ABSTRACT

SEISMIC MOTIONS FROM PROJECT RULISON

by

P. C. Loux

In the range from a few to a few hundred km, seismic measurements from the Rulison event are shown and compared with experimentally and analytically derived pre-event estimates. Seismograms, peak accelerations, and response spectra are given along with a description of the associated geologic environment.

Techniques used for the pre-event estimates are identified with emphasis on supportive data and on Rulison results. Of particular interest is the close-in seismic frequency content which is expected to contain stronger high frequency components. This higher frequency content translates into stronger accelerations within the first tens of km, which in turn affect safety preparations.

Additionally, the local geologic structure at nearby population centers must be considered. Pre-event reverse profile refraction surveys are used to delineate the geology at Rifle, Rulison, Grand Valley, and other sites. The geologic parameters are then used as input to seismic amplification models which deliver estimates of local resonant frequencies. Prediction of such resonances allows improved safety assurance against seismic effects hazards.

SEISMIC MOTIONS FROM PROJECT RULISON

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Introduction

Environmental Research Corporation provides scientific and engineering support to AEC's nuclear test program by predicting seismic motions from nuclear detonations. Predicting the motions for Rulison, the second Plowshare gas stimulation experiment, is one example of such support which we shall explore here.

Directly induced nuclear generated ground motions are strongly dependent on several factors: device energy release, source medium, device depth of burial, distance to the observation point, geology surrounding the observation point and geologic and geophysical parameters between the device and the area of interest.* Current ground motion predictive technology quantitatively accounts for all these factors except the last one--the transmission path geology. Although studies to delineate the effect of the parameter are in progress, the problem remains that even if this structure is known, satisfactory models are not always available to describe the detailed effect on the seismic motion.

Accurate prediction of the ground motion is imperative, because associated seismic hazards may well limit future Plowshare activity. We will have to assess accurately the probability of damage to property and certainly preclude the possibility of personal injury.

After a brief geographical, geological, and seismic instrument orientation, I propose to complete this presentation by showing you Rulison seismic data compared with pre-event estimates. Then we can explore methodology used for making estimates, and touch on the question of future seismic predictions for the Rulison area.

The first slide (Figure 1) shows the location of the seismic stations operated by the U.S. Coast & Geodetic Survey. Station locations were chosen for safety documentation, seismic wave propagation studies in this type of environment, and for calibration data for future Plowshare activity in this area. Generally, radial, vertical, and transverse components of ground velocity as a function of time were recorded at some 36 sites; with acceleration and displacement subsequently derived from these data. I believe it fair to summarize that USC&GS did a tremendous job in obtaining the seismograms.

*See References 1, 2, 3, 4, 5, and 6.

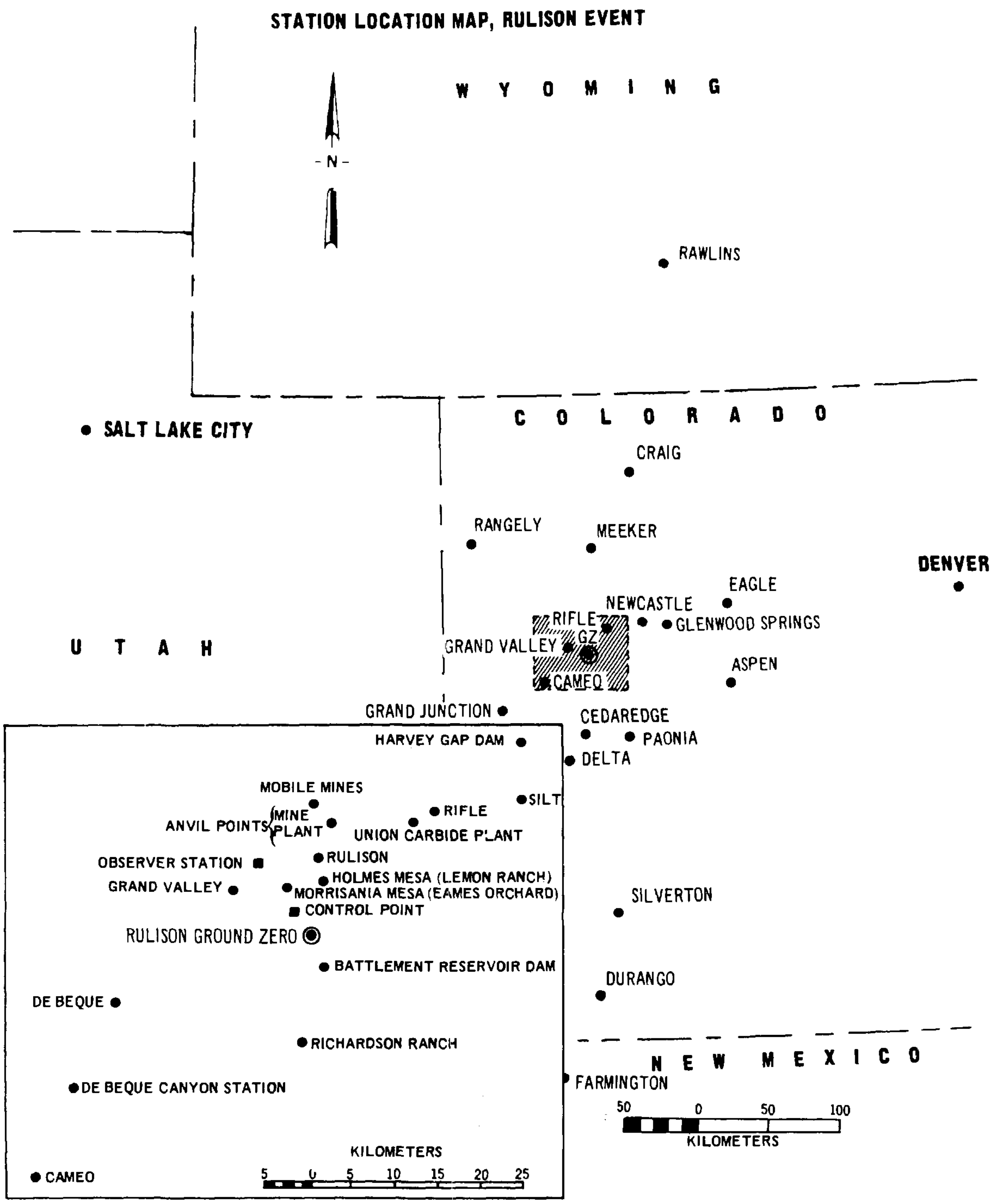

Figure 1. Station Location Map, Rulison Event

The insert in this map shows the emphasis on seismic instrumentation within the first 25 km or so. Of particular interest are the populated areas such as Grand Valley, Rulison, and local home sites, as well as industrial sites and earth structures.

The device was fired at a depth of some 8400 ft. in the Rulison gas field of the Piceance Creek Basin. With the seismic motions in mind, I would like to highlight the fact that this Basin is geologically comparable to the San Juan Basin of New Mexico where a similar experiment, called "Gasbuggy" was performed. Essentially flat-lying beds of shales, siltstones, and sandstones predominate in the geologic columns at both sites. As we shall see in a moment, this similarity in source medium and geology was one factor utilized for the Rulison ground motion predictions.

Data and Predictions

Let's now look at some of the Rulison seismic data. The next slide (Figure 2) depicts the seismic motion measured in the town of Rulison. Shown are the radial, transverse, and vertical com--ponents of surface motion, as a function of time. At the bottom of the figure we see the amplitude as a function of time of the instantaneous vector amplitude. From this curve you will note that the peak motion is 7/10 g; in the three following slides we will be discussing peak motion defined in this manner.

A conspicuous feature at the Rulison station is the strong 0.07 second vertical motion (with a wave velocity of about 5.5 km/sec) at the beginning of the trace, as compared with the horizontal-radial component. Other identifiable waves are seen at the right side of the figure. Appearing on the radial and vertical traces is a 0.15 to 0.2 second Rayleigh (surface) wave whose velocity is in the order of 2 km/sec. At the same time, on the transverse trace, is either a love or a horizontal (SH) shear wave. We note that this SH wave appears to be rather large, recalling our expectation that the nuclear source ought primarily to generate compressional waves. Coincidentally, this same phenomenon has recently come under study at the Nevada Test Site, where we are investigating physical mechanisms that might be generating the shear motion.

We will also be concerned with the seismic frequency content, because of its potential effect on structures such as houses, and other buildings, industrial plants, dams, etc. When we later view the response spectrum for each of these seismograms, we will be particularly interested in spectral peaks that may occur at reasonant frequencies of nearby structures.

Recalling that the peak motion will be defined as the peak of the vector trace, let's look at Rulison peak motions as a function of distance from the detonation. May I have the next slide, please. (Figure 3.) Ignoring the solid lines for a moment, we have the vector displacement peaks (circled points) plotted as a function of the straight line, or slant, distance from the shot point. The first observation is the rather well behaved decrease in amplitude, that is attenuation, with distance.

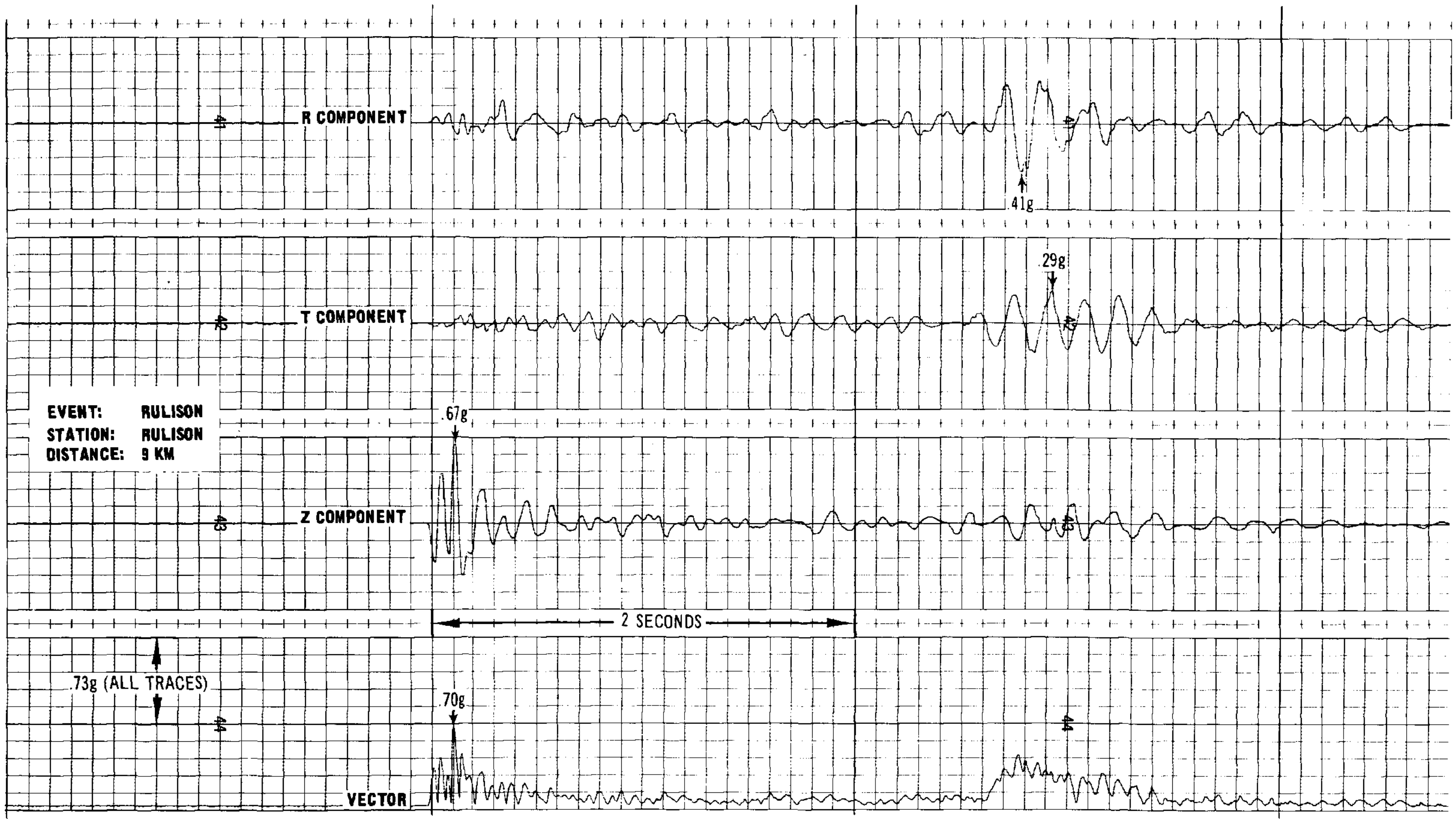

Figure 2. Rulison Station Seismogram

Those familiar with seismic motions know that this is often not the case, so that for Plowshare activity in particular, one has to be concerned with accurate prediction of amplitudes that depart on the high side of the average behavior. This average behavior is shown by the solid line labelled "observed data." For comparison we show the line labelled "40 kt NTS experience," which represents the average attenuation observed from over 95 experiments at the Nevada Test Site.[5] Compared with both the observed Rulison data and our NTS experience is the third line, called the "prediction." You will immediately see that the prediction is apparently not based on the average NTS experience. As a matter of fact it is based on the seismic data from the Gasbuggy Event. Briefly, the rationale for this is the unusual behavior of the Gasbuggy seismic data compared with our NTS experience, and also the similarity of the Gasbuggy and Rulison geologic environment. We shall see in a moment that unusual behavior appears in the velocity and acceleration data, and that Dr. Mueller's depth of burial and medium scaling analysis offers a good explanation.[1]

The next slide (Figure 4) shows the same type of information for the velocity peak amplitudes as a function of distance. Again, the prediction agrees quite well with the observed data, but for the velocities, we now see a significant departure from NTS experience with serious implications if NTS experience alone were used for the predictions. Assuming roughly that the energy in the seismogram is proportional to the peak velocity squared (not necessarily true) there would have been 25 times as much energy incident on structures at 10 km than would be predicted from NTS experience (from Figure 4, at 10 km the measured peak velocity is 5 times the NTS experience). A miscalculation in the damage assessment, such as this would cause, could have a permanently damaging influence on Plowshare activity.

On the next slide are shown the Rulison accelerations as a function of distance; again, good agreement between observed data and the prediction is obtained. The departure of the observed data from NTS experience is even more pronounced here than for the velocities. For example, at 10 km the measured acceleration is about 8 times higher than would have been estimated from NTS experience. Another way of expressing this is to note that the NTS yield that would have produced this acceleration (0.4 g) at 10 km, is not 40 kt but rather more than 1000 kt!

As indicated by Dr. Mueller in the preceding talk,[1] the predominant factors causing this departure from NTS experience, are the large depth of burial for Rulison, and the shale, siltstone geologic source environment. The effect of the large depth of burial is to enrich the high frequency seismic motion, a situation which finds expression in higher velocities and still higher accelerations. Sponsors of underground engineering applications (deep burial) will have to be concerned with high acceleration, especially at locations within the first 5 or 10 miles from the source, because of potential hazards to people and property. For cratering applications, no special problems arise, in that Mueller's theory predicts lower seismic amplitudes (attended by a shift toward lower frequencies) than are experienced from fully contained shots.

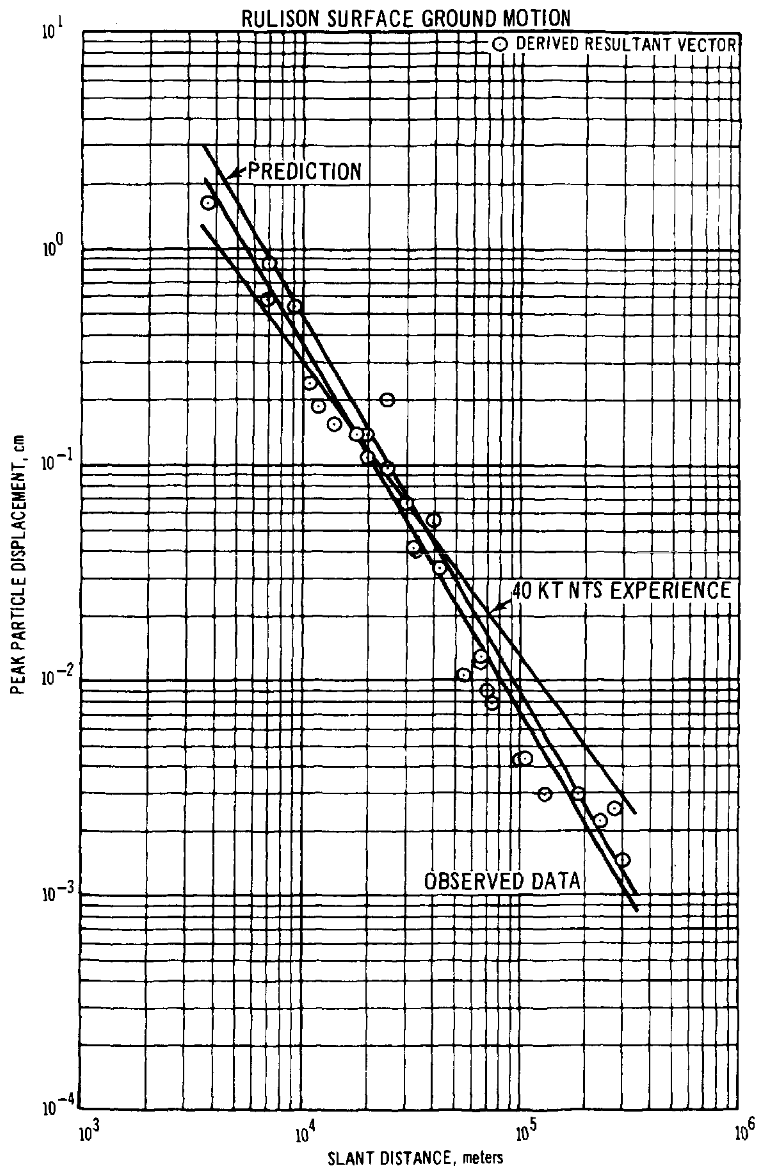

Figure 3. Observed Peak Particle Resultant Vector Displacement

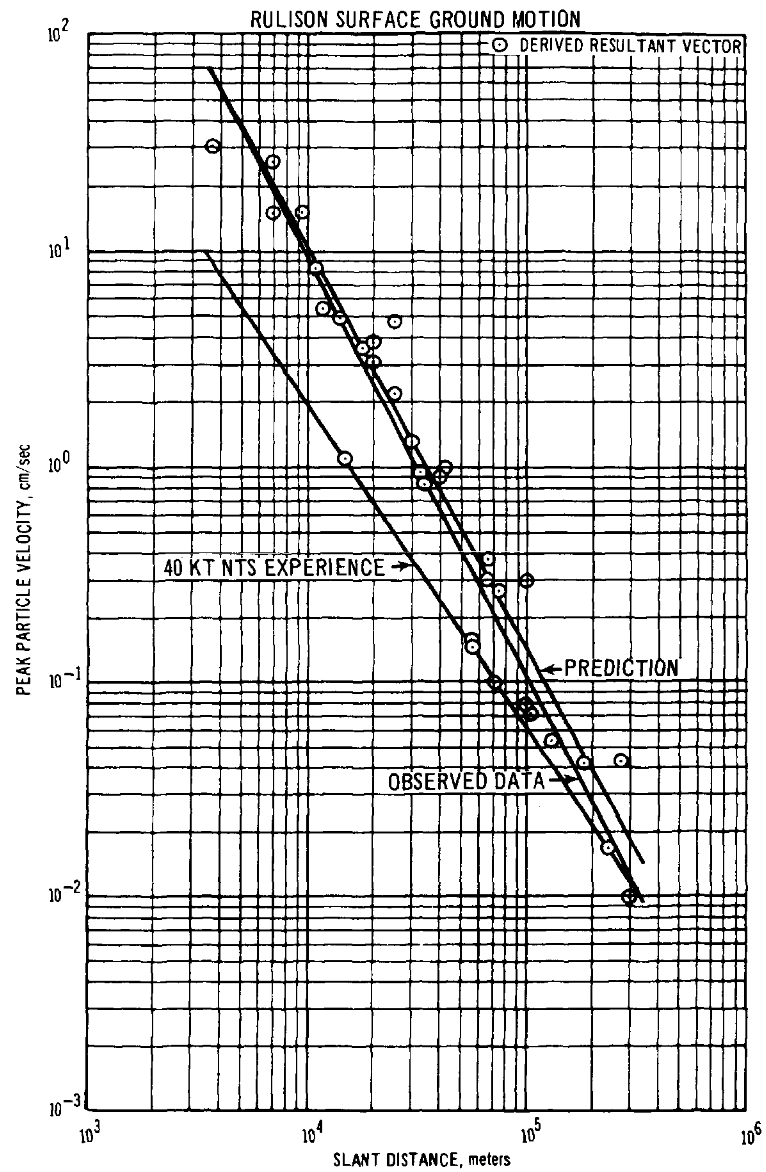

Figure 4. Observed Peak Particle Resultant Vector Velocity

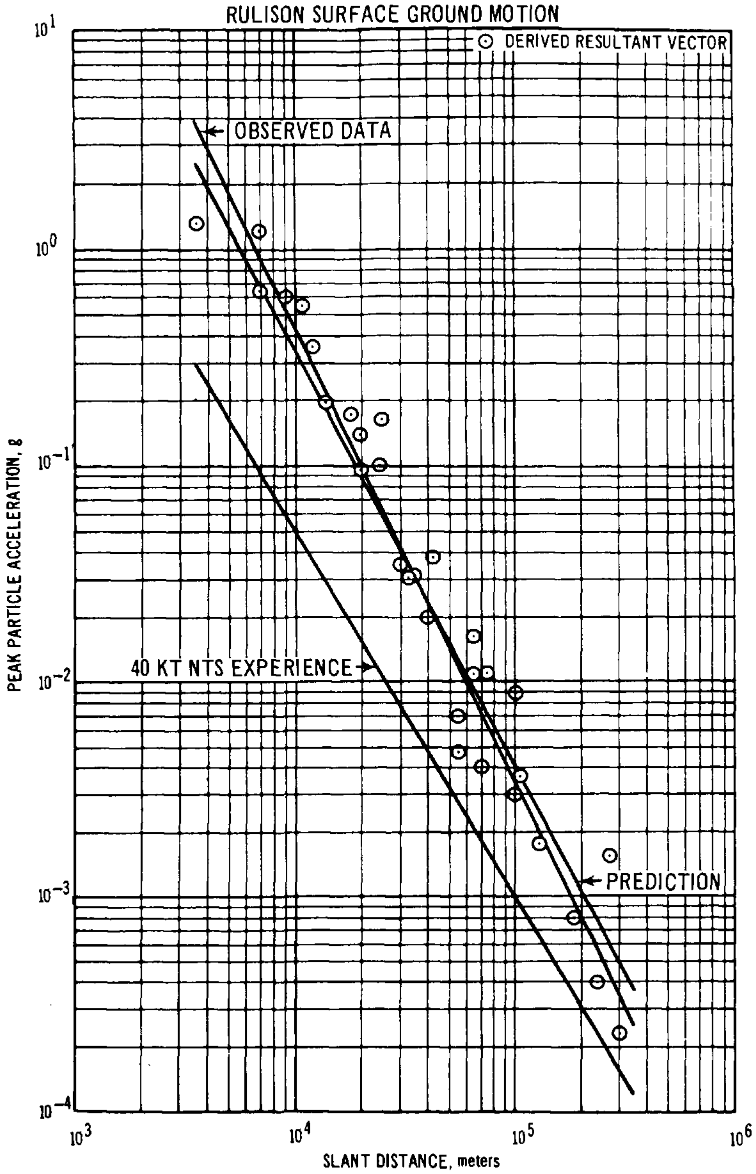

Figure 5. Observed Peak Particle Resultant Vector Acceleration

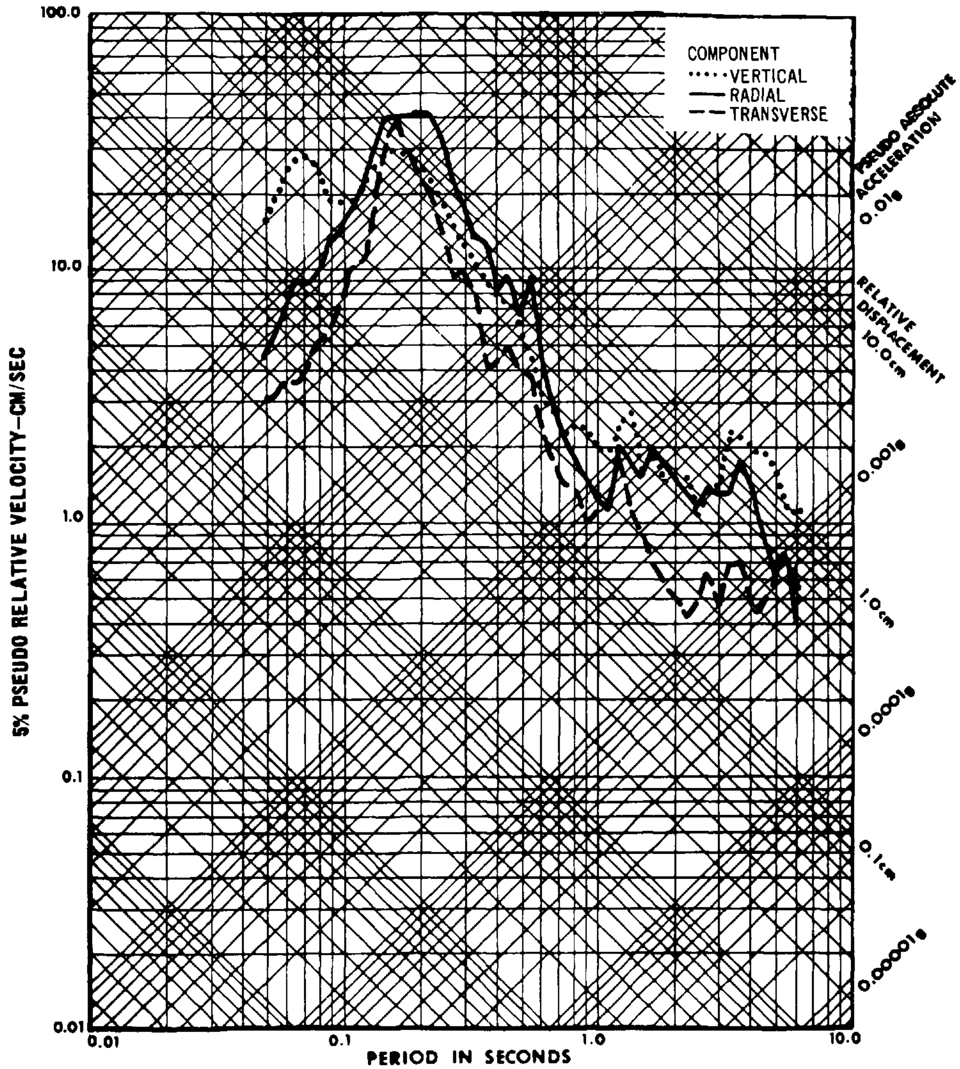

Figure 6. Station Rulison, Distance 9 km

Next slide please (Figure 6). As promised earlier, here are the response spectra for the Rulison station radial, transverse, and vertical seismograms shown in an earlier slide (Figure 2). Each spectrum represents the approximate velocity response of a simple, damped oscillator to the seismogram, as a function of the resonant period of the oscillator. In this case, the oscillator is damped at 5%. For those familiar with frequency domain representations of time histories (such as seismograms), the response spectrum turns out to be similar to the Fourier amplitude spectrum of the seismogram. The utility of the response spectrum lies in its analogy with the response of real structures to the ground motion. I'm sure that in a following paper, Dr. Blume will explore this point in more detail.

On the vertical component spectrum we see a spectral peak at about 0.07 seconds, caused by the strong primary wave on the vertical seismogram viewed earlier. The remaining predominant energy in the seismograms is contained in the surface wave motion (Rayleigh and SH) and this is evidenced by the spectral peaks in the neighborhood of 0.17 seconds.

I would now like to turn your attention to the prediction of the response spectrum for a few of the important locations in the vicinity of the Rulison experiment. The next slide (Figure 7) compares observed and predicted spectra, with the predicted spectrum based on the Gasbuggy Event spectra, depth of burial correction and also on estimates of seismic amplification caused by impedance contrasts in the near-surface geologic layering. The amplification is computed from analytical models describing seismic wave propagation through the layered system, underlying the station. Input parameters for the model, namely layer thicknesses and seismic velocities, were determined from standard reverse profile refraction surveys.

Also shown in this figure is the spectrum that would be expected on the basis of average Nevada Test Site (NTS) experience,[3] noticeably different from the Gasbuggy and Rulison data. In subsequent slides you will see that the prediction accuracy for the Rulison Event improved with distance. After the fact, we are now in a position to improve the close-in spectral predictions, in general, and in particular for this Rulison area. We can expect to be able to predict this shift in spectral period (in this case from 0.25 second to less than 0.2 seconds) as well as the higher amplitude (40 cm/sec versus 20 cm/sec) of the response spectrum peak. Indeed, further scrutiny of the Gasbuggy, Rulison, and other data should lead to explanation of this close-in seismic behavior which, until now, has not required careful study for safety purposes.

The next slide (Figure 8) gives the comparison for the town of Grand Valley, about 11 km from the source. Again the prediction of the spectral peak is within a factor of two for both the period and the amplitude of the peak.

In the next slide (Figure 9) the same type of information is shown for a station at Rifle, this time with very satisfactory agreement between the observed and predicted spectrum. We mentioned earlier that seismic amplification caused by near-surface

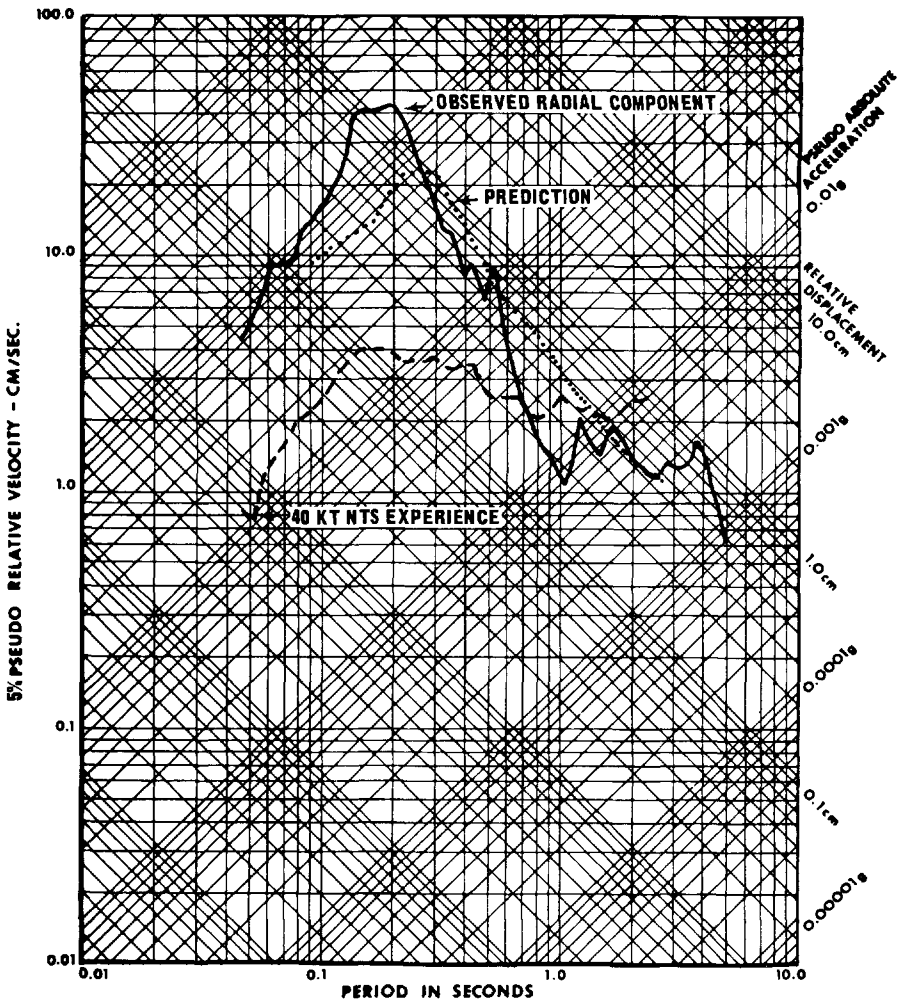

Figure 7. Response Spectra, Station Rulison, Distance 9 km

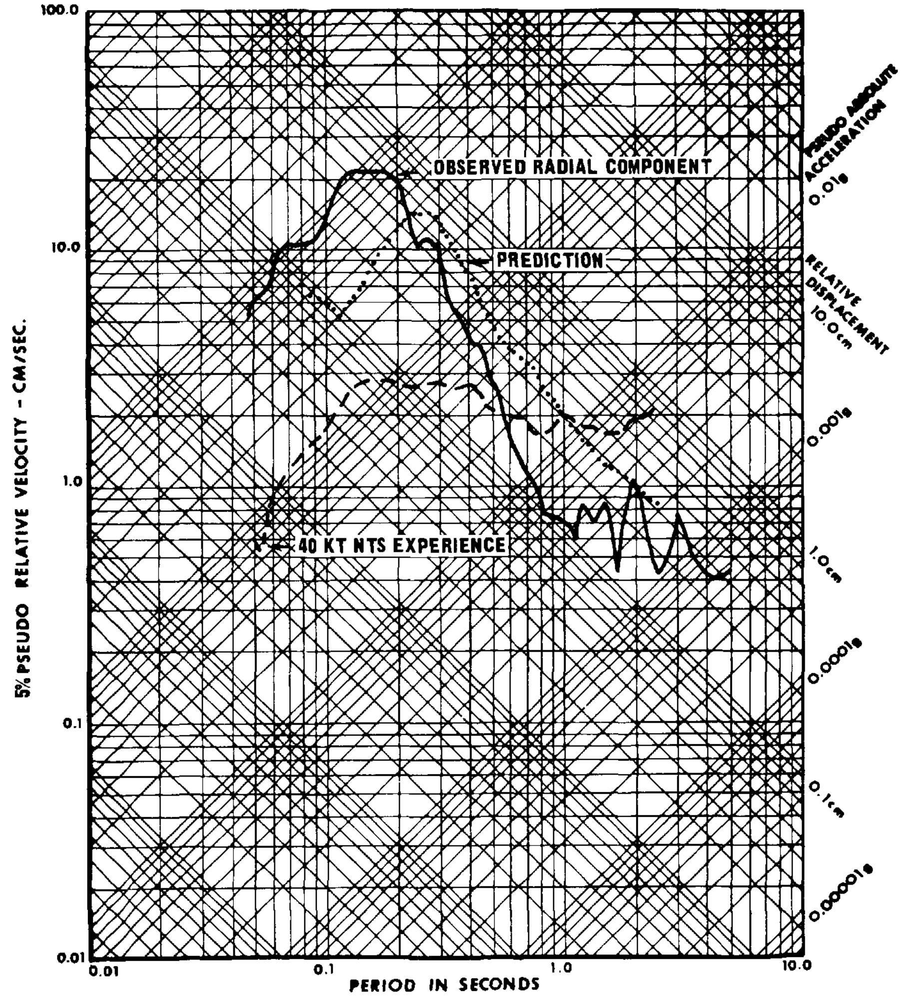

Figure 8. Response Spectra, Grand Valley, Distance 11 km

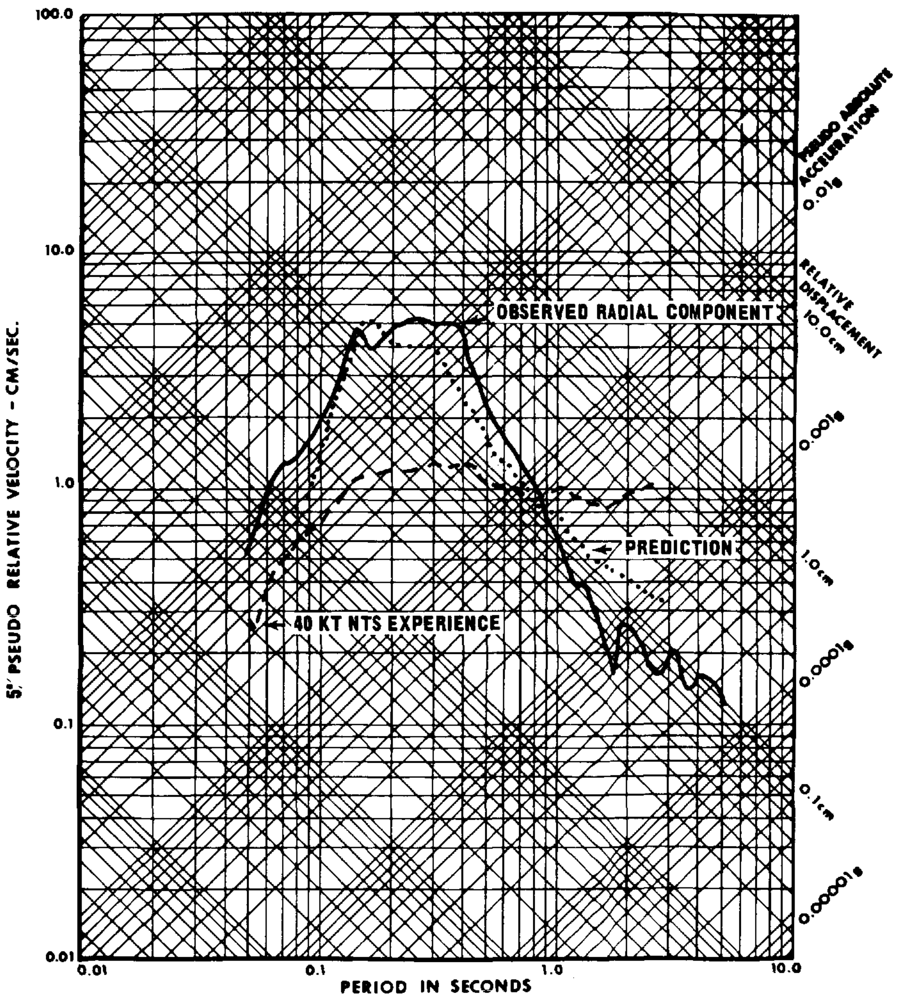

Figure 9. Response Spectra, Rifle (Top of Hill), Distance 20 km

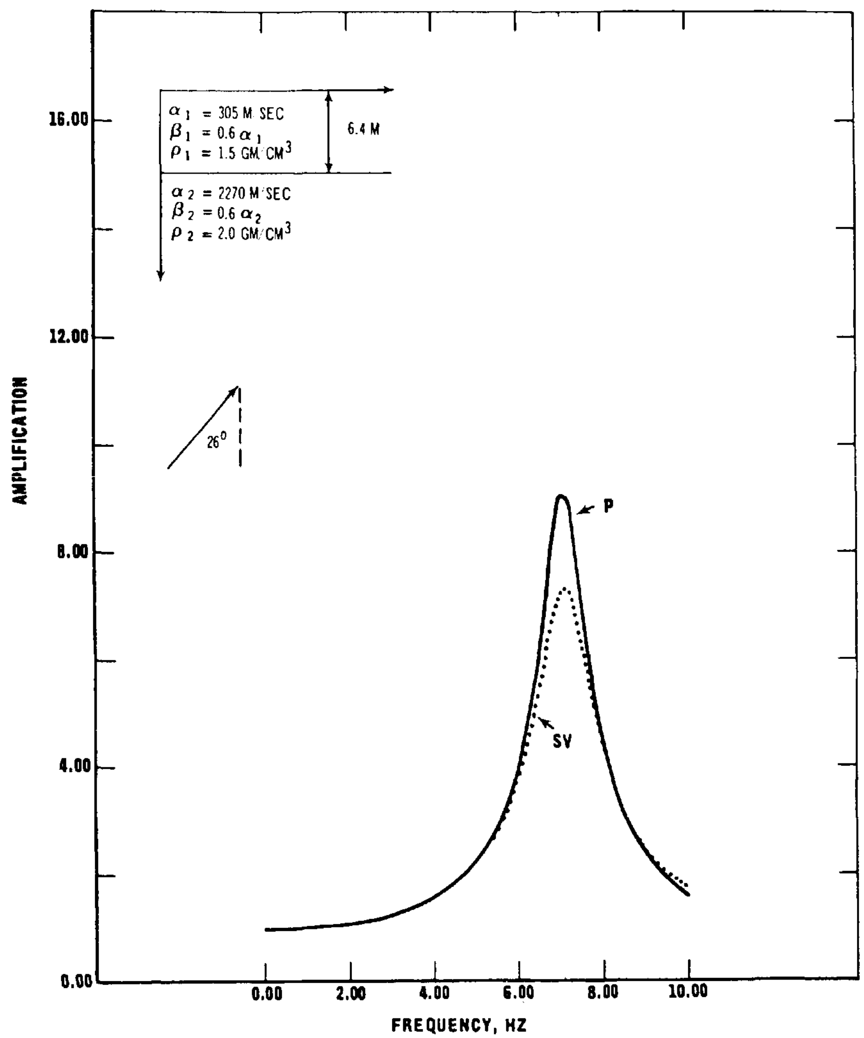

Figure 10. Horizontal Amplification versus Frequency, Rifle

layering was taken into account in the prediction of the response spectrum. To give you a feel for the amount of spectrum change caused by the station amplification we can look at the amplification correction curve for Rifle. Next slide please (Figure 10).

The layer thicknesses and elastic constants determined by a refraction survey are shown in the upper part of the figure. Using this information, the amplification computer models for compressional (P) and shear vertical (SV) waves deliver spectral amplifications that peak at about 0.14 second period (7 Hz). That this seismic amplification actually occurred is evident in the successful prediction of the response spectrum at this site.

In the next slide (Figure 11) we have the computed station resonance for the base of Harvey Gap Dam. This resonance enhances the response spectrum in the 0.1 to 0.16 period range (10 Hz to 6 Hz), and we can see that this is the case in the next slide (Figure 12). Our prediction is slightly higher than the observed data in this period range (0.1 to 0.16 sec), but it would have been significantly lower than the observed data without the station amplification correction.

Summary

Predicted seismic peak amplitudes and response spectra from the Rulison experiment are well verified by the observed data. Future seismic predictions for this area can be expected to be very accurate for single detonations of larger yield nuclear devices, with the provision that nuclear yield, shot depth of burial and geologic medium, site amplification effects and the close-in behavior of the (Gasbuggy and) Rulison data are all taken into account. Accurate estimates of seismic hazards are then possible.

Two additional points might be mentioned in connection with the ground motions from future detonations in this area. The first is the question of the reliability of the seismic prediction especially as it enters estimates of damage to structures. Much of the associated analysis that I, and Dr. Mueller in more detail, have touched upon, is performed on a statistical basis that includes a measure of the seismic data scatter. For a rough idea of the behavior of the data to be anticipated at Rulison sites, with the condition that the factors we have discussed are taken into account, one can expect seismic prediction accuracy to remain comfortably within a factor of two.

Another point is the question of multiple detonations at the Rulison site. The behavior of seismic motions from row charges is expected to differ from single bursts, and future studies will have to address this situation. Until this behavior is more completely understood, less confidence in seismic predictions from multiple charges will have to be tolerated.

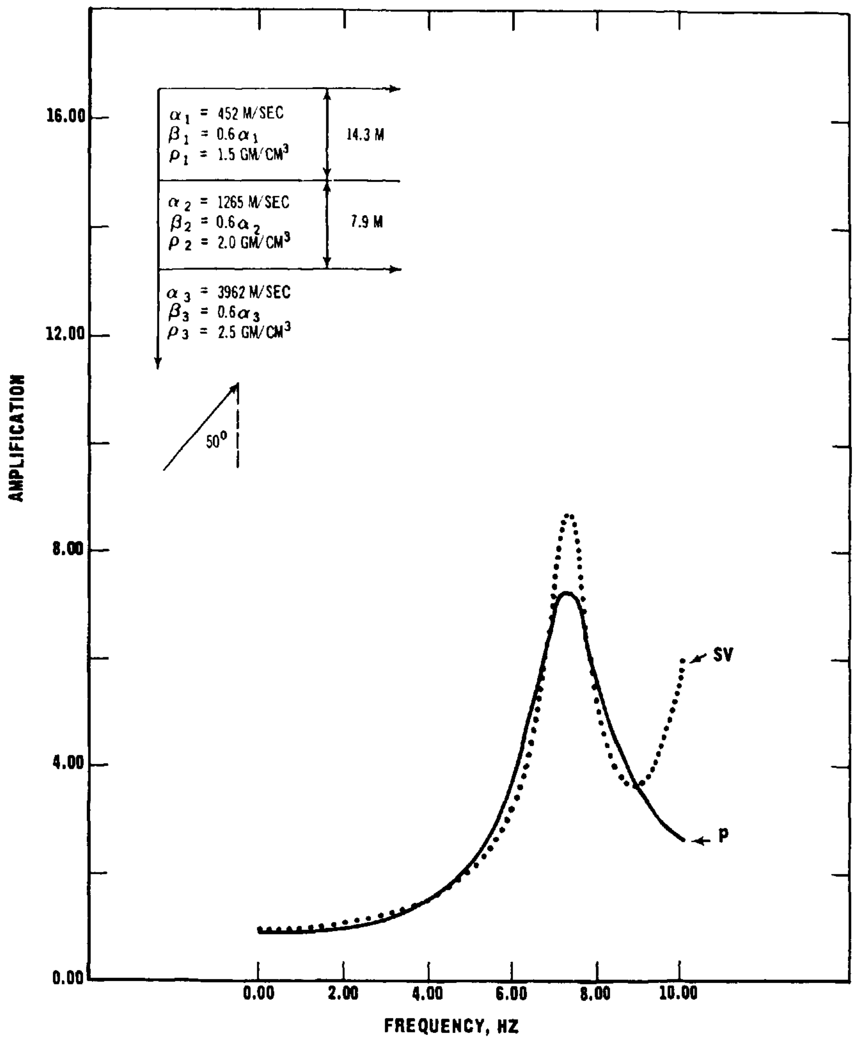

Figure 11. Horizontal Amplification versus Frequency, Harvey Gap Dam

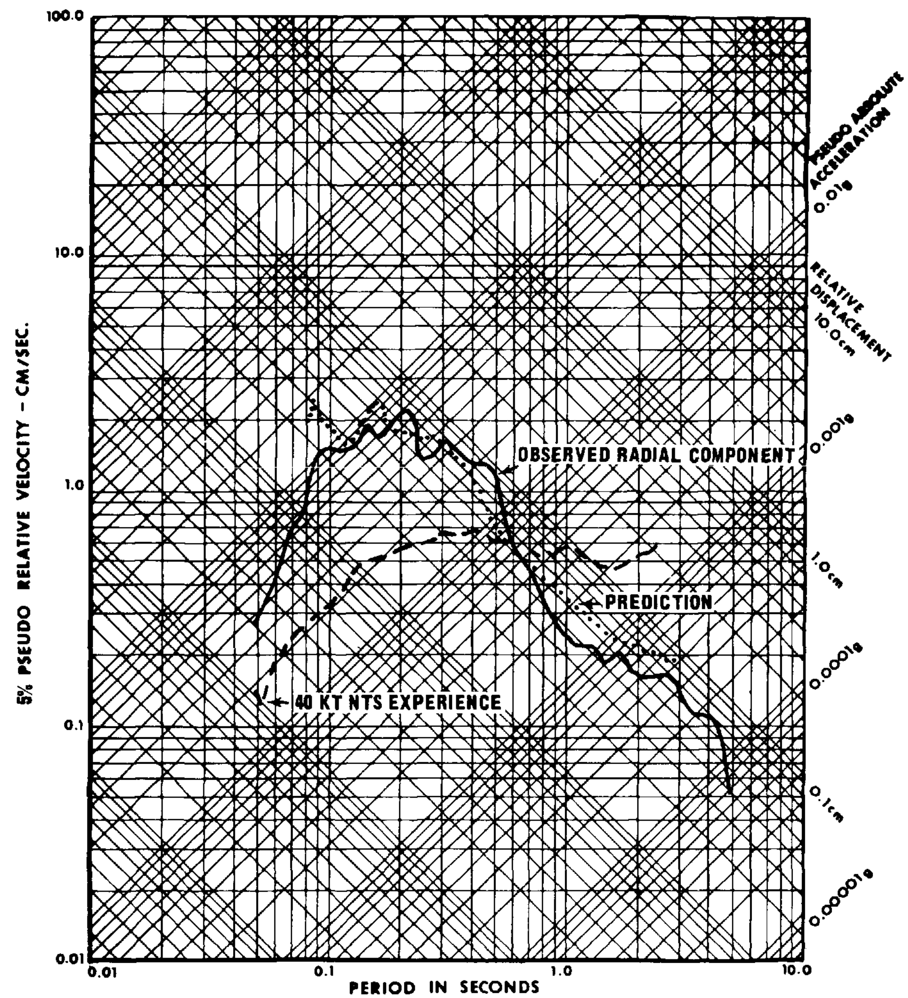

Figure 12. Response Spectra, Harvey Gap Dam, Distance 33 km

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