Addressing Geotechnical Challenges on Utah's Provo Reservoir Canal Enclosure Project

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ABSTRACT

The Provo Reservoir Canal Enclosure Project (PRCEP) replaced a 160-year-old, 21-mile (34-kilometer) -long open canal with a 126-inch (3200-mm) -diameter steel pipeline to help address public safety concerns, reduce evaporation and seepage losses, improve water quality, increase capacity, and provide a reliable water delivery system to help meet the growing water needs of more than one million end users along the Wasatch Front of Utah. The canal alignment is primarily located on unconsolidated ancient lake sediment deposits, alluvial fans, stream deposits, and landslide deposits from the Wasatch Front Mountains. This paper presents a detailed discussion of the geotechnical challenges associated with these geologic materials. The geotechnical challenges of the project were further complicated by the need to design and prepare bid documents for several alternative materials for the enclosure, with the goal of identifying the most cost effective method of construction and water conveyance for the project. These designs included precast concrete box culverts, cast-in-place concrete box culverts, non-cylinder reinforced concrete pressure pipe, and welded steel pressure pipe. With challenges properly addressed, this monumental $150 million landmark project was completed one year ahead of schedule.

INTRODUCTION

The Provo Reservoir Canal Enclosure Project (PRCEP) was a landmark construction, consisting of 21-miles (34 kilometers) of 126-inch (3200-mm) diameter steel pipeline. It was designed to enclose an open channel canal that was built in the early 1850's by Mormon Pioneers. The PRCEP has resulted in the prevention of approximately 8000 acre-ft, or 2.6 billion gallons (10 million cubic meters) of annual water loss from evaporation and seepage. Originally conceived as a 3-year project, pipe-laying was completed in early April 2012, one year ahead of schedule. The pipeline was tested and placed into operation in May 2012. With the completion of the new pipeline, there are now three primary water conveyance pipelines providing water to the municipality of Salt Lake Valley. The other two conveyance pipelines include the Jordan Aqueduct (with a design capacity of 270 cfs [7650 l/s]) and the Salt Lake Aqueduct (design capacity of 170 cfs [4810 l/s]). The PRCEP design capacity is more than double that of the Jordan Aqueduct and more than triple that of the Salt Lake Aqueduct.

The canal alignment is primarily located on unconsolidated ancient lake sediment deposits, alluvial fans, stream deposits, and landslide deposits from the Wasatch Front Mountains. Geological hazards identified along the alignment included the crossing of both historic and active landslides and debris flows, crossing and paralleling the Wasatch Fault, and differential settlement due to abrupt transitions from firm ground to soft silts and clays. The geotechnical challenges of the project were further complicated by the need to design and prepare bid documents for several alternative materials for the enclosure, with the goal of identifying the most cost effective method of construction and water conveyance for the project. Conduit materials considered included both precast and cast-in-place concrete box culverts, low-head non-cylinder reinforced concrete pressure pipe, AWWA C302, and welded-joint spirally-welded steel pressure pipe, AWWA C200.

Murdock et al. (2011) provides a comprehensive discussion on the overall process for selecting steel pipe as the most economical solution amongst the options considered. Canal hydraulics, design considerations, pipe materials, jointing options, corrosion protection, manufacturing considerations, transportation-and-hauling issues, and constructability are all discussed in this referenced paper. Budge and Rahman (2012), in their paper, further discuss the specifics of selection process and use of polyurethane lining and coating for corrosion protection of the steel pipeline. This particular companion paper focuses on the geotechnical challenges addressed during design and construction by CH2M HILL.

PIPELINE ROUTE

The 21-mile (34-kilometer) PRCEP starts at the Murdock Diversion at the mouth of the Provo Canyon, turns north and runs along the toe of the Wasatch Mountains through the cities of Orem, Lindon, Pleasant Grove, and Cedar Hills where it turns northwest, running through American Fork, Highland, and Lehi to the Point of the Mountain. The pipeline has primary connections to the Point of the Mountain Aqueduct and the Jordan Aqueduct and provides for deliveries across the Jordan River to the West side of the Salt Lake Valley. All three pipelines now supply the municipal needs of the Salt Lake Valley: the PRCEP, the Jordan Aqueduct, and the Salt Lake Valley Aqueduct all 3 share a similar corridor, approximately 1000-foot (300-meter) wide, along the Wasatch Front, east of Pleasant Grove (**Figure 1**).

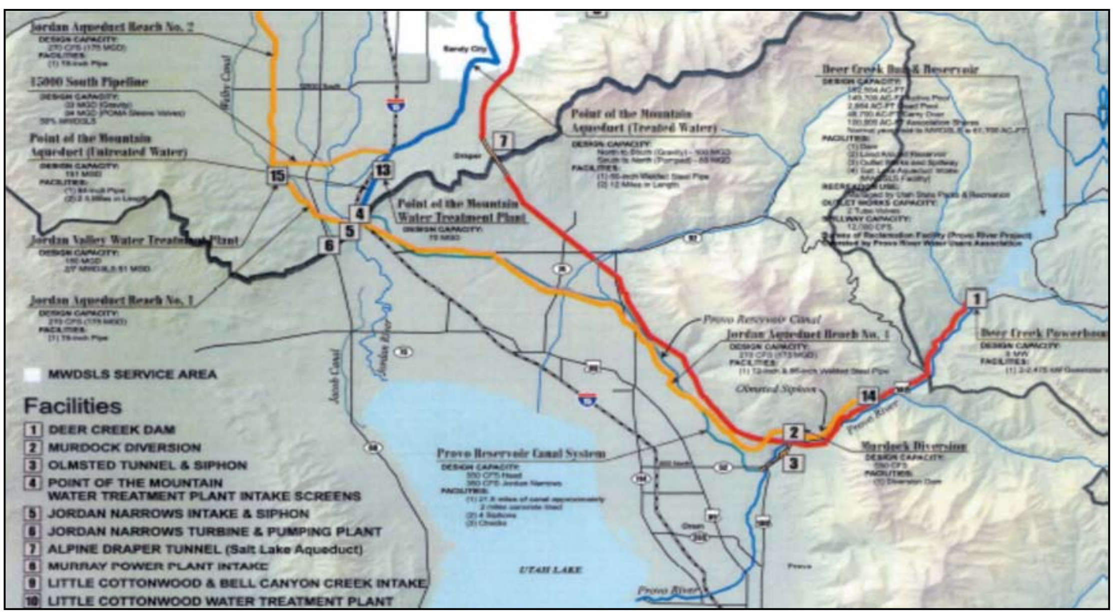

Figure 1 – Wasatch Front Pipelines

GEOTECHNICAL INVESTIGATIONS

The first geotechnical investigation was conducted in 2007 by Intermountain GeoEnvironmental Services, Inc. (IGES 2007). This study reported the pipeline alignment would cross the Provo segment of the Wasatch Fault zone and that "disruption of the canal alignment" could occur during a seismic event. It also identified a zone of landslide potential along the alignment in the vicinity of Pleasant Grove, but further reported no evidence of slope failures along the proposed alignment. It was concluded or interpreted that slope instability was not a primary design constraint or issue. During final design a design-level geotechnical investigation (GCI, 2009) was conducted at the direction of CH2M HILL to obtain additional subsurface information related to the landslide area and its potential impact on the PRCEP.

Soil Classification and Engineering Properties. The canal alignment is primarily located on unconsolidated ancient lake sediment deposits, alluvial fans, stream deposits, and landslide deposits from the Wasatch Front Mountains. Subsurface soil boring samples were collected (GCI, 2009) in the embankment along the canal alignment, and also at the bottom of the canal for the full length of the project. Laboratory testing of representative soils was conducted, determining particle size, in-place moisture and density conditions. Atterberg limit tests were conducted to assess plasticity of fine soils, and unconfined compression tests and direct shear tests performed to assess strength parameters of subsurface soils. To assess soil corrosion potential, soluble sulfate and pH tests were carried out.

Soils in the canal embankment and at the bottom of the canal ranged from gravels to clays. Table 1 provides a listing of the soil types encountered by region. Using a factor of safety of three, an allowable bearing capacity of 1,500 psf (70 kPa) was calculated using Hansen's modifications to Terzaghi's original bearing capacity formula. Settlement in fine-grained soils along the alignment was estimated using observation of in-situ soils during exploration and lab testing results. Lateral earth pressures were calculated using Coulomb's lateral active and passive earth pressures based on an assumed internal friction angle for the material. Friction angles characterized by lab tests ranged between 22 and 40 degrees. Lateral resistance against sliding was evaluated using published information based on relationship between internal friction angle values and soil type against concrete (Navy, 1986).

Table 1. Soil Types by Region of the Pipeline Alignment.

Region	Description
Within Provo Canyon and Along Orem Bench Area	Clayey Gravels (GC) and potentially Silty to Poorly Graded Gravels (GM, GP-GM)
Within North Orem and Lindon Areas	fine grained Sandy Lean Clay and Lean Clay (CL) and Silt (ML), with gravels and cobbles
Within Pleasant Grove Area and into Cedar Hill Area	Clayey Gravels (GC) with cobbles and occasional interbedded layers of Sandy Lean Clay (CL) and granular soils ranging from Silty toPoorly Graded Gravels (GM, GP-GM) and cobbles
Crossing the American Fork/Cedar Hills bench area	Lean Clays (CL), Silty Sand (SM), and Clayey, Silty and Poorly Graded Gravel (GC, GM, GP-GM)
Across the Highland bench area	Clayey Gravels (GC), transitioning to finer grained soils consisting of Sandy and Gravelly Lean Clay (CL) with interbedded Clayey Gravels (GC)

Region	Description
American Fork/Cedar Hills and Highland benches	Varied between granular deposits formed from the alluvial/deltaic deposits from the American Fork and Dry Creek drainages, and fine grained lacustrine lake deposit formed from Lake Bonneville
Remaining Alignment	Sandy Silts (ML) and Sandy Lean Clay (CL) with occasional interbedded gravels and sands

Information from GCI, 2009

GEOLOGIC HAZARDS

Portions of the 21-mile (34-kilometer) pipe and box culvert alignment pass through areas mapped by the Utah Geological Survey (UGS) as containing geologic hazards (Christenson and Shaw, 2008) that have the potential to affect post-earthquake functionality of the conveyance facility, the adjacent facilities, and the public. These include landslides, faults, high ground motion, and subsidence.

Fault Zone and Seismic Hazards. The PRCEP is located in an area of high seismicity, as the adjacent Wasatch fault zone is one of the longest and most tectonically active normal faults in North America (Black et al. 2001). The Provo segment of the fault is approximately 37 miles long and is currently believed to be capable of producing a magnitude 7.4 earthquake (USGS, 2006). Its slip rate is approximately between 1 and 5 mm/yr. This fault both crosses, and runs parallel to (less than 350 feet [110m] to the east of the alignment) the PRCEP alignment for over a mile (1.6 kilometers), and was therefore of major concern to the project. The largest estimated magnitude earthquakes in the project vicinity during recorded historic time were the magnitude 5.5 event in 1900 near Eureka (30 miles [48 km] southwest of Provo); the magnitude 5.0 quake in 1915 in Provo; and the magnitude 5.0 quake in 1958 (13 miles [21 km] northeast of Provo).

The Probabilistic Site Hazard Analysis (PSHA) contained in the geotechnical report (IGES, 2007) indicated that the expected Peak Ground Acceleration (PGA) along the PRCEP alignment ranged from 0.49 to 0.53g (where g is the acceleration due to gravity) for the maximum considered earthquake (MCE), defined as 2% probability of occurrence in 50 years, assuming a site class of “D”. A deaggregation of the seismic hazard for the IGES-reported MCE was performed and the results indicated that the mean magnitude of the MCE is 7.0, with a mean hypo-central distance ranging from 1.9 to 3.8 miles (3 to 6 km) from the PRCEP alignment (USGS, 2005). The modal magnitude was 7.4, with a modal distance ranging from 0.6 to 2.5 miles (1 to 4 km) from the PRCEP alignment. PSHA for seismic events was also performed with reduced 5% and 10% probability of occurrence in 50 years (975- and 475-year recurrence intervals) at Station 797+00, judged to be most representative of the entire alignment. The analyses are summarized in Table 2.

Table 2. Results of Probabilistic Site Hazard Analysis at Sta. 797+00.

Probability[1]	Recurrence (years)	PGA (%g)	PGV[3](inch/sec)[m/sec]	Magnitude[2]
2%	2,475	0.53	32 [0.8]	7.4
5%	975	0.39	21 [0.5]	7.2
10%	475	0.28	14 [0.4]	7.2

[1] Probability of occurrence in 50 years
[2] Modal magnitude determined from USGS deaggregation (USGS, 2005)
[3] Peak ground velocity

No borings were made to depths of 100 feet (30m) to determine shear wave velocity of the subsoils beneath the alignment, but published maps (Christenson and Shaw, 2008) were used to estimate that the shear wave velocity (Vs_{30}) of subsoils ranged from 675 to 1,540 feet/sec (205 to 470 m/sec), with a mean value of 920 ft/sec (280 m/sec). The Peak Ground Velocities (PGV) shown in Table 1 were calculated from the PGA for each of the recurrence intervals (ALA, 2005).

Landslide Hazards. According to the Utah Geological Survey (UGS), the PRCEP alignment is located within an area of mapped landslides for which "special studies to address landslide hazards are recommended prior to development for all facilities" (Christenson and Shaw, 2008). The largest mapped landslide hazard zone is located to the east of Pleasant Grove within the Wasatch Front. Historic landslides in the Pleasant Grove area have partially filled in the canal and/or damaged the concrete lining. A landslide in 1998 required extensive repairs to the canal, although the canal was not in operation at the time of the slide. During the 1995 to 1998 period, a number of Wasatch Front slides occurred including the Sherwood Hills slide, the Spanish Fork Canyon slides, and a number of slides in the area of Layton. These slides were attributed to above normal precipitation for the period between 1995 and 1998 (Ashland, 2003); excess precipitation saturates the slide mass, increasing the destabilizing gravitational force and lubricating the slide failure plane. Recent off-alignment slides have affected areas with similar Wasatch mountain-front geologic conditions including the 2005 slide in Cedar Hills in which a number of townhomes were damaged, and the 2006 North Salt Lake slide which also damaged a number of residential areas. Landslides could be triggered by precipitation as well as by seismic activity, so both possibilities were analyzed for the Pleasant Grove Landslide area.

<u>Precipitation-Induced Landslides.</u> No site-specific data were available within the landslide area (determination of slide slip rates, residual and peak soil strengths of the soils involved, slide limits, and depths of the sliding mass). CH2M HILL created an idealized cross section through the location of the 1998 slide, at Sta. 484+00. This cross section was done using three sets of available data: 1) a previous idealized cross section of the slide mass prepared for a Pleasant Grove water tank project, 2) approximate location of the 1998 slide on the PRC alignment, and 3) a project soil boring at Sta. 445+50 which was drilled to a depth of 60 feet (18m). The latter identified that soils up to 55 feet (17m) in depth consisted of sandy well-graded gravel with cobbles and sandy clay with gravel; and several shear zones were noted with some basal gravels, and blocks of Manning Canyon Shale were retrieved. Also, between 55 and 60 feet (17 and 18m) in depth, finely laminated sandy clay with gravel and clay, interpreted to be Lake Bonneville deep water sediment were present below the base of the slide. Table 3 shows assumed soil properties for generalized slope stability analysis.

Table 3. Assumed Soil Properties for Generalized Slope Stability Analysis.

Material	Moist Unit Weight (pcf)[kN/m^3]	Saturated Unit Weight (pcf) [kN/m^3]	Friction Angle (degrees)	Cohesion (psf)[kPa]
Landslide Deposits	110 [17.3]	135 [21.2]	28	1,000 [48]
Intact Shale	120 [18.8]	120 [18.8]	28	1,345 [64]

pcf – pounds per cubic foot
psf – pounds per square foot

Two slope stability analyses were performed with the SLIDE software (Rocscience 2009). It was observed that the predicted failure surface for the saturated case was at the approximate location of the 1998 observed failure, although the predicted extent was slightly greater than the observed failure area. These generalized results were considered indicative of the destabilizing effect of excess precipitation on the stability of the existing slopes within the landslide hazard zone. It was concluded that the portion of the PRCEP located within the mapped landslide hazard zone has the potential to be disrupted approximately 5 times over the 50-year design life, with damage consisting of pipeline rupture and other damage to approximately 1,000 feet (300m) of the pipeline.

<u>Seismically-Induced Landslides.</u> Though the Wasatch Fault Zone is considered a highly active seismic source, the record of historical seismicity suggested that the Wasatch Front-range slopes, through which the PRCEP would traverse, had not been exposed to high levels of ground motion during the 160-year history of the Provo Reservoir Canal. Therefore, CH2M HILL used the SLIDE software to back-calculate the pseudo-static yield acceleration with the generalized geologic profile of the site of the 1998 slide at PRCEP Sta. 484+00 (an estimated value of 0.15g was obtained.) Using American Lifeline Alliance guidelines (ALA, 2005), and the Newmark formulas in the Pipeline Research Council International guidelines (PRCI, 2004), both discussed in the next section, CH2M HILL estimated that the ground would displace between 14 and 24 inches during a design seismic event.

The maximum moment resulting from the transverse movement of the PRCEP pipeline during a seismic-induced or precipitation-triggered landslide was estimated to be close to 10 million kip-feet (13.7 million kilonewtons per meter), based on an assumed 1000-foot (300-m) slide width. This applied moment would be far in excess of the capacity of any of the conduit materials, and it was therefore assumed that the full portion of the pipe located within the landslide would fail or be disrupted and major sections of the 1000-foot (300-m) length would require replacement. Appropriate measures would therefore need to be taken.

<u>Dry Creek Landslide Zone</u>. A second landslide area was identified at Sta. 784+00 along the southern slope of the Dry Creek Siphon, consisting of poorly graded sand or poorly graded sand with clay, at a slope angle of 25 degrees. Again, per ALA (2005) and PRCI (2004) guidelines, a yield acceleration of 0.2g was utilized to approximate ground displacement between 7 and 12 inches (170 and 600mm) during a design seismic event, the displacement being longitudinal (parallel) to the pipeline alignment. This is considered to be more damaging according to ALA and PRCI guidelines.

Fault Offset and Tectonic Subsidence Hazards. The PRCEP alignment would cross 6 active faults (movement identified within the past 11,000 years). There were also 2 additional historic faults (displacement prior to past 11,000 years), identified by the presence of 10 feet (3m) of undisplaced sediment above the soils where displacement could be observed.

Average fault displacement was estimated to be 6.5 feet (2m) during a M7.4 event and 5 feet (1.5m) during the 475-yr design event. Design-basis fault offset was calculated to be 7.5 feet (2.3m); this displacement would be anticipated at 6 separate fault locations.

SEISMIC DESIGN GUIDELINES FOR WATER PIPELINES

Seismic design of water pipelines is not explicitly included in current American Water Works Association (AWWA) design standards. Since the 1980's, ASCE had the only significant reference document on seismic design of oil and gas pipelines (ASCE 1984). It wasn't until 1998 that the Pipeline Research Council Institute (PRCI) initiated a project to update seismic design guidelines for oil and gas pipelines with the goal of "incorporating advances in current engineering practice since the early 1980s and to create a document that can be regularly updated to take advantage of new research findings" (Honegger et al. 2002). Also in 1998, a cooperative agreement between the Federal Emergency Management Agency (FEMA) and ASCE formed the American Lifeline Alliance (ALA), with the stated goal of providing guidelines to address the issue that US water utilities have shown themselves to be prone to high damage rates whenever there is a significant permanent ground deformation or high levels of ground shaking, and to do so with a cost-effective approach. In late 2002, FEMA brought ALA under the Multihazard Mitigation Council through a public-private partnership with the National Institute of Building Sciences.

For seismic design and analysis of the PRCEP, CH2M HILL primarily made use of guidelines provided by the ALA (2005a and 2005b) as well as limited consultation of the PRCI documents (2004a and 2004b).

Pipe Function Class. The ALA guidelines classify the PRCEP as a transmission pipeline. The performance of the pipeline under earthquake conditions is related to its intended function and importance based on the Pipe Function Class presented in Table 4.

Table 4. Pipe Function Class and Design Category.

Pipe Function Class	Seismic Importance	Description
I	Very low to none	Pipelines that represent very low hazard to human life in the event of failure. Not needed for post earthquake system performance, response, or recovery. Widespread damage resulting in long restoration times (weeks or longer) will not materially harm the economic well being of the community.
II	Ordinary, normal	Normal and ordinary pipeline use, common pipelines in most water systems. All pipes not identified as Function I, III, or IV.
III	Critical	Critical pipelines serving large numbers of customers and present significant economic impact to the community or a substantial hazard to human life and property in the event of failure.
IV	Essential	Essential pipelines required for post-earthquake response and recovery and intended to remain functional and operational during and following a design earthquake.

Adapted from ALA (2005a)

Given that the majority of municipal water for the Salt Lake Valley passes through the PRC and the adjacent Jordan Valley and Salt Lake Aqueducts and that these facilities were not designed per current seismic design standards, CH2M HILL classified the PRCEP as Class III. The ALA guidelines further define Class III as:

- Supply sources providing water to a minimum of 1,000 service connections including residential, industrial, and business, or other customers; for which there is no redundant supply.
- Pipelines that serve as 'backbone' transmission between pump stations and tanks.
- Supply sources where serious damage would necessitate very long boil water notice time.
- Sub-transmission and transmission pipes and associated supply sources, the failure of which would release high pressure water and/or flood areas that may cause secondary disasters, impede potential emergency recovery, or evacuation of facilities.

In accordance with the ALA guidelines for seismic design of pipelines, a Function Class III pipeline subject to hazards associated with ground shaking, landslides, and fault offset should be designed in accordance with the design categories identified in Table 5.

Table 5. Recommended PRCEP Design Categories.

Seismic Hazard	Criteria[3]	PRCEP Value	Design Category[3]
Ground Shaking	$20<PGV^1\leq 30$	21 inches/second (530 mm/s)	B
Landslides – Perpendicular to Pipeline Alignment	$12<PGD^2$	14-24 inches (355-610mm)	C
Landslides – Parallel to Pipeline Alignment (Dry Creek Siphon)	$6<PGD^2\leq 12$	7-12 inches (180-300mm)	C
Fault Offset	$24<PGD^2$	90 inches (2300mm)	E

[1] Peak Ground Velocity (inches per second)
[2] Permanent Ground Displacement (inches)
[3] For transmission pipelines per Seismic Guidelines for Water Pipelines (ALA, 2005a)

SELECTION OF CONDUIT MATERIALS

The following sections present pipe material considerations as they relate to various geologic hazards identified by CH2M HILL along the PRCEP alignment.

Seismic Fragility Comparison of Pipe Materials. For seismic wave propagation, the seismic fragility of the various construction materials were estimated in general terms using the vulnerability functions and correction factors presented in ALA (2001). The relationship between the probability of component damage and the level of seismic hazard is referred to as a fragility relationship or fragility curve, as defined in ALA (2001). An analysis of the pipeline's fragility to seismic wave propagation was conducted to compare C200 welded steel pipe, C302 low-head non-cylinder concrete pressure pipe, and both cast-in-place and precast concrete box culverts, results of which are summarized in Table 6.

Table 6. Comparison of Fragility[1] of PRCEP Conveyance Material Alternatives to Seismic Wave Propagation.

Material	Joint	Correction Factor (K2)	Breaks Per 1000 feet (300m)
C200 Welded Steel Pipe	Arc Welded, Lap Welds, >12' Pipe Diameter, Non-Corrosive Environment	0.15	0.006
C302 Concrete Pipe	Rubber Gaskets[2]	0.80	0.031
Cast in Place or Precast Concrete Box Culvert	Concrete Joint with 6-inch (150-mm) Water Stops[2] or Rubber Gaskets	0.80	0.031

[1] The relationship between the probability of component damage and the level of seismic hazard is referred to as a *fragility relationship* or *fragility curve*, as defined by ALA (2001)

[2] data from asbestos-cement pipe (ALA 2001)

The comparison presented in Table 6 suggests that the concrete pipe and concrete box culverts would be expected to rupture 5 times as frequently as the welded steel pipe alternative during the design level of shaking for the Class III function class (975-year seismic recurrence interval). In other words, welded steel pipe would be 5 times more likely to withstand failure during a seismic event compared to the concrete pipe and box culvert alternatives. For a 21-mile (34-kilometer) alignment, this would represent an additional 2 or 3 ruptures per design seismic event, which was within the accuracy of this evaluation.

Pipe Material and Joint Comparisons for Seismic Design. The ALA recommendations for each of the design categories identified in Table 5 are summarized below in Table 7 for all conduit materials considered on the PRCEP. Tensile and buckling forces due to longitudinal seismic wave passage were analyzed. For continuous, restrained joint welded steel pipe, a factor of safety of 3.0 against buckling and tensile failure would be maintained even with a single lap-welded joint. Similarly, joint displacement estimates for the non-continuous, segmented concrete pipe and culvert options (assuming 20-ft segment lengths) would be on the order of ¼ to ½ inch (6 to 12.5mm). For a 40-ft box culvert segment, joint displacement would be on the order of ½ to 1 inch (12.5 to 25mm).

Table 7. PRCEP Design Category Recommendations.

Seismic Hazard	Conduit Materials		
	AWWA C200 Welded Steel	**AWWA C302 (noncylinder)**	**Concrete Box Culvert**
Ground Shaking	Single Lap Weld[5]	LJDC[3] >1/2 inch (12.5mm)	LJDC[3] >1/2 inch[1] (12.5mm) or 1 inch[2] (25mm)
Landslides – Perpendicular to Pipeline Alignment	Double Lap Weld[5]	Not Recommended	Not Recommended

Seismic Hazard	Conduit Materials		
	AWWA C200 Welded Steel	AWWA C302 (noncylinder)	Concrete Box Culvert
Landslides – Parallel to Pipeline Alignment (Dry Creek Siphon)	Double Lap Weld[5]	Not Recommended	Not Recommended
Fault Offset	Butt Weld[4]	Not Recommended	Not Recommended

a – 20-foot (6-m) segment length
b – 40-foot (12-m) segment length
c – Longitudinal joint displacement capacity (in excess of operational joint displacement capacity)
d – D/t maximum of 95. For pipe wall thinner than D/t=95, double-lap welding recommended
e – Weld thickness t should equal pipe thickness t

Conduit Materials in Geologic Hazard Areas. Based on the results presented above, CH2M HILL recommended the use of welded steel pipe as the only alternative for the 5,500 feet (1675 meters) of alignment within the landslide and fault offset hazard zones, regardless of which material was finally selected through competitive bidding for the remaining 20 miles (32 km) of the project. Double lap welded joints were recommended for both landslide and fault zones. Use of steel pipe in the hazard zones would reduce the chances of pipe rupture by 5 times compared to the use of concrete pipe or box culverts.

Differential Settlement and Conduit Material Options Outside Hazard Zones. Differential soil settlement was predicted along portions of the project alignment for the box culvert option (Murdock et al. 2011). The invert elevation of the box culvert option was dictated by the hydraulic grade line requirements at the existing turnouts, which forced the invert of the box culvert to remain at the approximate invert elevation of the existing canal. Enclosing the canal with a 10-foot (3-meter) tall box culvert, then adding a 1-foot (600-mm) -thick roof section, and covering it with 2 feet (0.6m) of earthfill created a finished grade elevation for the box culvert option that was approximately 3 to 5 feet (0.9 to 1.5 meters) above the existing canal bank. This 3- to 5-foot (0.9 to 1.5-m) -high finished grade embankment placed additional loads on normally consolidated silts and soft clays beneath the existing canal that was predicted to result in 2 to 5 inches of differential settlement over very short 30- to 40-foot (9 to 12-meter) reaches along the canal alignment. To counteract these areas of differential settlement, the design for the box culvert included reaches where the contractor would be required to over-excavate and replace silts and soft clays with a compacted select earthfill material.

The centerline of the steel and concrete pipeline options was placed approximately 1 or 2 feet (0.6m) below the invert of the existing canal. The completed backfilled conditions of the pipeline did not create an increased load along the canal alignment and greatly reduced the potential for differential settlement (Murdock et al. 2011).

Dry Creek Landslide Zone. The estimated seismically-induced landslide ground displacement would be in a longitudinal direction (parallel) to the PRCEP alignment and could displace between 7 and 12 inches (180 to 300mm). The estimated forces resulting from the longitudinal movement of the pipeline were compared to the design strength of the welded steel pipe, assuming the full 300-foot (90-m) -length of the slope was displaced. It was recommended that steel pipe with double lap welded joints be installed across the landslide zone that could be capable of withstanding the forces required to permit the soil to move past the pipeline, while the pipeline remains in place.

DESIGN FEATURES TO ADDRESS SPECIFIC GEOLOGIC HAZARDS

Creating flexible conditions along the steel pipeline alignment in areas of identified geological hazard was a key method to counter the effects of seismic activity. In landslide and fault offset areas, pipe-soil friction acting on the steel pipe was reduced by minimizing the depth of burial, reducing the backfill density, and creating a more flexible pipeline. Use of low-friction polyurethane coating on the steel pipe also reduced friction in areas of geologic hazards. The use of welded steel pipe also eliminated the need for lined drainage gullies to channel escaping water from a ruptured concrete conduit as it had zero-leakage welded joints; drainage would have been required for both the concrete pipe and box culvert options at the landslide zones.

At each of the six fault crossings along the alignment, trench excavation was oversized, and the steel pipe was backfilled with a loose well-graded granular material. Where possible an oversized trapezoidal excavation with side slopes of 60-degrees from horizontal was recommended. Because of the inherent uncertainty with definition of exact limits of geological hazards, it was recommended to extend the modified trench zone for at least 250 feet (75m) on either side of each of the six fault crossings. The oversized and loosely backfilled trench would permit movement of the pipe within the trench in the event of fault offset, thereby reducing the potential for pipe damage or rupture.

Due to the high D/t ratio of 288 of the steel pipeline, it was recommended that double lap-welded joints be used in lieu of the originally recommended butt joints (for D/t of 95 and less) for fault crossings because of possible fit-up difficulty. Additional cost and joint efficiency provided by butt-welding 126-inch (3200-mm) diameter pipe joints likely would not be realized compared to double lap-welded joints.

In landslide zones, particularly at the Dry Creek landslide hazard area, the longitudinal direction of the potential slope failure would result in tensile and compressive forces along the pipeline with concentrated stresses at the head and toe of the slope. Use of a modified trench with well-graded granular backfill on a 2:1 (H:V) slope would be problematic and likely generate additional concern with pipe backfill integrity in the presence of water flow within the trench and issues with pipeline settlement resulting in potential rupture at the head of the slope. CH2M HILL therefore recommended that light-weight controlled low strength material (unit weight less than 110 pcf [17.2 kN/m^3]) or cellular concrete be used to backfill the pipe in this area, along with the use of a double-layer of geotextile between the trench walls and the bedding, pipe zone and trench backfill (Figure 2).

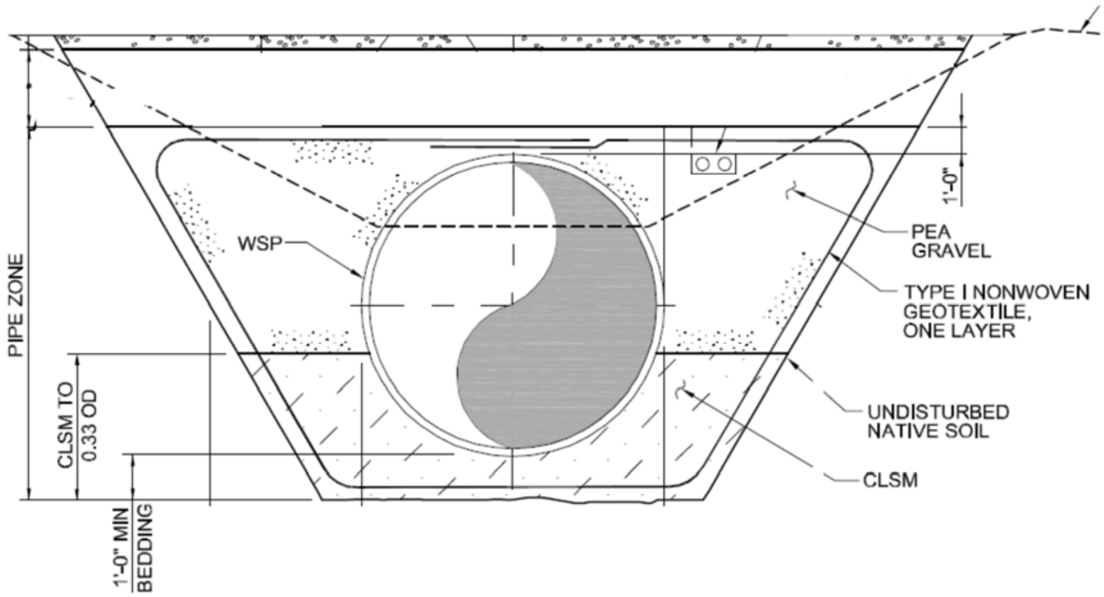

Figure 2 – Dry Creek Trench Detail

This double layered geotextile would facilitate movement of the natural slope past the pipe and trench backfill which in turn would reduce the tensile and compression forces acting on the pipe, thereby lowering the risk of pipe rupture. Since the steel pipeline would be fully welded and restrained, the lowered friction factor of using the geotextile would not affect design of a restrained joint. With both concrete pipe and box culverts, the lower friction factor would have required the implementation of a joint restraint system.

For the Pleasant Grove landslide hazard area, a portion of the PRCEP alignment was relocated from within the mapped hazard zone to parallel a portion of the Jordan Aqueduct which was believed to remain outside the toe of the existing slope. This would reduce both seismically-and-precipitation-induced landslide hazard risk to 60% of the pipeline previously located within the mapped hazard zone. Modified trench design was applied to the remaining 40% of the segment. Three subsurface inclinometers within the right-of-way of the affected sections of the landslide zone were installed so that post construction ground movement could be monitored. No movement has been detected to-date.

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