Introduction

The Waste Isolation Pilot Plant (WIPP) is a deep underground nuclear waste repository certified by the U.S. Environmental Protection Agency (EPA) to store transuranic defense-related waste contaminated by small amounts of radioactive materials. Located at a depth of about 655 meters below the surface, the facility is sited in southeastern New Mexico, about 40 kilometers east of the city of Carlsbad, New Mexico. The U.S. Department of Energy (DOE) managed the design and construction of the surface and underground facilities, and remains responsible for operation and closure following waste disposal.

The managing and operating contractor for the DOE at the WIPP, Westinghouse Electric Corporation, maintains two redundant seismic monitoring systems located at the surface and in the underground. This report discusses two earthquakes detected by the seismic monitoring system, one a duration magnitude 5.0 ($M_d$) event located approximately 60 km east-southeast of the facility, and another a body-wave magnitude 5.6 ($m_b$) event that occurred approximately 260 kilometers to the south-southeast (Figure 1).
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Figure 1: Seismic Source Zones
(after DOE/CAO, 1996)
Interpretation of the spectral response data from both events suggests amplification of very high frequency accelerations in the underground during both earthquakes.

The $M_d = 5.0$ Rattlesnake Canyon Earthquake occurred on January 2, 1992. Based on S-wave arrival times at the nearest station, the focal depth of the event was estimated to be $12 \pm 2$ km (Doser et al., 1992). The other earthquake was the April 13, 1995 $m_b = 5.6$ Alpine Texas event, reported at a focal depth of 13 km (NEIC, 1995). The Rattlesnake Canyon Earthquake was felt strongly throughout southeastern New Mexico and West Texas and was felt by WIPP site personnel at the surface. Potash miners working in mines located two hundred meters below the surface reported no detection of the event. On-site personnel also felt the Alpine Texas Earthquake. No damage occurred to the WIPP facility in either of the events, and both fell within seismic design criteria defined for the facility (Westinghouse, 1992).

**Geology and Seismotectonics**

The WIPP facility is located in the Permian basin of Southeastern, New Mexico and West Texas, where about 5,500 meters of mainly Paleozoic sedimentary stratigraphy overlie Precambrian basement. The underground repository is situated within the Permian-age Salado Formation, part of a 1,100 meter thick evaporite sequence consisting of primarily halite and anhydrite. Overlying the evaporite sequence is a 150 meter-thick redbed formation. Up to 5 meters of Quaternary-age sand and gravel overlay the redbeds, including an irregular zone of pedogenic calcrete. Shear wave velocities in surficial units
range from 140 to 600 m/s, while shear wave velocity measurements in the directly underlying redbeds range between 600 and 1200 m/s (DOE, 1990).

The basin is bounded on the east by the Central Basin Platform (CBP), a deeply buried NNW-SSE trending and internally faulted and folded horst. Vertical offsets on CBP boundary faults measure up to thousands of meters. Considered as a seismic source zone in the seismic design of the WIPP facility, early studies attributed instrumentally-measured seismicity within the CBP to oil and gas operations (Figure 1). Due to the depth of Rattlesnake Canyon Earthquake, Sanchez (1993) and Doser et al., (1992) postulated a tectonic source for at least some component of the seismicity in the CBP. First motion data for the Rattlesnake Canyon Earthquake yielded a focal mechanism solution consistent with motion along a fault within the north-northwest trending Western Platform fault zone, located at the western boundary of the CBP (Doser et al., 1992). Alternative interpretations of the earthquake are discussed in Sanford et al., (1993). North-northwest movement is also indicated in the focal mechanism solution for the Alpine Texas Earthquake, which occurred well to the south of the WIPP (NEIC, 1995).

Seismic Design of Drifts

Underground facilities consist of a system of north-south and east-west trending unlined drifts, measuring typically about 4-5 meters in height and up to 10 meters wide in main passageways. The central north-south drifts are elongated approximately 1550 meters, while the longest open east-west drifts are about 780 meters long. In response to deviatoric stress created by the excavation, creep closure and the altered stress field
results in a system of fractures surrounding the excavation. Rock bolts are used as ground support in the roof, and wire mesh is applied on sidewalls to control spalling. Four partially-lined shafts are used for waste handling, salt removal and ventilation. The upper portions of the shafts are lined with unreinforced concrete while the lower shaft within the Salado Formation is unlined.

The project initially evaluated a probabilistic seismic design; however, for the final design, the DOE selected a deterministic approach (DOE, 1990). A maximum peak ground acceleration of 0.1 g is used as the free-field input for the design response spectra, obtained by assuming a design basis earthquake (DBE) of magnitude 5.5, occurring 5.0 km directly under the facility. Bechtel (1981) used the response spectra developed for the surface in the seismic evaluation of the underground.

Bechtel's (1981) seismic evaluation of the underground facilities included both a historical review of tunnel damage and analytical and modeling approaches to identify performance design criteria. Historical performance of tunnels and relatively shallow mines are commonly used as an empirical measure of potential seismic performance of underground structures. Although these observations pertain to relatively shallow openings, relevant conclusions from the empirical studies suggest:

- Deep tunnels perform much better than shallow tunnels, and damage incidence decreases with increasing depth of overburden
- For peak ground accelerations equal to or less than 0.2g, ground shaking causes very little damage in tunnels (Power et al., 1998),
For peak ground accelerations between 0.2g and 0.6g, slight to heavy damage has been documented (Power et al., 1998),

Typical damage to engineered underground structures include cracking and spalling of engineered materials.

Numerical methods were used to calculate axial, flexural and shearing strains around the underground opening in response to ground motion. In a comparative analysis, Bechtel (1981) found that static strain analysis was more conservative. The evaluation was mainly used to assess the stability of the excavation with respect to personnel safety and waste operations. Bechtel (1981) concluded that common ground control practices would be effective mitigation against any potential ground motion experienced underground. More specific recommendations were directed at interfaces between lined and unlined portions of the shafts, particularly the shaft collar located near the surface.

Seismic Monitoring System

Two different types of strong-ground motion accelerographs are co-located at each seismic monitoring system (SMS) station: an Endahl system and a Kinemetrics system (Figure 2). The surface station is situated near the exhaust shaft while the underground station is located near the waste handling shaft along one of the main north-south drifts. Both underground and surface SMS stations are situated on a concrete slab.

The Kinemetrics system is a time-history accelerograph, that when activated, provides a continuous tape record of measured accelerations and frequencies. Calibrated to trigger when ground motion reaches 0.015 g's within a bandwidth (frequency range) between
Figure 2: Facility Layout and Location of Seismic Monitoring System (SMS) (after DOE/CAO, 1996).
1.0 and 10 hz, the trigger actuates an alarm at the same time it actuates the strong motion accelerograph magnetic recorder. Damping on the trigger is specified at 150% to produce a flat response in the frequency range of 1 - 10 hz. At the design basis earthquake acceleration of 0.10g, a switch at the surface location initiates closure of ventilation dampers to isolate the waste handling building. The switch is set to provide a flat response between 0.5 to 15 hz.

The Engdahl system consists of two recorders, a passive response spectrum recorder (RSR) and a passive peak acceleration recorder (PAR). Both Engdahl systems are calibrated to detect ground motion to 0.010 g's precision with ± 1.5% accuracy. The Engdahl peak acceleration recorder (PAR-400) measures transverse, longitudinal, and vertical components of ground motion within a nominal range of 0 - 26 hz. Peak acceleration is recorded on three individual scratch plates corresponding to each ground motion direction. The Engdahl spectral recorder also measures horizontal and vertical ground motion on three separate instruments; however, each instrument contains an array of 16 resonant scratch plates that are calibrated to frequencies in roughly 1 hz to 2 hz increments between a frequency range of 1 to 32 hz. Damping of the PAR instrument is nominally 60%, while the spectral recorder is nominally 2% damped.

**Seismic Response of Drifts**

Acceleration data presented in this section are documented in Westinghouse Electric Corporation facility reports (Westinghouse, 1992; Westinghouse, 1995). Verification of system performance included in the report addresses calibration, system damping and visual inspection of the instrumentation.
In both earthquakes, the reports verify that acceleration signatures on the Endahl scratch plates were consistent with ground motion input (Westinghouse, 1992). Tables 1 and 2 summarize Westinghouse data. Spectral response measurements are grouped into ranges to emphasize observable trends in the data.

**Rattlesnake Canyon Earthquake.**

Peak and spectral accelerations were recorded during the Rattlesnake Canyon Earthquake at both the underground and surface monitoring stations. The Kinemetrics time-history accelerograph was not activated at either location; consequently, no time-histories were generated.

**Surface Response.** In the Rattlesnake Canyon Earthquake, both the Engdahl response spectrum recorder (RSR) and the Engdahl peak acceleration recorder (PAR) documented accelerations between 0.01 and 0.06 g's. As shown in table 1, RSR spectral response measurements are generally lower than those recorded by the PAR peak acceleration instrument. The Engdahl peak acceleration recorder (PAR) showed accelerations of 0.06 g's (north-south), 0.04 g's (east-west), and 0.01 g's (vertical). Conversely, spectral accelerations below 0.02 g's dominated the RSR response over the 1 – 32 hz nominal frequency range of the instrument (Table 1).

The lack of response of the Kinemetrics system suggests that ground motion failed to exceed 0.015 g's between 1 - 10 hz at either the surface or subsurface seismic stations. Had the ground motion exceeded this threshold within this frequency range, the seismic
### Table 1: Surface and Underground Data - 1992 5.0 (Md) Rattlesnake Canyon Earthquake
Summarized Frequency Response of Engdahl Accelerographs
Epicentral distance - 50 km. Focal depth - 12 ± 2 km.

<table>
<thead>
<tr>
<th>Location and Type of Response</th>
<th>Measured Frequency Response (Hz)</th>
<th>Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North-South</td>
<td>East-West</td>
</tr>
<tr>
<td>Surface Spectral Response</td>
<td>1 - 32</td>
<td>0.00 - 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Response</td>
<td>0 - 26</td>
<td>0.06</td>
</tr>
<tr>
<td>Underground Spectral Response</td>
<td>1 - 13</td>
<td>0.00 - 0.02</td>
</tr>
<tr>
<td></td>
<td>16 - 32</td>
<td>0.04 - 0.11</td>
</tr>
<tr>
<td>Peak Acceleration</td>
<td>0 - 26</td>
<td>0.43</td>
</tr>
</tbody>
</table>

### Table 2: Surface and Underground Data - 1995 5.6 (mb) Alpine Texas Earthquake
Summarized Frequency Response of Engdahl Accelerographs
Epicentral distance - 220 km. Focal depth - 13 km.

<table>
<thead>
<tr>
<th>Location and Type of Response</th>
<th>Measured Frequency Response (Hz)</th>
<th>Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North-South</td>
<td>East-West</td>
</tr>
<tr>
<td>Surface Spectral Response</td>
<td>1 - 32</td>
<td>0.01 - 0.03</td>
</tr>
<tr>
<td></td>
<td>1 - 13</td>
<td>0.00 - 0.03</td>
</tr>
<tr>
<td></td>
<td>16 - 32</td>
<td>0.03 - 0.06^1</td>
</tr>
<tr>
<td>Peak Acceleration</td>
<td>0 - 26</td>
<td>0.04</td>
</tr>
<tr>
<td>Underground Spectral Response</td>
<td>1 - 32</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td></td>
<td>1 - 20</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>25 - 32</td>
<td>0.02 - 0.06^2</td>
</tr>
<tr>
<td>Peak Acceleration</td>
<td>0 - 26</td>
<td>0.08</td>
</tr>
</tbody>
</table>

1 Westinghouse (1995) suggests sensor amplification phenomenon on the surface instrument.
2 Westinghouse (1995) noted seating problems with the sensor.
trigger would have actuated the magnetic tape recorder on the unit. Consequently, the accelerations measured by the Engdahl system above 0.015 g are constrained outside the 1 - 10 hz bandwidth of the Kinemetrics seismic trigger. This range is between 10 hz and 32 hz, the 32 hz frequency being the higher nominal sensitivity of the two Engdahl instruments.

**Underground Response.** The Engdahl peak acceleration recorder (PAR) measured underground accelerations much higher than at the surface. As shown in table 1, the Engdahl PAR instrument recorded the following accelerations underground:

- North-South 0.43 g
- East-West 0.21 g
- Vertical 0.26 g

As on the surface, the lack of activation of the Kinemetrics time-history accelerograph in the underground suggests that ground motion failed to exceed 0.015g within a frequency range of 1-10hz. Based on the same reasoning, underground accelerations measured by the Engdahl system above 0.015g also appear to be related to the same higher frequency range between 10 hz and 32 hz. However, in this case, the Engdahl response spectrum recorder failed to confirm the peak acceleration results.

The Engdahl response spectral recorder showed little or no response despite the partially overlapping nominal frequency ranges of the PAR and RSR instruments (Table 1). The 1 to 32 hz response spectrum recorder should have detected the 0 to 26 hz
peak acceleration readings. As a possible explanation, Westinghouse (1992) noted that the PAR instrument possesses an effective bandwidth up to 50 Hz. Consequently, having ruled out instrument malfunction, they conclude the PAR instrument is detecting frequencies between 32 to 50 Hz and possibly higher octaves. Octaves between 32 - 50 Hz range from 64 – 100 Hz.

Another observation from the underground recordings concerns the higher readings on the measured north-south components of ground motion on both the spectral recorder and the peak acceleration recorder (Table 1).

**Alpine Texas Earthquake.**

The Alpine Texas Earthquake was a larger, but more distant event from the WIPP than the Rattlesnake Canyon Earthquake. Like the Rattlesnake Canyon Earthquake, the event did not trigger the Kinemetrics time-history accelerograph, but did trigger the passive mechanical recorders on the surface and in the underground. The effects of the earthquake were felt by personnel on-site at the surface, but were not detected by underground personnel. Again, the lack of response of the Kinemetrics system suggests that ground motion failed to exceed 0.015g/s between 1 - 10 Hz at either the surface or subsurface seismic stations. Consequently, frequencies and accelerations measured by the Endahl systems are again outside the Kinemetrics response envelope.

**Surface Response.** At the surface, both the Engdahl response spectrum recorder (RSR) and the peak acceleration recorder generally measured relatively lower levels of
acceleration from 0.01-to-0.03g's (Table 2). The vertical component of the spectral recorder measured slightly higher accelerations (0.03 – 0.06 g's) between 16 - 32 hz (Table 2).

**Underground Response.** Despite the relative quiescence of the Engdahl RSR sensors, table 2 shows that the north-south component on the Engdahl PAR measured a relatively high acceleration (0.078 g’s). With respect to the underground, observations from the Alpine Texas Earthquake show the following similarities to the Rattlesnake Canyon Earthquake:

- the higher acceleration occurs in the north-south drift
- the higher acceleration is measured by the peak acceleration recorder
- the larger north-south component of ground motion coincides with the north-south orientation of the drift system, and
- the frequency of the 0.078g recording is constrained to be above 32 hz, based on an effective bandwidth of the PAR instrument (1-50 hz) that extends beyond the spectral recorder’s nominal range (1-32 hz) (Westinghouse, 1995).

**Geomechanical Response**

Geomechanical instrumentation in the underground consists of extensometers, convergence points and fracture monitoring stations placed in the backs and the walls of the drifts and rooms. The fracture monitoring system is installed around ventilation overdrafts and drift intersections, locations of high static stress concentrations. In
general, the monitoring instruments possess from .001 inches to .005 inches precision. According to facility procedure, measurements of the geomechanical monitoring system are taken immediately following events such as the two earthquakes in 1992 and 1995. In both cases, visual inspection and monitoring data noted no disturbance in the underground (Westinghouse, 1992; Westinghouse, 1995).

The accelerations recorded by the peak acceleration recorder in the Rattlesnake Canyon Earthquake were as high as .43 g in the north-south drift. According to empirical data on tunnels, accelerations of this magnitude would be expected to induce measurable displacements either associated with spalling or movement on fractures within the pre-existing fracture zone surrounding the repository. The fact that these effects were not noted reinforces the suggestion that the higher accelerations recorded by the peak acceleration recorder must have occurred at high frequencies, at least greater than 32 hz and as high as 100 hz. High frequencies greater than 30 hz are associated with very small displacements, measured in thousandths of inches, and are typically less than .001 inches. In the frequency range between 10 hz and 30 hz, displacements are less than .008 inches.

As an aside and an indication of instrumentation sensitivity, fracture displacement measurements taken several weeks before and after the Rattlesnake Canyon Earthquake were evaluated. Converted to rates of movement, the data showed a conspicuous cyclic pattern over this time period with no perturbations around the time of the earthquake. Further investigation revealed that the cyclic pattern being recorded apparently represents the effect of tidal forces on the thick sequence of sedimentary deposits.
contained within the Delaware Basin. The pattern cycles with only a few days’ lag time between the new moon and full moon. At this sensitivity, we assume that the system is able to, in fact, measure very small displacements and would have been able to detect any motion resulting from the higher accelerations had there been any.

Discussion

The accelerations recorded by the peak acceleration recorder in the Rattlesnake Canyon Earthquake were unexpectedly high (0.21 to 0.43 g's), compared to surface accelerations measuring between 0.01g and .06g. Based on acceleration alone, this observation appears to contradict empirical evidence for less shaking in the underground. However, this paper points out that the accelerations are apparently being amplified within a high frequency region possibly between 32 - 100hz, which is associated with very small displacements. By this interpretation, less shaking and damage in deep mines is a result of smaller displacements being realized in the underground.

Previous reports on earthquake response of underground tunnels and mines to ground motion have been generally empirical and qualitative in nature. Reports on the subject have mentioned large events with severe ground motion felt at the surface that have been completely unnoticed by underground miners in the areas. Quantitative data are limited and are mostly related to relatively shallow tunnels. None of the studies directly address possible explanations for decreased shaking underground.
Theoretical factors relevant to the seismic response of an underground excavation include the wavelength and angle of incidence of the seismic waves, the frequency-dependent effect of ground motion wavelength, and the size of the cavity. This paper suggests that higher frequencies may be preferentially realized in the underground, possibly controlled by the orientation and/or size of the mined opening. In both earthquakes, higher measured accelerations also occurred in the north-south oriented ground motion component, relative to the east-west and vertical components. Directional factors that might be relevant include:

- the general northwest-southeast orientation of the Rattlesnake Canyon and Alpine Texas earthquake rupture zones, relative to the north-south oriented drift, and
- the orientation of the focal points relative to the facility layout, particularly the north-south drifts.

To assess these factors, the implied frequency range amplified in the underground (32-100 Hz) is converted to wavelengths and compared with drift dimensions (Table 3). Assuming the shear wave (S-wave) velocity and P-wave velocity of the Salado to be 2500 m/s and 5000 m/s, respectively, wavelengths in table 3 are calculated as follows:

<table>
<thead>
<tr>
<th>Type of Wave</th>
<th>Seismic Velocity (m/s)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>@32 s⁻¹</td>
</tr>
<tr>
<td>P-wave</td>
<td>5000 m/s</td>
<td>156</td>
</tr>
<tr>
<td>S-wave</td>
<td>2500 m/s</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 3: Wavelengths Calculated Based on Frequencies 32 s⁻¹, 50 s⁻¹ and 100 s⁻¹.
An angle of incidence normal to the front face of the north-south drift would exhibit transverse and vertical S-wave components much larger than the cross-sectional dimensions of the drift (Table 3). Width and height dimensions are 10 meters, and 5 meters, respectively, compared to S-wave wavelengths of 25 – 50 meters. In this same angle of incidence, the longitudinal P-wave propagates parallel to the north-south axis and along the floor of the drift with wavelengths much smaller than the drift's length (Table 3).

Conversely, assuming an east-west angle of incidence normal to the side face of the drift, wavelengths of the P-wave and vertical shear wave would be larger than the respective width and height dimensions of the drift. This orientation aligns the transverse S-wave component parallel to the axis of the drift along the eastern wall. The wavelengths associated with the transverse S-wave component are smaller than the drift's length in this orientation (Table 3).
Both the Rattlesnake Canyon and Alpine Texas earthquake’s focal depth and distance suggests a relatively shallow angle of incidence of the wave front. Located roughly 35-40 degrees to the southeast of the repository, the Rattlesnake Canyon event displayed the most oblique angle of incidence of the two events. In this orientation, a longitudinal P-wave component would be manifested parallel to the north-south drift axis. Oblique incidence would also result in a transverse S-wave component acting on the side face of the drift parallel to the north-south axis. The Alpine Texas event would represent a north-south incident wave front, resulting in dominant influence of the incident P-wave.

Resonance could be responsible for the increase in amplitude in the north-south drift if incident waves match the drift’s natural vibrating frequency. Based on acoustic theory, the wavelengths associated with the natural resonance frequency of the drift, calculated based on the length of the drift, are much larger (375 meters) than the wavelengths associated with the suspected frequency distribution in the underground. Consequently, resonance may not be responsible for the higher north-south oriented ground motion accelerations.

Alternatively, the northern and southern boundaries of the drift may represent reflective surfaces that result in constructive interference. Assuming some vertical component of the incident P-wave or transverse S-wave and an oblique or north-south oriented wave front, component waves will propagate along the floor of the axis of the north-south drift. As P-wave and transverse S-wave wavelengths are relatively small compared to the larger longitudinal axis of the north-south drift, a conduit for constructive interference of the incident waves and reflecting wave fronts is provided.
A more rigorous application of elastic wave propagation theory would need to consider factors such as generation of surface waves along the drift floor in response to the incident body waves, associated partitioning of energy along this interface, and the phase relationships of the incident and reflecting waves. Likewise, as the drift dimensions are comparable to or smaller than the incident wavelengths, diffraction-related wave phenomenon may also occur. The high strain rates associated with seismic wave propagation and the frequencies implied in the underground argue against inelastic response (damping) phenomenon in the Salado formation as a factor.

Conclusions

Surface and underground spectral response data from two earthquakes recorded at the WIPP suggest accelerations are amplified underground at very high frequencies. Based on recordings of the Engdahl peak acceleration recorder, these frequencies potentially range from 32 – 100 hz. This conclusion is consistent with Pratt et al. (1980), who stated that underground facilities are predisposed to significantly higher frequencies (50 – 100 hz) compared to frequencies that cause damage to surface facilities (1 – 10 hz).

At the surface half-space, constructive interference between converging and refracting wave fronts causes amplification of relatively large wavelengths. These wavelengths result in the characteristic 1 – 10 hz frequency range used in structural seismic design projects on the surface. Conversely, it is plausible that the smaller dimensions of an underground opening may control the wavelengths and frequencies realized in these
settings. S-wave ground motion components acting on the smaller dimensions of the
face and sides of a rectangular opening would be constrained to short wavelength, high
frequency ground motion. Longer wavelengths would induce less response, as observed
in the Rattlesnake Canyon and Alpine Texas earthquakes.

Conversely, amplitudes of ground motion propagating and vibrating along the longer
dimension of the drift may enable constructive interference. This condition results from
the longitudinal wavelength being much smaller than the length dimension. In the case
of the WIPP north-south drift, we would expect the largest response to be associated
with the fundamental resonant wavelength (375 meters). Although the resonant
wavelength and associated lower frequencies should have been manifested in the
underground, only the higher frequency, lower wavelength ground motion was
observed.

While the larger longitudinal dimension of the opening may allow constructive
interference, other factors may play a role in constraining wavelength and frequency
response. As suggested, these factors may be related to drift dimensions being
comparable to or smaller than the incident wavelengths and the complex interference
pattern between diffracted waves and wave components incident on the three-
dimensional interface. Whatever the cause, the observed correlation suggests lower
frequency ground motion would only be realized with an increase in all dimensions of
the underground rectangular opening.
This interpretation provides a possible explanation for the exceptional performance noted in empirical studies of earthquake damage to tunnels and mines, as well as the lack of felt historical reports in mines. Mines and tunnels are typically small openings. Displacements associated with such high frequencies are exceedingly small, and higher frequencies will be realized in underground mines and tunnels constrained by their dimensions and geometry. Other observations and conclusions resulting from this paper include:

- Existing empirical studies using mostly shallow tunnel data may overestimate the seismic vulnerability of deep underground mines (>600 m),

- The size, geometry and orientation of the underground opening in which an accelerograph is placed may dictate the response of the sensor in the different component directions. This suggests that seismic monitoring system design should consider this phenomenon,

- The frequency response of the underground opening should be considered in seismic evaluations, including evaluating the vulnerability of electrical and mechanical systems in the underground,

- Time-history accelerographs set for large frequency bandwidths (50-100hz) would provide better documentation of the range of spectral accelerations realized in the underground, relative to passive mechanical recorders, and
- Time-history accelerograph thresholds set at the lowest practical levels would be useful in establishing the spectral response of the underground to different seismic sources.

Last, the primary purpose of this paper has been to document the underground earthquake data for interested researchers. The Rattlesnake Canyon Earthquake and Alpine Texas event were not large events and predictably did not produce highly severe near field ground motion behavior. However, this study suggests that measurable data from events such as the Rattlesnake Canyon and Alpine Texas earthquakes provide useful insight that should be considered in seismic evaluation and seismic monitoring design. Indeed, more rigorous theoretical evaluation of the underground response in these two earthquakes is warranted.

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References


Nasu, N., 1931, Comparative Studies of Earthquake Motions Above Ground and in a Tunnel, Bulletin of the Earthquake Research Institute, Tokyo University, Vol. 9, pp. 454-472.


