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MISTY ECHO TUNNEL DYNAMICS EXPERIMENT

DATA REPORT

Volume 1

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ABSTRACT

Tunnel damage resulting from seismic loading is an important issue for the Yucca Mountain nuclear waste repository. The tunnel dynamics experiment was designed to obtain and document ground motions, permanent displacements, observable changes in fracture patterns, and visible damage at ground motion levels of interest to the Yucca Mountain Project. Even though the maximum free-field loading on this tunnel was 28 g, the damage observed was minor. Fielding details, data obtained, and supporting documentation are reported.

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This work was conducted in support of the Yucca Mountain Project at Quality Level I following procedures approved by the Sandia National Laboratories Nuclear Waste Repository Technology Department. This work applies to WBS element 1.2.4.1.2.

ACKNOWLEDGEMENT

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FOREWORD

The Yucca Mountain Site Characterization Project (YMP), which is managed by the Nevada Operations Office of the U. S. Department of Energy, is examining the feasibility of siting a repository for commercial high-level nuclear wastes at Yucca Mountain, on and adjacent to the Nevada Test Site (NTS). This work, intended to extend our understanding of the behavior of underground openings subjected to seismic loading, was funded jointly by the YMP and the Military Applications Weapons Test Program. This report summarizes one aspect of the Weapons Test Seismic Investigation project that was conducted in FY 89.

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1.0 INTRODUCTION

One of the primary concerns for the potential waste repository at Yucca Mountain is the dynamic behavior of the tunnels induced by seismic sources, including underground nuclear explosions (UNEs), blasting, and earthquakes. The seismic design peak particle velocities, which will be used in design of underground structures and openings, are expected to be less than or equal to 1 m/s, but it is of interest to the Yucca Mountain Site Characterization Project (YMP) to correlate the observed tunnel damage with higher amplitude ground motions.

Review of a great deal of the unclassified work on correlating tunnel damage to observed ground motions, reveals a large body of data for damage to underground openings in several materials at various ground motion levels from UNEs. Generally, these data were gathered in geologic media that are much different from what is present at Yucca Mountain and at ground motion levels substantially higher than those of interest to the YMP. In addition, most of the underground structures in these experiments had been hardened to allow them to withstand larger motions. Because the YMP tunnels are not expected to be hardened and the seismic design bases are expected to be much lower than the levels of interest to military structures, the applicability of the existing data base is limited. Further, the levels of ground motion correlated to observed damage were usually inferred from empirical prediction equations rather than actually measured.

The Tunnel Dynamics Experiment (TDE) consisted of observations made in two locations. The primary location was designed to provide data on observed ground motion levels in the tunnel and in the free-field, and to document the damage resulting from the loading. Ground motions were measured at four locations on the tunnel walls and one location in the free-field. Damage was assessed from measurement of permanent deformations in the drift, study of fracture density in boreholes, and from pre- and post-test documentary photography. Observations made at the secondary location consisted of measurement of changes in the dimensions of the opening and pre- and post-test documentary photography. The objective of this report is to document the damage sustained by these two tunnel sections.

Ideally, the TDE would be conducted in an exact replica of the tunnel section planned for the repository (i.e., constructed in the same type of rock, using the same construction techniques and with the same ground support system). In addition, the loading used in the experiment would be tailored to match, as closely as possible, the design basis loading for the repository drifts. To field this experiment under ideal circumstances, the test bed would be sited close to the proposed repository. This test site would be explored and characterized using the same laboratory and field techniques as planned for the repository. After characterization, several drifts would be constructed at the repository horizon. Finally, an explosive array would be designed to simulate design basis ground motions. In such an experiment, YMP would have absolute control and all project objectives could be satisfied completely.

Unfortunately, this ideal experiment is not feasible because of cost and political constraints. Fortunately, there are other activities conducted on the Nevada Test Site (NTS) that provide opportunities to address the

objectives of the TDE in a general fashion. Such an opportunity was the MISTY ECHO underground nuclear explosion.

MISTY ECHO was conducted in the N-Tunnel complex, beneath Rainier Mesa at the NTS. This experiment was conducted at 12:30 PM PST on December 10, 1988. All construction and survey support was furnished by the Defense Nuclear Agency (DNA) and their support contractors at the NTS. Design and oversight of the construction of the TDE was performed by personnel in Divisions 9311, 9325, 6311, and 6313 of Sandia National Laboratories. In addition, personnel from Science Applications International Corp. and Parsons Brinckerhoff Quade & Douglas, Inc. were involved in the conduct of this experiment.

The overall objectives and concerns of the MISTY ECHO experiment were independent of those of the YMP. This produced several disadvantages. The major disadvantage is the lack of control over the experiment.¹ The TDE had to be designed with respect to the location of MISTY ECHO and existing tunnels, rather than designing MISTY ECHO with respect to the TDE. The layout of the tunnels in the vicinity of MISTY ECHO is shown in Figure 1-1. (Throughout this report, figures and tables are placed at the end of each section.) Because existing tunnel sections were used, compromises (such as orientation with respect to the incoming ground shock, construction details, material properties, ground motion levels and multiple uses in drifts) had to be made in the design of the TDE. Given these limitations, two tunnel sections were chosen. The primary location (Figure 1-1) was selected because its distance from the shot was appropriate to provide the target ground motion amplitudes and its orientation was approximately perpendicular to the incoming ground shock, which is the most critical orientation for stability. Both active and passive measurements were made at this location. The primary disadvantage of this tunnel section is related to the fact that the opening had been loaded by an earlier explosion. The secondary location, shown in Figure 1-1, was chosen to study the behavior of a tunnel section in material that had not been pre-loaded. The location of this section was chosen based on empirical observations of DNA. The major disadvantages to this location were the fact that its orientation was nearly parallel to the ground shock wave front and that the expected ground motion amplitudes were smaller than the target amplitudes. Only passive measurements were made at this location.

It is obvious that the data collected in this experiment would have several limitations when applied to a repository at Yucca Mountain. These are summarized below:

- Material differences - The geologic material for this experiment is described as a partially saturated zeolitized (nonwelded) ashfall tuff. The repository drifts will be in a moderately to densely welded, devitrified ashflow tuff. The nonwelded tuff is massive in comparison to the stronger, though highly jointed welded tuff.

1. This does not imply a lack of cooperation on the part of the DNA. On the contrary, the support received on all aspects of this experiment was excellent.

- Source differences - The true concern for the repository is seismic loading due to earthquakes. Although the ground motion amplitudes (accelerations, velocities and displacements) generated by the UNE are similar to those expected for a design basis earthquake, the frequency content of the motions induced by the two sources is different. In general, UNE ground motions consist of a relatively narrow band of dominant frequencies. The earthquake-generated ground motions have a fairly wide band of dominant frequencies and tend to be composed of lower frequencies than UNE ground motions.
- Tunnel construction details - The method of construction and the supports for the tunnel used in this experiment are different from what is currently planned for the repository drifts. In general, the support system in the TDE drift was designed for weaker rock subjected to more severe loading than what is expected for the repository. Consequently, the TDE drift is hardened more than a repository drift would be.²

Based on the limitations above, it is clear that these data are not directly applicable to the emplacement drifts in the Yucca Mountain repository. However, at the very least, these data will fill a void in the data base of the YMP: namely, the correlation of observed tunnel damage with ground motion levels for a specific tunnel. Analysis and interpretation of these data will further the understanding of the behavior of underground structures to seismic loading, which will be useful to the YMP.

The Quality Assurance (QA) level of this work was designated at level I (SNL Nuclear Waste Repository Technology (NWRT) Dept. QALA 044). The TDE was fielded in accordance with Experiment Procedures (EPs) 0018 and 0020 and all associated YMP QA documents. The personnel involved in design and oversight of the activities performed in support of this experiment were familiarized and certified in accordance with the existing SNL NWRT YMP procedures. DNA support contractor personnel involved in the actual construction, survey, and photographic work were not familiarized nor certified. However, all of these efforts were directed, and the records generated were reviewed, by certified personnel.

The objective of this report is to present all data obtained in the TDE, although some analysis also is presented. The experiment description will be given in Chapter 2. Data are presented in Chapter 3 and conclusions are given in Chapter 4. The final corrected set of ground motion data, 5% damped pseudo relative velocity (PSRV) response spectra, and power density spectra are included in Appendix A. Appendix B contains a description of the ground-motion data-processing techniques used and Appendix C contains field and calibration records for the tunnel convergence work.

2. *The combination of the weaker rock and the stronger ground support may be compensating effects when determining the fidelity of this experiment as a simulation of an actual repository drift.*

Figure 1-1. General Layout of Tunnels in the Vicinity of the MISTY ECHO Working Point

2.0 EXPERIMENT DESCRIPTION

2.1 Location and General Description

The layout of the N-Tunnel complex in the vicinity of the MISTY ECHO experiment is shown in Figure 1-1. The primary location of the TDE was at CS 56+00 in the U12n South extension drift. At this location, ground motion, permanent displacement, tunnel convergence, borehole inspections, documentary photography, and high-speed photography³ measurements were made. The elevation of the working point (WP) was 11 m above the invert⁴ of this drift. Approximately 12 m of drift centered about station CS 56+00 was examined for damage. The angle of incidence of the incoming shock wave from the explosion was approximately perpendicular to the axis of the tunnel. A secondary location was at CS 2+84 in the U12n.22 Bypass drift. The axis of this tunnel was approximately parallel to the incoming shock wave. Roughly 12 m of drift were examined at this location. Tunnel convergence, borehole televiewer, and documentary photography measurements were made in this drift.⁵

2.2 Tunnel Configuration

2.2.1 Construction Details

Tunnel construction details are shown in Figure 2-1. This section was initially driven in 1984 with a tunnel boring machine. The corners were mined at a later date. Rock bolts, 1.8 m long and 2.2 cm in diameter, were placed in the back⁶ on a random pattern during the initial mining. Hardening bolts, 4.9 m long and 2.9 cm in diameter, were added at a later date. These hardening bolts are nominally spaced on 1.2 m centers. As indicated on the figure, all bolts were fully grouted with resin. The tunnel back to the spring line⁷ was lined with 4 to 10 cm of fiber-reinforced concrete over a 5 X 5 cm woven wire mesh. Below the spring line, the woven wire mesh was placed over the fiber-reinforced concrete on both ribs⁸. There was approximately 0.3 m of loose material above the tunnel invert. Photographs of this tunnel section before construction of the TDE are shown in Figures 2-2 and 2-3. Figure 2-2 is an overall photograph of this tunnel section looking toward the tunnel face⁹ (left rib ground motion gage location between tool boxes and the

3. This portion of the experiment was fielded and supervised by DNA. SNL provided input on the location and other aspects of the experiment. Documented SNL NWRT YMP QA procedures were not written for the fielding of the high-speed cameras.

4. The invert is the floor of the tunnel.

5. Note that all tunnels in the N-Tunnel complex are continuously pumped to remove excess water. Approximately 24 hours before detonation of MISTY ECHO, these pumps were shut off. This allowed water to collect in both drifts of the TDE.

6. The back is the roof of the tunnel.

7. The spring line is the point in the tunnel where the radius of curvature of the ribs change.

8. The ribs are the walls of the tunnel. The left rib is on the left side of the tunnel as one faces the tunnel heading. The right rib is the opposite.

9. The tunnel face is the tunnel heading.

portable restroom). Figure 2-3 is a close-up photograph of the left rib near the gage mount location. This photo shows the wire mesh and the rock bolt spacing used in the construction of this tunnel.

Figure 2-4 shows the construction details of the secondary location (CS 2+94 in U12n.22 Bypass drift). This drift was excavated in 1988 using conventional drill and blast methods. Dywidag rock bolts 2.5 cm in diameter and 3 m long were placed on 1.2 m centers as shown. These bolts were fully grouted with resin cartridges. This drift was unlined and has 5 X 5 cm wire mesh approximately three-quarters of the way around. Figure 2-5 is an overall photograph of this section of tunnel looking toward the tunnel face. This photograph provides a good view of the overall reinforcement used in this drift.

2.2.2 Material Properties Description

2.2.2.1 General

Fennix and Scisson geologists gathered and interpreted the geologic data in the MISTY ECHO area for the DNA. The information pertinent to the TDE is summarized below.

Rainier Mesa is part of a topographically high area known as the Belted Range. The mesa is composed of a series of Tertiary-age volcanic rocks deposited on an irregular surface of Precambrian and Paleozoic sedimentary rocks. Recurring eruptions, during the Miocene Epoch, from several different volcanic centers in southern Nevada deposited ash-fall and ash-flow tuffs on the irregular pre-Tertiary surface. The older tuffs reflect the topography of this surface and commonly display depositional synclines and anticlines. Higher in the stratigraphy, the tunnel beds rarely exhibit dips greater than 15 degrees. Tunnel-level faults are thought to result from tectonic stress or of differential compaction of tuffs over the pre-Tertiary topography. In general, displacements on these faults are on the order of 0.1 to 10 m. Throughgoing faults in N-Tunnel have been mapped in drifts and drill holes with an average apparent spacing of 60 to 100 m. The average strike of these faults is N 20-30° W.

Stratigraphy in the vicinity of the WP is shown in Figure 2-6. The descriptions of the units shown in this figure are given in Table 2-1. The WP for MISTY ECHO was placed in Unit 4 of the tunnel beds (Tt4) at the interface of a massive calcalkaline ash-fall tuff (noted as subunit 4J) and a thick bedded sequence of calcalkaline and peralkaline ash-fall tuffs (subunit 4H). The welded ash-flow tuff units of the Rainier Mesa Member (Tmr) and the Grouse Canyon Member (Tbg) are approximately 290 m and 86 m, respectively, above the WP. The upper extent of zeolitization is approximately 58 m above the WP. Pre-Tertiary dolomites are located approximately 368 m beneath the WP. The regional water table is estimated to be 575 ±150 m below the WP.

The geologic map of the tunnel level in the vicinity of the MISTY ECHO experiment is presented in Figure 2-7. The WP is situated between two widely separated fault systems. The fault east of the WP has a stratigraphic offset of approximately 12 m in the vicinity of MISTY ECHO and the closest approach of this fault is 45.7 m below the WP. This fault is thought to have a surface trace which passes 192 m to the east of surface ground zero. The west fault

has approximately 6 m of stratigraphic offset in the vicinity of the WP. The closest approach of this fault is 76 m, above the WP. This fault does not have a known surface trace.

2.2.2.2 TDE Vicinity

The stratigraphy of the immediate area of the primary location of the TDE is shown in Figure 2-8. There are primarily three subunits of tunnel bed tuffs present.¹⁰ These are Tt4H, Tt4J and Tt4K. Subunits 4H and 4J were described above. Subunit 4K is described as a zeolitized calkalkaline and reworked ash-fall tuff. The physical properties of these three were determined on cores taken from drill holes in the vicinity of the WP. These drill holes were UE12n#14 (vertical hole drilled from the surface, Figure 2-6) and U12N.23UG-1 (horizontal hole drilled from near the TDE to the WP, Figure 2-7). The properties for these subunits are summarized in Table 2-2. These properties were determined from analyses performed by Terra Tek Research using standard laboratory and field techniques.

2.3 Experiment Configuration

2.3.1 Ground Motion

The ground motion gages were placed at station CS 56+00. Gages were mounted on the ribs, back, and invert of the tunnel. In addition, one free-field measurement was made. The cross section of this experiment is shown in Figure 2-9. Gages used for the measurement of the tunnel wall motions were mounted on aluminum plates such that the plate and gage canister assembly were flush with the tunnel wall. The free-field gage was placed in a drill hole below the tunnel invert. All gages were oriented with respect to the tunnel axis. The axis of the incoming shock wave was approximately perpendicular to the tunnel axis. Upward vertical motion was measured as positive. Motion perpendicular to the tunnel and outward (away from the explosion) was measured as positive radial motion. Motion toward the tunnel portal was measured as positive transverse motion.

Gage mounts for the tunnel measurements were fabricated from a 1.3 cm thick, 30.5 cm diameter aluminum plate. This plate was attached to the tunnel walls with three anchor bolts, 2.9 cm in diameter and 61.0 cm long. The gage mounting block was secured to a piece of aluminum channel and the whole assembly bolted to the center of the plate. The plate and the channel were fabricated such that all gage assemblies (for the tunnel measurement stations) were oriented in the same manner with respect to the axis of the tunnel. A drawing of the gage mounts is shown in EP 0018 (see Appendix B of this report). The procedure used to mount the tunnel face gages is discussed below.

The tunnel lining was removed from the gage locations before the gages were placed. Figures 2-10 through 2-13 (right rib, left rib, back and invert, respectively) are photographs of the gage mount locations after the lining was removed and before the plate was installed.¹¹ After the tunnel surface was

10. Note, these same subunits are present between the TDE and WP (Figure 2-7).

11. At the time these photographs were taken the mounting bolts for the gage mounts were already in place.

prepared, holes were drilled for the mounting bolts and these bolts were grouted into position using resin cartridges. The mounting plates were then installed and oriented. Orientation was achieved with the assistance of a survey crew. Figures 2-14 through 2-17 are photographs taken of the mounting plates in place, before the placement of the grout. When proper orientation was achieved, the edges of the plate were sealed with sulfa-set to provide a form for a grout pour. Two tubes were placed in this form. One tube was used as a fill tube, the other as a bleed tube. Rock-matching grout, designated as HLS-LR-RMG-CC, was pumped behind the gage plates (through the fill tube) until it started flowing from the bleed tube. This operation was performed to ensure that a uniform surface of contact between mounting plates and rock face existed. Following the installation of these plates, gages were prepared and mounted in the aluminum channel. Photographs of the tunnel face gages before placement are shown in Figures 2-18 through 2-24.¹² Figures 2-25 through 2-28 are the photographs of the final mounting of the gages on the tunnel walls.

The free-field gage was placed in a 20.3 cm diameter drill hole at a depth of 9.1 m below the tunnel invert. This depth was chosen based on past observations that the effect of the tunnel is not observed in ground motions recorded at distances of 1 to 2 tunnel diameters. The gage was oriented in the same coordinate system as the tunnel measurement stations. After the proper orientation was achieved, the same rock-matching grout used for the other gage mounts was used to backfill around the gage and the extent of the drill hole.¹³ Figures 2-30 through 2-32 are photographs of the gages and canister before installation in the drill hole.

Sensors used in the TDE were Sundstrand Q-FLEX model 1400 accelerometers. Signals from these sensors were transmitted over about 160 m of cable to the instrumentation alcove where they were input into telemetry (TM) boxes, amplified, and recorded directly on analog tape. Timing and control signals were supplied by the DNA. Figures 2-33 through 2-35 show the schematic representation of the details of the data acquisition system. The identifying information (including model and serial numbers) for each piece of equipment used in this experiment is shown in Table 2-3. Figures 2-36 and 2-37 are photographs of the instrumentation rack used to record the ground motion data from this experiment.

2.3.2 Surveys

The survey data collected in this experiment consisted of locating survey pins along a 12 m section centered about station 56+00. In addition, tunnel cross sections were measured at various points within this 12 m. The survey pins used in this effort were the existing rock bolts placed at approximately the same height as the gages mounted on the ribs. These bolts

12. Note, three photographs show the sensing elements of the three gages used at locations on each rib. To protect the gages on the invert, a waterproof canister was fabricated and is shown in Figure 2-24. No photographs were taken of the gages used on the back before placement because of a gage problem that was remedied after this particular photography session.

13. Bolts to left of drill hole are mounting bolts for gage on invert. Drill hole was de-watered before installation of the gage.

are nominally spaced at 1.2 m on center and are embedded roughly 4.9 m into the rib. The location and designation of these bolts are shown in Figure 2-38. Gage plate mounting bolts were also used as survey pins. All mounting bolts for the gages on the left rib and invert were used in the survey. Because of visibility problems, concerns for maintaining accuracy, and general logistics,¹⁴ only two of the bolts were surveyed on the back gage mount and one bolt surveyed on the right rib mount.

The primary objective of these measurements was to determine gross permanent displacements, should they occur. The surveys performed in this effort were designated as third order, or the standard accuracy specified for construction surveys. Within an individual survey, the accuracy is within a centimeter. From the pre-test to the post-test survey the accuracy is within 3 cm.

Post-test control for the survey was established by finding a pre-test control point that did not move as a result of the explosion. For this experiment that point was near the portal, but still inside N-Tunnel. The traverse in the tunnel was rerun from this point, and new coordinates established for all survey points beyond this control point. The movement of the TDE survey markers were determined using the pre- and post-test coordinates.

2.3.3 Tunnel Convergence

The configuration of tunnel convergence measurement points as well as locations of the boreholes that were inspected by televiewer are shown in Figures 2-39 and 2-40. The primary location of the measurements was at station CS 56+18.5, and the secondary location was at CS 2+84 in the U12n.22 Bypass drift (location 2 on Figure 1-1). The configuration of convergence measurement points was essentially the same in both drifts. At each location, six holes about 3.8 cm in diameter and 48 cm deep were drilled for installation of the tape extensometer anchors: one each in the back and the invert, and two in each rib. At the secondary location the anchors in the invert and back were placed in the center of the cross section; at the primary location they were placed approximately 1 m off-center to avoid interference with the ventilation duct. The anchors, consisting of short lengths of rebar fitted on the ends with eyebolts, were grouted to the rock along nominal 15 cm lengths using resin cartridges. A typical anchor installation is shown in Figure 2-41. The depth of the holes was overdrilled to permit inspection of the condition of the rock surrounding the anchors. This inspection was conducted approximately 2 weeks after the holes were drilled and the results of these inspections are included in Appendix C.

14. The main control for the survey was in the center line of the rail line in the tunnel. This tunnel section was in a high traffic area and the survey work was conducted at a time when grout was being poured at the WP - a higher priority than the TDE. Trains were running by this location at 15 min. intervals, which made the survey difficult. Establishment of a second line, parallel to the main control line in the center of the tunnel, would have introduced additional errors into the survey. The judgement was made at the time that the limited number of points surveyed as accurately as possible would be preferable to all points surveyed with reduced accuracy.

Convergence measurements at the primary location were made from the invert to the back (stations 1-2 on Figure 2-39), left rib to right rib at two elevations (3-4 and 5-6), and invert to left and right ribs (1-3 and 1-4). The same measurements were made at the secondary location, along with measurements from the back to the ribs (stations 2-5 and 2-6 on Figure 2-40). These companion measurements were not made at the primary location because they were obstructed by the ventilation duct in the back and other conduits mounted on the left rib. Photographs of these anchors are shown in Figures 2-41 through 2-48.

The convergence measurements began on November 15, 1988, and ended on January 2, 1989. Measurements were made over five consecutive working days before the shot and again afterwards, and approximately weekly throughout the remainder of this period. A detailed description of the procedures used to make the measurements is given in EP-0020 (Appendix B).

The extensometer used was a Sinco model no. 50, shown in Figure 2-49. Its major components are a perforated steel engineer's tape, a dial-gauge caliper, and a compression spring with vernier for controlling tape tension. Its accuracy is ± 0.13 mm, according to the manufacturer. The instrument was calibrated in the laboratory before and after the field measurements in a manner detailed in EP-0020 (see Appendix B). All calibration measurements were within acceptable limits. Results of the calibration are presented in Appendix D.

2.3.4 Borehole Inspection

Boreholes 10 cm in diameter and 9 m deep were drilled into each rib at the same locations as the convergence measurements. Cross section drawings of the location of these boreholes are shown in Figures 2-39 and 2-40. Figures 2-43, 2-44, 2-47, and 2-48 are photographs of these boreholes. These holes were inspected using a borehole video system before and after the explosion to assess the extent of changes to the rock mass surrounding the tunnel that might have occurred as a result of the loading.

The borehole televiewer system is shown in Figures 2-50 through 2-53. Its components are listed in Tables 2-4 and 2-5, and keyed to the figures by number. The televiewer is a black-and-white SNL-modified system that includes a downhole scanner, a power supply, video monitors, and a video cassette recorder. The downhole scanner is capable of variable light intensity and remote focus. It is not waterproof. The camera that was used primarily, Hydro Products' model TC-135, is capable of rotating 180 degrees in a plane axial to the borehole, from side-view to downhole to side-view. As a backup, a Cohu model 4510 camera with a direct-downhole fisheye lens was also used.

2.3.5 Photography

Still photographs were taken at various times throughout the fielding process of this experiment. These photographs have two basic objectives. The primary objective is to document the extent of the damage observed in the drift by comparing the pre- and post-test photographs. The second is to have a record of the electrical connections, gage mounts and other aspects of this experiment in case of future questions. The photographs used for the primary objective were taken between stations CS 55+80 and CS 56+20. These photos

covered sections of the ribs and the back in this area. The final series of pre-test photographs was taken November 29, 1988, 11 days before the event. The post-test photos were taken December 14, 1988, 4 days after the event. In addition, a series of pre- and post-test photographs were taken in the U12n.22 Bypass drift, at the convergence measurement location discussed above.

2.3.6 High-Speed Photography

As mentioned earlier, the DNA fielded the high-speed photography experiment associated with the TDE. This experiment was designed to photograph the immediate vicinity of the ground motion gage on the left rib (3700-2). The elevation view of this experiment is shown in Figure 2-54. The cameras were located at 56+18. The ground motion gage, photo target, and free-fall reference indicators were all located at about station 56+00. In addition a white backdrop used to provide contrast and improve visibility was located at station 55+95.

The cameras used for this experiment were FASTAX-II model 46001, rotating-prism, full-frame 16 mm cameras. Lenses were 13 mm Century Paragon, set at an aperture of f/4.0. The frame rate was set at 2000 frames/s, yielding an effective exposure time of 1/6000 s/frame. An electronic speed control within the camera maintains the selected speed to within $\pm 1\%$ after approximately 0.35 s from the start-up signal. Lighting for these cameras was provided by twelve Sylvania FF-33 long-duration (approximately 1.75 s) flash lamps with custom reflectors. The film used for this experiment was Eastman high-speed 16 mm color negative, type 7294 in 30.5 m rolls. The flash lamps and cameras were installed on a shock-mitigating mount that was suspended 3 m above the invert.

The free-fall reference indicators consisted of a single lead brick and several orange and black golf balls. The golf balls were stored in PVC pipe above the ground motion gage. The lead brick was designed as the primary gravity reference. The golf balls were added at a later date to ensure that an adequate number of reference points would remain in the field of vision for the duration of the film. An electrical signal was used to release the lead brick. A mechanical linkage between the PVC pipe and the brick was used to release the golf balls.

The cameras were started at 0.5 s before detonation. This same signal initiated the flash lamp package and the gravity reference indicators. A zero time signal initiated a small flash bulb which was placed in the camera field of view as the zero time reference.

Table 2-1

DESCRIPTION OF STRATIGRAPHIC UNITS PRESENT IN THE VICINITY OF MISTY ECHO

<u>Map Symbol</u>	<u>Stratigraphic Unit</u>	<u>Thickness m</u>	<u>Lithologic Description</u>
Tmr	Rainier Mesa Member, Timber Mountain Tuff	113.4	Upper portion, densely to moderately welded ash-flow tuff; lower portion nonwelded to partially welded, vitric ash-flow tuff.
Tp	Paintbrush Tuff	190.8	Vitric bedded ash-fall and reworked ash-fall tuff and tuffaceous sandstone.
Tbg	Grouse Canyon Member Belted Range Tuff	10.0	Densely welded ash-flow tuff.
Tt5	Tnl beds Unit 5	24.4	Vitric, bedded ash-fall tuff.
Tt4	Tnl beds Unit 4	61.6 (above WP) 72.2 (below WP)	Zeolitized, bedded ash-fall and reworked ash-flow tuff.
Tt3	Tnl beds Unit 3	47.2	Zeolitized, bedded ash-fall and reworked ash-flow tuff.
Tbt	Tube Spring Member Belted Range Tuff	3.4	Zeolitized, bedded ash-fall tuff.
Tt2	Tnl Beds Unit 2	68.0	Zeolitized, bedded ash-fall and reworked ash-flow tuff.
Tyf	Tuff of Yucca Flat (formerly Tuffs of Crater Flat)	90.0	Zeolitized, nonwelded to partially welded ash-flow tuff.
Tot	Older Tuff Units	87.2	Zeolitized, bedded ash-fall and reworked ash-fall tuff, and nonwelded to partially welded ash-flow tuffs.
Ddl	Devil's Gate Fm.? Nevada Fm.?		Recrystallized dolomite

Table 2-2

MEDIA PROPERTIES IN THE VICINITY OF THE TDE^aDrill Hole UE12n#14^b

Unit	Extant m	Numbr of Meas	P-wave km/s	S-wave km/s	Poisson Ratio	Nat. ρ ^e g/cc	Bulk Mod. MPa	Young's Mod. -MPa	Unc. Comp. Str. -MPa	Water Content- % wet weight	Sat. %	Air Voids %
Tt4K	41.4	9 (5)	2.94	1.42	0.35	1.89	16336	10129	21.6	19.5	97.9	0.7
Tt4J	7.9	2	2.72	1.31	0.35	1.99	14723	9128	11.0	17.4	98.7	0.5
Tt4H	6.8	2	2.80	1.37	0.34	1.83	14347	9321	17.5	22.2	98.8	0.5

Drill Hole U12n23UG-1^c

Unit	Depth m	Number of Meas	P-wave km/s	S-wave km/s	Poisson Ratio	Nat. ρ g/cc	Bulk Mod. MPa	Young's Mod. -MPa	Unc. Comp. Str. -MPa	Water Content- % wet weight	Sat. %	Air Voids %
Tt4K	304.9	10 (9)	2.74	1.14	0.40	1.97	14790	6902	11	17.5	97.5	0.8
Tt4J	137.0	10	2.77	1.10	0.41	1.92	14732	6337	10	19.2	98.0	0.8
Tt4H	75.3	6 (5)	2.92	1.36	0.36	1.91	16285	9609	23	18.5	97.6	0.9

a. This table was derived from the material property data gathered for DNA. Data were given for several samples taken within each subunit. Simple averages of these data were calculated and are shown in the table. Values for the moduli and Poisson ratios were calculated from the average values of density and measured velocities using relationships between the various elastic constants.

b. UE12n#14 is a vertical drill hole from the surface to near the WP.

c. U12n23 UG-1 is a horizontal drill hole from near the TDE to the WP.

d. Numbers shown are total number of samples taken. Numbers in parentheses are the number of samples that had a full set of parameters given. These numbers were used in the averages shown in the table.

e. Nat. ρ is density at natural water content.

Table 2-3

MISTY ECHO TDE GROUND MOTION EQUIPMENT INVENTORY LIST

Equipment Description	Manufacturer	Bar Code	Control Number	Model Number	Serial Number
Accelerometer	Sundstrand	NONE	NONE	QA1400	1176
Accelerometer	Sundstrand	NONE	NONE	QA1400	1184
Accelerometer	Sundstrand	NONE	NONE	QA1400	1608
Accelerometer	Sundstrand	NONE	NONE	QA1400	1610
Accelerometer	Sundstrand	NONE	NONE	QA1400	1613
Accelerometer	Sundstrand	NONE	NONE	QA1400	1619
Accelerometer	Sundstrand	NONE	NONE	QA1400	1621
Accelerometer	Sundstrand	NONE	NONE	QA1400	1622
Accelerometer	Sundstrand	NONE	NONE	QA1400	1624
Accelerometer	Sundstrand	NONE	NONE	QA1400	1626
Accelerometer	Sundstrand	NONE	NONE	QA1400	1628
Accelerometer	Sundstrand	NONE	NONE	QA1400	1630
Accelerometer	Sundstrand	NONE	NONE	QA1400	269
Accelerometer	Sundstrand	NONE	NONE	QA1400	322
Accelerometer	Sundstrand	NONE	NONE	QA1400	339
Degausser	Ampex	NONE	404397	SE10	NONE
Demod	EMR	V901659	12664	4130-01-9	428
Demod	EMR	V826969	12663	4130-01-9	503
Dual RK PWR CTL	Sandia	V821558	13581	NONE	NONE
EM Rack	Hoffman	V826418	16035	2928T	NONE
Oscilloscope	TEK	V826318	12447	7403N	B073155
Power Supply	HP	S609225	10246	6267B	9961
Power Supply	HP	V826354	10247	6267B	9965
Range Tmng Unit	Sandia	V826352	030507	TA703	NONE
Spec Anal PI	Singer	V826350	12661	T1 7	U-32207
Spec Analyzer	Singer	V826349	12660	MF 5	U-31987
TM Box	Sandia	NONE	NONE	PNE	03
TM Box	Sandia	NONE	NONE	PNE	05
TM Box	Sandia	NONE	NONE	PNE	07
TM Box	Sandia	NONE	NONE	PNE	17
TM Box	Sandia	NONE	NONE	PNE	20
Tape Recorder	B & H	S511313	11445	M14G	865
Time Base	TEK	NONE	NONE	7B50	B132300
Time Code Gen	Moxon	S512268	12658	540	5001014A
Vert Amp	TEK	NONE	NONE	7A16A	B020501

Table 2-4

BOREHOLE VIDEO SYSTEM EQUIPMENT INVENTORY LIST*

<u>Item</u>	<u>Description</u>
1	Television Monitor, monochrome, Panasonic, Model WV760
2	Television Monitor, monochrome, Panasonic, Model WV760
3	Lens Control Panel (shop made)
4	Camera Control Unit, Hydro Products, Model TP-135
5	Lighting Control Panel (shop made)
6	Video Cassette Recorder, VHS, Panasonic, Model NV-8200
7	System Power Supply, Lambda, Model LH124FM
8	Connector Panel (shop made)

* These items are shown in Figures 2-52 and 2-53.

Table 2-5

BOREHOLE SCANNER PARTS LIST*

<u>Item</u>	<u>Description</u>
1	Television Camera, Hydro Products, Model TC135
2	Clamp, Lamp, Front, Scanner (shop made)
3	Clamp, Lamp, Rear, Scanner (shop made)
4	Clamp, Centralizer, Scanner (shop made)
5	Drill Stem Adapter, Scanner (shop made)
6	Housing, Lamp, Scanner (shop made)
7	Lamp Quartz Halogen, 150 Watt, # FCS

* These items are shown in Figures 2-50 and 2-51.

Figure 2-1. Tunnel Construction Details for the Primary TDE Location - Station 56+00 U12N South Extension Drift

RB's - ROCK BOLTS

FG - FULLY GROUTED

NOTE - AREA WAS BOLTED USING 1.8 m Lg. x 2.2 cm ϕ RB's WHEN MINED w/ TBM ON RANDOM PATTERN. HARDENING BOLTS WERE ADDED AT LATER DATE.

Figure 2-2. Overall View of TDE at Station 56+00 Before Construction of Experiment

Figure 2-3. Left Rib of U12N South Extension Drift at Station 56+00

Figure 2-4. Tunnel Construction Details for the Secondary TDE Location -
Station 2+84 U12n.22 Bypass Drift

walls with three anchor bolts, mounting block was secured to a pie assembly bolted to the center of the fabricated such that all gage assembly were oriented in the same manner with drawing of the gage mounts is shown. The procedure used to mount the tunnel

The tunnel lining was removed were placed. Figures 2-10 through 2-12 (Figures 2-10 through 2-12 respectively) are photographs of the removed and before the plate was installed.

10. Note, these same subunits are present before

11. At the time these photographs were taken, the subunits were already in place.

Figure 2-5. Overall View of U12n.22 Bypass Drift Near Station 2+84

Figure 2-6. Stratigraphy in the Vicinity of MISTY ECHO

Figure 2-7. Tunnel Level Geologic Map of Southern N-Tunnel

75°
 FAULT ARROW INDICATES
 ANGLE & DIRECTION OF DIP
SUBUNIT CONTACT

 0 10 20

Figure 2-8. Stratigraphy in the Immediate Vicinity of the TDE

Figure 2-9. Cross Section and Layout of the TDE Ground Motion Experiment - Station 56+00 (Looking away from portal)

Figure 2-10. Gage Mount Area on Right Rib, Lining Removed, Mounting Bolts in Place

Figure 2-11. Gage Mount Area on Left Rib, Lining Removed, Mounting Bolts in Place

Figure 2-12. Gage Mount Area on Back, Lining Removed, Mounting Bolts in Place

Figure 2-13. Gage Mount Area on Invert, Lining Removed, Mounting Bolts in Place

Figure 2-14. Right Rib Gage Mount Area with Mounting Plate in Place

Figure 2-15. Left Rib Gage Mount Area with Mounting Plate in Place

Figure 2-16. Back Gage Mount Area with Mounting Plate in Place

Figure 2-17. Invert Gage Mount Area with Mounting Plate in Place

Figure 2-18. Gages for Station 3700-2, Left Rib - View of Transverse and Vertical Gages

Figure 2-19. Gages for Station 3700-2, Left Rib - View of Transverse and Radial Gages

Figure 2-5.

Figure 2-20. Gages for Station 3700-2, Left Rib - View of Transverse, Vertical and Radial Gages

Figure 2-21. Gages for Station 3700-4, Right Rib - View of Transverse, Vertical and Radial Gages

Figure 2-22. Gages for Station 3700-4, Right Rib - View of Transverse and Vertical Gages

Figure 2-23. Gages for Station 3700-4, Right Rib - View of Radial, Transverse and Vertical Gages

Figure 2-24. Gages for Station 3700-5, Invert - View of Radial, Transverse and Vertical Gages and Waterproof Canister

Figure 2-25. Completed Mounting of Station 3700-4, Right Rib

Figure 2-26. Completed Mounting of Station 3700-2, Left Rib

Figure 2-27. Completed Mounting of Station 3700-1, Back

Figure 2-28. Completed Mounting of Station 3700-5, Invert

Figure 2-29. Drillhole Used for Installation of the Free-field Measurements,
Station 3700-3

Figure 2-30. Gages for Station 3700-3, Free-field - View of Radial, Vertical and Transverse Gages

Figure 2-31. Gages for Station 3700-3, Free-field - View of Gages and Electrical Connections Inside Canister

Figure 2-32. Final Assembly of Gage Canister Used for Station 3700-3, Free-field

Figure 2-33. Schematic of the Timing and Control System Used for the TDE Ground Motion Data Acquisition

Figure 2-34. Schematic of the TDE Data Acquisition System - Stations 3700-1, 3700-2 and 3700-3

Figure 2-35. Schematic of the TDE Data Acquisition System - Stations 3700-4 and 3700-5

Figure 2-36. Front View of Equipment Rack Used to Record Ground Motions in the TDE (Note shock isolation mounting of rack)

Figure 2-37. Rear View of the Equipment Rack Used to Record Ground Motions in the TDE

Figure 2-38. Location of Survey Markers Used in the TDE

Figure 2-39. Cross Section at Station 56+18, U12N South Extension Drift Showing Extensometer Anchor Holes and Boreholes for Visual Inspection

Figure 2-40. Cross Section at Station 2+84, U12n.22 Bypass Drift Showing Extensometer Anchor Holes and Boreholes for Visual Inspection

Figure 2-41. Invert Anchor 1TE1, Station 56+18, Primary Location

Figure 2-42. Back Anchor 1TE2, Station 56+18, Primary Location

Figure 2-43. Left Rib Anchors (1TE3 and 1TE5) and Inspection Borehole 1B1, Station 56+18, Primary Location

Figure 2-44. Right Rib Anchors (1TE4 and 1TE6) and Inspection Borehole 1B2, Station 56+18, Primary Location

Figure 2-45. Invert Anchor 2TE1, Station 2+84, Secondary Location

Figure 2-46. Back Anchor 2TE2, Station 2+84, Secondary Location

Figure 2-33. Schematic of the T

Figure 2-47. Left Rib Anchors (2TE3 and 2TE5) and Inspec Station 2+84, Secondary Location

Figure 2-48. Right Rib Anchors (2TE4 and 2TE6) and Inspection
Station 2+84, Secondary Location

Figure 2-49. Tape Extensometer Used for Tunnel Convergence Measurements

Figure 2-50. Side View of the Borehole Scanner Used in the TDE (Numbers correspond to items listed in Table 2-5)

Figure 2-51. End View of the Borehole Scanner Used in the TDE (Numbers correspond to items listed in Table 2-5)

Figure 2-52. Front View of Borehole Video System Console (Numbers correspond to items listed in Table 2-4)

Figure 2-53. Rear View of Borehole Video System Console (Numbers correspond to items listed in Table 2-4)

Figure 2-54. Elevation View of the High-speed Camera Experiment

3.0 PRESENTATION AND DISCUSSION OF DATA

3.1 Ground-Motion Data

A total of 60 channels of ground motion data were recorded for approximately 13 minutes on analog tape.¹⁵ Of these data, 180 seconds (60 s before zero time and 120 s after zero time) were digitized using 7.5% and 15% discriminators.¹⁶ The sample rate for the digitization was 1000 points per second. Based on the sampling theorem (Stearns and David 1988), this rate should be adequate to define a data frequency of approximately 400 Hz.¹⁷ As will be discussed below, frequencies observed in the data are generally below 400 Hz.¹⁸

Most of the observed ground motions exceeded the pre-test estimates and the majority of the amplified channels were overdriven. Therefore, all data processed for this experiment were taken from the lowest amplification. Some of these unamplified channels also were overdriven. The voltage controlled oscillator (VCO) subcarrier frequencies used in the recording system are a proportional-bandwidth system with a $\pm 7.5\%$ deviation to bandedge. The bandedge is not a hard limit. Signals may extend beyond the bandedge and still be valid, provided they do not interfere with the signals on an adjacent subcarrier. Excursions beyond the bandedge can sometimes be recovered by using 15% discriminators instead of the 7.5% discriminators. This entire data set was digitized using both types of discriminators. Examples of the differences observed in the data that result from changing the discriminator are discussed below.

The maximum radial accelerations recorded at stations 3700-2 and 3700-3 exceeded the bandedge on the unamplified channels. These accelerations, digitized using 7.5% discriminators, are shown in Figures 3-1 and 3-2. Note that the amount of acceleration lost appears to be relatively small (this is apparent by the lack of a noticeable constant slope in the corresponding velocity plots). Re-digitized accelerations, using 15% discriminators, are shown in Figures 3-3 and 3-4. The acceleration time histories reach a single maximum value rather than the "squared off" maximum of the accelerations in Figures 3-1 and 3-2. The fact that the change in the velocities determined from these accelerations is small indicates that the amount of acceleration "lost" in the bandedge provided only a minor contribution to the peak velocity.

Motions recorded at station 3700-1 had significant high frequencies superimposed on the signal. This high frequency was unique to the motions

15. Fifteen gages were fielded. There were two amplifications/gage and two recordings made of each channel. Because most of the amplified channels were overdriven, the unamplified channels were analyzed.

16. A discriminator is a device in which amplitude variations are derived in response to frequency variation.

17. The sampling theorem states that analog signals should be sampled at a rate greater than twice the highest frequency observed in the data.

18. Although the recording system was only calibrated to 100 Hz, the response of this system is thought to be good up to the natural frequency of the gage (500 Hz).

recorded at this station and may be related to imperfections in the gage mount. Figure 3-5 shows the radial acceleration, digitized with 7.5% discriminators, recorded at station 3700-1. Clearly visible in this signal is the high frequency mentioned above. The velocity determined from this record appears to be reasonable in amplitude and shape. The re-digitized acceleration record, using the 15% discriminator (Figure 3-6), is somewhat more reasonable in appearance (i.e., high frequencies removed), but the amplitude is much less (Figure 3-6). Note, the velocity is only slightly different (either in shape or amplitude) from the previous one (Figure 3-5). The vertical and transverse accelerations are shown in Figures 3-7 through 3-10. These accelerations also exhibit a great deal of noise and show a significant difference in amplitude with the change in discriminators (with a smaller change in velocity). The amplitudes of the accelerations from the 15% discriminator appear to be low and the frequency content of the accelerations from the 7.5% discriminator are difficult to interpret in a meaningful manner. For this reason, the acceleration amplitudes recorded at station 3700-1 are considered questionable. The velocities, however, are relatively insensitive to the changes in these accelerations and are consistent with data from the other stations.

The final set of raw data selected for processing was assembled in the following manner. If the maximum acceleration did not exceed bandedge, the data were digitized with the 7.5% discriminators. Where the maximum accelerations exceeded the bandedge, 15% discriminators were used. Two data records did not fit in these categories. Vertical accelerations recorded at stations 3700-1 and 3700-2, digitized with 7.5% discriminators, could not be processed to yield reasonable¹⁹ integrals. These data, digitized with the 15% discriminators, did provide reasonable integrals and were used in the processing operation. While the reasons for this are not clear, these records are consistent with the other time histories in the data set and considered correct.

While every effort was made in the data-acquisition process to obtain the highest quality data, there are sources of error that cannot be eliminated with the hardware. These sources of error include the recording system components (e.g., VCOs, transmission links or the tape machines) and quantizing error in the analog-to-digital conversion. These errors are corrected in the processing effort using various techniques. The data from this experiment were processed using the following steps: 1) Spurious signals were removed from the raw accelerations and preliminary data corrections were made (trend removal and zero average shifts); 2) Power density spectra were run on these acceleration data to determine the limits used in the finite impulse response filters; 3) The data were filtered; and 4) Further baseline corrections were made until "reasonable" first and second integrals were determined. Initial corrections and filtering were performed on the data recorded between -30 and 50 s. Final corrections were made on the data between -10 and 25 s. For the most part, ground motions of interest occur at

19. "Reasonable", in this context, is a somewhat subjective term. There is a good deal of engineering judgment and experience that enters into data processing. In this experiment, other independent sources of data (permanent displacements and tunnel convergence measurements) were used to help guide the processing and determine the integrals.

times between 0 and 5 s. The details of the data corrections are given in Appendix D.

Power density spectra are used to determine the frequency content of the data, and the noise present in the data. These spectra were calculated on the -30 to 50 s time scale. The spectrum of the noise is determined from the signal recorded between -30 and 0 s. The spectrum of the data and noise is calculated from the signal recorded between 0 and 50 s. The difference of these two spectra provides the spectrum of the data without noise. The ratios of the data to the noise spectra are then plotted versus frequency and used to determine the high and low pass frequency limits used in filtering the data. In general, frequencies where the signal-to-noise ratio is less than 1.0 are filtered out of the data.

Plots of signal-to-noise ratio versus frequency calculated for these data are shown in Figures 3-11 through 3-25. Table 3-1 summarizes the low pass cutoff frequencies used in filtering the noise from the data. In general, the filter code performs a low pass filter on the data, decimation (a decrease in the sample rate), and then a high pass filter. The frequency cutoff for the high pass filter could not be determined from the signal-to-noise ratio plots.²⁰ Therefore, only low pass filtering was done on these data. In addition, no decimation was performed on the filtered data. Corrected acceleration, velocity and displacement time histories, on 10 s and 2 s time bases are shown in Figures A-1 through A-30. Pseudo relative velocity response spectra (PSRVs) calculated at 5% damping are shown in Figures A-31 through A-45. Power spectrum plots of the corrected and filtered acceleration data are shown in Figures A-46 through A-60. As noted earlier, the gages were aligned with respect to the tunnel axis. The convention used here is to identify the components of the data are with respect to the axis of the explosion. The components are identified as either AV, A-352.3 or A-262.3. A-352.3 corresponds to radial motion (perpendicular to the tunnel axis) and A-262.3 corresponds to transverse motion (parallel to the tunnel axis).

Discussion of Ground Motion Data

Before the data are discussed, it is useful to review the basic phenomena of underground explosions. The explosion liberates large amounts of energy as heat. This thermal radiation fills the emplacement volume and is absorbed by the surrounding medium which is then vaporized. This high-temperature and pressure vapor rapidly expands radially and becomes a compressive shock front. As the shock front propagates away from the detonation point, the thermal energy in the shock wave heats a larger volume of material and the pressure at the front decreases. Five basic regions may be defined based on the damage sustained by the host media (Glasstone, 1971): 1) the cavity surrounds the detonation point and consists of vaporized and melted material; 2) crushed material is present in the next region; 3) material that is extensively cracked makes up the fracture zone; 4) material

20. The data correction algorithm used on these data had the effect of high pass filtering the data. Studies of the effect of this algorithm on the data are documented in Appendix C. These data were altered to some extent by the algorithm. In our judgement, these changes were not deleterious to the accuracy of the data.

that experiences permanent deformations make up the plastic deformation zone; and 5) the final region is the elastic or seismic region. Theoretically, deformation is only temporary with the passage of the shock front in this final region. This experiment was located in the elastic zone.

The above description deals with the initial outward disturbance in the media, namely the compressive or P-wave. At the completion of the growth of the cavity, the medium experiences a stress relief or relaxation. Empirical studies have identified the end of the cavity growth as the point at which the observed radial displacement is at its first maximum which also corresponds to the duration of the initial half-cycle of the radial velocity. For a homogeneous, isotropic half space, this disturbance would produce relatively simple radial and vertical ground motion, and, in theory, no transverse ground motion. In a layered, anisotropic medium, such as is present for the TDE, reflections and refractions occur at the layer interfaces. These reflections and refractions produce mode conversions at the interfaces. Thus a relatively simple P-wave loading is transformed into a complex wave train composed of several different compression and shear waves.

Table 3-2 shows arrival times, times of first radial and vertical velocity peak, length of initial half-cycle of radial velocity, and maximum amplitudes of the measured ground motions. The major observations from this table are listed below.

- As would be expected, the signal arrives first at the left rib (the location closest to the explosion), then at the gages on the invert and in the free-field, followed by the gages on the back and the right rib. There is a maximum of 5 ms difference in arrival times from the left to right ribs.
- The average propagation velocity of the wave front as calculated by the distance divided by the arrival time, is 2.74 km/s. This approximates the average value of the reported P-wave speeds of the tunnel material (Table 2-2, Drill Hole U12n23 UG-1 and UE12n#14).
- The maximum radial and vertical velocity propagates at an average velocity of 2.41 km/s. This velocity corresponds to the loading wavespeed of the material for the average stress level between the WP and TDE.
- Expansion of the cavity (as determined from the initial half-cycle of radial velocity, discussed earlier) has completed and the material relaxation has begun at about 0.377 s. This indicates that only about 0.2 s of the observed ground motion is associated with the explosion-generated wave front. The remainder of the time history is associated with the relaxation of the media and the reflection and refraction of the various waves.
- The loading experienced by this tunnel section is summarized in the free-field ground motion parameters. Namely, maximum radial acceleration, velocity, and displacement are 27.6 g, 2.3 m/s and 13.0 cm, respectively; maximum vertical acceleration, velocity, and displacement are 8.8 g, 0.6 m/s and -9.7 cm; maximum transverse acceleration, velocity, and displacement are 4.3 g, -0.5 m/s and

-8.5 cm. All maximum amplitudes were generated by the initial outward compressive wave.

The free-field ground motions measured in the TDE define the loading on the tunnel. Comparison of free-field motions and tunnel wall motions indicate when and how tunnel motion deviates from free-field motion. It is important to identify differences in these motions to allow for proper compensation in design of shock isolation systems for equipment that may be installed in the tunnel. Comparisons of free-field and tunnel motion will be done in several ways. These will include study of the ratios of peak values, time history comparisons, PSRV comparisons, and study of three-dimensional hodographs.²¹

Table 3-3 shows the ratio of peak tunnel face motions with respect to the free-field motions. The observations from this table are summarized below.

- In terms of acceleration and velocity amplitudes, the largest radial motions occurred on the left rib and the smallest on the right rib. The radial acceleration and velocity amplitudes on the left rib are, on average, 30% greater than the free-field values. The maximum radial displacement was measured on the back while the radial displacement of the other tunnel walls are about the same as the free-field displacements.
- The maximum vertical tunnel wall motion occurs on the invert. The invert acceleration is 3.5 times the free-field value and the invert velocity is a factor of 5.2 greater than the free-field velocity. Vertical velocities recorded on the other tunnel walls vary from approximately equal to the free-field velocity (right rib) to about 50% greater than the free-field value (on the back). Vertical accelerations vary from 20% less to about 2 times greater than the free-field value. Vertical displacements measured on the tunnel walls were about 10% less than the free-field value.
- Maximum transverse acceleration on the left rib was 6.4 times the free-field value. Transverse acceleration on the invert was about 5 times the free-field acceleration. Transverse velocities and displacements measured on the left rib were about 40% greater than the free-field values. Transverse velocities on the invert were about 20% greater and displacements were 60% less than the free-field values. The transverse motions on the back were about 40% less than the free-field motions and right rib motions were about 20% less than the free-field values.

Comparisons of time histories recorded on the tunnel walls (plotted as solid lines) and the corresponding free-field motions (plotted as the chain dashed lines) are shown in Figures 3-26 through 3-34. These figures show accelerations on a time scale of 0.15 to 0.4 s; velocities on a 1 s time scale; and displacements on 2 s time scale. In general, tunnel-wall motions,

21. A hodograph is a plot of displacement in one plane at a specific time vs. displacement in another plane at the same time. A series of these displacement points describes the path of a particle over a given time.

are similar to free-field motions in terms of both frequency and amplitude. The primary differences between the tunnel wall and free-field motions occur in the initial 0.5 s of motion.

The largest difference between the tunnel and free-field motions was observed in the vertical motion of the invert (Figures 3-26 through 3-28). In the first cycle of motion it is apparent that the invert moved differently than the free field. The shape of the acceleration time history (Figure 3-26) is characteristic of spall²² (i.e., the negative dwell between 0.2 and 0.3 s) but the dwell acceleration amplitude of 8.5 g is too large. In addition, the corresponding radial and transverse measurements (Figs. 3-29 and 3-32) do not exhibit the normal characteristics associated with spall. It appears that the vertical motion is the result of a localized material failure, either in the gage mount grout or in the rock. More analysis is required to fully understand the observed phenomena. Note that, after this initial excursion, both the free field and the invert essentially track one another.

Ratios of PSRVs are shown in Figures 3-35 through 3-37.²³ These plots show all tunnel wall PSRVs normalized to the free-field PSRV.²⁴ With the exception of the gage mounted on the invert, all vertical tunnel PSRVs (Figure 3-35) are approximately the same as the free-field PSRV. The vertical PSRV calculated for the invert shows a large enhancement over the free-field at frequencies between about 2 to 50 Hz. The free-field and tunnel PSRVs calculated for radial motions (Figure 3-36) are all essentially 1.0 with the exception of the left rib measurement that shows a slight enhancement in pseudo velocities at frequencies greater than 10 Hz. Ratios of transverse PSRVs show more variation (Figure 3-37) than those calculated for radial motions, but the variation is still not as great as observed for the vertical motion on the invert.

Hodographs are shown in Figures 3-38 through 3-42. These hodographs were calculated for the initial 2 s of motion. The solid curve on these figures is the three-dimensional hodograph. Each symbol (after the initial symbol) on the solid curve represents an additional 0.1 s. The dashed lines represent the projection of the hodograph in the various two-dimensional planes. The free-field hodograph is shown in Figure 3-38. Hodographs for the left and right ribs are shown in Figures 3-39 and 3-40, respectively. The

22. *Spall occurs when a compressive wave impinges on a free surface. A tensile wave is propagated back into the material. Rock, which is weak in tension, will fail under the load of this tensile stress. The failed rock will continue its motion until gravitational forces become larger than the motion imparted by the tensile wave. The rock will then free fall back to the surface. Spall is characterized in ground motions by a negative dwell of -1 g in the vertical acceleration time history. This dwell is followed by an abrupt acceleration reversal which is indicative of rejoin. During the dwell in the vertical motions, horizontal motions exhibit a relatively constant motion followed by the abrupt reversal associated with rejoin.*

23. *PSRVs show the response of a single degree of freedom system subjected to a base motion. They are used to estimate structural response to a ground motion input. For this exercise, the PSRVs are used to compare the frequency content of the tunnel wall motions and the free-field motions.*

24. *A value of 1 on these plots indicates that the two PSRVs are equal. If the ratio is greater than 1, the tunnel PSRV exceeds the free-field PSRV. If the free-field PSRV is greater than the tunnel PSRV, the ratio is less than 1.*

hodograph for the back is shown in Figure 3-41. The invert hodograph is shown in Figure 3-42. In general, hodographs for the free field, right rib, and the left rib show similar behavior. The largest movement is in the radial direction. The least movement occurs in the transverse direction and vertical movement is intermediate. Hodographs for the invert and the back are similar. Both have significant vertical components and relatively small transverse components. These hodographs indicate that the ribs moved with the free field while the invert and the back deviated from the free field initially.

3.2 Surveys

3.2.1 Permanent Displacements

Component displacements of the rock bolts used as survey markers are given in Table 3-4.²⁵ These values are plotted in Figures 3-43 through 3-46. In general, these markers were displaced away from the source, toward the tunnel face and down. The largest displacements occurred in the outward direction (Figure 3-43). Displacements were approximately 6 cm on the left rib and 5 cm on the right rib. The rock bolts were displaced laterally (Figure 3-44) toward the tunnel face, by about 3 cm for both the right and left ribs. Vertical displacements (Figure 3-45) were primarily downward and were between 0 and 4 cm on the left rib and between 0 and 1 cm on the right rib.²⁶ Vector displacements (i.e. the change in slant range) are shown in Figure 3-46. Vector displacements on the left rib range from about 6 to 7 cm. On the right rib the variation in the vector displacements was from about 5 to 6 cm.

Component displacements of the mounting bolts are summarized in Table 3-5. There were three bolts on each mount. Because of limited visibility at the setup point of the theodolite, only one bolt on the right rib mount was surveyed and only two bolts were surveyed on the back. All of the bolts on the left rib and the invert were visible and were surveyed. The displacement reported for the bolt closest to the right rib on the back mount appears to be inconsistent with the other bolt on this mount and is not used nor included in this table. Outward displacements are largest on the left rib. Vertical displacements are largest on the invert and are of opposite sign relative to the other bolts. Lateral displacements are approximately the same for all the bolts. The average displacements of the mounting bolts for the left rib mount and the single bolt on the right rib are plotted in Figures 3-43 through 3-46. These displacements are consistent with the displacements of the rock bolts.²⁷

Permanent displacements can be used to estimate the change in the drift dimensions as a result of the loading. These measurements are comparable to

25. Raw survey data for these measurements are provided in Appendix F.

26. Recall that the accuracy of these surveys is ± 3 cm. The fact that the survey is not accurate enough to confidently measure these displacements is not as important as the fact that these displacements are this small.

27. Remember that the rock bolts in the tunnel walls were 4.9 m long and the gage mounting bolts were 0.6 m long. For this particular experiment, it appears that the length of the rock bolt made very little difference in the amount of displacement observed.

the tunnel convergence measurements, but are much less accurate. These values are an indication of the relative motion of the survey points. The comparison of the tunnel convergence from these two independent data sources will provide a consistency check on the data sets and will provide some additional insight to the movement observed in the tunnel convergence measurements.

Tunnel convergence, as determined from permanent displacement data, was calculated by subtracting the post-test distance between two survey points from the pre-test distance. If the difference is positive, convergence occurred or the tunnel dimension defined by the two survey points was reduced. A negative difference indicates that the tunnel dimension actually increased. The emphasis was placed on the radial component (movements perpendicular to the axis of the drift) and the vertical component. Motions parallel to the axis of the drift (the transverse component) do not provide an indication of tunnel convergence.

Convergence calculated from the permanent displacement of the gage mounts is presented in Table 3-6. The distance between mounts on the invert to the back and ribs was reduced by 4 cm in the vertical direction. Both markers on the invert and back were displaced the same amount in the radial direction, indicating no relative displacement. The convergence noted on the measurements from the left rib to the invert and the left rib to the back was 2 cm. The distance from the invert to the right rib and the back to the right rib actually increased. This is because the gage mounts on the invert and the back were displaced a smaller amount than the gage mount on the right rib. The fact that no convergence was noted in the vertical direction in the measurements from the back to the ribs and from rib to rib indicates that the major vertical movement in the drift was in the invert. This observation is consistent with the ground-motion data.

Tunnel convergence determined from the permanent displacement of rock bolts is summarized in Table 3-7. Most of these markers show a convergence of about 1 cm in the rib-to-rib dimension along the drift section.

In summary, permanent displacements of all markers indicate that the tunnel section was translated, as a unit, away from the explosion (about 5 cm), toward the tunnel face (about 3 cm), with essentially no change in elevation. The left rib moved approximately 1 cm farther than the right rib, indicating a reduction in the opening in the rib-to-rib dimension. No relative horizontal displacement was observed between the back and the invert. Vertical displacements indicated that the back and ribs experienced essentially no vertical movement. The invert, however, moved upward approximately 4 cm relative to the other markers, resulting in a reduction in the vertical dimension of the opening.

3.2.2 Cross-Section Measurements

Tunnel cross sections were measured at 1.2 m intervals along the primary section of drift. The objective of these measurements was to measure any large changes in the tunnel opening that resulted from the loading. As is apparent from the permanent displacement data above, the displacements experienced in this drift were small, too small to observe in the cross-section measurements. Therefore, the cross section data were of no use for

the objectives of this experiment and will not be presented here. (Pre-test cross sections are provided in Appendix F).

3.3 Tunnel Convergence

Convergence measurements for the primary and secondary locations are presented in Figures 3-47 and 3-48, respectively. Note the relative magnitudes of maximum convergence: 45 mm at the primary site, compared to 2.4 mm at the secondary site.

Figures 3-49 and 3-50 show detail of the measurements made before the shot. These data indicate the accuracy of the measurements, assuming that the openings were stable. According to the manufacturer, the accuracy of the tape extensometer is ± 0.13 mm. Most of the pre-shot measurements fall within this error band centered around zero²⁸ with the exception of measurements involving the floor anchors in both locations. Possible explanations for the scatter are nonrepeatability in point of contact of the extensometer with each eyebolt, disturbance of the anchors, operator error, and unstable conditions in the rock.

- The extensometer operators suspected that the point of contact of the extensometer clip with each anchor eyebolt might not have been repeatable because humidity, which was extremely high at the secondary location, caused the eyebolts to corrode, resulting in rough surfaces on which the clip could catch.
- Anchor disturbance may contribute to measurement scatter for anchors in the invert because a greater length must protrude from the hole to accommodate the fill material overlying the bedrock, and because this location is particularly susceptible to interference.
- Differences between operators in aligning and reading the instrument probably contributed some measure of random variation.
- A final possible cause for variation is unstable conditions in the rock. This is highly unlikely in the South extension drift, which was mined 4 years ago (November 1984) and is well supported, but is more likely in the U12n. 22 Bypass drift, which was mined only 11 months before this experiment (January 1988). Note that most of the pre-shot convergence measurements at this site were within the error band except the last measurements involving the floor anchor (Figure 3-50). These measurements can be seen as the start of a trend that continued after the shot (Figure 3-48), suggesting loosening of the rock around that anchor.

It is likely that all of these factors contributed, to some degree, to the data scatter observed. Although the data scatter is larger than the stated accuracy of the instrument, it is still two orders of magnitude smaller than the largest convergence measured.

28. Note that this simple comparison is biased by assuming that the first measurements made were absolute.

At the primary location, several pre-shot data points for convergence between anchors 3 and 4 are missing. This is because measurements were physically obstructed by the high-speed camera equipment.

Post-shot measurements between anchors 5 and 6 at the primary location are suspect because the eyebolt on anchor 6 was visibly bent (this occurred between button up and reentry-likely caused by the explosion). The magnitude of this effect is difficult to assess because the layout of the tunnel fixtures allowed no other measurements from anchor 6.

Discussion of Results

At the primary location, the greatest closure was measured between the invert and the left rib (the side closest to the explosion), and between the invert and the back. Both cross-drift measurements showed moderate closure, and the measurement between the invert and the north rib showed slight divergence. Attribution of directional movement to different parts of the cross section is complicated by the lack of roof-to-rib measurements. In general, the trends observed in these data agree with those observed in the study of the permanent displacement data.

Figure 3-51 shows displacements at the primary location relative to the first post-shot measurements. From these data, it appears that the opening quickly returned to a static state after the shot, with the exception of the back. The roof-to-floor separation was still converging at approximately 0.03 mm/day when data gathering was terminated, about 8 weeks after the shot. This is likely due to settling of a shallow slab, possibly delineated by a 0.3 m deep fracture that was logged before installation of the extensometer anchors (see Appendix D). Deep-seated movement along joints is unlikely to be the primary source because measurements between other points around the drift indicated that the ribs and invert returned to relative stability just after the shot.

Convergence measurements at the secondary location (Figure 3-48) showed virtually no movement except in the invert, which heaved about 2 mm. Although the heave was probably amplified by the explosion, discernible motion began several days earlier. The movement also appears to be transient. Convergence measurements involving the invert anchor reached maxima during a 10 day period following the explosion, and then fell back toward their original positions. Measurements involving the invert anchor were still diverging at about 0.02 mm/day when data-gathering stopped. Movements in the floor may have been affected by ongoing excavations in the drift, resulting in increased traffic and changing hydraulic conditions (the openings are pumped continuously).

3.4 Data Consistency

At this point it is useful to study the three data sets discussed above to determine if they provide a consistent picture of the phenomena observed in the experiment. It is important to understand that these three data sets are independent. This fact is obvious in the case of the permanent displacement data and the tunnel convergence measurements. It may not be quite as obvious in the case of the permanent displacements and the ground motion measurements. The ground motion data were corrected to yield reasonable integrals (as defined by experience and judgement - see Appendix C for details). The

residual displacements were then checked for consistency against the permanent displacements. None of the ground motion time histories was forced to yield a specific displacement.

Residual displacements²⁹ determined from the second integral of the acceleration data are compared in Figure 3-52 with the measured permanent displacements $\pm$ accuracy of the survey. A majority (8 of 12) of the residual displacements are within the accuracy of the measured permanent displacement. The four measurements that do not agree are radial and transverse measurements at station 3700-2, the radial measurement at station 3700-4, and the transverse measurement at station 3700-5. These four records could be forced to yield displacements that agree with the permanent displacements. This is not considered to be a reasonable option because of the relatively low accuracy of the survey and the arbitrary nature of the changes that would be necessary to yield desirable results. The fact that the majority of the residual displacements fall within the accuracy bounds of the permanent displacements is considered good agreement and an indication of consistency between these data sets.

Figure 3-53 summarizes the comparison of the convergence data with the convergence determined from the permanent displacement data. The open circles with error bars represent the vector sum of the radial and vertical convergence values determined from the permanent displacement data. The solid circles and squares represent the component permanent displacements. The tunnel convergence measurements agree well with these permanent displacement data. Tunnel dimensions were reduced in the rib-to-rib and invert-to-back directions. The increase in the right rib-to-invert dimension registered in the convergence measurements was mirrored in the radial permanent displacement data. The convergences determined from the permanent displacements of the rock bolts agree, within the accuracy of the survey measurements, with the tape extensometer measurements.

3.5 Borehole Inspection

Figures 3-54 and 3-55 summarize the features mapped in the boreholes before and after the shot. These figures are compiled from information taken from the field logbook and from viewing videotapes of the boreholes after the field sessions.

Although the holes were nominally 9.1 m deep, surveys stopped short of the end in three of the four boreholes. The survey in borehole 1B1 (primary location, left rib) stopped at 7.7 m where standing water was encountered. Although it would have been possible to blow the water out with compressed air and survey the last 1.4 m, it was decided that this would not be necessary; because the rock was found to be virtually unfractured beyond the first 0.7 m, it was unlikely that the last 1.4 m would reveal any remarkable features. The survey in borehole 2B1 (secondary location, west rib) stopped at a depth of 1 m because the hole was so sinuous that the televiewer probe could not be inserted beyond this point. The survey in borehole 2B2 (secondary location,

29. These displacements were determined from the corrected ground motion data plotted on a scale of 0 to 25 s. Note, no permanent displacements were determined for station 3700-3 (free-field measurement).

east rib) stopped at 5.5 m because water was pouring into the hole through a fracture at this point.

Because the intent of the survey was to investigate the extent of changes to the rock mass caused by seismic loading, the borehole logs concentrate on the presence of fractures. Visible attributes of the intact rock such as variations in shade and relative contents of lithic fragments were not logged because they would not be affected by the shot, therefore yielding no useful information about effects of the loading.

The lack of color and low resolution of the televiewer system permitted very little elaboration on the properties of the fractures, such as infilling. The difficult task of interpreting ground conditions using the televiewer apparatus is evidenced by the frequent listings of "possible fractures" on Figures 3-54 and 3-55. These were features that had a linear form, but that could not be verified because of the resolution of the instrument, or that could not be traced to the other side of the borehole. Conditions that made fractures difficult to discern include the short depth of field of the lens, undulations in the borehole walls (which aggravated difficulties caused by the short range of focus and also might have obscured fractures when viewed at an oblique angle), lack of contrast in some cases, borehole fogging, and the tendency of the probe to move in a stick-slip fashion. Note that some fractures that were logged in the pre-shot survey were not seen later in post-shot inspections, suggesting that information was being missed. Conversely, fractures logged for the first time in the post-shot survey might not all be attributable to the inception of new fractures; some or all could have simply been missed previously.

Discussion of Results

Comparison between the pre- and post-shot borehole inspections at the primary location show measurable differences in the near-surface conditions. Changes deeper into the rock are less definitive. In borehole 1B1, the borehole on the near-blast side, fracture apertures increased by as much as 3 cm. Changes were confined to the first 0.6 m of rock, with the exception of several possible hairline cracks and one narrow, shallow-dipping fracture noted at about 7 m depth. On the other side of the drift, in borehole 1B2, a new near-surface fracture (0.2 m depth) was noted after the shot. Other possible fractures noted in this hole after the shot do not match those logged before the shot.

At the secondary location, no fractures were found pre-shot. Post-shot, no changes were noted except one possible hairline crack at about 3.4 m depth in hole 2B2.

3.6 Photography

3.6.1 Documentary Photography

Photographs were taken at approximately 3 m intervals along the axis of the tunnel.³⁰ At each of these sections, photos were taken of the tunnel

30. The coverage of the individual photographs varies somewhat; 3 m is a rough average.

walls from the right rib/invert interface, around the tunnel to the left rib/invert interface. In addition, "overall" photographs were taken at either end of the TDE. Figures 3-56 and 3-57 show the approximate coverage of the photographs and the figure number corresponding to the photograph as presented here. The lower figure number in a particular block corresponds to a pre-test photograph; higher numbers correspond to a post-test photo. The "overall" views will be presented first.

Figures 3-58 through 3-61 are "overall" photographs of the TDE. Figure 3-58 was taken before the event at about station CS 56+20, looking toward the portal. The work bench, ground motion gages, cabling, photo target, and backdrop for the high-speed camera are visible in this photograph. This view, after the event, is shown in Figure 3-59. The right rib of this tunnel section sustained no visible damage. Some large pieces of the lining spalled off the left rib and are visible behind the wire mesh. Also visible in this photo are some small pieces of debris on the invert. Figures 3-60 and 3-61 are pre- and post-test photographs of this tunnel section taken from about station CS 55+80, looking toward the tunnel wall. The observations noted above are visible in these photos. The usefulness or integrity of this drift appears unaffected by the seismic loading experienced.

The photographs of the individual sections will be presented in a section at a time, beginning at CS 55+80. The pre-test photographs for a section will be followed by the post-test photos for that section.

CS 55+80 to CS 55+90

Pre-test photographs for the tunnel section between CS 55+80 and CS 55+90 are shown in Figures 3-62 through 3-66. Figure 3-62 shows the right rib, from near the invert, to a height of about 3 m. Survey markers L and M are visible. Figure 3-63 shows the right rib of the tunnel wall looking toward the back, above the section shown in the previous photo. A view of the back and the right rib side of the vent line is shown in Figure 3-64. Figure 3-65 shows the left rib side of the back, from the vent line to the survey pins. Survey pins A and B are visible. The left rib, from the survey pins down to near the invert, is shown in Figure 3-66. Survey pins A and B are visible in this photograph as well.

Post-test photographs for this section are shown in Figures 3-67 through 3-72. The correspondence between the pre- and post-test photographs was shown in Figures 3-56 and 3-57. The damage observed in this section is visible on Figures 3-68 through 3-72. No damage is observed in Figure 3-67. The damage is relatively minor on the right rib side of the vent line (Figs. 3-68 and 3-69), with some cracks in the lining visible. The visible cracks on the left rib side of the vent line, on the back (Figs. 3-70 and 3-71) indicate a somewhat higher level of damage. These cracks are somewhat wider and some of the painted lining has spalled off. The most damage observed in this section is seen in Figure 3-72. Pieces of the lining and some minor pieces of rock have spalled off the left rib.

CS 55+90 to CS 56+00

Pre-test photographs for this section are shown in Figures 3-73 through 3-77. The right rib near the invert to about 3 m above the invert is shown in

Figure 3-73. Survey pins M through P are visible. Figure 3-74 shows the right rib above the previous photo up to the vent line. The back on the right rib side and above the vent line is shown in Figure 3-75. The left rib from the vent line to near the invert is shown in Figures 3-76 and 3-77. Survey markers C through E and a portion of the high-speed camera experiment are visible in these photos.

Figures 3-78 through 3-84 are the post-test photographs for the section. No visible damage is present on the right rib from the invert to the vent line (Figures 3-78 and 3-79). Cracks are visible in the lining and some of the lining spalled off above the vent line, on the back (Figures 3-80, right rib side of vent line, and 3-82, left rib side of vent line). Some minor cracking is apparent on the left rib in the region between the survey markers and the vent line (Figure 3-81). On the left rib, from the survey pins to the invert, some more severe damage is observed (Figure 3-83). In general this damage consists of the lining and some rock spalling off the rib. Figure 3-84 is a close-up view of the damage present near the ground motion gage.

CS 56+00 to CS 56+10

Pre-test photographs of the tunnel section are shown in Figures 3-85 through 3-89. The right rib, from near the invert to about 3 m above the invert, is shown in Figure 3-85. The gage mount area (above the CS 56+00 sign) and survey pins P, Q, and S are visible in this photo. Figure 3-86 shows the right rib from the gage mount to the vent line. The back, above the vent line, is shown in Figure 3-87. The left rib from the vent line to the survey pins is shown in Figure 3-88. Survey pins E through G are visible. The left rib, from near the invert to about 3 m above the invert, is shown in Figure 3-89. Survey pins D through G and J, as well as the gage mounting plate, are visible.

Figures 3-90 through 3-96 are the post-test photographs for this section. As in the other sections, there is no visible damage on the right rib from the invert to the vent line (Figures 3-90 and 3-91). Above the vent line on the back, there is cracking and some spalling of the lining (Figures 3-92 and 3-94). Some minor cracking is visible on the left rib, from the vent line to the level of the survey pins (Figure 3-93). The most noticeable damage occurred on the left rib from the invert to about 3 m above the invert. Figures 3-95 and 3-96 show the damage in this area. As in the other section, the lining and some rock has spalled off in places.

CS 56+10 to CS 56+20

Figures 3-97 through 3-101 show the pre-test photographs of this tunnel section. Figures 3-97 and 3-98 show the right rib, near the invert to the vent line.³¹ Photographs of the back above the vent line and the left rib from the vent line to near the invert are shown in Figures 3-99 through 3-101.³² Survey markers G through I are visible in these photos.

31. Visible in Figure 3-97 is one of the boreholes used in the borehole televiewer work.

32. The apparatus visible in Figures 3-100 and 3-101 is the mount for the high-speed camera.

Post-test photographs of this tunnel section are shown in Figures 3-102 through 3-108. The damage observations for this section of tunnel are very similar to the previous section. There is no noticeable damage on the right rib (Figures 3-102 and 3-103). Damage, in the form of minor cracking and some spallation of the lining, begins to occur on the back (Figures 3-104 and 3-106). More severe damage, in the form of fairly large pieces of lining and some rock spalling, occurs on the left rib (Figures 3-105, 3-107 and 3-108).

In summary, damage was relatively minor in this section of drift. Some pieces of shotcrete lining and rock spalled off the back and the left rib. Small pieces of debris were visible on the invert and on the vent line. There was no visible damage to the right rib. Several small rock fragments spalled into borehole 1B1 (left rib, Figure 3-109). There was no corresponding debris in the hole drilled in the right rib.

A review of the photographs taken at the secondary location indicated only minor changes in the vicinity of the anchors. The only rock spalling found post-test was a single slab (0.5 X 0.3 X 0.05 m) that was resting on anchor 2TE4. Overall pre- and post-test views of this tunnel section are shown in Figures 3-110 and 3-111. Observable damage in this drift was much less than in the primary drift. A stress-relief fracture located above a nearby alcove showed no observable changes post-test. Figures 3-112 and 3-113 show the pre- and post-test views of this fracture.

3.6.2 High-speed Photography

The high-speed cameras returned approximately 380 ms (after zero time) of data. A failure in the power box resulted in power loss at about 350 ms after zero time. The internal timing light generator stopped functioning at about 380 ms. After this time, the cameras continued to run, exposing film without reference to the exact camera speed or elapsed time. Therefore, any images after about 380 ms do not provide any useful quantitative data.

The film with the clearest image was digitized. The gravity reference indicators provided a horizontal reference plane from which radial displacement could be determined. The clarity of the image was insufficient to determine a useful vertical displacement. The digitized horizontal displacement is shown in Figure 3-114. Also shown in this figure is the radial displacement from station 3700-2. There is very good agreement between these two measurements. The primary difference occurs in the arrival time. This difference may be the result of flash delay at zero time or some variation in the frame rate of the camera. These data are differentiated to yield velocity as well. Three velocity curves were derived. First, all data points were used in the differentiation. Next, the sample rate was decreased to every fifth point and finally, to every tenth point. These three time histories are compared to the radial velocity measured by station 3700-2 in Figure 3-115. The first two velocities derived from the film are noisy. This is related to the difficulty in accurately determining the displacement from the film (clarity of the image). The third image is more similar to the time history from station 3700-2.

Figures 3-116 and 3-117 show selected frames from the high-speed film. Figure 3-116 shows the left rib at the time of detonation. Visible in the figure are the gravity reference indicators (lead brick and golf balls), photo

target indicating the location of station 3200-2, and the visible zero time reference indicator. Figure 3-117 shows the same view 350 ms later. This is approximately the time of maximum displacement. Visible in this frame are the gravity reference indicators and pieces of the tunnel lining which spalled from the left rib and the back as a result of the loading.

Table 3-1.

LOW PASS FILTER CUTOFF FREQUENCIES USED IN PROCESSING MISTY ECHO GROUND MOTION
DATA

<u>Station</u>	<u>Gage</u>	<u>Limit in Hertz</u>
3700-1	AV	281
	A-262.3	None
	A-352.3	None
3700-2	AV	346
	A-262.3	None
	A-352.3	281
3700-3	AV	100
	A-262.3	161
	A-352.3	161
3700-4	AV	None
	A-262.3	300
	A-352.3	None
3700-5	AV	375
	A-262.3	None
	A-352.3	None

Table 3-2.

ARRIVAL TIMES AND PEAK AMPLITUDES DETERMINED FROM THE TDE GROUND MOTION DATA

Station	Location	Slant Range m	TOA s	Vert ^a Acc g	Vert Tpk ^f Vel m/s	Vert Disp cm	Rad Acc g	Rad Tpk Vel m/s	T/2 ^g s	Rad ^b Disp cm	Trans Acc g	Trans Tpk Vel m/s	Trans ^c Disp cm	
3700-1	Back	497.23	0.182	13.7 ^d	0.9	0.215	8.6	32.0?	1.9	0.210	0.396	16.2	17.2? ±0.3 ^e 0.203	-5.1
3700-2	L. Rib	493.31	0.179	-18.1	0.8	0.204	-8.1	35.6	3.2	0.203	0.372	14.2	0.7 0.199	12.3
3700-3	F. Field	495.06	0.180	8.8	0.6	0.205	-9.7	27.6	2.3	0.204	0.366	13.0	-0.5 0.201	-8.5
3700-4	R. Rib	499.22	0.184	7.2	0.6	0.212	-7.4	18.0	1.8	0.210	0.384	13.2	-0.5 0.210	-6.3
3700-5	Invert	495.06	0.180	30.5	3.1	0.209	10.9	-31.9	1.9	0.202	0.369	13.0	0.6 ?	3.8

a. Positive vertical motion is upward

b. Positive radial motion is away from source

c. Positive transverse motion is toward portal

d. Question marks indicate questionable value

e. ± indicates equal positive and negative peaks

f. Tpk is the time-of-peak

g. T/2 is the length of the initial half cycle.

Table 3-3

RATIO OF TUNNEL WALL MOTION TO FREE-FIELD MOTIONS

Station	Location	Vert Acc	Vert Vel	Vert Disp	Rad Acc	Rad Vel	Rad Disp	Trans Acc	Trans Vel	Trans Disp
3700-1	Back	---	1.5	0.9	---	0.8	1.2	---	0.6	0.6
3700-2	L. Rib	2.1	1.3	0.8	1.3	1.4	1.1	6.4	1.4	1.4
3700-4	R. Rib	0.8	1.0	0.8	0.7	0.8	1.0	0.8	1.0	0.7
3700-5	Invert	3.5	5.2	1.1	1.2	0.8	1.0	5.2	1.2	0.4

Table 3-4

PERMANENT DISPLACEMENTS OF ROCK BOLTS USED AS SURVEY MARKERS

Survey Point	Outward Disp-cm	Lateral Disp-cm	Vertical Disp-cm
A	-5.7	3.0	1.1
B	-5.8	3.0	0.5
C	-6.1	2.6	0.6
D	-6.4	2.9	0.7
E	NOT FOUND POST-TEST		
F	-6.2	3.0	0.5
G	-6.1	3.0	1.6
H	-6.2	3.1	1.1
I	-5.2	3.9	2.9
J	-5.9	3.2	-0.1
K	-6.8	2.0	3.8
L	-4.8	3.0	0.5
M	-4.9	3.0	0.3
N	-5.0	3.1	0.3
O	-4.8	2.9	0.3
P	-5.2	3.1	0.9
Q	-5.3	3.1	0.8
R	NOT FOUND POST-TEST		
S	-5.2	3.0	0.8

Table 3-5

PERMANENT DISPLACEMENTS OF GAGE MOUNTING BOLTS

Location	Outward	Lateral	Vertical
	Disp - cm	Disp - cm	Disp - cm
<hr/>			
<u>Left Rib:</u>			
2:00 bolt	6.2	3.0	0.6
6:00 bolt	6.1	3.0	0.4
10:00 bolt	6.4	2.7	0.1
<u>Back:</u>			
Inside	4.7	3.2	0.3
<u>Invert:</u>			
2:00 bolt	4.7	2.7	3.7
6:00 bolt	4.7	2.7	4.2
10:00 bolt	4.6	2.9	3.7
<u>Right Rib:</u>			
2:00 bolt	5.2	3.2	0.0
<hr/>			

Table 3-6

TUNNEL CONVERGENCE CALCULATED FROM RELATIVE MOTION OF GAGE MOUNTS*

<u>Location</u>	<u>Outward - cm</u>	<u>Vertical - cm</u>	<u>Vector - cm</u>
Invert-to-back	0	4	4
Invert-to-left rib	2	4	4.5
Invert-to-right rib	-1	4	4.1
Back-to-right rib	-1	0	-1
Back-to-left rib	2	0	2
Left rib-to-right rib	1	0	1

* Positive value indicates convergence

Table 3-7

TUNNEL CONVERGENCE CALCULATED FROM RELATIVE MOTION OF ROCK BOLTS USED AS
SURVEY MARKERS*

<u>Marker</u>	<u>Outward - cm</u>	<u>Vertical - cm</u>	<u>Vector - cm</u>
A to L	0	1	1
B to M	1	0	1
C to O	1	0	1
D to P	1	0	1
J to S	1	-1	1.4

* Positive values indicate convergence

Figure 3-1. Radial Acceleration and Velocity Data from 3700-2 using 7.5% Discriminators - MISTY ECHO

Figure 3-2. Radial Acceleration and Velocity Data from 3700-3 using 7.5% Discriminators - MISTY ECHO

Figure 3-3. Radial Acceleration and Velocity Data from 3700-2 using 15% Discriminators - MISTY ECHO

Figure 3-4. Radial Acceleration and Velocity Data from 3700-3 using 15% Discriminators - MISTY ECHO

Figure 3-5. Radial Acceleration and Velocity Data from 3700-1 using 7.5% Discriminators - MISTY ECHO

Figure 3-6. Radial Acceleration and Velocity Data from 3700-1 using 15% Discriminators - MISTY ECHO

Figure 3-7. Vertical Acceleration and Velocity Data from 3700-1 using 7.5% Discriminators - MISTY ECHO

Figure 3-8. Vertical Acceleration and Velocity Data from 3700-1 using 15% Discriminators - MISTY ECHO

Figure 3-9. Transverse Acceleration and Velocity Data from 3700-1 using 7.5% Discriminators - MISTY ECHO

Figure 3-10. Transverse Acceleration and Velocity Data from 3700-1 using 7.5% Discriminators - MISTY ECHO

Figure 3-11. Ratio of Signal-to-Noise versus Frequency for the Raw Data, Station 3700-1 - Vertical Motion

Figure 3-12. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-1 - Radial Motion

Figure 3-13. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-1 - Transverse Motion

Figure 3-14. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-2 - Vertical Motion

Figure 3-15. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-2 - Radial Motion

Figure 3-16. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-2 - Transverse Motion

Figure 3-17. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-3 - Vertical Motion

Figure 3-18. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-3 - Radial Motion

Figure 3-19. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-3 - Transverse Motion

Figure 3-20. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-4 - Vertical Motion

Figure 3-21. Ratio of Signal-to-Noise versus Frequency for the Raw Data, Station 3700-4 - Radial Motion

Figure 3-22. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-4 - Transverse Motion

Figure 3-23. Ratio of Signal-to-Noise versus Frequency for the Raw Data,
Station 3700-5 - Vertical Motion

Figure 3-24. Ratio of Signal-to-Noise versus Frequency for the Raw Data, Station 3700-5 - Radial Motion

Figure 3-25. Ratio of Signal-to-Noise versus Frequency for the Raw Data, Station 3700-5 - Transverse Motion

Figure 3-26. Comparison of Vertical Free-field and Tunnel Wall Accelerations

Figure 3-27. Comparison of Vertical Free-field and Tunnel Wall Velocities

Figure 3-28. Comparison of Vertical Free-field and Tunnel Wall Displacements

Figure 3-29. Comparison of Radial Free-field and Tunnel Wall Accelerations

Figure 3-30. Comparison of Radial Free-field and Tunnel Wall Velocities

Figure 3-31. Comparison of Radial Free-field and Tunnel Wall Displacements

Figure 3-32. Comparison of Transverse Free-field and Tunnel Wall Accelerations

Figure 3-33. Comparison of Transverse Free-field and Tunnel Wall Velocities

Figure 3-34. Comparison of Transverse Free-field and Tunnel Wall Displacements

Figure 3-35. Ratios of Tunnel Wall/Free-field PSRVs for Vertical Motions

LEGEND

----- Back/Free Field
----- Left Rib/Free Field
----- Right Rib/Free Field
----- Invert/Free Field

Figure 3-36. Ratios of Tunnel Wall/Free-field PSRVs for Radial Motions

LEGEND

- - - - - Back/Free Field
 - . - . - Left Rib/Free Field
 - - - - - Right Rib/Free Field
 - - - - - Invert/Free Field

Figure 3-37. Ratios of Tunnel Wall/Free-field PSRVs for Transverse Motions

LEGEND

----- Back/Free Field
----- Left Rib/Free Field
----- Right Rib/Free Field
----- Invert/Free Field

Figure 3-38. Three-Dimensional Hodograph for the Initial 2 s of Motion - Free-field Measurement (Note: Each square represents a change in time of 0.1 s)

Figure 3-39. Three-Dimensional Hodograph for the Initial 2 s of Motion - Left Rib Measurement (Note: Each square represents a change in time of 0.1 s)

Figure 3-40. Three-Dimensional Hodograph for the Initial 2 s of Motion - Right Rib Measurement (Note: Each square represents a change in time of 0.1 s)

Figure 3-41. Three-Dimensional Hodograph for the Initial 2 s of Motion - Tunnel Back Measurement (Note: Each square represents a change in time of 0.1 s)

Figure 3-42. Three-Dimensional Hodograph for the Initial 2 s of Motion - Tunnel Invert Measurement (Note: Each square represents a change in time of 0.1 s)

Figure 3-43. Outward Displacements of Survey Markers on the Ribs

Outward Displacement of Survey Markers on the Left Rib

○ GAGE MOUNT

Outward Displacement of Survey Markers on the Right Rib

Figure 3-44. Lateral Displacements of Survey Markers on the Ribs

Figure 3-45. Vertical Displacement of Survey Markers on the Ribs

○ GAGE MOUNT

Figure 3-46. Vector Displacement of Survey Markers on the Ribs

Vector Displacement of Survey Markers on the Left Rib

□ GAGE MOUNT

Vector Displacement of Survey Markers on the Right Rib

Figure 3-47. Convergence Measurements Made at the Primary Location, Station 56+18

Figure 3-48. Convergence Measurements Made at the Secondary Location, U12n.22 Bypass, Station 2+84

Figure 3-49. Pre-Shot Convergence Measurements Made at the Primary Location, Station 56+18

Figure 3-50. Pre-Shot Convergence Measurements Made at the Secondary Location, U12n.22 Bypass, Station 2+84

Figure 3-51. Post-Shot Convergence Measurements Made at the Primary Location, Station 56+18

Figure 3-52. Comparison of Permanent Displacements of Gage Mounting Bolts and Residual Displacements Taken from Ground Motion Time Histories

LEGEND

○ PERMANENT DISP. MEAS.

△ RESIDUAL DISP.

Figure 3-53. Comparison of Permanent Displacements of Gage Mounting Bolts and Tunnel Convergence Measurements

LEGEND

- VECTOR PERMANENT DISP. MEAS.
- △ CONVERGENCE MEAS.
- RADIAL PERMANENT DISP. MEAS.
- VERTICAL PERMANENT DISP. MEAS.

Figure 3-54. Results of Pre-Shot Borehole Inspections

Figure 3-55. Results of Post-Shot Borehole Inspections

Figure 3-56. Layout of Documentary Photography at the Primary Tunnel Section of the TDE, Left Rib

Figure 3-57. Layout of Documentary Photography at the Primary Tunnel Section of the TDE, Right Rib

-184-

Figure 3-59. Overall View of the TDE Taken at Station 56+20 - Post-Test

-199/200-

Pre-Test

-185-

Figure 3-60. Overall View of the TDE Taken at Station 55+80 - Pre-Test

-201/202-

3 - Pre-Test

6+00 - Pre-Test

-203/204-

Figure 3-61. Overall View of the TDE Taken at Station 55+80 - Post-Test

-186-

Figure 3-47.

Figure 3-62. Right Rib, Invert-to-Spring Line from 55+80 to ~55+90 - Pre-Test

Figure 3-63. Right Rib, Spring Line-to-Vent Line from 55+80 to ~55+90 - Pre-Test

Figure 3-64. Tunnel Back, Right Rib Side of Vent Line from 55+80 to ~55+90 - Pre-Test

Figure 3-65. Left Rib, Spring Line-to-Vent Line from 55+80 to 55+90 - Pre-Test

Figure 3-66. Left Rib, Invert-to-Spring Line from 55+80 to ~55+90 - Pre-Test

3-67. Right Rib, Invert-to-Spring Line from 55+80 to 55+90 - Post-Test

Figure 3-68. Right Rib, Spring Line-to-Vent Line from 55+80 to 55+90 - Post-Test

Figure 3-69. Tunnel Back, Right Rib Side of Vent Line from 55+80 to 55+90 - Post-Test

Figure 3-70. Left Rib, Spring Line-to-Vent Line from 55+80 to ~55+90 - Post-Test

Figure 3-71. Tunnel Back - Left Rib Side of Vent Line from 55+80 to 55+90 - Post-Test

Figure 3-72. Left Rib, Invert-to-Spring Line from 55+80 to 55+90 - Post-Test

Figure 3-73. Right Rib, Invert-to-Spring Line from 55+90 to ~56+00 - Pre-Test

Figure 3-74. Right Rib, Spring Line-to-Vent Line from 55+90 to ~56+00 - Pre-Test

Figure 3-75. Tunnel Back, Right Rib Side of Vent Line from 55+90 to ~56+00 - Pre-Test

Figure 3-76. Left Rib, Spring Line-to-Vent Line fro

Figure 3-77. Left Rib, Invert-to-Spring Line from 55+90 to 56+00 - Pre-Test

Figure 3-78. Right Rib, Invert-to-Spring Line from 55+90 to ~56+00 - Post-Test

Figure 3-79. Right Rib, Spring Line-to-Vent Line from 55+90 to ~56+00 - Post-Test

Figure 3-80. Tunnel Back, Right Rib Side of Vent Line from 55+90 to 56+00 - Post-Test

Figure 3-81. Left Rib, Spring Line-to-Vent Line from 55+.

Figure 3-82. Tunnel Back - Left Rib Side of Vent Line from 55+90 to 56+00 - Post-Test

Figure 3-83. Left Rib, Invert-to-Spring Line from 55+90 to 56+00 - P.C.

Figure 3-84. Close-up of Damage to Left Rib from 55+90 to 56+00 - Post-Test

Figure 3-85. Right Rib, Invert-to-Spring Line from 56+00 to 56+10 - Pre-Test

Figure 3-86. Right Rib, Spring Line-to-Vent Line from 56+00 to ~56+10 - Pre-Test

Figure 3-87. Tunnel Back, Right Rib Side of Vent Line from 56+00 to 56+10 - Pre-Test

Figure 3-88. Left Rib, Spring Line-to-Vent Line from 56+00 to 56+10 - Pre-Test

Figure 3-89. Left Rib, Invert-to-Spring Line from 56+00 to 56+10 - Pre-Test

Figure 3-90. Right Rib, Invert-to-Spring Line from 56+00 to 56+10 - Post-Test

Figure 3-91. Right Rib, Spring Line-to-Vent Line from 56+00 to 56+10 - Post-Test

Figure 3-92. Tunnel Back, Right Rib Side of Vent Line from 56+00 to 56+10 - Post-Test

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Figure 3-93. Left Rib, Spring Line-to-Vent Line from 56+00 to ~56+10 - Post-Test

Figure 3-94. Tunnel Back - Left Rib Side of Vent. Line from 56+00 to 56+10 - Post-Test

Figure 3-95. Left Rib, Invert-to-Spring Line from 56+00 to 56+10 - Post-Test

Figure 3-96. Close-up of Damage to Left Rib from 56+00 to ~56+10 - Post-Test

Figure 3-97. Right Rib, Invert-to-Spring Line from 56+10 to 56+20 - Pre-Test

Figure 3-98. Right Rib, Spring Line-to-Vent Line from 56+10 to ~56+20 - Pre-Test

Figure 3-99. Tunnel Back, Right Rib Side of Vent Line from 56+10 to ~56+20 - Pre-Test

Figure 3-100. Left Rib, Spring Line-to-Vent Line from 56+10 to ~56+20

Figure 3-101. Left Rib, Invert-to-Spring Line from 56+10 to 56+20 - Pre-Test

Figure 3-102. Right Rib, Invert-to-Spring Line from 56+10 to 56+20 - Post-Test

Figure 3-103. Right Rib, Spring Line-to-Vent Line from 56+10 to ~56+20 - Post-Test

Figure 3-104. Tunnel Back, Right Rib Side of Vent Line from 56+10 to 56+20 - Post-Test

Figure 3-105. Left Rib, Spring Line-to-Vent Line from 56+10 to 56+20 - Post-Test

Figure 3-106. Tunnel Back - Left Rib Side of Vent Line from 56+10 to 56+20 - Post-Test

Figure 3-107. Left Rib, Invert-to-Spring Line from 56+10 to 56+20 - Post-

Figure 3-108. Close-up of Damage to Left Rib from 56+10 to 56+20 - Post-Test

Figure 3-109. Rock Fragments that Spalled into Borehole 1B1 During the Explosion

more of the

Figure 3-111. Overall View of the Secondary Location of the TDE Looking Away from the Portal - Post-Test

Figure 3-114. Comparison of Radial Displacement Digitized from the High-speed Photography and the Radial Displacement Derived from the Acceleration Measured at Station 3700-2

LEGEND

--- Ground Motion Record
 — High-speed Film

Figure 3-115. Comparison of Radial Velocity Derived from the High-speed Photography and the Radial Velocity Derived from the Acceleration Measured at Station 3700-2

Figure 3-116. Still Photograph of the Left Rib at Time of Detonation (Taken from the high-speed photography experiment)

Figure 3-117. Still Photograph of the Left Rib 350 ms After Detonation (Taken from the high-speed photography experiment)

4.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary

The objective of this experiment was to correlate observed tunnel damage with measured ground motions. To achieve this objective, transient ground motion, absolute permanent displacement, and convergence (relative permanent displacement) measurements were recorded. In addition, borehole and photography studies were conducted to document tunnel damage. Two tunnel sections were used. All of the above-mentioned measurements were made at the primary section. This section was the closest to the source of the two. It was oriented at approximately 90 degrees to the axis of the incoming ground shock. Only passive measurements (i.e. no motion measurements) were made in the secondary section. This section was approximately parallel to the axis of the incoming ground shock at a greater distance from the source. The results obtained are summarized for each tunnel section.

Primary Section

- The maximum radial free-field amplitudes of acceleration, velocity, and displacement of the side-on loading at the primary tunnel section were 27.6 g, 2.3 m/s, and 13.0 cm, respectively.
- In general, motions measured on the tunnel walls had larger amplitudes (but similar frequencies) than free-field motions in the first cycle of motion. The most notable difference between free-field and tunnel motions was in the vertical motion of the invert where the maximum velocity was five times the free-field maximum. After the initial cycle of motion, the free-field and tunnel wall motions were essentially the same.
- The tunnel section was translated away from the explosion (approx. 5 cm) and toward the tunnel face (approx. 3 cm). There was very little change in elevation in the ribs or the back. The invert was displaced upward about 4 cm.
- The seismic loading slightly reduced the overall dimensions of this drift. This was observed in both the tunnel convergence measurements and in the analysis of the permanent displacement data. The trends observed in both data sets were identical. The maximum change measured in the tunnel convergence experiment of the TDE was 4.5 cm.
- Damage observed in the boreholes was confined to the near-surface portion of the hole. The largest changes occurred in borehole 1B1 (the hole closest to the explosion) where some fracture apertures increased by as much as 3 cm. A new fracture at 0.2 m depth in the right rib borehole was also noted.
- Damage noted on the photographs was confined mostly to the back and the left rib. This damage was expressed as spalling and cracking of

the fibercrete lining as well as some portion of the underlying rock.

In general, these separate data sets provide a consistent picture of the dynamic response of this tunnel section. Residual transient displacements compare favorably with the absolute permanent displacements; convergence measurements and convergence calculated from permanent displacement data compare favorably; and observance of damage in the boreholes compare favorably with observations of damage on the tunnel walls.

Secondary Section

- There was virtually no change in the dimensions of the secondary drift as a result of the loading.
- No damage was observed in the boreholes or in the photographs. One exception was the presence of a 0.5 X 0.3 X 0.05 m rock slab resting on one of the convergence anchors.

4.2 Conclusions

The TDE was a successful experiment. The data gathered in support of the experiment consisted of 15 channels of processed motion measurements, 25 permanent displacement measurements, 189 convergence measurements, surveys of four boreholes, and documentary photography. In general, the data from this experiment provide a consistent picture of the dynamic response of the primary tunnel section. The results from each data set complemented the others. Residual transient displacements compare favorably with the absolute permanent displacements; convergence measurements and convergence calculated from permanent displacement data compare favorably; and observance of damage in the boreholes compares favorably with observations of damage on the tunnel walls. The fact that all data sets are consistent lends credibility to the results obtained.

The results of this experiment show that there was only minor damage from the seismic loading experienced by this drift. This damage did not threaten the continued use of the tunnel and in fact this section has been in continuous use since the experiment was conducted.³³

It is important to note that the loading experienced by the tunnel in this experiment is significantly above the design basis ground motions currently under consideration for underground openings at the repository. The Seismic Design Basis Working Group (Subramanian et al, 1988) specified controlling earthquake motions for the exploratory shaft (ES) at 0.3 g and 0.3 m/s for horizontal acceleration and velocity. In an earlier study performed by Blume and Associates (1985), predictions of maximum horizontal ground accelerations and PSRVs were generated for postulated design basis earthquake loading on repository facilities. These accelerations ranged from 0.25 to 0.65 g. The maximum free-field acceleration measured in the TDE was 28 g, which is between 40 and 90 times greater than any of the design basis accelerations. The free-field velocity measured in the TDE is approximately 7

33. Some additional rock bolts were installed as a precautionary measure after the explosion.

times the velocity specified for ES design. A comparison of a predicted 5% damped PSRV response spectra for the design basis earthquake (maximum acceleration of 0.4 g) from the Blume study and those calculated from the TDE free-field measurement is shown in Figure 4-1.³⁴ This comparison shows that, for radial motions, at frequencies between 0.4 and 100 Hz,³⁵ the TDE was subjected to a much more severe environment than expected for the YMP tunnels.

As stated in Chapter 1, direct comparison of the results of this experiment and the dynamic behavior of the planned tunnels for the Yucca Mountain repository is somewhat tenuous. It is clear from this experiment, however, that underground openings can be designed to withstand relatively large ground motions with very minor damage and no loss of function. Had the TDE been subjected to the design ground motions currently under discussion for the repository, it is unlikely that any damage would have been observed (as was the case for the secondary location).

4.3 Recommendations

The data presented in this report have been analyzed to verify that the results are consistent with past observations and that the results reflect the phenomena expected and observed. These data should now be analyzed in the context of the Yucca Mountain repository. This analysis should encompass:

- 1) comparison of the actual dynamic response differences of the welded tuff at Yucca Mountain versus the tunnel bed tuff of the TDE;
- 2) comparison of the tunnel details (e.g., ground support, opening dimensions, method of mining, etc.) between proposed Yucca Mountain tunnels and the TDE tunnels; and
- 3) evaluation of the current proposed designs for Yucca Mountain tunnels using the measured ground motions in the TDE

If the results of 1 and 2 above indicate significant differences and the possibility of greater damage than observed in the TDE, some thought should be given to some three-dimensional finite element calculations of the repository openings subjected to the measured TDE loading.

34. A similar comparison for the design basis UNE could be made with essentially the same conclusions. The design basis earthquake is considered here because it produces the largest motions.

35. Note, the characteristic frequency of this drift is about 120 Hz. Recall that frequencies up to about 500 Hz were observed on some of the time histories.

Figure 4-1. Comparison of PSRV Response Spectra Calculated for Design Basis Earthquake Ground Motions (Blume, 1985) and Free-field Ground Motions Measured in the TDE.

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