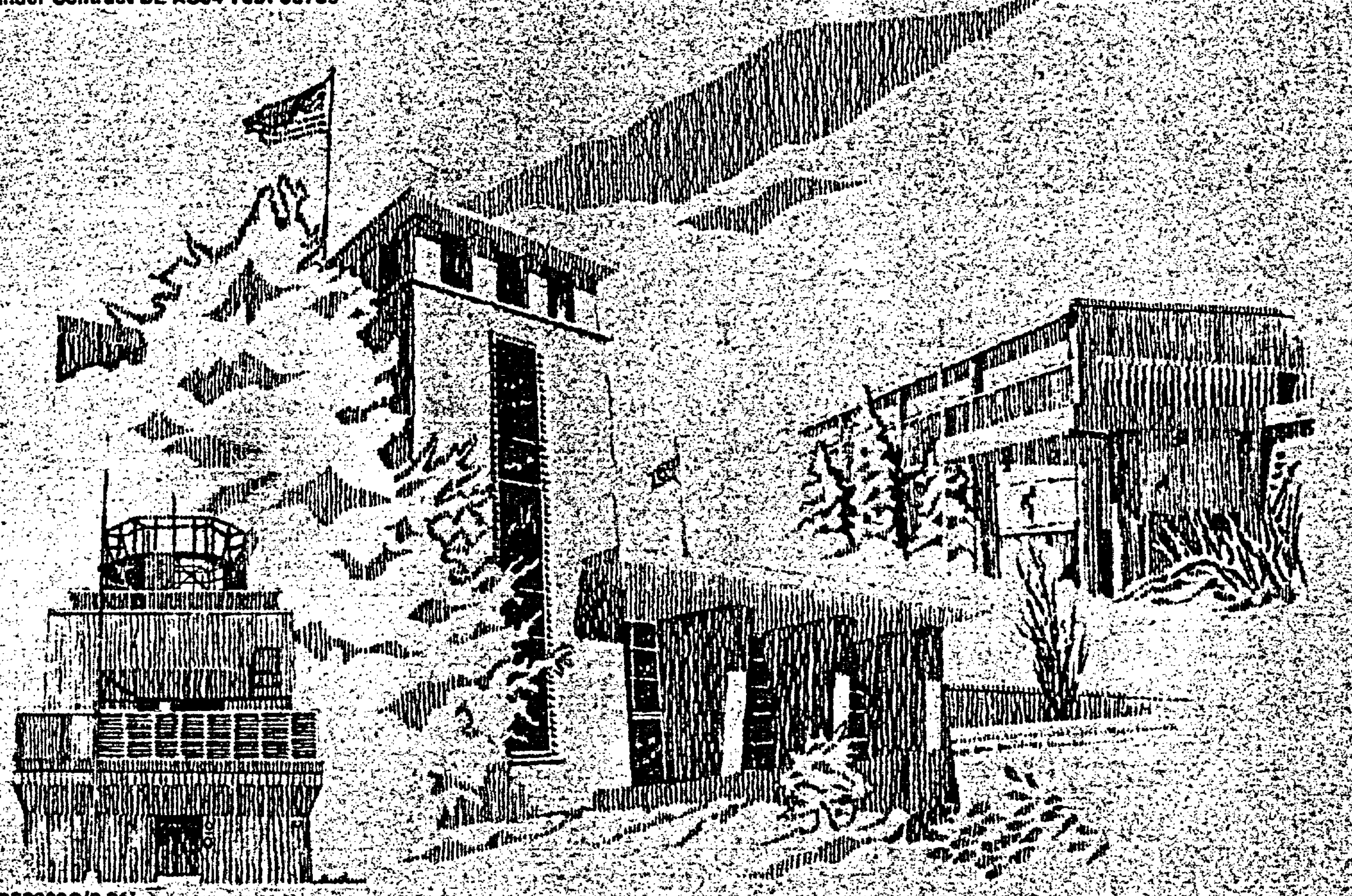
for the United States Department of Energy
under Contract DE-AC04-76DP00789



SF2900Q(8-81)

SAND81-2214
Unlimited Release
Printed January 1982

GROUND MOTION FROM EARTHQUAKES AND UNDERGROUND NUCLEAR WEAPONS TESTS: A COMPARISON AS IT RELATES TO SITING A NUCLEAR WASTE STORAGE FACILITY AT NTS

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ABSTRACT

Ground motion generated by a magnitude 4.3 earthquake at Massachusetts Mountain on the Nevada Test Site was measured at the control point and compared with ground motion generated at about the same distance by four underground nuclear weapons tests. The depth of the earthquake was between 4 and 4.6 km. The resulting signal at the distance considered was almost entirely body-wave components and had little or no contribution from the surface wave. The motion from the relatively shallower weapons tests had a signal with a pronounced surface-wave component. Comparison of the Pseudo Relative Response Velocity (PSRV) plots shows the earthquake signal richer in high frequencies and the weapons-test signals richer in low frequencies. If relationship between ground motion from the two sources can be confirmed for other earthquakes, weapons test ground motion could be used to estimate earthquake ground motion for magnitudes for which probability of occurrence in a given monitoring period would be very small.

GROUND MOTION FROM EARTHQUAKES AND UNDERGROUND NUCLEAR WEAPONS TESTS: A COMPARISON AS IT RELATES TO SITING A NUCLEAR WASTE STORAGE FACILITY AT NTS

Introduction and Background

If a nuclear waste storage facility is to be located at the Nevada Test Site, it must be designed to withstand both ground motion from natural earthquakes and that generated by underground nuclear weapons tests. Conversely, a facility must be designed and located where its vulnerability to ground motion would in no way inhibit weapons testing, even at yields above those now permitted under the terms of the Threshold Test Ban Treaty.

The Nuclear Regulatory Commission has not yet established the design response criteria for a nuclear waste storage facility. While a separate risk analysis will have to be done for a storage facility, the procedures specified by NRC for reactors can be expected to be used for a storage facility even though the applied criteria may be different.

The design response criteria for reactors consider only natural earthquakes. The maximum ground motion expected from the Design Basis Earthquake is defined for a reactor site based on the historic record of earthquakes. That motion is used, together with design response spectra specified by NRC, to prescribe the motion for which the reactor must be designed. The NRC design response spectra, normalized to 1 g for maximum vertical and horizontal accelerations, are shown in Figures 1 and 2.[1,2] The design spectra were derived by envelopment of spectra measured on a representative set of historic earthquakes, then adding one standard deviation.[3] Thus, the design spectrum probability level is 84.1%. It is expected that this same earthquake data base would be used for a waste facility.

There are four distinct differences between natural earthquakes and weapons tests that must be taken into consideration:

1. The timing of weapons tests is known and controlled, while that of an earthquake is not.
2. The seismic source location for a nuclear weapons test is precisely known, while that of an earthquake is not.
3. A conservative upper limit on explosion energy has been predetermined, while the energy of an earthquake depends on the area of fault slippage and can only be approximated from the estimated magnitude, location, and length of faults.
4. The safety aspects of weapons tests are under the control of an experienced test organization.

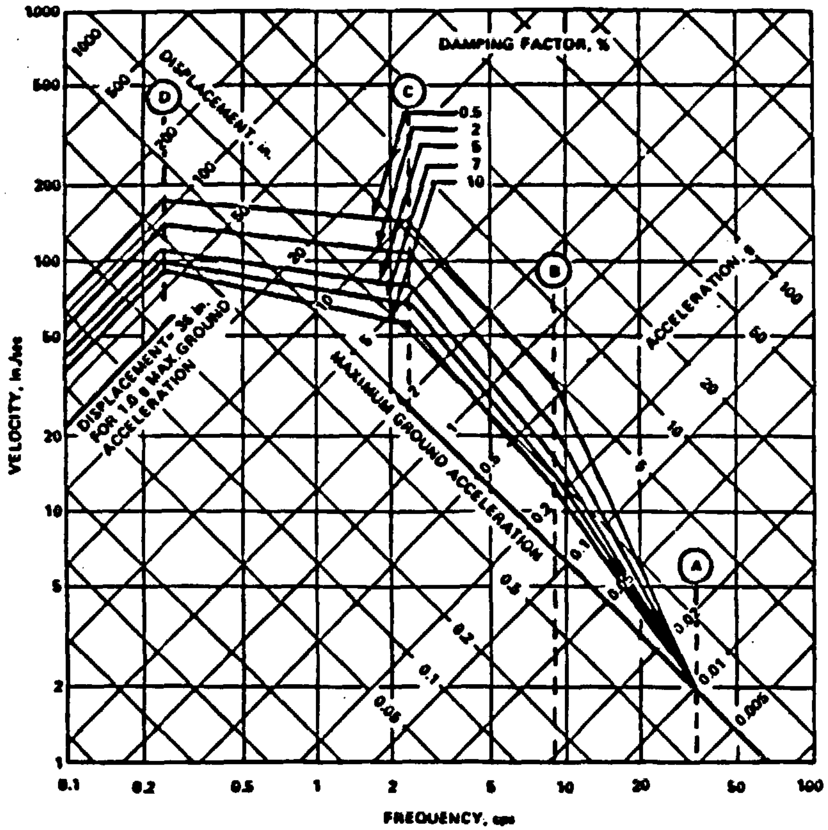

Figure 1. Horizontal Design Response Spectra - Scaled to 1-g Horizontal Ground Acceleration

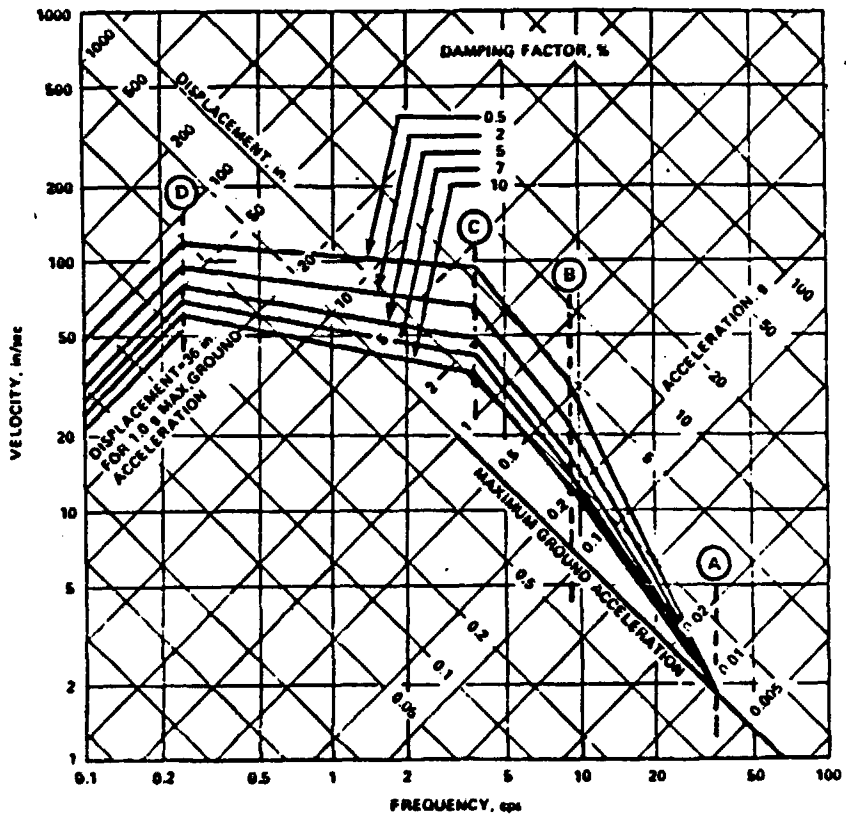

Figure 2. Vertical Design Response Spectra - Scaled to 1-g Horizontal Ground Acceleration

These differences permit evacuation of a waste facility for weapons tests, thus reducing to zero the probability of injury to personnel. Also, any portion of a facility susceptible to damage from weapons-test ground motion can be secured for the event. Thus, there is less need to be as conservative with regard to design response criteria for weapons-test-generated ground motion as for that generated by natural earthquakes. Using a prediction equation developed from a large data base of ground motion measured on NTS from past weapons tests in the tuffs and rhyolite lavas of Pahute Mesa, it was postulated that an appropriate Design Response Criterion would be a peak vector acceleration of 0.75 g with an 84.1% probability that 0.75 g would not be exceeded.[4] This would allow a waste storage facility to be as close as 6.3 km (slant distance) from a 700-kt underground nuclear detonation.[4] Compared with the extensive bank of data on ground motion from nuclear weapons tests, data providing complete waveforms from moderate sized natural earthquakes at NTS is especially scarce, particularly at distances relatively close to the earthquake.

An NTS Earthquake

On August 5, 1971, an earthquake occurred on the test site at Massachusetts Mountain at 17 58 17.1 GMT. The depth is variously reported as 4 km and 4.6 km.[5,6] The body-wave magnitude (M_b) was reported as 4.3, and the duration magnitude (M_d) as 3.5. The latter is approximately equal to the Richter local magnitude (M_L).[6] Three determinations of epicenter were made; they are shown in Table 1.[6-8]

Among the recordings at United States Geological Survey stations were two at the Control Point (CP-1). The azimuths and distances from the three possible epicenters are also shown in Table 1. An average depth to the source of 4.3 km was used in calculating the Slant Distance.

The measurements were made at stations designated CP-1A and CP-1H. The former used a Coast and Geodetic Survey accelerograph; the latter, a National Geophysical Company Model 21 (NCG-21) system. The stations were located on dolomitic rock and oriented so that positive motion on the channel labeled R was north and channel T was east. The two stations were separated by 336 m so they did not experience precisely the same motion.

Data from the horizontal measurements have been rotated so that positive motion is away from the earthquake epicenter on the record labeled radial 288. R-288, and clockwise about the epicenter on the channel labeled tangential 288. R-18. The first is the number of degrees rotated; the second is the azimuth of the positive direction. The vertical, radial, and tangential acceleration, velocity, and displacements as a function of time for the two stations are shown in Figures A-1, A-2, and A-3. The vector sum (square root of sum of the squares of the three components) as a function of time is shown in Figure A-4. Peak positive and negative values of acceleration, velocity, and displacement, together with the vector sums of the two horizontal (2-d) components and all three components (3-d) are listed in Table 2.

Table 1

Azimuth and Distances From Stations to Reported Epicenters

Source Ref	Coordinates Nevada East Grid (m)	Surface Elevation (m)	Azimuth to CP-1A (°)	Horizontal Distance (km)	Slant Distance (km)	Azimuth to CP-1H (°)	Horizontal Distance (km)	Slant Distance (km)
6	N240,477 E212,664	1250	286.71	6.100	7.480	283.98	6.260	7.630
7	N237,938 E214,525	1237	299.14	8.820	9.830	297.05	8.910	9.930
8	N239,406 E212,791	1237	295.34	6.600	7.900	292.62	6.770	8.020

Table 2

Peak Values of Acceleration, Velocity, and Displacement

	CP-1A					CP-1H				
	V	R (288°)	T (18°)	3-d Vector	2-d Vector	V	R (288°)	T (18°)	3-d Vector	2-d Vector
Accel (g)	+0.00538 -0.00792	+0.0189 -0.0232	+0.0260 -0.0134	0.0250	0.0249	+0.00990 -0.00619	+0.0172 +0.0184	+0.0228 +0.0157	0.0258	0.0256
Vel (cm/s)	+0.191 -0.167	+0.602 -0.542	+0.688 -0.452	0.849	0.839	+0.233 -0.182	+0.529 -0.451	+0.590 -0.505	0.667	0.659
Displ (cm)	+0.0155 -0.0121	+0.0351 -0.0332	+0.0345 -0.0727	0.0766	0.0766	+0.0173 -0.0161	+0.0325 -0.0447	+0.0310 -0.0757	0.0804	0.0804

The vertical component of motion is noticeably smaller than the horizontal components which are in agreement with the interpretation that the earthquake resulted from left-lateral or right-lateral movement along the fault.[6]

Figure A-5 shows the Pseudo Relative Response Velocity (PSRV) for the three components at the two stations. A comparison with PSRVs from weapons tests will be made together with an extrapolation of the PSRV to a larger magnitude earthquake.

Before comparing measured earthquake ground motion with nuclear ground motion, it is in order to explore some of the relations between the two. Earthquake Richter magnitude is ordinarily determined from peak displacement of the wave and its period by the relation.[9]

$$M_L = \log(\Delta/t) + B \tag{1}$$

where Δ is the peak displacement in microns, t the period in seconds, and B a factor related to the distance between the epicenter and the sensor. For the distances of concern here, $B \approx 1.47$.[10] Peak displacements obtained from Table 2 and periods measured in Figures A-1, A-2, and A-3 give magnitudes for the three components and two stations as follows:

	CP-1A	CP-1H
Vertical	3.38	3.43
Radial	3.53	3.59
Tangential	3.84	3.86

One distinct feature of these records is the absence of a distinct surface wave. The surface wave develops at a horizontal distance from the energy source equal to about five times the depth to the source. Here the distance between source and sensor was only about two times the depth to the source. Hence, the magnitudes above are body-wave magnitudes (M_b). They are less than the M_b and more nearly the M_d of References 5 and 6.

The Richter local magnitude (M_L) can be related to a body-wave magnitude by[10]

$$M_b = 1.7 + 0.8\,M_L - 0.01\,M_L^2 \tag{2}$$

Thus, an M_L of 3.4 is equivalent to an M_b of 4.4 of References 5 and 6. But if M_b from the radial component is 3.55, as noted above from CP-1A and CP-1H, the equivalent M_L is only 2.4. Because the latter estimate was made from only CP-1A and CP-1H, whereas the $M_b = 4.3$ from References 5 and 6 was obtained from several stations, only the latter will be used subsequently.

For nuclear explosions in rock, Rodean's data relates yield (W) in kilotons to M_b approximately as[11]

$$M_b = 3.87 + \log W^{3/4} \tag{3}$$

Thus, an M_b of 4.3 could be expected from a yield of about 3.8 kt. Rodean's data, from which the above expression was derived, came from a single station approximately 225 km from NTS. A better expression for the purpose here could possibly be obtained from measurements made at stations located on NTS.

In Figure A-5, it can be seen in the PSRVs that the peak velocity occurs at a period between 0.1 and 0.4 s. An examination (discussed later) of PSRVs for ground motion from underground nuclear explosions has shown that at about a constant distance from the source there is no significant trend in period of the peak with an increase or decrease in source energy. Local geology causes sufficient variation to mask any trend if, indeed, one exists. Thus, it seems reasonable to assume that for earthquakes any trend in period with magnitude at a constant distance would also be masked by variations in geology.

With this assumption, M_L and M_b can be calculated using Eqs (1) and (2) if we choose an appropriate Δ and t for the former. To achieve reasonable agreement with the $M_L = 3.5$ and the $M_b = 4.3$ of References 5 and 6, we have chosen $t = 3.1$ s and $\Delta = 338$ μm (both are the average of the radial component from CP-1A and CP-1H), and give $M_L = 3.51$ and $M_b = 4.38$. By keeping t constant and changing Δ, an equivalent M_L, M_b, and equivalent nuclear yield can be determined for that maximum displacement.

In Figure 3 (the framework for a PSRV), the values of M_L corresponding to a given displacement has been added to the right-hand displacement scale. Equation (2) allows values of M_b to be added, and Eq (3) an equivalent yield. Although a PSRV represents the response of a structure to a motion at its base, the displacement asymptote represents the maximum ground displacement input. Thus, for the radial PSRV at CP-1A (Figure A-5), the asymptote is 0.04 cm, corresponding to $M_L = 3.5$. Again, the values given by the earlier estimates agree with those derived from the values of the asymptote. The yield indicated by the asymptote is larger than that estimated above. After examining PSRVs in the next section, an extrapolation to a larger magnitude will be shown.

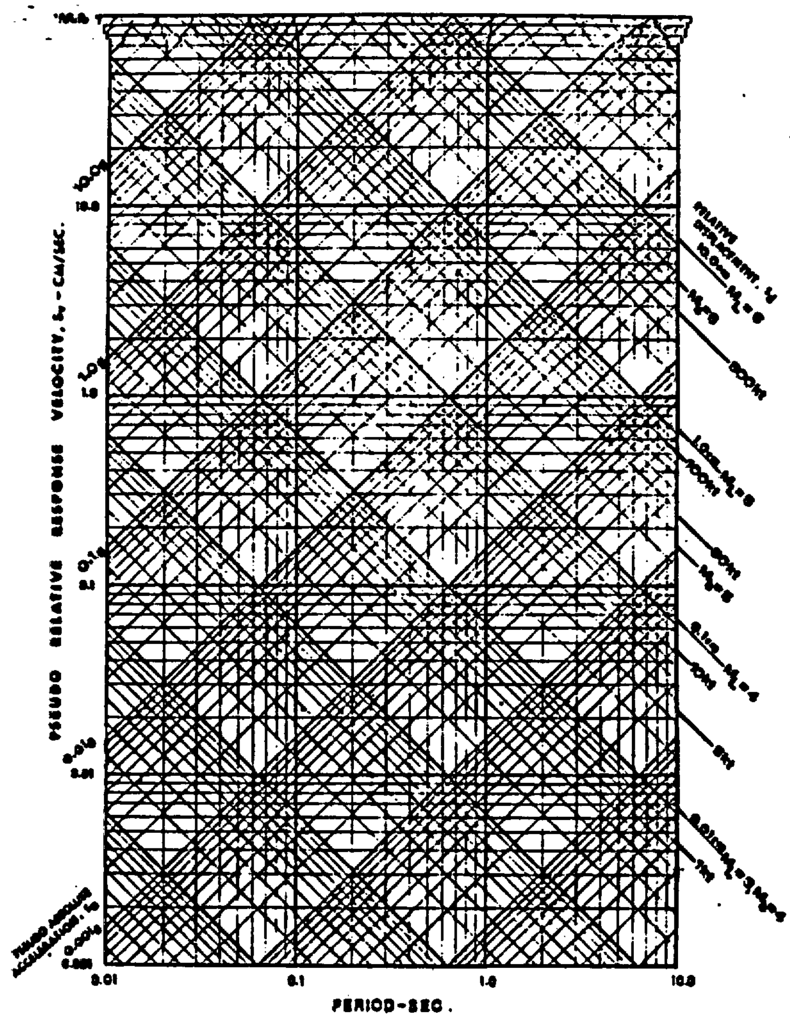

Figure 3. PSRV Framework

Comparison of Ground Motion From Earthquake and Weapons Tests

There exists data from four events at NTS near the yield range of the estimated earthquake equivalent, and at about the same distance. Figure 4 is a vertical planar cross section showing the relative locations of the events with respect to sensor locations. The three estimates of the earthquake-source location are also shown with respect to the sensors that made those measurements. It is obvious from the figure that the nuclear sources are much shallower than the earthquake sources. Thus, since a surface wave becomes prominent at about five burst depths, the signals from nuclear events would be expected to have a considerable portion of their seismic energy in the surface wave while signals from the earthquake would have little. To avoid using classified information, the events will be referred to simply as A, B, C, and D. A and C were detonated in tuff, and B and D in alluvium. Measurements were made at Station W-11, located on alluvium. The yields of events A, B, C, and D were 7, 10, 21, and 8.5 kt, respectively.

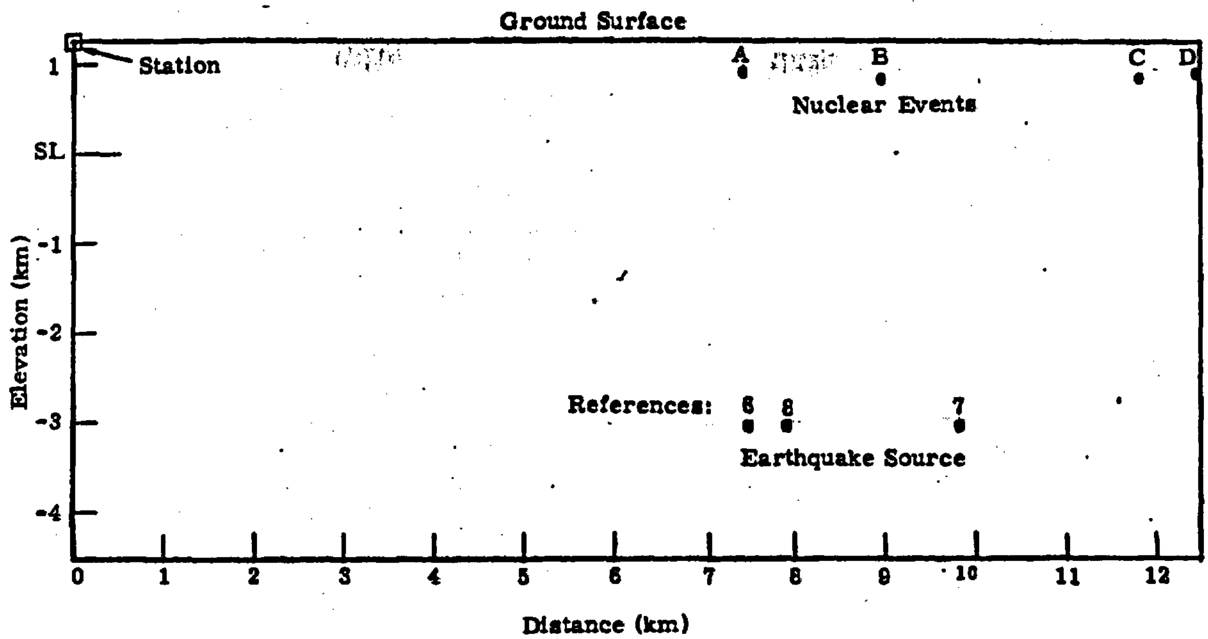

Figure 4. Vertical Cross Section Showing Relative Positions of Nuclear and Earthquake Sources With Respect to Measurement Station

In Figures 5 through 8 the PSRV for the vertical component of the earthquake is compared with its correspondent for Events A, B, C, and D. The velocity and displacement of the motion from the nuclear tests in each case larger than the velocity and displacement from the earthquake, and by an amount that is clearly a function of yield. Acceleration, on the other hand, is smaller than for the earthquake and in a manner that appears to be an inverse function of yield. The period of the earthquake signal has a broad peak from 0.18 to 0.37 s, whereas the peak period of the weapons test signals is sharper and longer, ranging from 0.5 to 0.9 s. This reflects the body wave of the earthquake versus the surface wave of the weapons test.

It was noted earlier that because the earthquake resulted from strike-slip motion, the vertical motion was small relative to the horizontal motion. Thus, it seemed in order to compare in Figures 9 through 12 the PSRVs for the radial component. Here the velocity peaks are more nearly equal. Otherwise the observations above for the vertical component apply to the radial as well.

The asymptotes on the acceleration and displacement legs of a PSRV represent the peak values of those parameters in the incident wave. If those asymptotes are extended inward to an intersection (A in Figure 13), the intersection can be described in terms of P and u (the period and velocity) on their respective scales. P and u for A were determined at Station W-11 (the same station represented in Figures 5 through 12) for six events with yields ranging over nearly an order of magnitude. The results are shown in Table 3 for each component.

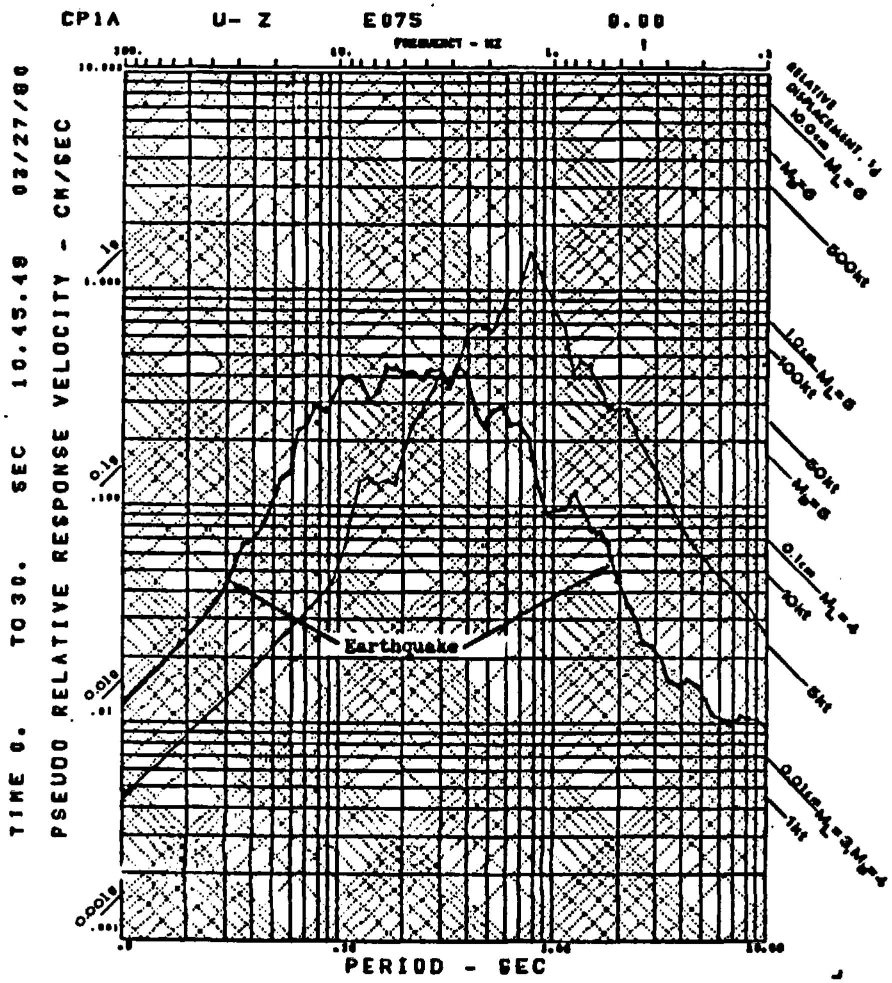

Figure 5. Comparison of PSRVs for Vertical Component for Earthquake and Event A

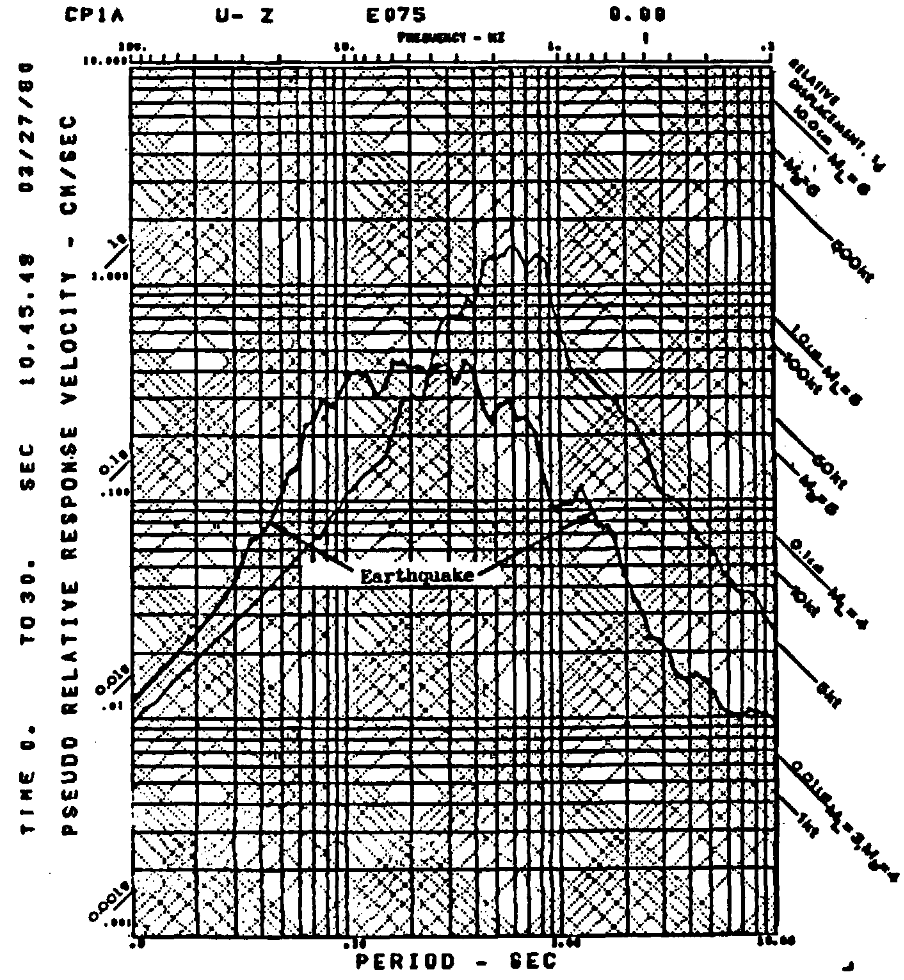

Figure 6. Comparison of PSRVs for Vertical Component for Earthquake and Event B

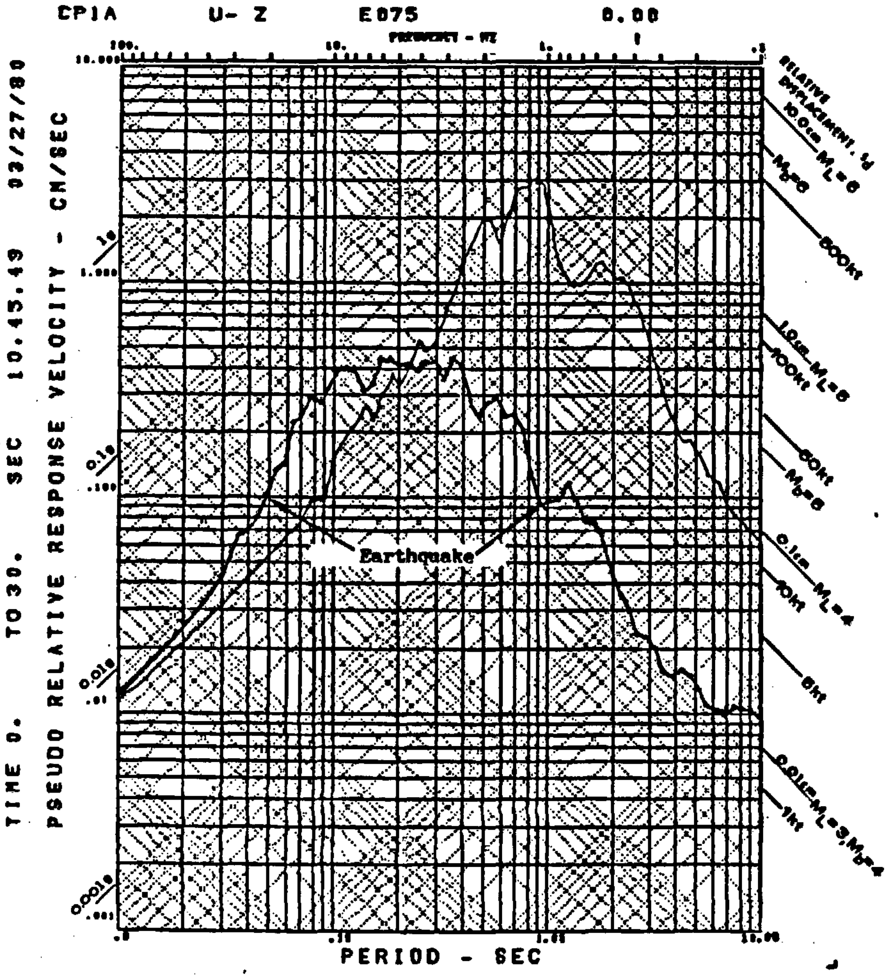

Figure 7. Comparison of PSRVs for Vertical Component for Earthquake and Event C

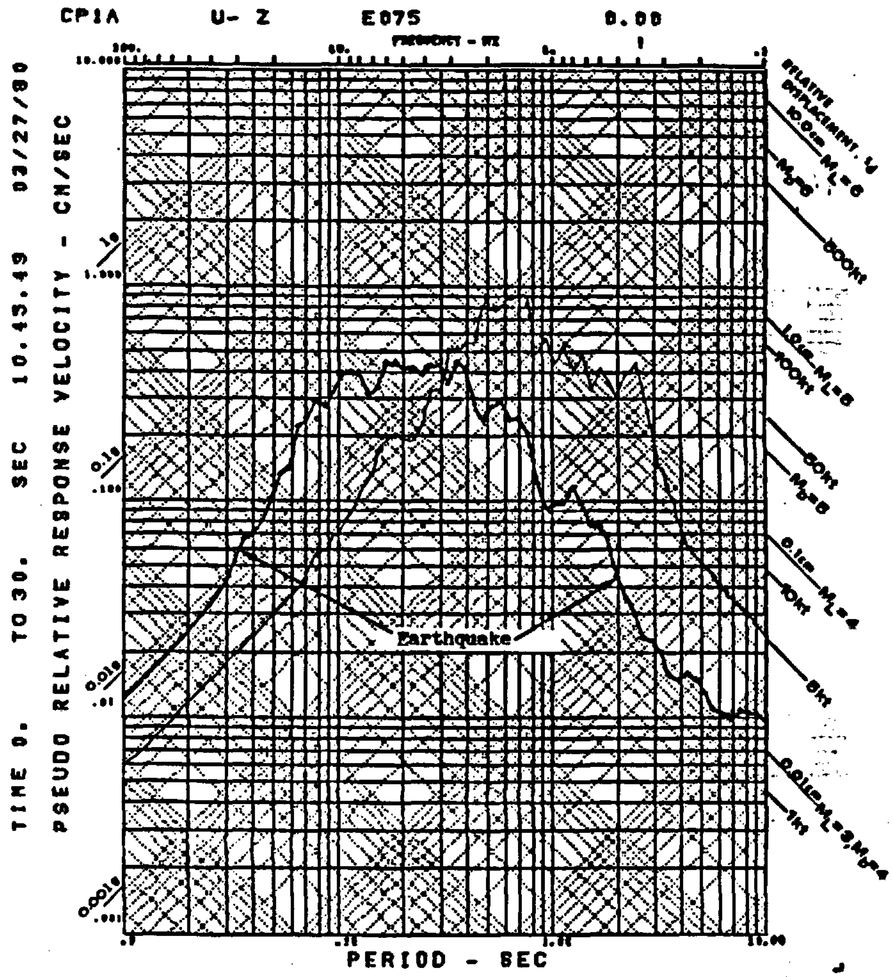

Figure 8. Comparison of PSRVs for Vertical Component for Earthquake and Event D

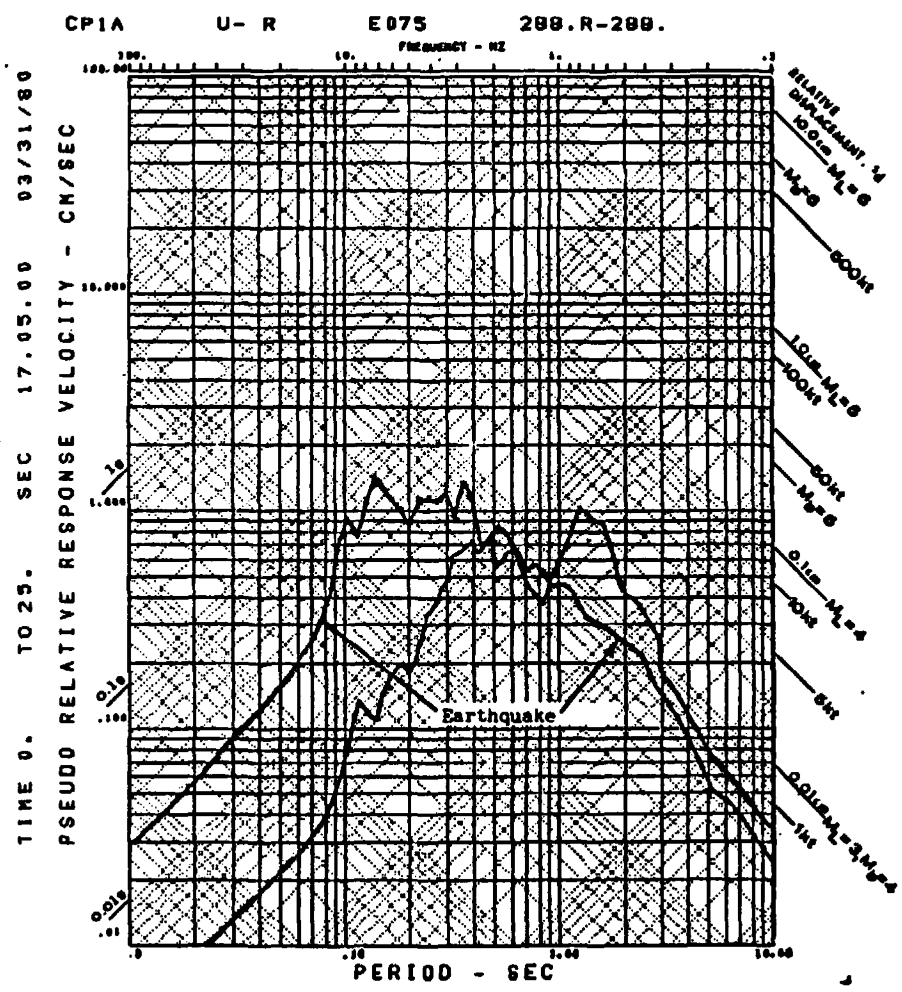

Figure 9. Comparison of PSRVs for Horizontal Component for Earthquake and Event A

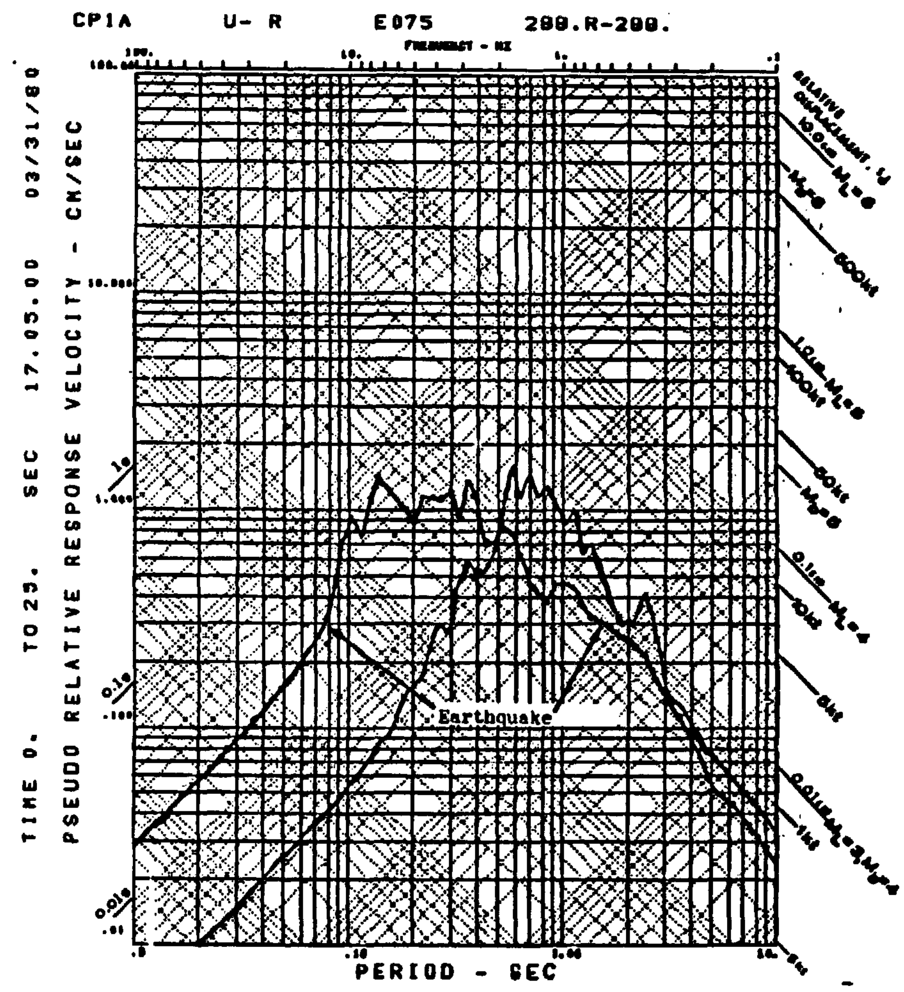

Figure 10. Comparison of PSRVs for Horizontal Component for Earthquake and Event B

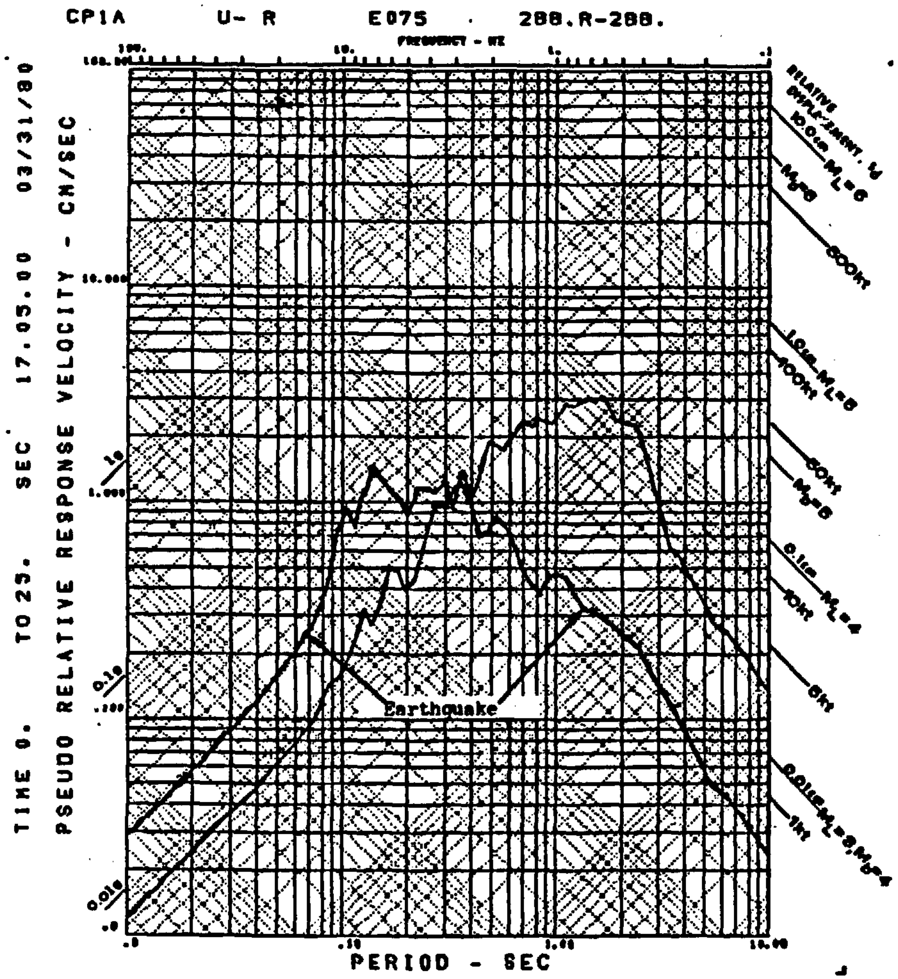

Figure 11. Comparison of PSRVs for Horizontal Component for Earthquake and Event C

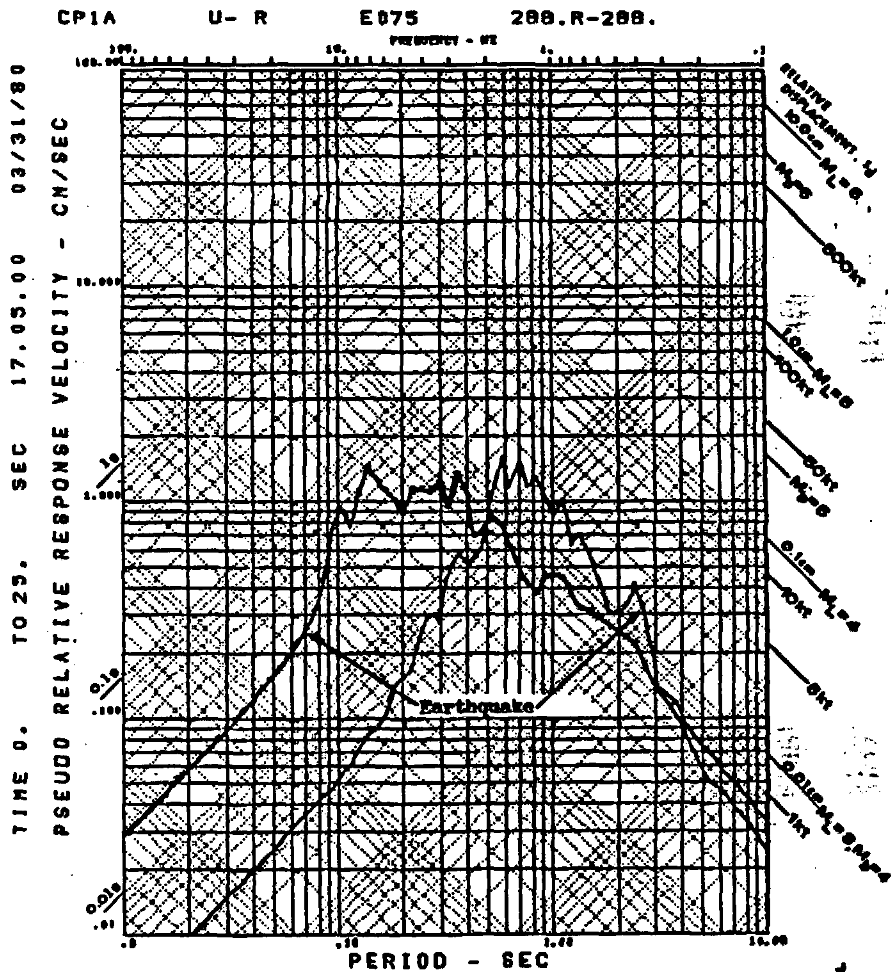

Figure 12. Comparison of PSRVs for Horizontal Component for Earthquake and Event D

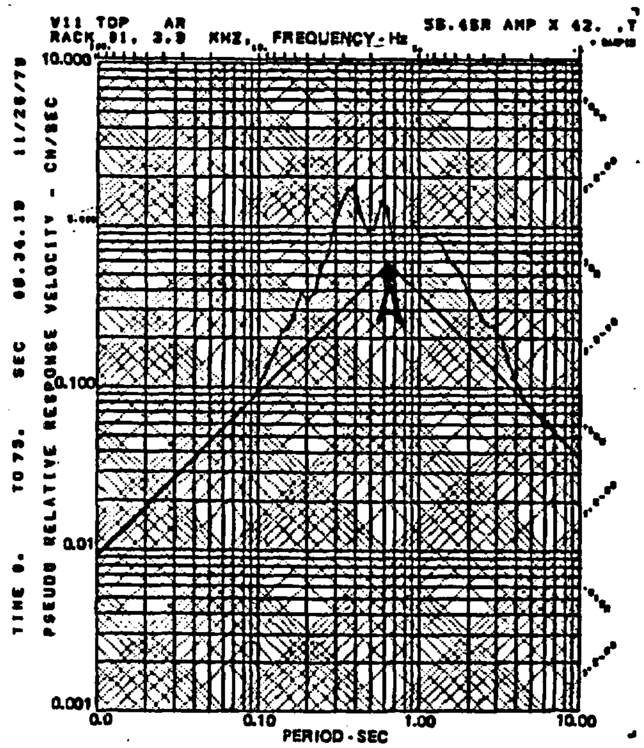

Figure 13. Intersection of Acceleration and Displacement Asymptotes of a Typical PSRV

Table 3

Period and Velocity for Intercept "A"

Yield (kt)	Range (km)	Period (s) V	Period (s) R	Period (s) T	Velocity (cm/s) V	Velocity (cm/s) R	Velocity (cm/s) T
7.5	7.476	0.75	0.90	0.72	0.31	0.40	0.41
8.5	9.619	0.70	0.85	0.65	0.30	0.40	0.24
10.0	8.950	0.52	0.65	0.52	0.50	0.55	0.55
13.7	12.499	0.70	0.75	0.75	0.60	0.90	0.90
37.0	8.529	0.70	0.88	0.75	2.80	3.30	1.80
62.5	6.047	0.75	0.80	0.75	3.10	5.00	2.50

The events were chosen for their closeness to Station W-11 and as at distances comparable to the distances of CP-1A and CP-1H from the earthquake. The table shows that over these distances P does not change much with yield, and that velocity is roughly proportional to yield. Thus, if the PSRV in Figure 13 was for a 10-kt event, the PSRV for a 100-kt event at the same nearby distance would have its intersection at a velocity larger by about a factor of 10, and with about the same period. Without evidence to the contrary, let us assume that the same observations apply to motion from earthquakes.

To estimate the effect of an earthquake on a nuclear waste facility, assume that a facility is to be located at about the same distance from a fault as CP-1 is from the epicenter of the Massachusetts Mountain earthquake. Further, assume that the Design Basis Earthquake will be one that produces 0.75 g at the facility, with a probability of 84.1% that 0.75 g will not be exceeded. Using the horizontal radial PSRV for CP-1A (the lower one in Figure 14), the PSRV can be raised until the acceleration asymptote (the left one) is at 0.75 g (the middle PSRV). The original data from which Design Response Spectra were derived shows that the increase corresponding to one standard deviation is no more than a factor of 2.[3] Thus, by raising the middle PSRV by a factor of 2 to get the upper one in Figure 14, we have a spectrum for a Design Basis Earthquake which must be contained beneath the Design Response Spectrum. It can be seen in Figure 14 that the displacement asymptote falls at about $M_L = 5.6$.

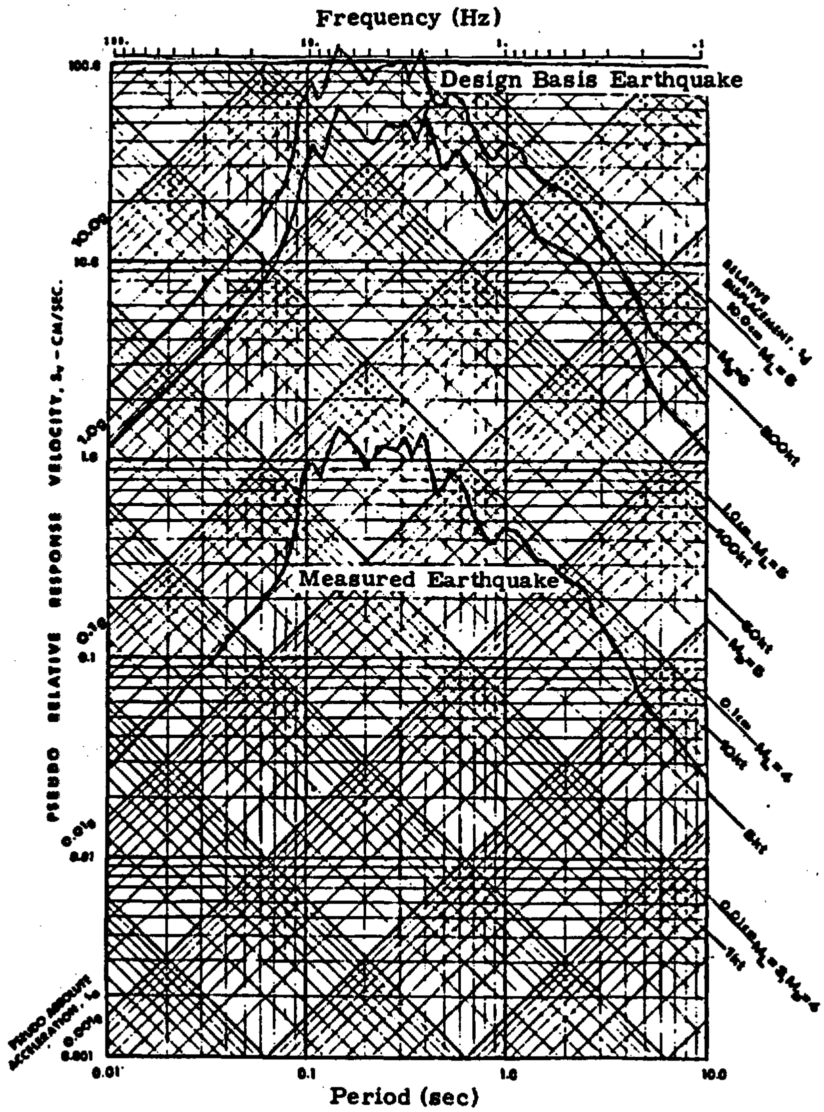

Figure 14. Development of a Design Basis Earthquake From Data Measured on an Earthquake of Smaller Magnitude

Richter[10] found that the frequency of earthquake occurrence in a 300 000 km^2 area of southern California could be described by

$$\log N = 4.77 - 0.85\ M \tag{6}$$

where N is the number of events per year. Greensfelder found that for southern Nevada the frequency was described by[12]

$$\log n = 2.92 - 0.96\ M \tag{7}$$

where n is the number of events per year per 1 000 km^2. For a magnitude 6 earthquake, this gives a frequency of 0.00145 earthquakes/yr/1000 km^2, or one magnitude 6 earthquake in about 700 yr. Richter's equation gives 0.00158 earthquakes/yr/1000 km^2, or about one in 650 yr. Thus, there is a less than 1 in 20 chance of a magnitude 6 earthquake during the 30-yr period that material is being emplaced in the repository. Once the material is emplaced, and after a repository has been sealed, the stored material can be expected to survive several g's, or even tens of g's.

A 1000-km^2 area represents roughly one-quarter of the area of NTS. A radius comparable to the distance from CP-1 to the epicenter of the Massachusetts Mountain earthquake describes a circle with an area of about 300 km^2; consideration of such an area further reduces the frequencies calculated above. In considering such a small area, attention must be given to locations of known faults rather than assuming a statistical distribution.

Reporting historical earthquakes in southern Nevada from 1932 to 1973, Greensfelder cited only one in the magnitude 6.0 to 6.9 range located at a point southeast of Alamo, Nevada -- about 160 km from NTS.[12] King's listing covered the period from 1950 to 1971 and noted the largest earthquake occurred at essentially the same location on August 16, 1966 with a magnitude of 5.6.[8] It is not clear whether or not these were the same earthquake.

Typical surface structures are built to carry vertical loads, and are therefore much more resistant to vertical motion than to horizontal motion. Earthquake-resistant design consists mainly of increasing resistance to horizontal motion. It was noted that the Massachusetts Mountain was a strike-slip (horizontal motion) earthquake, and that at CP-1 the horizontal motion was stronger than the vertical. Records from four additional stations were examined and peak-to-peak values of acceleration determined. Vertical acceleration was compared with horizontal motion by $\alpha = (a_r^2 + a_t^2)^{\frac{1}{2}} / a_v$ (shown in Table 4), where a is peak-to-peak acceleration.

Table 4

Comparison of Vertical and Horizontal Motion

Station	Distance (km)	α
CP-1A	8.817	4.34
Beatty, Hardrock	69.923	1.22
Beatty, Alluvium	71.067	5.26
Squires Park, Las Vegas	108.920	6.23
Tonopah Church	171.343	4.21

With the exception of the Beatty Hardrock station, it appears that the motion retains much of its dominant horizontal characteristic. If this is typical of other strike-slip earthquakes, then buildings will be more vulnerable to that type of earthquake than to earthquakes of the thrust-fault type. The Design Response Spectra of Figures 1 and 2 show the horizontal to be about 1.6 times the vertical. The table of earthquakes on which the figures were based does not indicate which were strike-slip and which were thrust-fault earthquakes.[3] Data from the San Fernando earthquake of 1971 (which was predominately a thrust-fault type) were included and in two of three cases showed smaller vertical than horizontal motion, but by smaller ratios than for the one being considered here.[13]

Summary and Recommendations

The Nuclear Regulatory Commission has not yet established the design response criteria for nuclear waste storage facilities. The procedures are expected to be similar to those NRC has specified for nuclear reactors, even though the criteria used in the procedures may be different. Designs of reactors need to consider only natural earthquakes, whereas the design of an NTS waste facility must consider nearby weapons tests in addition. There are distinct differences in the two sources of ground motion. The source of a weapon's test is known precisely in time, location, and energy, and the test safety is in the hands of an experienced test organization. The opportunity to evacuate personnel and secure vulnerable structural elements or contents allows less conservatism with respect to weapons tests.

Ground-motion measurements made at the control point on an NTS earthquake of August 1971 have been examined. The magnitude of the earthquake was about 4.3; its focal point was between 4 and 4.6 km deep and between 6 and 10 km from the control point. The earthquake resulted from strike-slip (horizontal) motion; the peak-to-peak vertical acceleration was only about 40% of the horizontal. Peak displacement from the earthquake was from body waves, but nuclear weapons tests are relatively much shallower; at comparable distances, the peak displacement is from surface waves.

A comparison of the motion from the earthquake measured at the control point was made with motion from four nuclear weapons tests at comparable distances with yields 7, 8.4, 10.1, and 21.3 kt. The vertical velocity and displacement from weapons tests is always larger than the velocity and displacement from the earthquake, and by an amount that is clearly a function of yield. Acceleration is always larger for the earthquake; the period is shorter because the motion is from the body waves. The relations between the radial components are similar.

Relationships between earthquake magnitudes and yields of weapons tests show that an $M_b = 4.4$ earthquake would correspond to a yield of about 3.8 kt. These relationships permit using measured motion from a small earthquake to estimate the ground motion from a larger magnitude earthquake. The relationship between magnitude and yield was derived from data at a single station about 160 km away. A similar relation derived from on-site data may be a more appropriate one, and its determination is recommended.

It had earlier been determined that an appropriate design criterion for weapons test ground motion would be 0.75-g peak vector acceleration at a 0.5 sigma probability level. If for earthquakes it is assumed that the same 0.75 g were to apply to a radial component at the 1-sigma level, it has been shown that this would correspond to about an $M_L = 5.6$ earthquake. Two approaches to the occurrence frequency of earthquakes (one for southern Nevada and the other for southern California) show that one magnitude 6 earthquake could be expected in 700 yr or in 650 yr. The data from which these estimates were made were gathered over relatively large areas. Consideration of the small area close to a repository, ~10 km, would require attention to known faults.

Conclusions should not be based on a single earthquake; therefore it is recommended that earthquake records for the region be searched for others at comparable distances to see if the data base can be broadened. The strike-slip earthquake considered here shows a horizontal component about 2.5 times the vertical. Since the seismotectonics of southern Nevada results in predominantly strike-slip movement, the additional data should be examined to be certain horizontal motion is not being underestimated. If the examination of additional close-in earthquake data verifies the relationships between earthquake and weapons test ground motion observed here, then weapons test ground motion could be used to estimate earthquake ground motion for magnitudes for which probability of occurrence in a given monitoring period would be very small.

References

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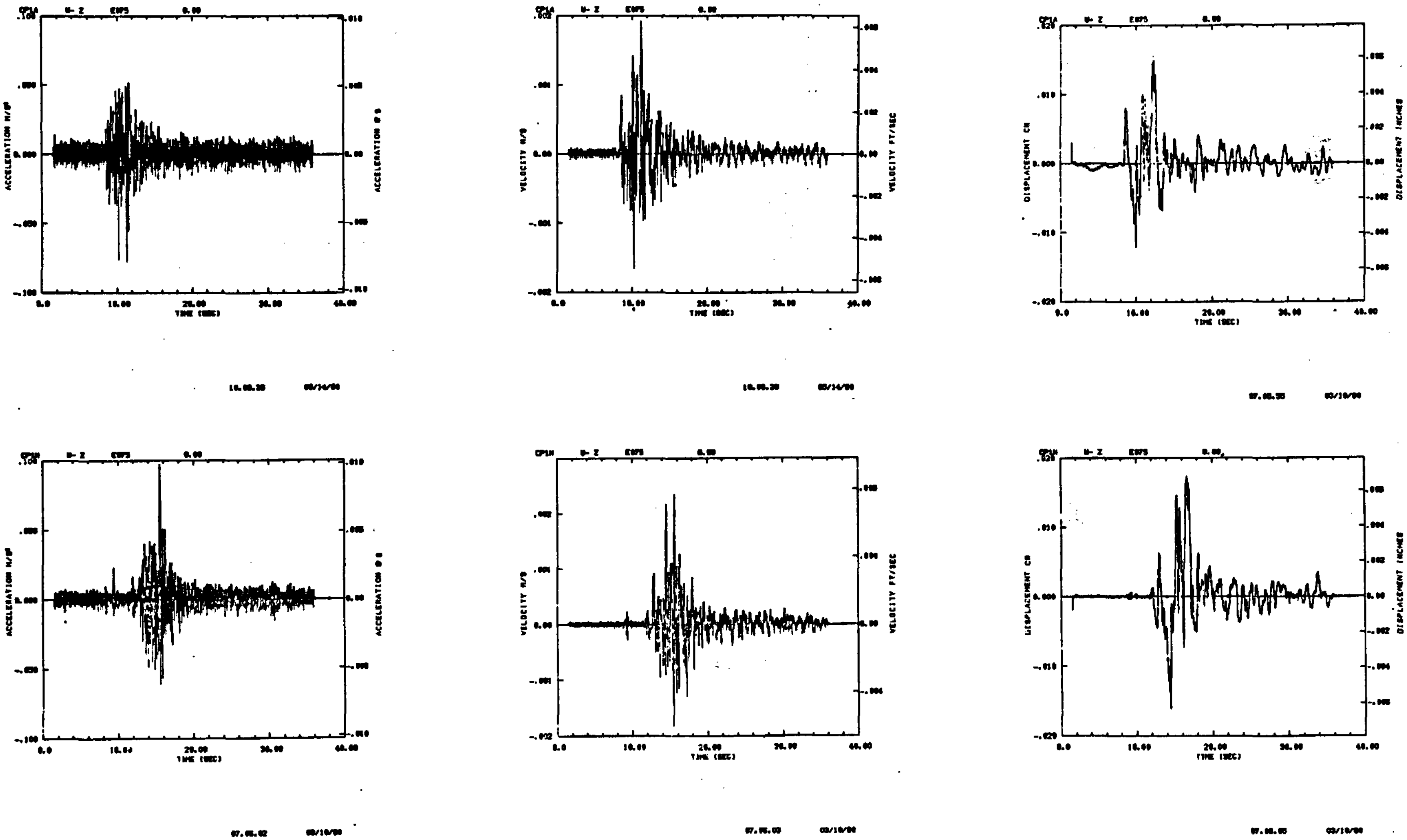

Figure A-1. Vertical Motion

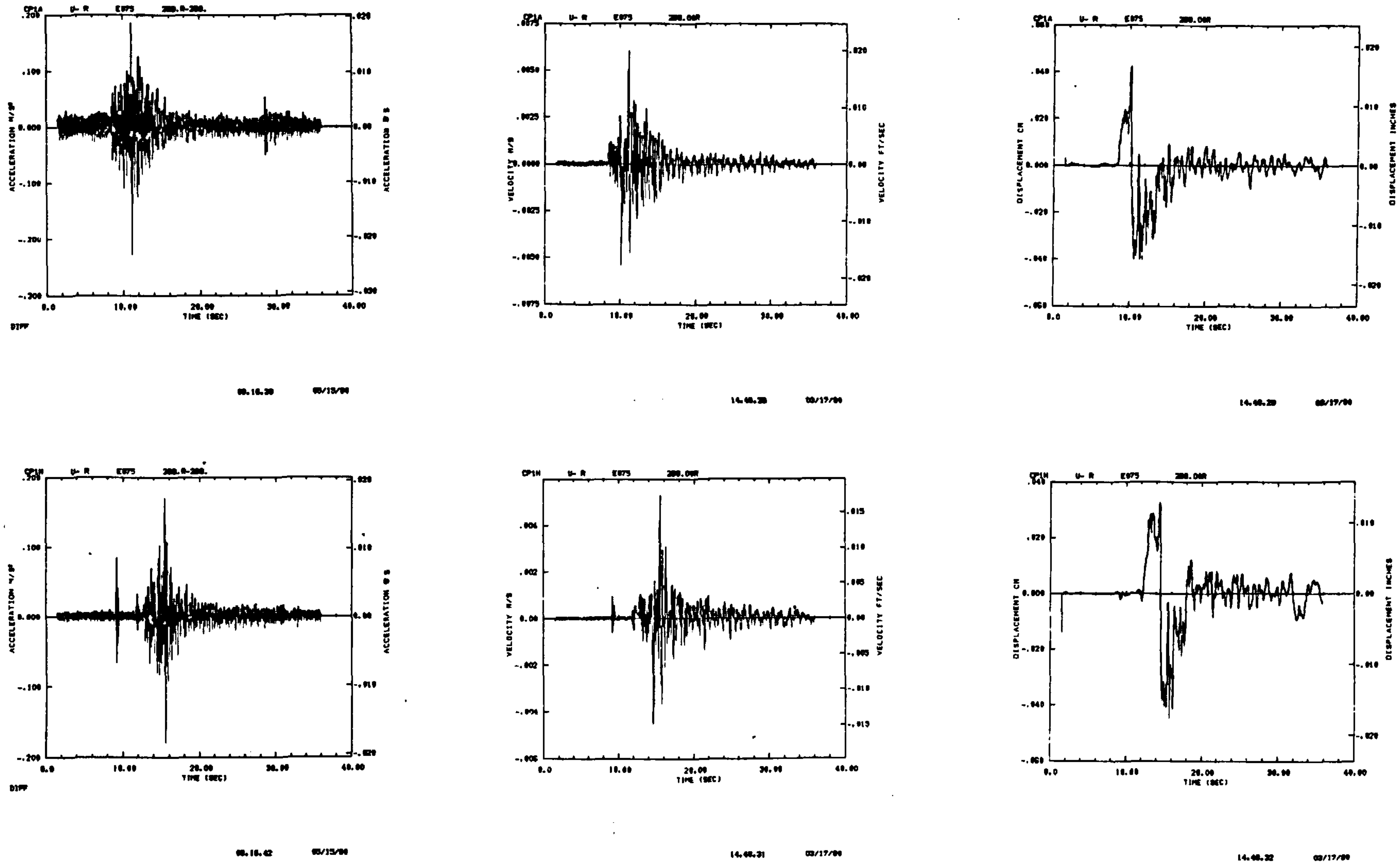

Figure A-2. Radial Motion

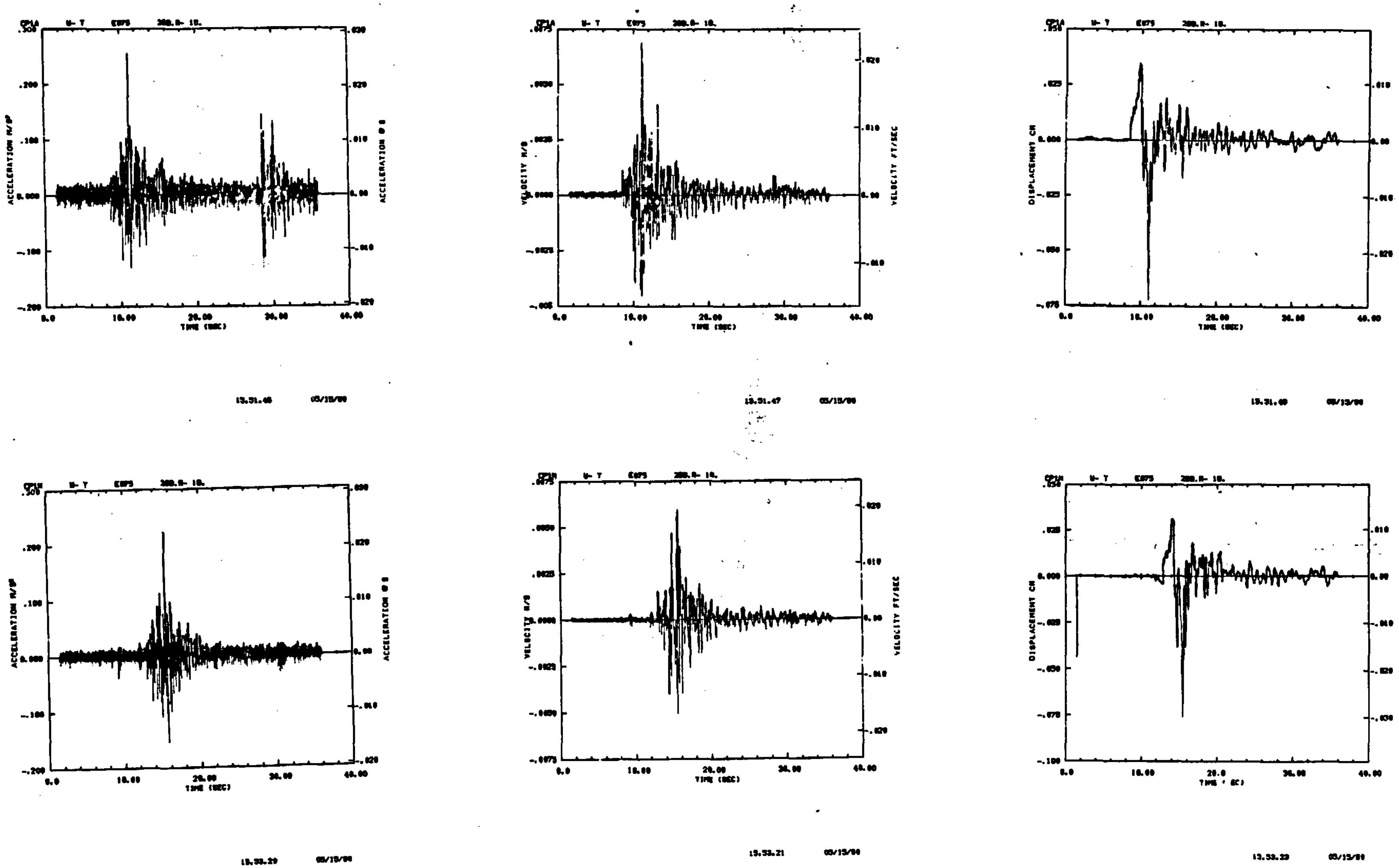

Figure A-3. Tangential Motion

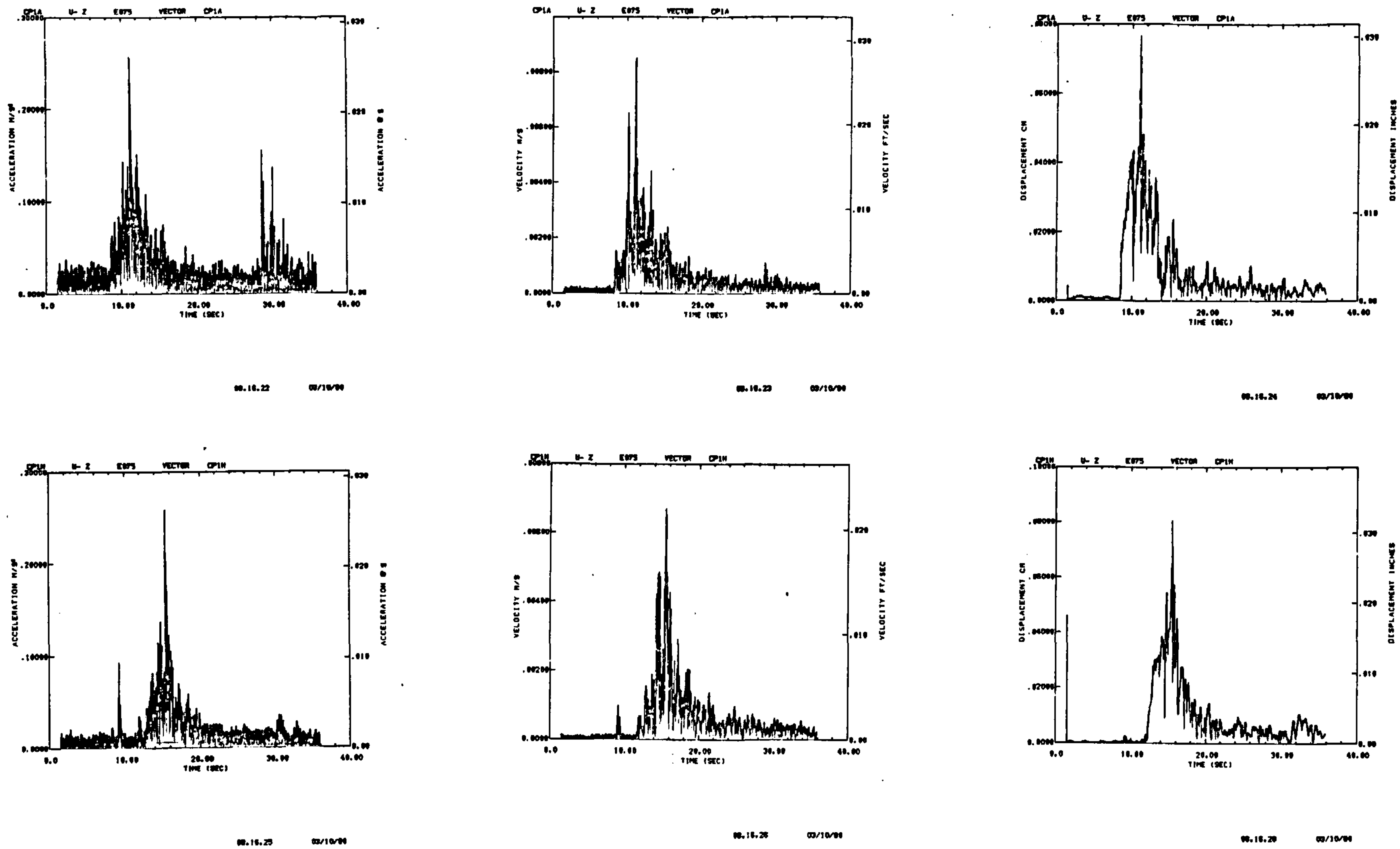

Figure A-4. Vector Motion Magnitude

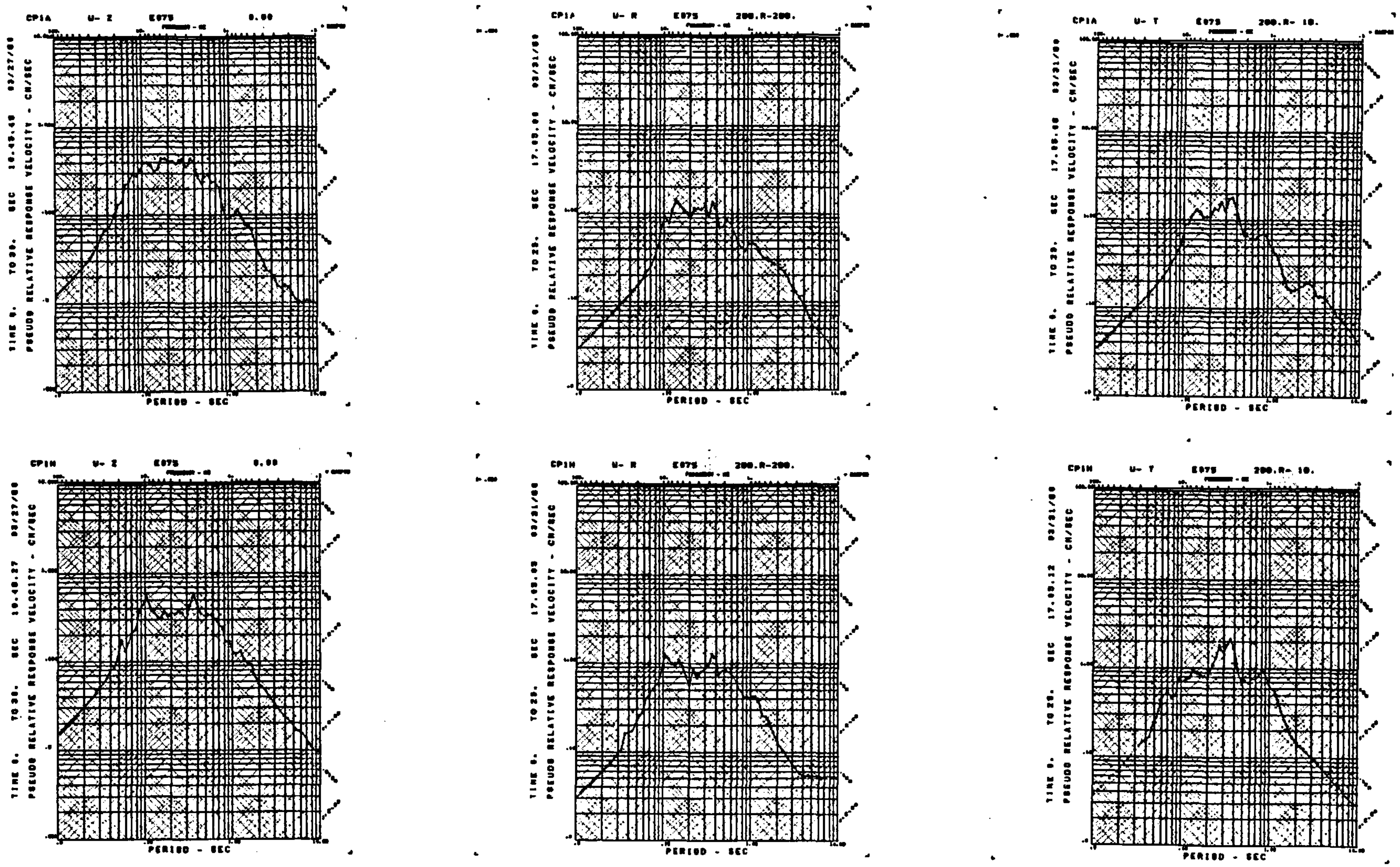

Figure A-5. PSRV's for Vertical, Radial, and Tangential Motion

Figure A-5

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