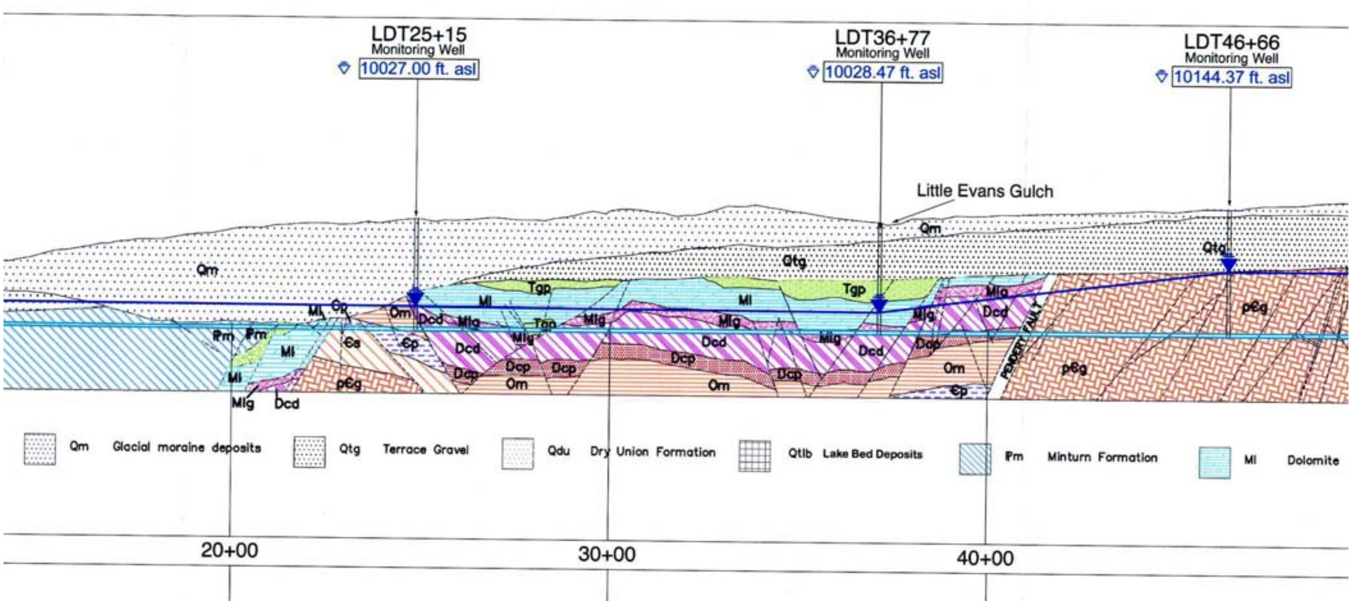
RECLAMATION
Managing Water in the West

Potential Failure Modes and Effects Analysis Leadville Mine Drainage Tunnel

Leadville, Colorado
Great Plains Region



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

FINAL DRAFT June 2008

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Authorship, Checking and Certification of this Document

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Certification Signature. Certification signatures are those of the persons who co-facilitated the risk analysis. These signatures signify that Reclamation methodology, processes, and requirements were followed. In addition, these signatures verify that qualifications of the persons making various probability estimates were appropriate. The purpose of endorsing qualifications is to reduce the potential for inappropriate estimates, or conflicts, arising from limited qualifications that might result in total rejection of risk analysis findings.

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Contents

Description of Study

This report documents the Potential Failure Modes and Effects Analysis (PFMEA) performed for the Leadville Mine Drainage Tunnel (LMDT) near Leadville, Colorado. A PFMEA is an examination of "potential" failure modes and their effects (consequences) for an existing project works by a team qualified to evaluate the structures and site conditions. It is based on a review of existing data and information (including geology, design, analysis, construction, structural behavior, and operations), first-hand input from operations personnel, and site examinations.

The process is conducted in a team setting, where interactions enhance and draw out the breadth of experience brought to the table by a group of qualified individuals, and includes the following:

- Review of all available background material.
- Identification of potential modes of failure.
- Discussion of the likelihood of the potential failure modes, listing the favorable factors (conditions making the probability of failure mode "less likely") and the adverse factors (conditions that make the probability of failure "more likely").
- Determining the likely consequences for each potential failure mode.
- Categorizing each potential failure mode according to its likelihood of developing and consequences should it develop, and documenting the rationale behind the categorization.
- Identifying opportunities for risk-reduction, monitoring enhancement, data collection, and/or analyses to enhance the project safety or understanding of the project risks.

"Risk", by definition, includes both likelihood and consequences. Thus, **a PFMEA is in essence a qualitative risk assessment**, since both the likelihood of the potential failure modes occurring, and the consequences should they occur are examined (but not quantified). The "risk" categorization procedure is discussed in more detail later in this report.

Participants

<u>The following members comprised the PFMEA core team:</u>
Gregg A. Scott, P.E., Senior Technical Specialist, Facilitator
Michael Gobla, P.E., Geotechnical Engineer, Co-Team Leader, mining specialty
Richard Wiltshire, P.E., Geotechnical Engineer, soil mechanics specialty
M. J. Romansky, Geotechnical Engineer, rock mechanics specialty
Mark Vandeberg, P.G., Engineering Geologist, Co-Team Leader, geology specialty
Lloyd Crutchfield, Supervisory Engineering Geologist, geology specialty

In addition, the following individuals provided input for specific issues:
Kevin Atwater, Civil Engineer, tunnel analysis
Roger L. Torres, P.E., Geotechnical Engineer, slope stability analysis
Jack Touseull, P.E., Geotechnical Engineer, evaluation of tunnel plug (Sta 4+62)
Gene Csuti, Electrical/Electronics Engineer/Technician, Leadville Mine Drainage Tunnel Water Treatment Plant

Project Description

The LMDT is an underground excavation constructed during World War II and the Korean War to drain groundwater from metal mines located near Leadville in Lake County, Colorado. Although it was originally operated as an open drain, collapse of a portion of the tunnel roof in 1968 led to installation of a porous bulkhead downstream of the collapse, and an extraction well upstream of the collapse. A water treatment plant was constructed adjacent to the tunnel portal to treat the mine-contaminated drainage flows from both the tunnel and extraction well.

Normal faulting occurs in the Leadville, Colorado mining district along northerly trends, with displacements of several hundred feet. This cuts the district into several irregular compartmentalized blocks. Groundwater flow across the faults is typically restricted by impervious fault gouge. Minerals were deposited along the faults and fissures, and along open bedding planes in sedimentary formations. The largest ore bodies were on top of the “Leadville (Blue) Limestone” in the western part of the district, while smaller gold veins were more prevalent in the eastern part of the district.

Gold was discovered in the Leadville area in 1860. Continued mining in the area through the end of the 19th Century and beginning of the 20th Century resulted in the development of deep underground mines to remove rich ores of silver, lead, and zinc. Constant pumping was required to keep water out of these mines, which eventually became economically impractical. Metal shortages during World War II resulted in renewed interest in these mines for the war effort. The Bureau of Mines was tasked with constructing a drainage tunnel to dewater the mines in preparation for renewed production. A portal site was selected for the drainage tunnel about 1½ miles north of the town of Leadville, and tunneling began in December of 1943. A geologic section along the alignment of the Leadville Mine Drainage Tunnel (LMDT) is attached as Figure 1, and a plan map of the tunnel and Leadville area is attached as Figure 2.

The first 650 feet of tunnel was excavated through glacial deposits and terrace gravels. At about 30 feet, water bearing glacial deposits were encountered which ultimately produced about 50 gal/min inflow. However, the first significant tunnel inflow occurred along the contact with the Weber shales and sandstones, 350 to 650 feet into the excavation, where a flow of 200 to 300 gal/min was encountered. The first 335 feet of tunnel was constructed as a 10-foot-wide by 11½-foot-high modified horseshoe shape. In an effort to save time and money, the dimensions were reduced to 9-foot-wide by 10½-foot-high thereafter. Tunneling was very slow through the gravel deposits. Tunnel construction encountered additional difficulties in the rock sections. At about Station 21+00 the crown of the tunnel collapsed. An overlying basin filled with loose soil and water allowed “running” ground to enter the tunnel, which necessitated construction of a bypass through this area. Poor tunneling conditions were encountered in areas of faulting and fractured rock. Top headings, temporary bulkheads, advance grouting to control water inflow, heavy timber supports, spiling, gunite, and other ground control measures were used in various combinations through the worst rock. Two piece steel rail sets were used in sections requiring lighter support. The Pendery Fault was crossed at about Station 40+70. At about Station 65+70, a zone with heavy water flow was encountered that washed in fragments of quartzite and white porphyry, filling the tunnel for 40 feet. The tunnel was advanced through this zone to Station 66+00, but at that point all available funds had been expended, and tunneling stopped in 1945.

In September 1950, tunneling resumed due to metal shortages encountered during the Korean War and the possibility that the mines would need to be re-opened. After re-stabilizing portions of the tunnel excavated under the first contract, the tunnel was advanced. Once again, difficulties were encountered in sheared and faulted sections of rock, requiring heavy timber supports similar to those used in the first phase of excavation. Light steel sets were used in sections requiring lighter support. Sections of the tunnel were reduced in size, the smallest cross section being 7½ feet wide by 8¾ feet high. Exploratory holes were drilled in an attempt to connect with the Blonger Shaft, but no water inflow was encountered. Laterals were constructed to connect to the Ponsardine Raise, Hayden Shaft, and Robert Emmet Shaft. A bend in the tunnel occurs near the Robert Emmet Shaft and the tunnel continues easterly, connecting to the New Mikado Shaft at a total length of almost 11,300 feet. The total rise from the portal to the end face is about 26 feet, from approximately elevation 9,970 feet at the portal to 9,996 feet at the Mikado Shaft. The tunnel was completed in 1952. Later that year a connection was driven to the bottom of the Blonger Shaft. The Blonger Drift was found to be completely filled with soft shale and timbers, explaining why no water was encountered during the connection drilling. The Bureau of Mines continued maintenance work, repairing cave-ins and keeping the tunnel open until 1959. However, the benefits of the drainage tunnel were never completely realized, as mining in this section of the district never really resumed to any significant level.

The Bureau of Reclamation acquired the LMDT in 1959, with the intent of including the water rights associated with the drainage water as part of the supply for the Fryingpan-Arkansas Project. However, these water rights were actually never obtained due to senior claims. In taking over the tunnel, it was stipulated that “Reclamation has no present intention of spending any funds on the maintenance and repair of the tunnel." However, during the 1960s, surface sinkholes developed due to collapse of the tunnel, threatening State Highway 91 which passes over the tunnel about 535 feet upstream of the portal. Reclamation drilled several holes through the highway and backfilled voids with hydraulic fill and grout. The surface sinkholes were also backfilled.

Prior to construction of the water treatment plant, the tunnel discharged directly into the East Fork of the Arkansas River. The tunnel effluent contains concentrations of heavy metals that exceed water quality standards. As owner of the tunnel, Reclamation was required to bring the discharge into compliance with the Clean Water Act of 1972. Between 1978 and 1979, the collapsed material in the first 500 feet of tunnel was removed, and the tunnel shored up. A bulkhead, constructed of steel beams and wooden timbers, was installed 466 feet from the tunnel entrance (Station 4+66) to reduce tunnel discharge. During 1991 and 1992, the water treatment plant and improvements to the tunnel were constructed by Reclamation. This included a new steel-framed wood-lattice bulkhead backfilled with a gravel and cobble filter at Station 4+61, and concrete lining of the entire tunnel downstream of the bulkhead.

The water treatment plant has operated successfully since its construction, providing clean discharge to the river. However, since about 2003, there has been a gradual rise in the water level near the old mine workings (referred to as the "Mine Pool"), as illustrated in Figure 3. Based on monitoring wells, this higher water level is transmitted down the tunnel at least as far as Station 46+66 (monitoring well LDT 46+66), below which the water level drops (monitoring well LDT 36+77). The water level along the tunnel is also shown in Figure 1. Concerns have been raised that if the difference in water level is due to a blockage caused by tunnel collapse, rupture of the blockage under a continued increase in the Mine Pool level could lead to adverse consequences near the tunnel portal. These concerns prompted this PFMEA study.

Major Findings and Understandings

During the PFMEA session, discussions took place and information was uncovered that resulted in a greater understanding of the conditions and issues related to (1) the LMDT, (2) identified potential failure modes, and (3) the likelihood for adverse consequences. At the conclusion of the session, each participant was asked to provide their most significant conclusions regarding the study. These are captured below.

- The PFMEA process allowed the team to pull out a lot of information buried in old correspondence, organize the available information, and engage in meaningful discussions. The fact that all team members were able to come to consensus on the major issues is a good indication that, based on the available evidence, conditions are reasonably well understood.

- There likely is a collapse in the tunnel forming a blockage between Stations 36+77 and 46+66. Ground water levels measured in observation wells located at Stations 36+77 and 46+66 indicate to date that a maximum differential hydraulic head of approximately 119 feet is being held back by the blockage. It is unlikely that the Pendery Fault or any of the rock units in this section are pervious enough to drain the water from the tunnel. However, rather than at the Pendery Fault (Stations 40+70 to 40+95) which was concrete lined, the most likely blockage location is just downstream between Stations 38+50 and 40+70 in the Parting quartzite, where a section of 46 consecutive timber sets showed signs of dry rot in 1955. The rotting timber is credited for ultimate collapse of a 20-foot zone which initiated near Stations 40+35 to 40+40. Six light steel sets were placed in the vicinity of the collapse, but the recommended replacement of all 46 timber sets was never completed. Thus, the blockage could extend for a significant distance along the tunnel. Increased leakage into California Gulch, presumably along fractured rock associated with the Pendery Fault, is further evidence that the tunnel collapse is downstream of the fault. This flow would be expected if tunnel water was getting to the fault zone, which would be more unlikely if the collapsed zone extended through and upstream of the fault.

- The limit on the height of the Mine Pool will likely be controlled by the contact of low rock cover areas with overlying terrace gravels. The gravels are significantly more pervious that the underlying rock formations, and water rising to the contact will be quickly bled off through the gravel along the bedrock contact. The exact location for this water level control is unknown, as it likely occurs somewhere off the tunnel alignment where geologic information is sparse.

- The collapsed section of tunnel under and downstream of Colorado State Highway 91, remedial backfill and grout, double bulkhead, and concrete lining form a long and robust plug in the downstream portion of the tunnel, which is very unlikely to "blow out", even if the full head from the Mine Pool were to be transmitted to this location.

- A tunnel blockage formed by collapse is likely to have high shear strength due to interlocking of the larger angular fragments, making a shear failure through the material unlikely. It is estimated that only a few lb/in^2 of shear strength is needed for tunnel blockage lengths of 50 feet or more (about 5 times the tunnel diameter) to resist the hydrostatic pressure.

- Seepage erosion or "piping" of materials in and adjacent to the tunnel appears to be unlikely. Blockage materials near the Pendery Fault may be "cemented" by metal precipitates. Even if the materials were internally unstable, and the fines washed through, the remaining mixture of coarse angular blocks and gravel size material would limit the amount of flow through the blockage. Materials in the downstream tunnel are contained by the bulkheads and adjacent filter material. This is supported by the fact that water exiting the tunnel through the bulkhead has always been observed to be clean. In addition, the coarser gravels adjacent to the tunnel will convey a lot of water without moving particles.

- Even though there is a lack of specific engineering test data on the geologic materials near the tunnel portal (and test data would be very difficult to obtain in the gravel materials), this area is likely to remain stable. The pervious terrace gravels in the portal area are underlain by the rock surface of the Minturn formation (Weber sandstones and shales) which slopes away toward the river. The groundwater level in the gravels follows the rock surface, dropping toward the river downstream of about Station 6+35 (see Figure 4). The water level at the timber lattice bulkhead has not risen more than about 2 or 3 feet above the tunnel invert, regardless of the fact that the water level at Station 10+25 has exceeded 70 feet above the tunnel invert. Portal slope stability analysis using high groundwater levels approaching a fully saturated condition indicate adequate factors of safety. Considering the actual history of low ground water levels, the factors of safety are considered to be conservative.

- Seismic loading contributes little to the risk at the LMDT. The simultaneous occurrence of a large earthquake and high groundwater levels in the portal area, both of which are needed to approach unstable slope conditions, is a remote possibility. The earthquake hazard in the Leadville area is not high, and it is unlikely an earthquake would trigger other potential failure modes. The combination of sloping bedrock overlain by porous gravels results in a groundwater system where high water levels are very unlikely to occur.

- With recent improvements to the Early Warning System (EWS), there should be plenty of advance warning of dangerously developing conditions. Three separate parameters are tied to an automated alarm: (1) the water level in the well at Station 10+25, (2) the turbidity of the water entering the treatment facility which includes the combined flow from the dewatering well and the tunnel leakage, and (3) the rate of the combined flow entering the treatment facility. If the change in any of these parameters exceeds the predetermined levels, an automatic alarm call is generated to the plant operators who will quickly evaluate the situation. If the situation is judged to be dangerous, a siren on site will be manually activated to evacuate the area. **However, additional guidance needs to be put in place to help the operators decide when to activate the siren.** The people that would need to be evacuated are in a relatively small area (The Village at East Fork and water treatment plant) near the tunnel portal.

- Although it is believed that groundwater levels near the portal cannot rise to dangerous levels, monitoring is considered to be a prudent risk management activity, and **it is recommended that the ground water wells at Stations 3+00, 4+70, and 6+35 be evaluated to ensure reliable information is being obtained, and if so, instrumented with pressure transducers and the data be tied into the existing Early Warning System (EWS)**.

Risk Categorization

A categorization matrix was developed at the beginning of the exercise as a means of ranking the "risk" posed by the potential failure modes in a relative sense. This is shown in Table 1 and described below.

Risk Categorization Matrix for Public Safety

Table 1. Risk Categorization Matrix

CONSEQUENCES OF FAILURE	FAILURE MODE LIKELIHOOD			
	RULED OUT	LOW	MODERATE	HIGH
LEVEL 3 Consequence Category		Low Likelihood Level 3 Consequences	Moderate Likelihood Level 3 Consequences	High Likelihood Level 3 Consequences
LEVEL 2 Consequence Category		Low Likelihood Level 2 Consequences	Moderate Likelihood Level 2 Consequences	High Likelihood Level 2 Consequences
LEVEL 1 Consequence Category		Low Likelihood Level 1 Consequences	Moderate Likelihood Level 1 Consequences	High Likelihood Level 1 Consequences
No Significant Consequences				

Consequence Descriptions

- **No Significant Consequences –** No significant economic consequences or impacts to the downstream population
- **Level 1 –** No significant economic impacts to the downstream population; water use may be impacted locally
- **Level 2 –** Downstream water use possibly impacted; possible damage to State Highway 91, dwellings in The Village at East Fork, and the water treatment plant downstream of the tunnel portal

- **Level 3 –** Major damage possible to State Highway 91, to dwellings in The Village at East Fork, and to the water treatment plant; possible loss of life; downstream water use possibly impacted to a significant extent

Likelihood Descriptions

- **Ruled Out –** The physical conditions do not exist for its development or the likelihood is so remote as to be non-credible
- **Low (Unlikely) –** The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to its development
- **Moderate (Neutral) –** The fundamental condition or defect is known to exist, indirect evidence suggests it is plausible, but evidence is not weighted toward likely or unlikely
- **High (Likely) –** There is direct evidence or substantial indirect evidence to suggest it has occurred and/or is likely to occur

Those potential failure modes that fall into the “Ruled Out” category with respect to likelihood typically require no further action. Those that fall into the “No Significant Consequences” category may require some action if the likelihood is moderate to high, in order to avert erosion of public confidence. Those potential failure modes that fall in the high likelihood and high consequence category in the upper right hand red-shaded box of the risk matrix are the most dangerous, and likely require immediate action. Proceeding diagonally down toward the bottom left corner of the risk matrix, the risks become increasingly less, and so does the need for action. Monitoring is considered to be an appropriate risk management strategy for potential failure modes that fall into the green- or blue-shaded boxes. For potential failure modes that fall into the yellow- or orange-shaded boxes, additional strategies for long-term risk reduction should be considered.

Potential Failure Mode Evaluation

The PFMEA team brainstormed potential failure modes associated with possible adverse impacts to areas downstream of the LMDT. The team then evaluated each potential failure mode in detail, reviewing conditions and factors related to the development of each along with the possible consequences of failure. All potential failure modes were categorized, using judgment and general team consensus, based upon the weight and strength of each piece of favorable or adverse evidence, the performance record related to that failure mode, and the likely magnitude of potential adverse consequences.

During the brainstorming session, it became apparent that there were two key pieces to the likelihood of adverse consequences that could apply to several of the identified potential failure modes. These included: (1) the likelihood that a blockage upstream near the Pendery Fault could rupture, resulting in a rapid increase in the tunnel water pressure downstream of the blockage and a rise in the groundwater level above the downstream portion of the tunnel (which is currently flooded), and (2) the likelihood that the early warning system would fail to provide ample warning of a dangerous condition and a timely evacuation of The Village at East Fork should the need arise. Therefore, these "pieces" of potential failure mode development were evaluated separately. The ultimate classification of the follow-on potential failure modes was then influenced by these evaluations.

In order to show how these two key pieces fit with the other pieces of the potential failure modes, event trees were developed. An event tree shows the progression of events that would need to occur for failure to result. The event trees are contained in Appendix A, and can be used with the potential failure mode descriptions to gain a better understanding of what it would take for a failure condition to manifest.

Evaluation of Blockage Near the Pendery Fault

Description

A blockage due to tunnel collapse near the Pendery Fault fails, resulting in a rapid rise in the downstream tunnel water pressure followed by a rise in the groundwater level above the downstream portion of the tunnel. This could result from: (1) an increase in the upstream Mine Pool level above historical levels due to rapid melting and infiltration of a heavy snowpack, (2) a surge of water upstream of the blockage caused by collapse of abandoned mine workings and drainage paths, or (3) a major earthquake. Failure of the blockage results from either seepage erosion ("piping") of the blockage debris, or shear failure through the blockage debris under the increased hydrostatic or seismic loading.

Adverse Factors Making the Events "More Likely"

- The differential head drop from Stations 46+66 to 36+77 indicates there is likely a blockage in the tunnel due to roof collapse between these two locations. The team could not envision another mechanism that would lead to a 119-foot head differential.
- Movement of particles across the lens of a borehole camera, which was lowered down boreholes adjacent to the tunnel upstream and downstream of the Pendery Fault, suggested higher velocity flow downstream near Station 36+77 than upstream near Station 46+66, suggesting pooling of water in the upstream area indicative of a blockage and possible sediment deposition.
- Evidence suggests that water is flowing along (parallel to) the Pendery Fault (i.e. increased flows to California Gulch and limited communication of dye tracer tests between the Mine Pool and tunnel portal), indicating there is a possible tunnel blockage downstream of the Pendery Fault.
- Untreated timber supports and blocking were used in areas of heavy ground loads. Bureau of Mines correspondence from 1955 indicates a cave-in near Stations 40+35 to 40+40 in the Parting quartzite was caused by collapse of rotted timber supports. Only 6 sets were replaced in this

area, although 46 sets showed signs of dry rot. The timber supports become less effective with time, and may have already collapsed.

- The worst problems with mud and water inflow were encountered in the Parting quartzite. Figure 5, a construction photograph, shows "running" ground encountered in the quartzite. Over time, a tunnel collapse and blockage in this zone would not be unexpected.
- Rock on the hanging wall of a fault is generally more fractured. The dolomite on the downstream (hanging wall) of the Pendery Fault is blocky and likely unstable if the tunnel supports fail.
- Although not large, there is a change in water chemistry between Stations 46+66 and 36+77, which suggests a physical blockage in the tunnel between these locations, with more mixing downstream.
- The debris from the Parting quartzite is likely non-plastic, which would make it more susceptible to seepage erosion. Side pressure, which would increase the normal stress and shear strength of the material comprising the blockage, was not observed during tunneling.
- There is potential for further increases in the Mine Pool head, which would provide an even greater differential head across a tunnel blockage.
- There could be interconnection between the Mine Pool and the tunnel as evidenced by the water levels in the Robert Emmet Shaft closely following the tunnel monitoring wells (Figure 3).
- A major earthquake in the area could increase the hydraulic loading on a tunnel blockage, or reduce the strength of the blockage through settlement and an increase in pore pressures. If the material settled enough, water could flow over the top of the blockage and erode the material down to invert level.
- A large area of the mine workings could collapse suddenly and rapidly raise the water level in the Mine Pool. This occurred at the New Jersey Zinc Co. Sterling Hill mine in the 1980s resulting in an 80-foot increase in water level due to collapse of a stope. If this occurred at the LMDT, a larger head (perhaps with a hydrodynamic component) could be transmitted against the upstream face of the tunnel blockage.

Favorable Factors making the Events "Less Likely"

- The tunnel was reported to be "concreted" and open through the Pendery Fault in 1955; it is unlikely that a collapse has occurred in this zone.
- Based on the length of tunnel reported to contain dry rot timber supports, a considerable length of tunnel (up to about 200 feet, from Stations 38+50 to 40+75) could be collapsed. A long collapse zone would be more stable.
- When the tunnel would collapse during construction, large lengths of the tunnel (50 to 100 feet) would fill with debris and stabilize. This occurred typically in the glacial soil zones, the quartzite, and in fractured porphyry.
- If the Mine Pool water is impounded against a tunnel blockage, mixing of low-pH and pH-neutral water would precipitate clay-size particles that could "cement" the blockage debris, making it more stable.

- A collapse zone in the Parting quartzite would contain a mixture of irregularly shaped blocks, gravel, and sand-sized particles that would likely form a "filter" as the finer particles catch against the coarser particles, making such a zone less susceptible to seepage erosion. Even if the mixture was internally unstable and the fines were washed out, the remaining assemblage of coarse interlocked particles would limit flow through the blockage, and would retain high shear strength.
- Observed failures of concrete bulkheads begin with the onset of leakage along the roof/bulkhead surface. This initial leakage increases as the channel is eroded and enlarged. This typically takes weeks or even months. The same is expected for a collapse "bulkhead". A gradual increase in water level downstream of the blockage would be observed in the monitoring wells.
- The maximum head on the upstream side of a tunnel blockage is limited by the elevation of the contact between bedrock and the overlying pervious terrace gravels which would quickly drain away any excess head. The exact elevation and location of this control is unknown, as it likely occurs at a low bedrock cover area off the tunnel alignment.
- The apparent rise in the Mine Pool elevation in recent years could be the result of coming out of a drought that gripped the area up until about 2003. Water levels recorded in the Robert Emmet Shaft dating back to 1995 show that the levels were higher (about Elevation 10,140) than the subsequent five years and declining at that time. If earlier data could be found, it might show that in fact the Mine Pool has been at elevated levels in recent decades, similar to those currently observed.
- The seasonal rise in the Mine Pool water elevation is limited by the amount of snowmelt that infiltrates the rock; most of the snowmelt leaves as surface "runoff". In recent history, the water level at Station 46+66 has not risen more than about 15 feet from the previous year and this occurs over a period of several months. Thus, the differential head should not rise quickly, and there should be time to react if an unusually high infiltration or mine pool level occurs.
- The tunnel downstream of Station 36+77 is full of water. Thus, a wall of muck and water would not shoot down the tunnel if the tunnel blockage were to breach. Rather, an increase in the downstream tunnel pressure followed by a gradual rise in the downstream groundwater levels above the tunnel would be more likely. The downstream water decreases the differential head across the blockage and reduces the potential for piping and shear failure.
- Collapses in the mine workings which contain the Mine Pool were commonplace, and many were inaccessible a few years after they were mined out. The rock was not stable and was not well supported, since only temporary access was needed, and mine economics dictated the minimum needed to extract the rock and ore. This likely provides some impediment to flow through the system.

- There is no reason to believe the LMDT is completely open in other areas. Additional collapsed areas and blockages of the tunnel would limit flows to the downstream tunnel reaches from the Mine Pool even if a blockage near the Pendery Fault were to breach. For example, based on the water level data in Figure 4, there may be resistance to flow between Stations 10+25 and 6+34 (both intercept the tunnel but appear to record different elevations, although the well at 10+25 is pumped). In addition, in 1979 a well at Station 6+65 was drilled to 98 feet into the tunnel where water 6 feet deep was seen to be flowing. While waiting for well screen, a sinkhole appeared adjacent to the drill rig and the hole was lost.
- The seismic hazard in the Leadville area is not high. Estimated peak horizontal ground surface accelerations are as follows: 500-year = 0.05g, 2,500-year = 0.15g, and 10,000-year = 0.35g. The accelerations experienced underground are expected to be less than these values by at least half (based on experience at other sites, and the fact that in theory ground motions double when reflecting off a horizontal ground surface). The hydrodynamic pressures exerted by the earthquake shaking would act on both sides of the blockage, since it is submerged. Therefore, the chances of an earthquake rupturing the blockage appear to be small.

Likelihood Category

The PFMEA team classified the likelihood of this series of events as **Low to Moderate**, depending on the length of tunnel that is blocked near the Pendery Fault (a long tunnel blockage would lead to a low category, and a short tunnel blockage would lead to a moderate category). Since this is the first series of events for a number of potential failure modes, it should be noted that this controls the likelihood of those modes, and they cannot have a higher likelihood than this.

Rationale (Key Factors)

A blockage of the LMDT due to tunnel collapse downstream of the Pendery Fault is likely. There is a long stretch of poor ground downstream of the Pendery Fault where the timber supports were reported to be in poor condition in the 1950s due to dry rot. In addition, there is a drop in the tunnel water level across this zone. Although a blockage is likely, the chances of breaching the blockage followed by a large rapid increase in the downstream tunnel water pressure and a rise in the groundwater level above the downstream portion of the tunnel are considered to be low to moderate because: (1) the tunnel muck forming the blockage has a low to moderate chance of failing under increased head. It likely consists of a well-graded mixture of rock blocks, gravel, and sand sized particles which will form a "filter". Even if the fines were to wash out under increased differential head, the coarse angular interlocking rock particles that remain would limit the amount of flow through the zone and would retain high shear strength. The longer the blockage is, the higher the resistance to shearing and the lower the chances of seepage erosion or breach, and (2) there is not an unlimited supply of water in the Mine Pool directly connected to the LMDT. Much of the old mine workings are likely collapsed, and others do not have a direct hydraulic connection to the LMDT. The amount of water that can infiltrate during any given season is limited, and the level to which the Mine Pool can rise is limited by the elevation of the bedrock contact with the overlying pervious terrace gravels.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis

Because this represents the initial series of events for a number of potential failure modes, the PFMEA team came up with the following list of potential measures to mitigate or better understand the likelihood of this initial phase of failure mode development. This is not to say that they are all recommended for implementation, but rather they form a list of ideas that can be considered during any future risk mitigation.

- Drill large-diameter holes into the tunnel and examine the extent of tunnel blockage with a remote crawler camera.
- Pump the Mine Pool down to reduce the load on the tunnel blockage (currently planned as an interim risk reduction measure).
- Construct a permanent concrete bulkhead upstream of the Pendery Fault designed to take the load from a maximum level Mine Pool (currently in the planning stages).
- Raise the water pressure in the downstream portion of the tunnel to reduce the differential head across the tunnel blockage (while ensuring the water levels and gradients near the portal remain low).
- Drill holes into the tunnel near the Pendery Fault blockage zone through which gravel and grout are injected to form a tunnel plug capable of withstanding the differential head with more certainty.
- Determine limiting bedrock cover for water levels upstream of blockage.
- Restore drainage from the Canterbury Tunnel. When driven in the 1920's, the Canterbury Tunnel intercepted a water flow in the vicinity of the Pendery Fault averaging about 1300 gal/min throughout the year, and the mine operators in the district recognized a marked reduction in recharge rate.

Evaluation of Early Warning System

Description

The consequences of several potential failure modes were tied to the effectiveness of the Early Warning System (EWS). Therefore, the PFMEA team evaluated the likelihood of the EWS being unsuccessful as a separate part of the failure mode process. With recent improvements to the EWS, it consists of the following features:

- The water level in the dewatering well at Station 10+25 is remotely monitored through electronic instrumentation. If the water level in the well rises more than 70 feet above the tunnel invert, or if there is greater than a 5-foot change in the water level (upward or downward) in any 60 minute period, an alarm is triggered.

- The turbidity of the water entering the water treatment plant is monitored continuously. This water represents combined flows from the dewatering pump at Station 10+25 and from the tunnel through the timber lattice bulkhead. If the turbidity NTU exceeds 30, an alarm is triggered.
- The combined flow entering the water treatment plant from the dewatering well and tunnel bulkhead is monitored continuously. If the flow increases by more than 100 gal/min during any 60 minute period (with no change in operations), an alarm is triggered.
- If an alarm is triggered, an auto-dialer is activated to send out an alarm message to the four water treatment plant staff on call. The auto-dialer calls the first person's pager, waits 2.5 minutes for phone acknowledgement, then calls that person's cell phone and again waits 2.5 minutes for acknowledgement. If that person does not acknowledge the alarm, the auto-dialer proceeds to the next contact on the list. If the alarm has not been acknowledged, the auto-dialer repeats the process a second time. If there is still no response, the auto-dialer begins calling home phone numbers for each of the operators. There is no delay between calls to the home phone numbers. The Mount Elbert Powerplant, which is staffed 24 hours per day 7 days per week, is called if there is no acknowledgement of the alarm after each home phone is called. If it gets to this point, approximately 40 minutes has elapsed since the alarm was triggered. The whole process is repeated if the alarm is not reset at the plant within 90 minutes.
- Once a staff member receives and acknowledges an alarm, they travel to the plant from Leadville to assess the situation, if not already there. If the situation is judged to be serious, the siren is manually activated to evacuate The Village at East Fork. Currently, an Emergency Action Plan has been drafted, but it needs to be finalized to help guide the decision on when to activate the siren.
- The area and hillside near the tunnel portal is inspected daily for signs of seepage, slumping, bulging, or other indications of changing conditions.
- Once the siren is activated, people in The Village at East Fork will need to recognize the danger and evacuate in a quick and orderly fashion. The siren has been tested to ensure that it can be easily heard by residents of The Village at East Fork, and that the populace recognizes what it means.

Adverse Factors making Unsuccessful EWS Initiation "More Likely"

- The water treatment plant is only staffed four days a week, Monday through Thursday during business hours. If an alarm is triggered, most likely someone will need to respond and travel to the plant during off hours.
- The warning system depends on correct operation of a number of electronic components to inform someone that an alarm has been triggered. It is unlikely that all of these components will be 100 percent reliable.

- Once someone responds to an alarm, they must make an evaluation and judgment as to how serious the situation is, and then make a decision as to whether to activate the siren. This takes time and requires a judgment call.
- A final Emergency Action Plan providing guidance on when to activate the siren has not been completed.

Favorable Factors making Unsuccessful EWS Initiation "Less Likely"

- The autodialer system is connected to three sources of power, 1) service power to the plant, 2) direct connection to an uninterruptible power supply, and 3) battery backup with 1.5 hour full-load supply. If one supply is lost, it rotates to the next.
- The autodialer system has four internal checks, 1) auto-dialer power fault, 2) auto dialer battery fault, 3) auto-dialer phone line fault, and 4) auto-dialer card fault. In addition, plant operating personnel verify the operation and alarm status for the auto-dialer system at the end of each plant shift. They also periodically verify auto-dialer operation and status (by calling the auto-dialer) during evenings and weekends. There have been no cases of auto-dialer failure since construction of the plant.
- The monitoring and alarm system results in approximately 8 to 12 call-outs per year for plant operating personnel (related to plant operations, not tunnel stability issues). All plant personnel live within approximately 40 minutes travel time of the plant. Since implementation of the auto-dialer call out procedures identified above, all alarms have been responded to within approximately 1 hour (or less) of alarm initiation. A call-out has never reached the Mt. Elbert Powerplant.
- There are three independent parameters being monitored to detect a potentially dangerous situation, any one of which could trigger an alarm if it is out of the normal range as defined by the triggering criteria. The chance of detecting a change in conditions is good.
- Public meetings have been held to discuss the siren and what it means. People in The Village at East Fork are aware of what they need to do if the siren goes off.
- There are two evacuation routes out of The Village at East Fork to the main highways. If one gets cut off, people can still get out of the area.
- The alarm thresholds are thought to be set at conservatively low levels, and conditions are not expected to change rapidly. Thus, there should be time to evaluate the situation and make a good call on the need to evacuate.
- A Draft Emergency Action Plan (EAP) has been prepared. (However, it is currently not on site, and needs to include additional information to help guide the decision on when to activate the siren.)

Likelihood Category

The PFMEA team judged there to be a **Low** likelihood that the EWS would fail to provide warning of a dangerous situation in a timely manner. The team also considered the chances of people failing to evacuate once the siren sounded to be

Low. Since this forms the last step in many of the identified potential failure modes, and would effectively reduce the potential for loss of life to a low likelihood, the highest consequence category for those potential failure modes for which the system provides warning would be Level 2 (i.e. economic damages and impacts to water use).

Rationale (Key Factors)

There appears to be adequate redundancy in the system to trigger an alarm if something changes significantly and transmits a message to someone who can respond. The threshold limits are set low enough that there should be time to react and make a good decision on whether to activate the siren.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis

The PFMEA team discussed the EWS in detail. The weak link in the system seems to be the decision criteria to be used in deciding when to activate the siren. Although it is expected there would be plenty of time to evaluate the situation and make a decision, in the unlikely chance that things are changing rapidly, additional guidance on making this decision would be helpful to the water treatment plant staff. Review of the Draft EAP to ensure it contains the proper guidance, and timely finalization of the document would be important risk management activities.

Potential Failure Mode No. 1 – Breach in Upstream Tunnel Blockage results in "Blowout" of Downstream Bulkheads

Description

Breach of a tunnel blockage near the Pendery Fault results in an increase in head and flow in the downstream tunnel, which breaches the downstream tunnel blockages and bulkheads, and results in high flows out of the tunnel portal. Since this potential failure mode results from breach of a blockage near the Pendery Fault, and the early warning system is relied upon as mitigation, see also the previous sections that address these issues. The event tree in Appendix A also indicates how these events fit together in the failure progression.

Adverse Factors that make the Potential Failure Mode "More Likely"

- There is about 119 feet of differential head in the LMDT between Stations 36+77 and 46+66. If a tunnel blockage in this area were to breach, there would likely be increased pressure in the downstream tunnel, perhaps followed by an increase in the groundwater level above the downstream portion of the tunnel.
- According to "design code", the allowable effective head for the bottom board of the timber lattice bulkhead currently visible in the tunnel is only 19 feet above the tunnel invert (assuming no drainage at the bulkhead).

- A borehole camera inserted into the tunnel at Stations 25+15, 36+77, and 75+05 indicated the tunnel was open in these locations. Thus, there may not be additional blockages to impede the flow of water down the tunnel.
- If the tunnel were completely open, flows of over 7,500 gal/min (1,000 ft^3/s) could exit the tunnel portal (assuming over 100 feet of driving head at the Mine Pool).
- The dewatering well at Station 10+25 could be rendered inoperable from the influx of water pressure.

Favorable Factors that make the Potential Failure Mode "Less Likely"

- It is estimated that over 100 feet of the tunnel is blocked where it passes under State Highway 91 near Station 5+65. The blockage includes collapsed gravel and soil material, and sand and gravel placed in the voids. It is unlikely that this length of tunnel blockage would breach due to an increase in tunnel water pressure upstream.
- Photos indicate the first timber bulkhead near Station 4+66, which is no longer visible in the tunnel, was braced against steel sets placed downstream of the bulkhead, with gravel fill placed upstream (and subsequently also downstream) of the bulkhead. This bulkhead appears to be quite robust, as shown in Figure 6.
- The downstream tunnel below the Pendery Fault area blockage is full of water. A "bore wave" of water and muck will not travel down the tunnel. Rather, the likely impact would be an increase in the downstream tunnel water pressure and perhaps a rise in the groundwater level above the downstream portion of the tunnel.
- The new timber lattice bulkhead at Station 4+61 consists of multiple independent boards, most of which would need to break to release the upstream filter and tunnel blockage material. This is not a water tight bulkhead where hydrostatic pressure can build up behind the boards, but rather a containment system for the upstream pervious filter material, and thus the loading on the boards is not likely to be high. Although "design code" suggests a limiting height on the water pressure the boards should be designed to resist, on the average the boards will likely support about 2½ times the code value even under a water-tight case.
- There could be additional blockages between the Pendery Fault and State Highway 91, especially in the vicinity of shallow bedrock cover (Stations 10+25 to 21+00) and the Leadville Limestone (Stations 22+00 to 22+50) where problems were encountered during tunneling, that would impede any flow coming down the tunnel. The dewatering well at Station 10+25 has become inoperable on occasion, and a collapse is suspected of being the cause.
- Full flow exiting the tunnel portal would likely not be possible, as it would require transport of all caved and collapsed material downstream to and out of the portal. This material would have to pass through four curves and changes in direction at the Station 21+00 bypass area. In addition, the

blockage material in the 11-foot b 12-foot tunnel would need to pass through the 8-foot by 8-foot concrete lined section of the tunnel.

- If a rise in the downstream tunnel water pressure was detected, an attempt at pumping from the dewatering well at Station 10+25 would likely be performed in an effort to lower the water level.
- There are three wells near station 10+25 that would serve as "surge shafts" to relieve transient pressures that might be transmitted to the tunnel blockages and bulkheads. In addition, it is estimated it the ground water would go artesian before enough head could build up to move the blockages.
- Flows through the timber lattice bulkhead have been clear, indicating the filter material is effective in preventing movement of fines through the blockage.

Consequences

Flows out of the tunnel would graze and possibly damage the left side of the water treatment plant (looking downstream), then spread out through the area between the detention pond and the East Fork of the Arkansas River. There are about four dwellings in the direct path between the tunnel portal and the river (see Figure 7). It is anticipated the early warning system would be effective in detecting a change in conditions that could lead to this potential failure mode, and that people in these dwellings would be evacuated well in advance of significant flows impacting this area. However, the dwellings in line between the tunnel portal and the river could suffer significant damage.

Risk Categories

The team considered the likelihood of this potential failure mode developing to be **Low**. If in fact this potential failure mode were to develop, the resulting consequences are judged to be **Level 2**.

Rationale (Key Factors)

The Low likelihood category is based on the fact that over 100 feet of the downstream tunnel is blocked, including two bulkheads installed to retain this material, and the fact that the downstream tunnel is filled with water, preventing a "bore wave" from traveling down the tunnel and colliding with the downstream blockage and bulkhead zone. Although it is expected that the early warning system (EWS) would provide timely evacuation of people from the affected area (see previous evaluation), there would likely be significant economic damage to a few buildings and dwellings, resulting in Level 2 consequences.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis

While the PFMEA team was assembled and the potential failure mode was fresh in their minds, the following potential actions were identified. Again, it should be noted that these are not all recommended for implementation, but rather provide a list of possible actions to be considered during future risk mitigation activities. In addition to the actions identified previously for the Evaluation of Blockage Near the Pendery Fault, the following were identified:

- Move dwellings currently in direct line with the tunnel portal.
- Move water treatment plant.
- Build a training dike or wall to direct flows around the potentially affected buildings.
- Obtain more information on downstream material and blockages to confirm the strength of this material.
- Add a vertical beam down the center of the timber lattice bulkhead (anchored above and below) to improve its moment capacity.

Potential Failure Mode No. 2 – Breach in Upstream Tunnel Blockage results in Rapid Erosion Breach of Downstream Slope Materials

Description

This potential failure mode begins in a similar manner to Potential Failure Mode No. 1, except that as the increased water pressures reach the downstream blockages and bulkheads, they hold. The groundwater levels and flow rates could then rise along the outside of the tunnel. If erosion of the material at the downstream slope face begins, progressive erosion and slumping of material or "piping" could progress upstream until a connection was made to the tunnel upstream of State Highway 91, resulting in a rapid release of water. A potential additional complication could involve collapse of the concrete tunnel lining downstream of the bulkheads (from the portal, Station 0+54, to Station 4+61), resulting in sinkholes that shorten the seepage path to the tunnel upstream of the highway. Since this potential failure mode involves the breach of an upstream tunnel blockage and operation of the early warning system, see previous evaluations of these issues. See also the event tree in Appendix A.

Adverse Factors that make the Potential Failure Mode "More Likely"

- When the sinkholes were repaired near the highway in the 1960s, several areas above the tunnel were grouted to prevent further settlement of the material. These grouted zones could form a "roof" for piping development above the tunnel crown.
- The steel sets placed along with the first timber bulkhead in 1978 and additional sets placed in 1990 are spaced at about four feet maximum. At this spacing, shear failure of the concrete tunnel lining is possible at the intersection between the floor and wall with a rise in groundwater less than that required to saturate the slope.
- If the flows and gradients adjacent to the tunnel are sufficiently large, the soil materials could be erodible.

Favorable Factors that make the Potential Failure Mode "Less Likely"

- The permeability of the terrace gravels surrounding the tunnel is high and the underlying bedrock surface slopes down away from the tunnel portal area toward the river. This would tend to carry any additional buildup of groundwater down below the tunnel toward the river.
- On occasions when the dewatering well at Station 10+25 has been shut down, the water level has risen as high as 80 feet above the tunnel invert at that location with no change in the water level at the downstream lattice bulkhead (about 2½ feet above tunnel invert), and no observable seepage on the downstream slopes adjacent to the tunnel portal.
- The piping resistance and stability of the terrace gravel and glacial moraine near the tunnel portal are likely quite high. These materials are likely quite broadly graded, such that natural filters would tend to form. If the fines were to erode out, the remaining material would be coarse with high shear strength.
- Movement of materials near the tunnel portal due to seepage has not been observed at this site. The only time material adjacent to the tunnel has been observed to move has been as a result of tunnel collapse.

Consequences

If indeed this potential failure mode were to develop, a large quantity of water would likely flow through the tunnel portal area. It would likely be more spread out than for Potential Failure Mode No. 1. Thus, there would likely be less damage to each individual building, but more dwellings would be affected. Since the early warning system (EWS) is expected to be effective in evacuating people before life-threatening flows materialized, no loss of life is expected.

Risk Categories

The team considered the likelihood of this potential failure mode developing to be **Low**. If it were to develop, the consequences were judged to be **Level 2**.

Rationale (Key Factors)

The Low likelihood of failure is based primarily on the high permeability of the terrace gravel near the portal and the underlying sloping bedrock surface that would tend to drain the excess water below the tunnel. This is evidenced by the water level at the lattice bulkhead (Station 4+61) which doesn't change significantly even with a large increase in the head at Station 10+25. Although there would be economic damage to dwellings in The Village at East Fork should this potential failure mode manifest, the early warning system would most likely result in timely evacuations.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis

Though not necessarily recommended for implementation, the following list provides possible actions to be considered during any risk mitigation programs.

- Obtain more information on downstream slope material and blockages to confirm the strength and piping resistance of this material.

Potential Failure Mode No. 3 – Breach in Upstream Tunnel Blockage results in High Downstream Groundwater Levels and Slope Instability

Description

Breach of an upstream tunnel blockage near the Pendery Fault could result in increased water pressure in the downstream portion of the tunnel and a rise in the adjacent groundwater level. Given that the downstream tunnel blockage under State Highway 91 and the bulkheads hold, the groundwater level outside of the tunnel could then rise to unprecedented levels. The increase in pore pressures within the gravel soils near the portal could result in slope instability, and movement of earth materials and water into and adjacent to the tunnel portal area. See also previous evaluations of breach of an upstream tunnel blockage, the early warning system, and the event tree in Appendix A.

Adverse Factors that make the Potential Failure Mode "More Likely"

- It is uncertain if the dewatering well at Station 10+25 could keep up with the increase in water from the upstream portion of the tunnel, and there is a chance that the well would be disrupted and rendered inoperable by the sudden influx of water pressure.
- The bedrock surface directly under the highway does not appear to slope as steeply as it does closer to the portal; there may be a tendency for higher water levels in this location.
- Shear strength values used in slope stability analyses are assumed values, not based on testing.

Favorable Factors that make the Potential Failure Mode "Less Likely"

- A pump test performed at Station 6+35 indicated a high permeability in the gravels at about 50 feet/day. With this high permeability and the underlying bedrock surface which slopes away from the portal, it is unlikely that a significant head of water could build up in the portal area.
- Reasonably conservative shear strengths were selected for slope stability analysis based on Reclamation's experience with gravelly soils. Average friction angles for gravels from Reclamation laboratory testing range from about 34 degrees with more than 12 percent non plastic fines (passing the No. 200 sieve) to 41 degrees for gravels without significant fines[1].
- Excavation for a pipeline in the spring of 2008 resulted in nearly vertical unsupported slopes up to about 25 feet high in the glacial moraine material, indicating high strength with a component of cohesion, as shown

[1] *Design of Small Dams*, Third Edition, U.S. Department of the Interior, Bureau of Reclamation, Government Printing Office, Denver, Colorado, 1987.

in Figure 8. It would be very difficult to collect and test samples of this material, but this excavation reveals a lot about its strength.

- Two-dimensional slope stability analyses for slip surfaces extending through the highway area, and with the groundwater a few feet below the ground surface (i.e. nearly saturated ground conditions) produced the following favorable factors of safety (with no cohesion):

Low friction angle estimate 32 degrees for glacial moraine 35 degrees for terrace gravel	Best estimate friction angle 40 degrees for glacial moraine 38 degrees for terrace gravel
1.5	2.0

- It is unlikely the groundwater conditions could ever be as severe as assumed for the slope stability analyses due to the high permeability of the terrace gravel and the tendency for the water to drain away at the portal.
- Using available ground contours, a cross section was sketched from the tunnel downstream of Station 10+25 to the northwest toward dwellings associated with the Village at East Fork. Comparing this section to a section along the tunnel alignment indicated very similar geometry. Thus, the slope stability analyses are applicable to potential slope instability that could impact these dwellings.

Consequences

Several dwellings in The Village at East Fork are “tucked in” near the base of the slope to the left (west) of the tunnel portal. The contours of the slope in this area are such that any large scale slope failures would move directly toward and impact these dwellings. In addition, State Highway 91 would likely be affected.

Risk Categories

The likelihood of failure mode development was judged to be **Low**. The consequences from major slope failure were judged to be **Level 2**.

Rationale (Key Factors)

The primary rationale for the Low likelihood assignment was the slope stability analyses, and the favorable factors of safety that were calculated. Even with reasonably conservative shear strengths and conservative groundwater levels, the analyses indicate the slopes should be stable with a reasonable margin of safety. Although damage to dwellings in The Village at East Fork could occur, chances are good that a rise in groundwater level near the LMDT portal would be detected and the dwellings evacuated before a major slide occurs.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis

The following list represents possible actions identified by the PFMEA team for consideration during future risk mitigation actions.

- Install horizontal drains in the slopes to the left of the tunnel portal to help ensure their stability under increased groundwater levels.
- Install a monitoring well downslope of the tunnel to the left of the tunnel portal (looking downstream) to measure groundwater levels in the slope above the most vulnerable dwellings. Alternatively, monitor the water level in the supply well for The Village at East Fork, about 700 feet WSW of the portal.
- Install and maintain additional numerous weep holes in the downstream concrete tunnel lining so that the first 450 feet of tunnel will act as a drain to keep water pressures from building up and destabilizing the slope.
- Move the dwellings closest to the toe of the slope away from this area.

Potential Failure Mode No. 4 – Breach in Upstream Tunnel Blockage results in Leakage of Contaminated Water into Downstream Areas

Description

Breach of a tunnel blockage near the Pendery Fault results in higher water pressures in the downstream tunnel and higher groundwater levels above the downstream portion of the tunnel. The blockage under State Highway 91 and bulkheads hold, but water contaminated with heavy metal concentrations seeps through the pervious gravels into low lying areas, possibly exiting at Evans Gulch, Little Evans Gulch, or more likely the tunnel portal. It is likely that water will also flow up and out of the monitoring wells at Station 10+25 and downstream and across the highway. Water could also flow toward California Gulch if the groundwater levels over the downstream portion of the tunnel rose to high enough levels.

Adverse Factors that make the Potential Failure Mode "More Likely"

- Monitoring flumes are upslope of the tunnel location in Evans Gulch and Little Evans Gulch. Seepage outbreaks in these areas would not be detected by the flumes.
- The permeable nature of the glacial and terrace gravels would convey water readily.
- The collars of the monitoring wells at Station 10+25 and downstream are lower than the water levels upstream of the Pendery Fault based on recent measurements.

Favorable Factors that make the Potential Failure Mode "Less Likely"

- Breakout of flows into Little Evans Creek or Evans Creek is unlikely. Little Evans Gulch is about 2,000 feet upstream of State Highway 91, and there is about 200 feet of coarse alluvium over the tunnel at this point. Evans Gulch is downstream of Highway 91, but has historically been a "losing" stream.

- The monitoring well at Station 10+25 would indicate a rise in the groundwater level. This level is monitored 24/7, and changes out of the ordinary will trigger an alarm and investigation.
- The combined flows from the tunnel bulkhead and dewatering well at Station 10+25 are measured as they go into the water treatment plant. An increase in flow due to higher tunnel pressures or groundwater levels would likely show up and trigger an alarm.
- Seepage that surfaces at the toe of the slope near the portal and detention pond would likely be noticed by plant personnel or residents.
- The Water Treatment Plant could likely handle some limited increase in flow, especially near the tunnel portal.

Consequences
There would be no economic damage to dwellings in The Village at East Fork if this potential failure mode were to develop. However, water quality and use could be impacted locally, depending on the amount of water that was leaking into the water courses and the time it took to recognize the issue and handle the surface leakage.

Risk Categories
The likelihood of failure mode development was judged to be Moderate to High, given that a blockage upstream near the Pendery Fault is breached. However, recall that the chances of a blockage at the Pendery Fault breaching were considered to be Low to Moderate. Thus, the overall likelihood for this potential failure mode can be no higher than **Moderate**. The consequences are considered to be **Level 1**.

Rationale (Key Factors)
The primary rationale for the likelihood category is that the downstream tunnel blockage (under State Highway 91) and bulkheads are likely to hold if the tunnel pressure rises, and the groundwater will likely seek other exit points if the downstream groundwater level rises. The most likely exit points would be through the more pervious gravels to low lying areas near the portal.

Opportunities for Risk Reduction, Monitoring Enhancement, Data Collection, and/or Analysis
The PFMEA team identified the following possible actions that could be considered during risk mitigation actions:

- Install flow measuring flumes in Evans Gulch and Little Evans Gulch downslope from the tunnel.
- Install a redundant monitoring well near Station 4+66 (currently planned).
- Ensure material is available locally to allow construction of “sand bag” containment systems with the possibility to pipe contaminated material to areas where it can be handled and treated.

Potential Failure Mode No. 5 – Earthquake Triggers Slope Instability near Tunnel Portal

Description

A major earthquake causes instability of a large portion of the slope adjacent to the downstream tunnel portal resulting in impacts to this area. Based on analysis results, it is extremely unlikely that this could be triggered under normal groundwater conditions. The only conceivable failure scenario the team could imagine involved elevated groundwater conditions near the portal due to breach of a blockage upstream near the Pendery Fault from seismic loading, followed by a major aftershock which could trigger slope instability.

Adverse Factors that make the Potential Failure Mode "More Likely"

- Using a pseudo-static seismic coefficient of 0.35g (equal to the peak horizontal ground acceleration for a 10,000-year recurrence interval), a high groundwater level near the ground surface, and the lower shear strength estimates (which included 2 lb/in^2 cohesion), the calculated factor of safety for major slip surfaces near the portal that would extend up to the highway is less than 1.0 (about 0.89). A factor of safety less than 1.0 indicates a limited amount of slippage is possible (for the given extreme set of assumptions).

Favorable Factors that make the Potential Failure Mode "Less Likely"

- Several unlikely events need to occur concurrently for this potential failure mode to have a reasonable chance of developing (high downstream groundwater levels, a major remote earthquake and aftershock, weak soil conditions, and sufficient displacement to fail the slope).
- Even in the unlikely event that the ground water levels were high, the soil strengths were at the low end of the estimated values, and a 10,000-year earthquake hit the area, the results would not be catastrophic. Given a yield acceleration for the soil mass of about 0.2g (using lower shear strength and high ground water estimates), empirical relationships[2] indicate maximum displacements would be on the order of 0.7 inches. It is generally accepted that it takes predicted displacements at least on the order of 6 to 12 inches before stability is considered to be threatened.
- The duration of a major earthquake is likely too short to breach a blockage upstream near the Pendery Fault, cause a rise in the downstream groundwater and produce enough displacement to fail the slope. Therefore, an aftershock would be needed to trigger slope instability. Aftershocks are expected to be of smaller magnitude than the main shock in this area of the country.
- With best estimate soil shear strengths, even the peak horizontal ground acceleration for a 10,000-year earthquake produces a pseudo-static factor

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[2] Jibson, R.W., "Regression Models for Estimating Coseismic Landslide Displacement," *Engineering Geology* Vol 91, pp. 209-218, 2007.

of safety greater than 1.0. Earthquakes at a 2,500-year recurrence interval and less produce factors of safety greater than 1.0 even with all other assumptions conservative. Slippage is unlikely with a factor of safety greater than 1.0.
- A high groundwater level near the portal is unlikely under any scenario, due the pervious nature of the gravels in this area and the sloping bedrock surface that carries water down under the portal area. Thus, the factors of safety are likely considerably higher than those calculated (which all included a high groundwater level).

Risk Category and Rationale

This potential failure mode was **Ruled Out**. It was not considered plausible since the only way the team could envision it might occur is if a whole series of unlikely events occurred simultaneously: (1) a major remote earthquake occurred with a high level of ground shaking and a strong aftershock, (2) the groundwater in the portal area was high at the time of the earthquake, (3) the strengths in the soil materials in the portal area are lower than presently thought to be the case, and (4) displacements were larger than predicted by current methods.

Potential Failure Mode No. 6 – Seepage Erosion into Tunnel Causes Sinkholes and Loss of the Highway

Description

Under this scenario, high groundwater outside the tunnel would result in a gradient that could carry soil material into the tunnel and through the lattice timber bulkhead. The loss of material between the tunnel and the highway would then result in voids that could stope to the surface, creating sinkholes that would affect State Highway 91. For this to occur, the water pressure outside the tunnel would need to be higher than inside.

Risk Category and Rationale

This potential failure mode was **Ruled Out** without developing lists of Adverse and Favorable Factors. It is considered to be extremely unlikely for the following reasons:

- Filter material was placed behind the timber lattice bulkhead, and seepage exiting at the bulkhead has been clear since its installation in 1992.
- The tunnel under the highway is filled with collapsed gravel material and injected fill. It is unlikely material could move into or through this zone.
- The bulkhead area is monitored; if material were moving through the bulkhead, it would likely be noticed, an evaluation made, and remedial measures taken if appropriate.
- The area between the tunnel and highway has been treated, including injection of cement grout. This treatment is likely to prevent sinkholes from progressing up to the roadway.

- It is not clear how a condition could develop with higher pressures outside the tunnel than inside.

Potential Failure Mode No. 7 – Flow at Tunnel Portal Plugs Off, Raising Groundwater and Causing Slope Instability

Description

For this potential failure mode to initiate, impervious fines would need to be carried into the tunnel, filling the voids in the downstream tunnel blockage and porous bulkhead, and plugging weep holes in the concrete lining to the point where drainage through the tunnel is further impeded, raising the groundwater level outside the tunnel to new highs and leading to slope instability. The initial water level outside the tunnel would need to be higher than inside the tunnel, and the tunnel would need to be acting as a drain for the slopes near the portal.

Risk Category and Rationale

This potential failure mode was **Ruled Out** without developing lists of Adverse and Favorable Factors. It is considered to be extremely unlikely for the following reason:

- There is not a significant tendency for flow to "drain" into the downstream portion of the tunnel; it is likely draining off through the gravel material. Additional plugging of the material in the tunnel would likely have minimal effect on the groundwater level.

Summary

The team assembled to perform the Potential Failure Modes and Effects Analysis (PFMEA) for the Leadville Mine Drainage Tunnel (LMDT) identified seven potential failure modes that could affect the population near the tunnel portal (and possibly downstream). Each potential failure mode was classified according to the likelihood of its development, and the consequences of failure (the two components of "risk"), based on categories developed for this study. Four of the identified failure modes would be initiated by breach of a blockage in the tunnel that likely exists just downstream of the Pendery Fault. The likelihood of a blockage existing and breaching in this area was evaluated separately, and forms a part of the evaluation for these four potential failure modes. The consequences for several of the identified potential failure modes depend on how effective the Early Warning System (EWS) is in (1) detecting impending failure and (2) resulting in evacuation of the potentially affected population. Therefore, the EWS was also evaluated separately, and this evaluation affected the consequence categorization. The event trees contained in Appendix A indicate how these two pieces fit with the other events needed for failure mode development.

The team used its best judgment based on the available information to categorize the potential failure modes. The results of the evaluations are summarized in Table 2. The most uncertainty is associated with the evaluation of a blockage near the Pendery Fault, where it was necessary to infer the likely conditions from other data. It should be noted that three potential failure modes were Ruled Out as being so unlikely as to not be plausible. No potential failure modes with High Likelihood were identified. In general, the risks associated with the project appear to be on the low side (but not negligible). Thus, monitoring appears to be an appropriate risk management strategy. Key conclusions are summarized in the Section of this report titled, "Major Findings and Understandings". For each potential failure mode, possible risk reduction actions, monitoring enhancements, data collection, and/or analyses were identified that could be used to reduce the risk, confirm the evaluations made by the team, or better understand the risk (see listing associated with each potential failure mode). None of these were considered to be critical to the safe operation of the LMDT facility at this time, but could be considered during risk mitigation studies. The exception is related to the Emergency Action Plan (EAP), which is currently in draft form. Although the EWS will likely trigger an alarm indicating something has changed significantly, it is not clear that water treatment plant operating personnel will have enough guidance as to how serious the situation might be, and when it is appropriate to activate the siren to evacuate The Village at East Fork. Thus, **it is recommended that the EAP be reviewed by the technical project staff to ensure sufficient guidance is covered, and the EAP be finalized as soon as possible.** Since monitoring is an important risk management activity, **it is recommended that the ground water wells at Stations 3+00, 4+70, and 6+35 be evaluated to determine if reliable information is being collected, and if so instrumented with pressure transducers and the data be tied into the existing Early Warning System (EWS) as soon as possible**.

Table 2. Risk Categorization Summary by Potential Failure Mode (PFM)

CONSEQUENCES OF FAILURE	FAILURE MODE LIKELIHOOD			
	RULED OUT	LOW	MODERATE	HIGH
LEVEL 3 Consequence Category	PFM #5 – Earthquake triggers slope instability			
LEVEL 2 Consequence Category	PFM #6 – Seepage erosion leads to loss of highway PFM #7 – Tunnel drainage plugs leading to slope instability	PFM #1 – Rupture of D/S blockage and bulkheads PFM #2 – Rapid seepage erosion of materials adjacent to portal PFM #3 – Rise in groundwater triggers slope instability		
LEVEL 1 Consequence Category			PFM #4 – Rise in groundwater results in contaminated leakage from ground surface	
No Significant Consequences				

Note: If the Early Warning System is unsuccessful, the consequences for PFM #1, #2, #3, and #7 would elevate to Level 3.

References

A large number of references were reviewed by team members prior to the PFMEA session. A good summary and listing of these references is contained in a separate report prepared for this study[3]. In addition, all analyses performed prior and subsequent to the team session[4] were reviewed to ensure risk estimates were consistent with the results.

[3] "Existing Condition of the Leadville Mine Drainage Tunnel," prepared by Michael Gobla and Mark Vandeberg," Bureau of Reclamation, Technical Service Center, Denver, Colorado, DRAFT May 2008.

[4] "Results of Geotechnical and Structural Analysis, Leadville Mine Drainage Tunnel," prepared by M.J. Romansky, Roger Torres, Jack Touseull, and Kevin Atwater, Bureau of Reclamation, Technical Service Center, DRAFT June 2008.

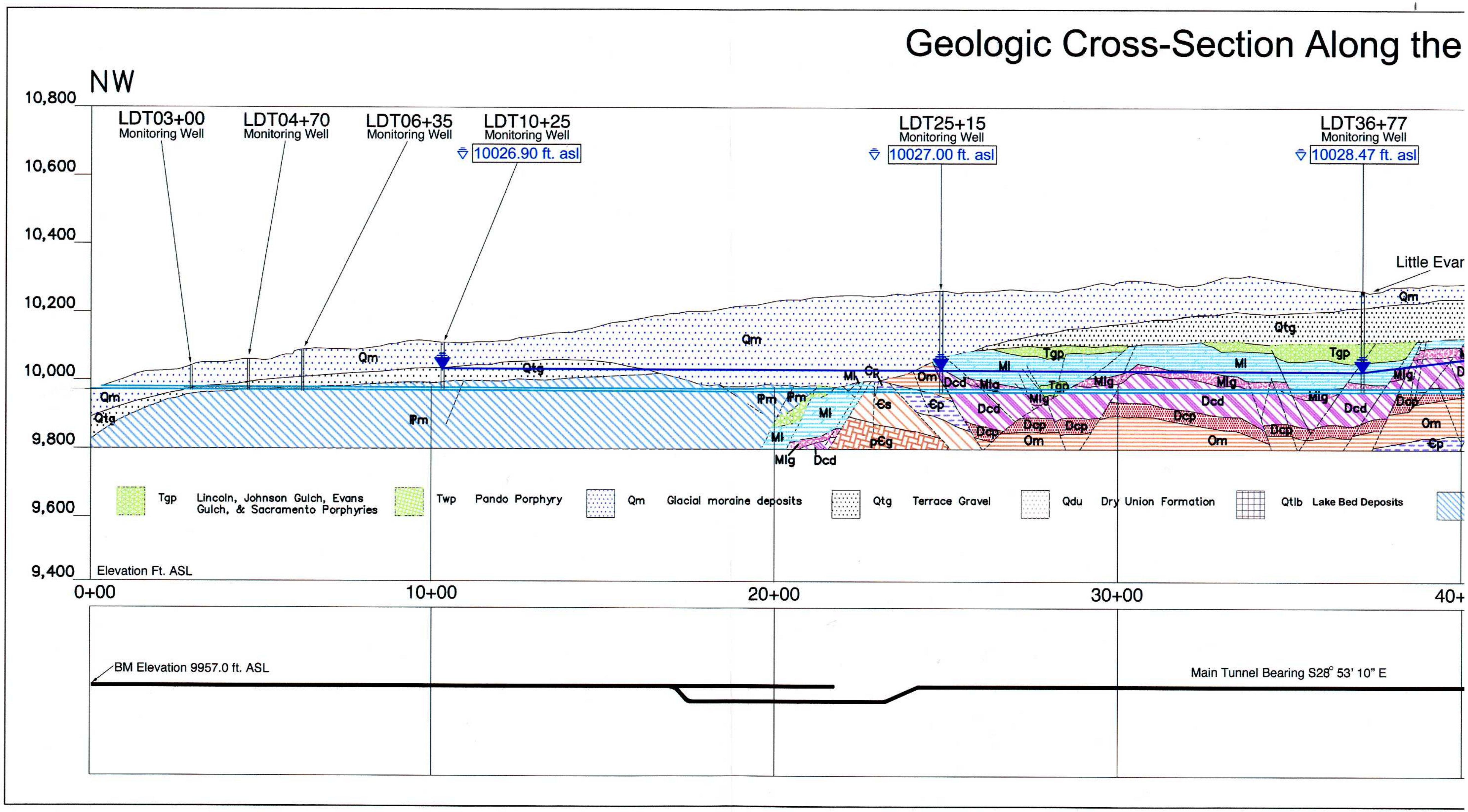


Figure 1a. Geologic Cross Section along Leadville Mine Drainage Tunnel Alignment

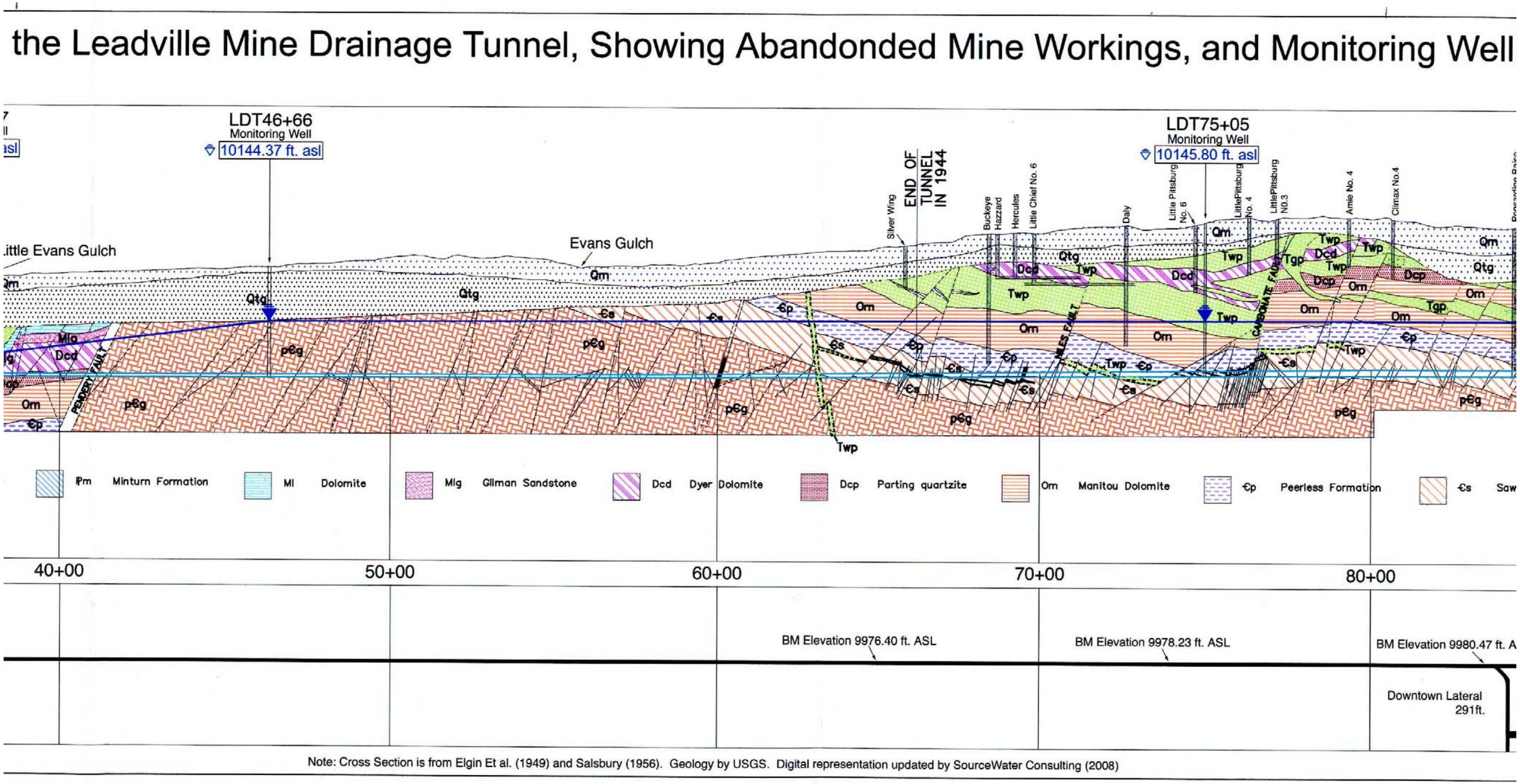


Figure 1b. Geologic Cross Section along Leadville Mine Drainage Tunnel Alignment (cont.)

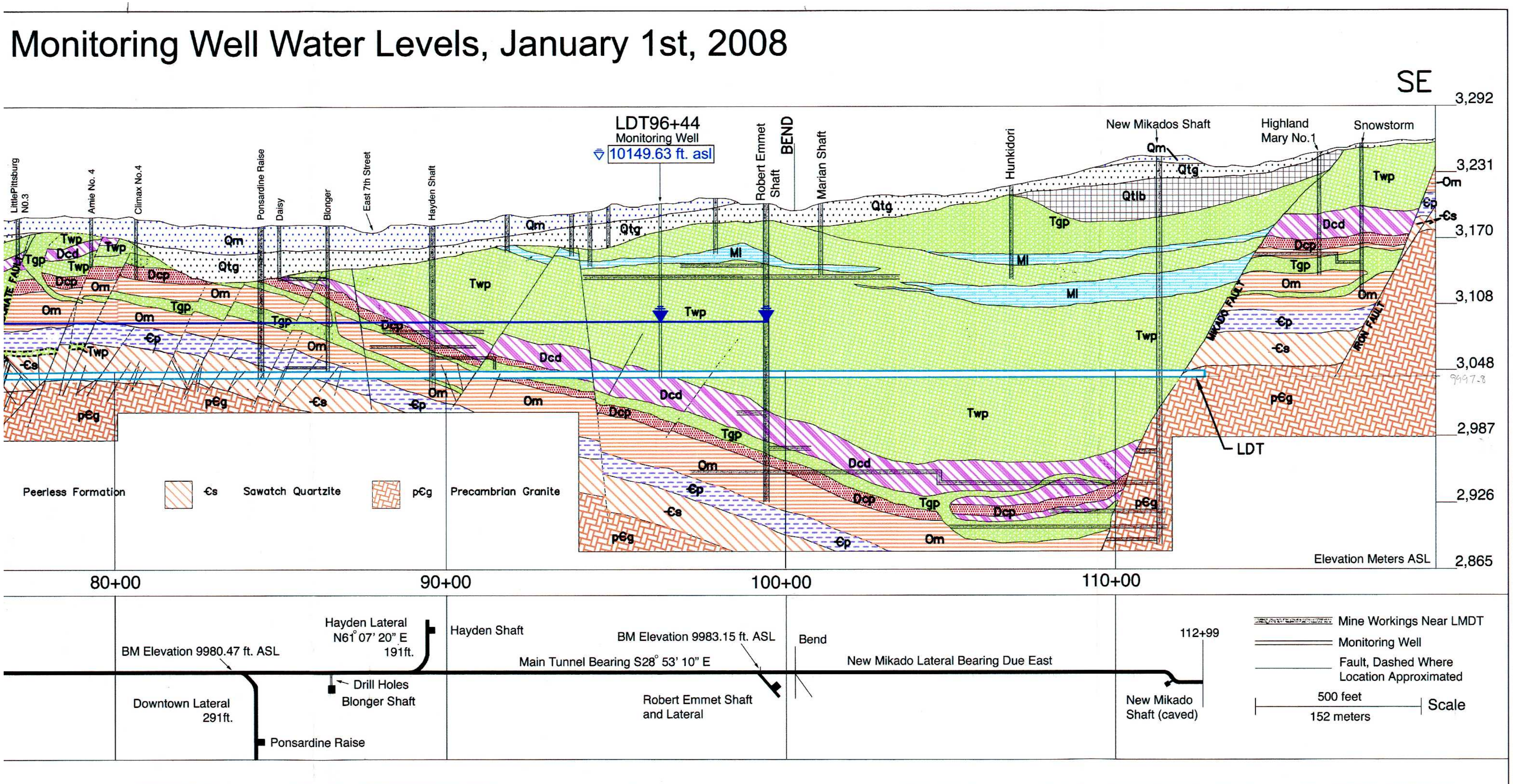


Figure 1c. Geologic Cross Section along Leadville Mine Drainage Tunnel Alignment (cont.)

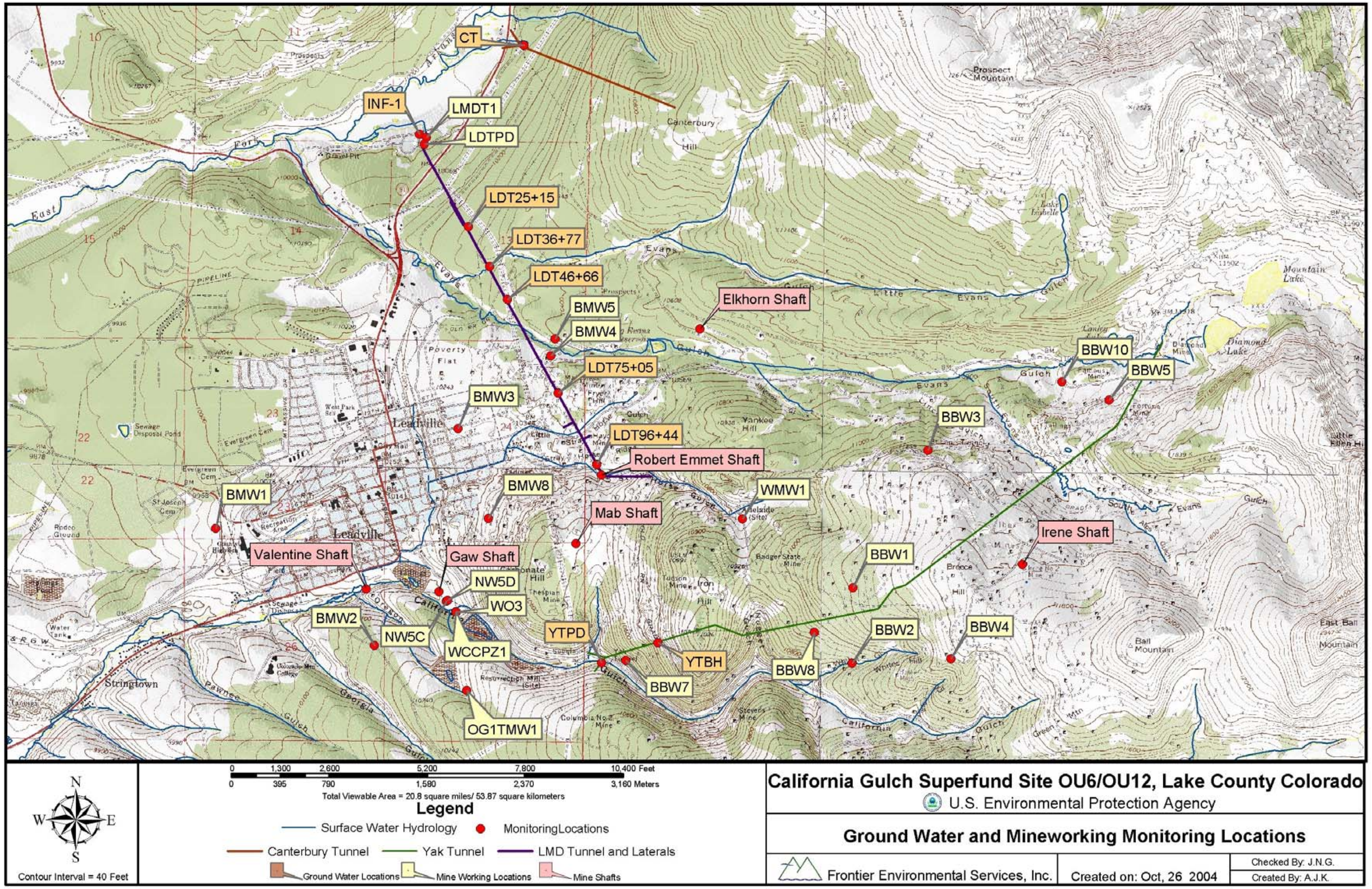


Figure 2. Plan Map of Tunnel and Leadville Area

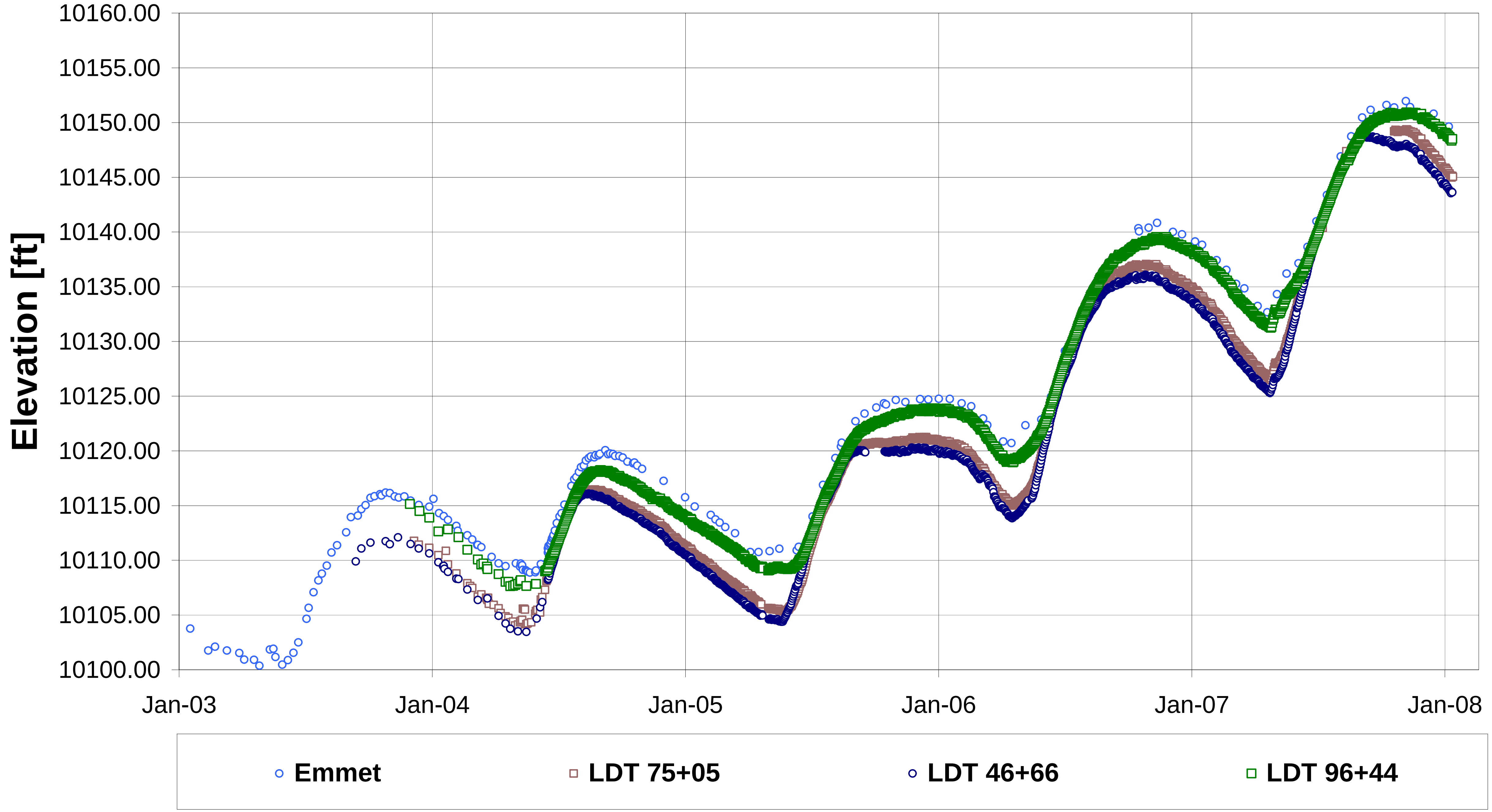


Figure 3. Water Levels in the Upstream Tunnel

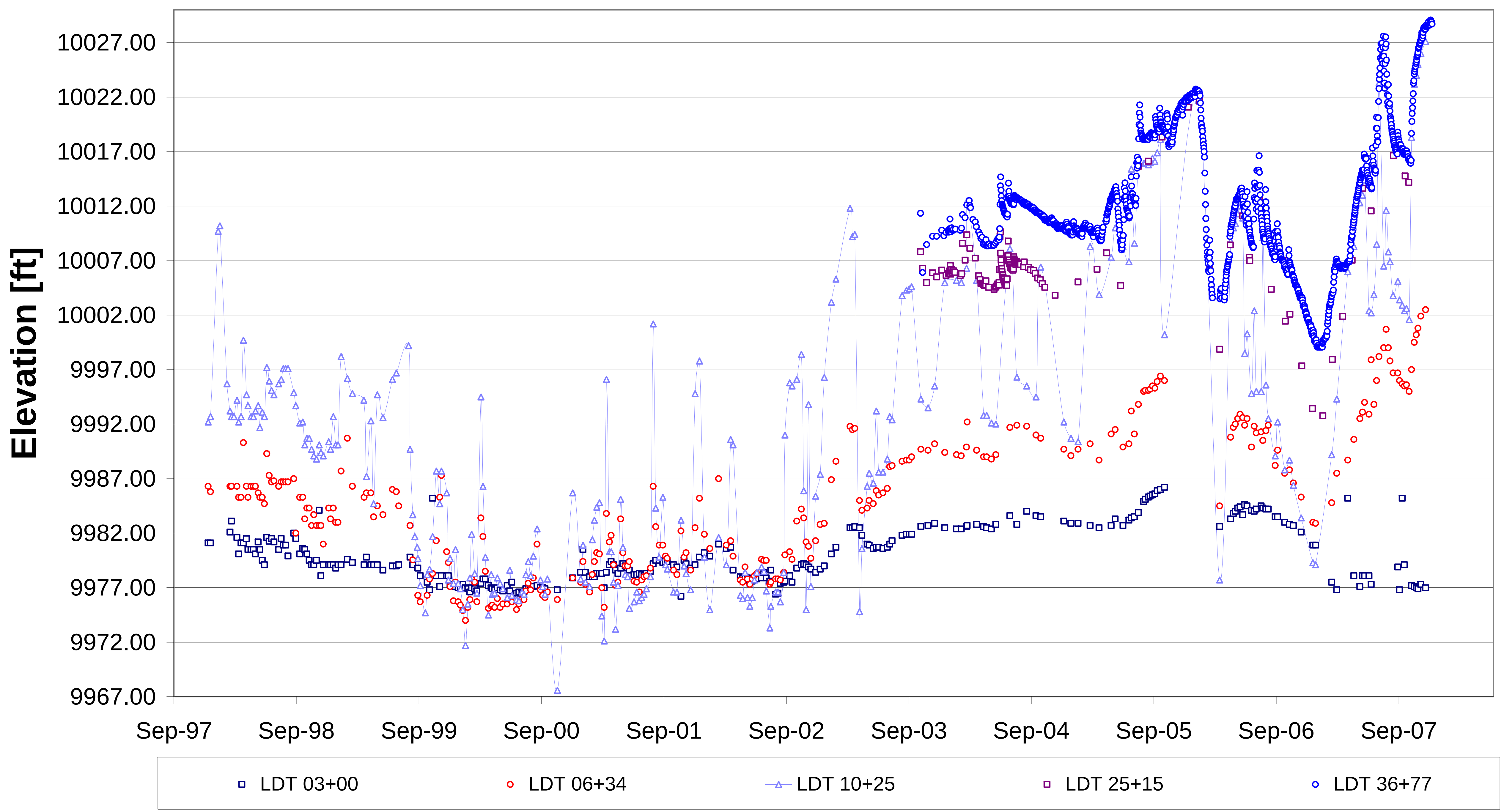


Figure 4. Water Levels in the Downstream Tunnel

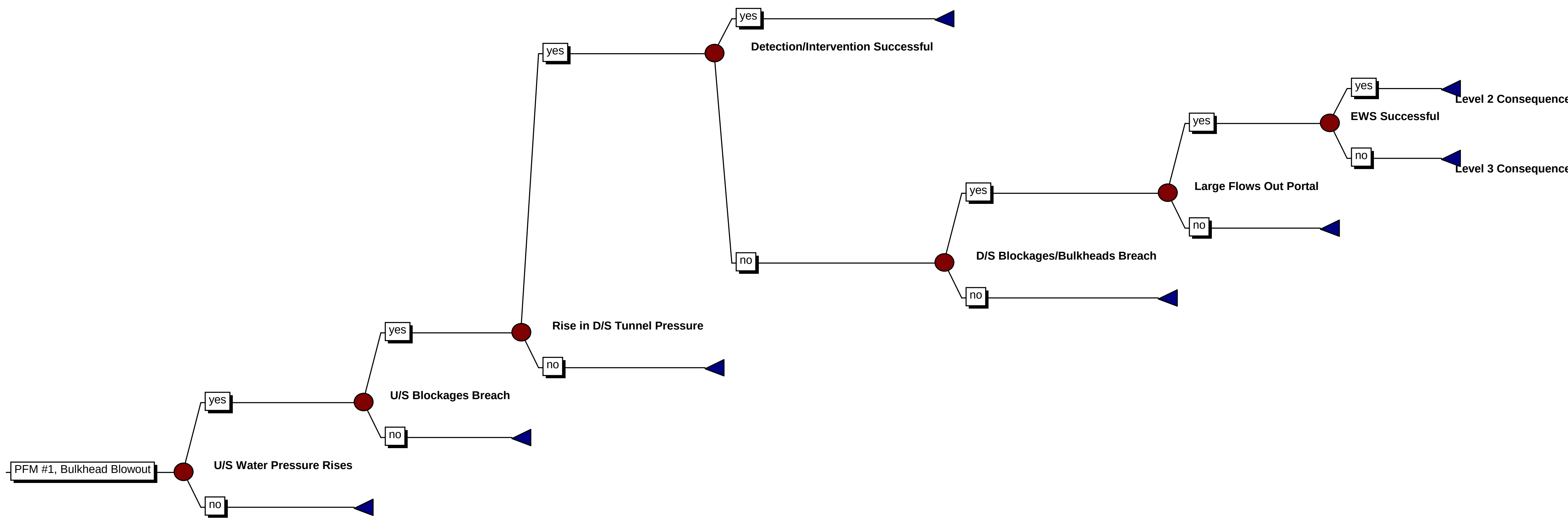
Figure 5. Running Ground in the Parting quartzite (approximate date August/September 1951)

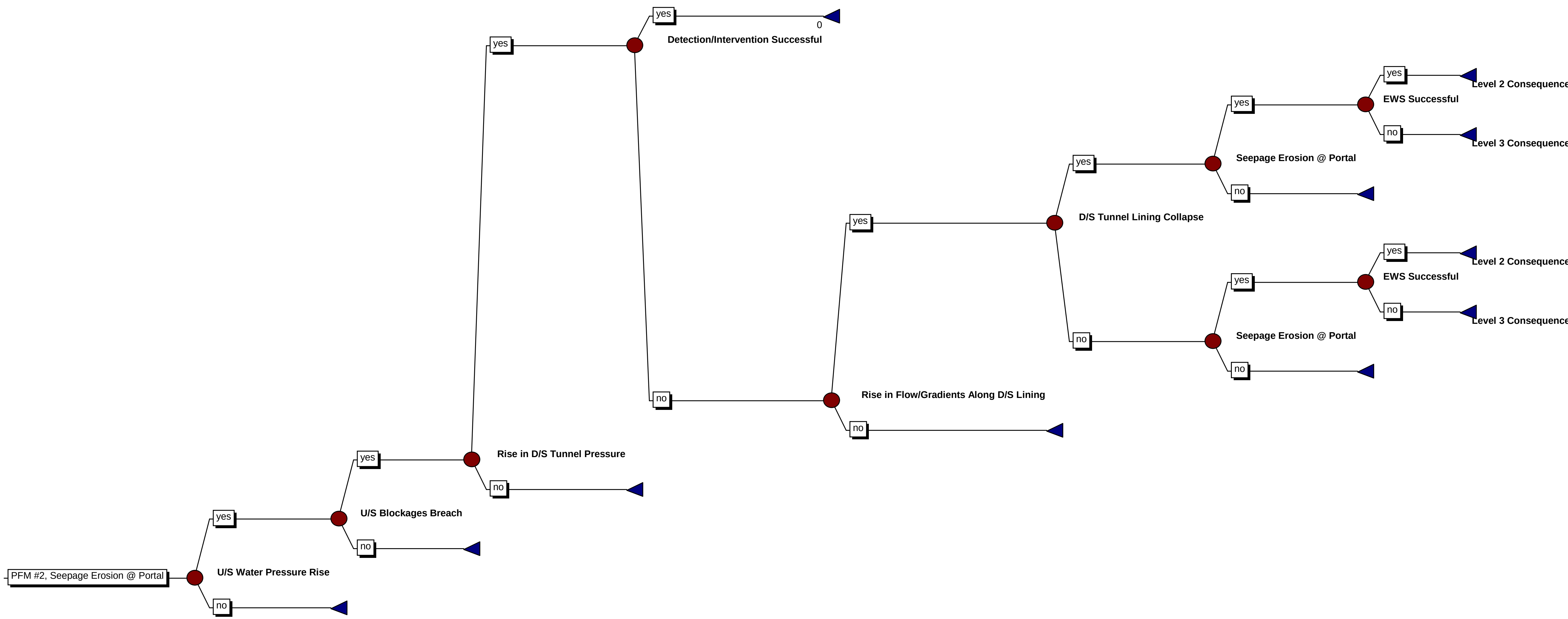
Figure 6. Bulkhead at Station 4+66 (date noted on photo)

Figure 7. Recent Aerial View of Tunnel Portal Area

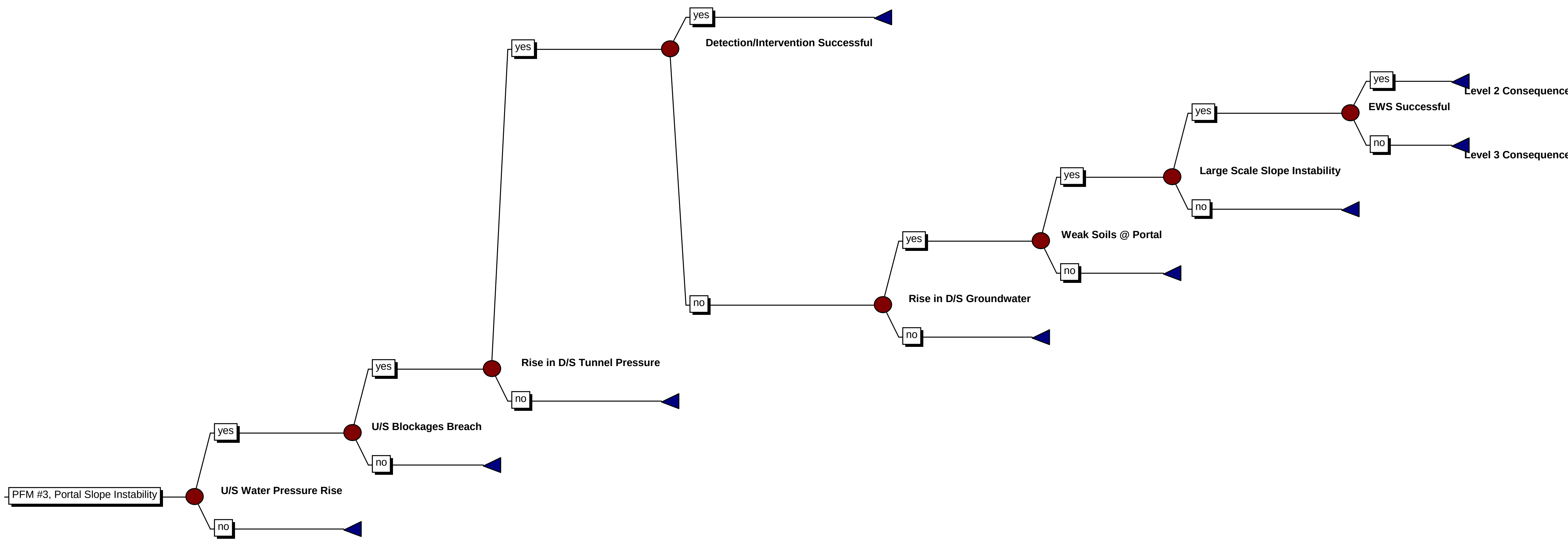
Figure 8. Excavation into the Glacial Moraine at Leadville for installation of a pipeline under Highway 91 along the alignment of the LMDT (late spring 2008)

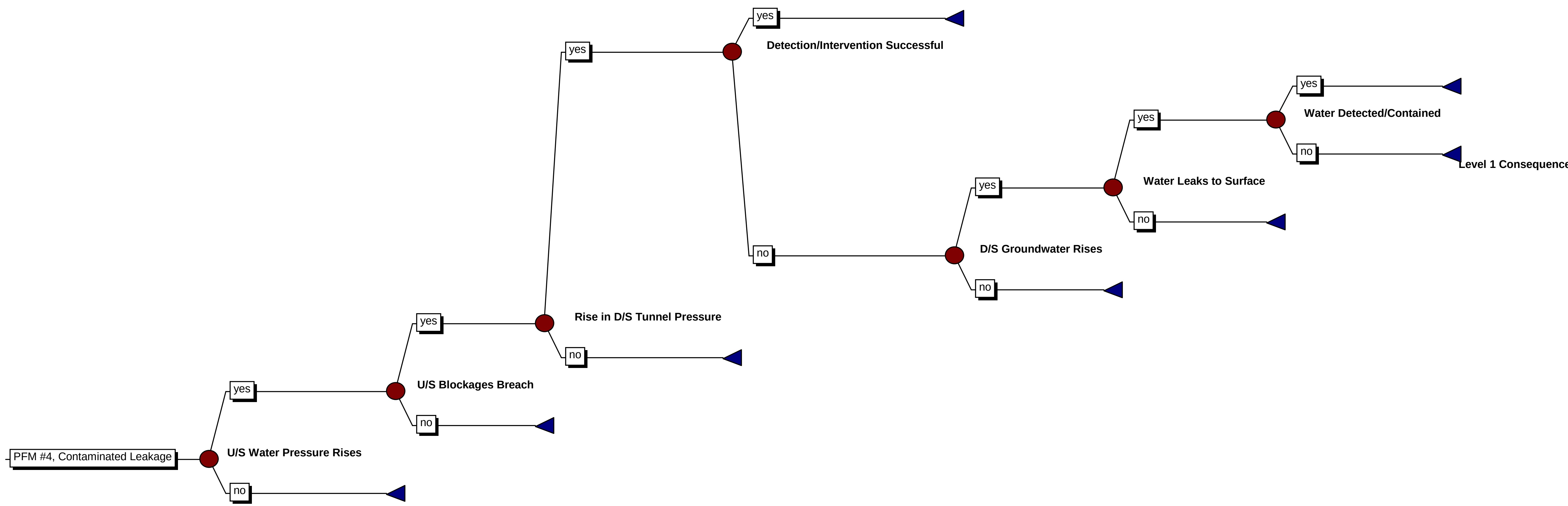
Appendix A
Event Trees

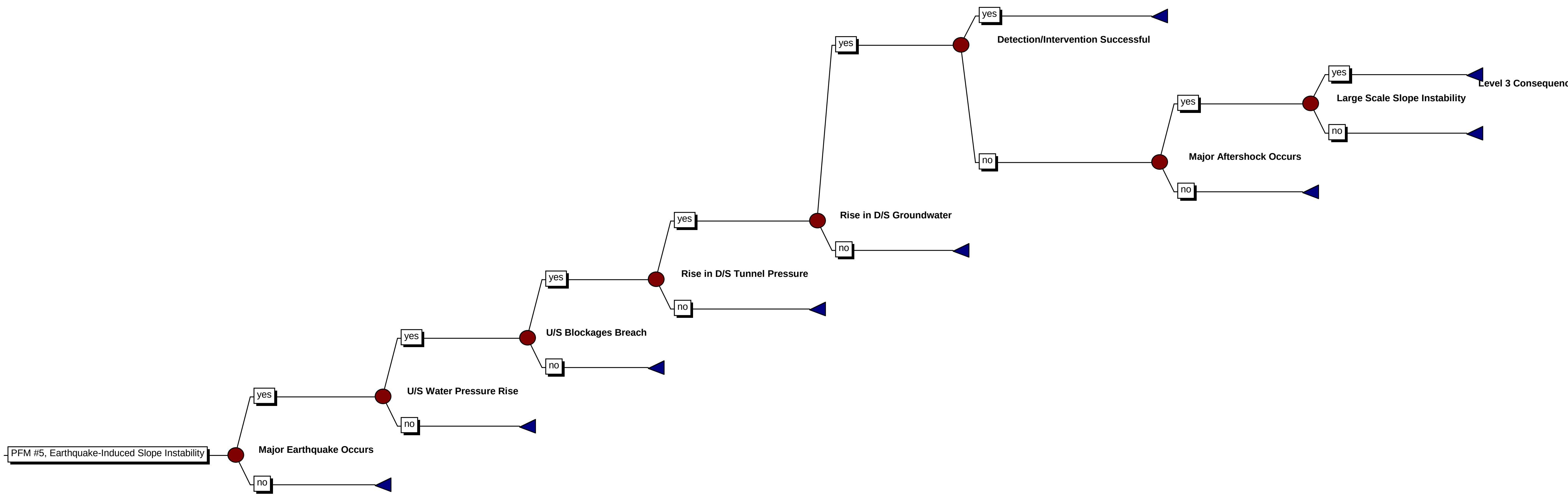

PFM #1, Bulkhead Blowout
U/S Water Pressure Rises
yes
no
U/S Blockages Breach
yes
no
Rise in D/S Tunnel Pressure
yes
no
Detection/Intervention Successful
yes
no
D/S Blockages/Bulkheads Breach
yes
no
Large Flows Out Portal
yes
no
EWS Successful
yes
no
Level 2 Consequences
Level 3 Consequences

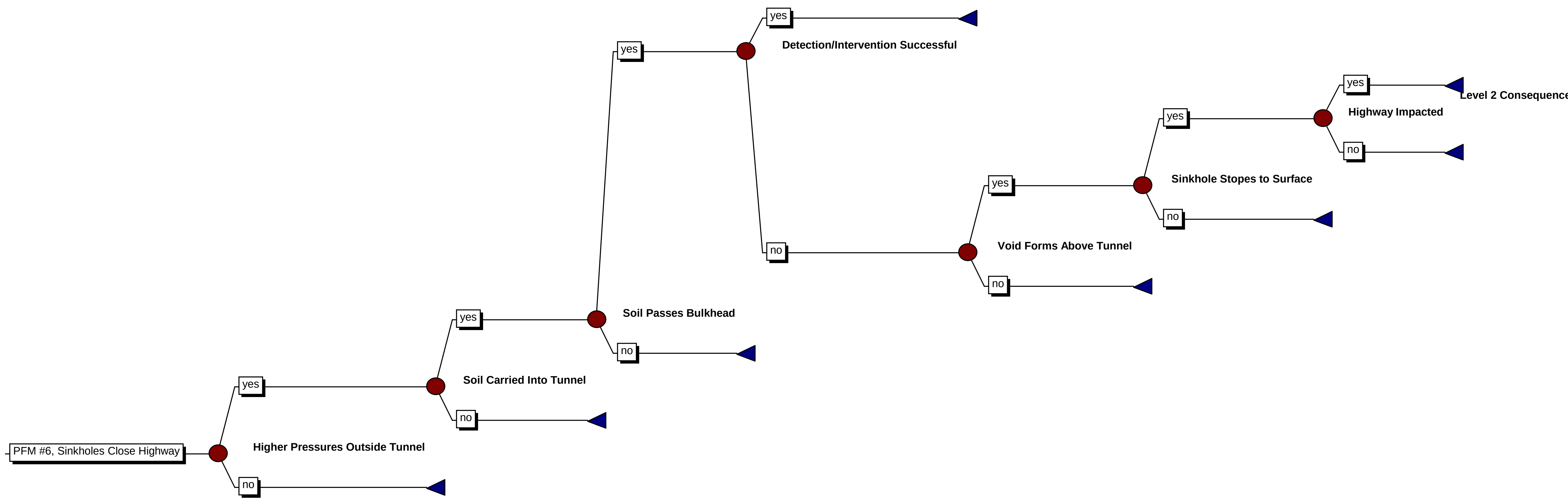


PFM #2, Seepage Erosion @ Portal
U/S Water Pressure Rise
U/S Blockages Breach
Rise in D/S Tunnel Pressure
Detection/Intervention Successful
0
Rise in Flow/Gradients Along D/S Lining
D/S Tunnel Lining Collapse
Seepage Erosion @ Portal
EWS Successful
Level 2 Consequences
Level 3 Consequences
yes
no

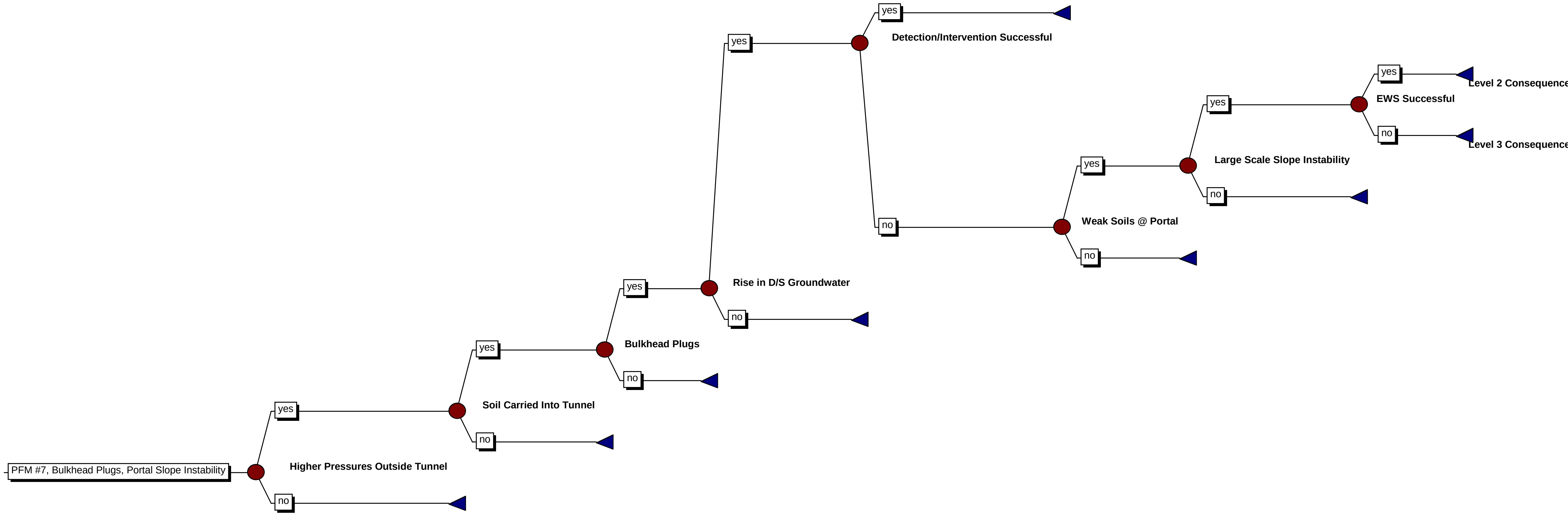

PFM #3, Portal Slope Instability
U/S Water Pressure Rise
yes
no
U/S Blockages Breach
yes
no
Rise in D/S Tunnel Pressure
yes
no
Detection/Intervention Successful
yes
no
Rise in D/S Groundwater
yes
no
Weak Soils @ Portal
yes
no
Large Scale Slope Instability
yes
no
EWS Successful
yes
no
Level 2 Consequences
Level 3 Consequences


PFM #4, Contaminated Leakage
U/S Water Pressure Rises
yes
no
U/S Blockages Breach
yes
no
Rise in D/S Tunnel Pressure
yes
no
Detection/Intervention Successful
yes
no
D/S Groundwater Rises
yes
no
Water Leaks to Surface
yes
no
Water Detected/Contained
yes
no
Level 1 Consequences


PFM #5, Earthquake-Induced Slope Instability
Major Earthquake Occurs
yes
no
U/S Water Pressure Rise
yes
no
U/S Blockages Breach
yes
no
Rise in D/S Tunnel Pressure
yes
no
Rise in D/S Groundwater
yes
no
Detection/Intervention Successful
yes
no
Major Aftershock Occurs
yes
no
Large Scale Slope Instability
yes
no
Level 3 Consequences



PFM #6, Sinkholes Close Highway
Higher Pressures Outside Tunnel
yes
no
Soil Carried Into Tunnel
yes
no
Soil Passes Bulkhead
yes
no
Detection/Intervention Successful
yes
no
Void Forms Above Tunnel
yes
no
Sinkhole Stopes to Surface
yes
no
Highway Impacted
yes
no
Level 2 Consequences


PFM #7, Bulkhead Plugs, Portal Slope Instability
Higher Pressures Outside Tunnel
Soil Carried Into Tunnel
Bulkhead Plugs
Rise in D/S Groundwater
Detection/Intervention Successful
Weak Soils @ Portal
Large Scale Slope Instability
EWS Successful
Level 2 Consequences
Level 3 Consequences
yes
no