SECTION
0.1 PROTECTION FROM NATURAL HAZARDS
(WAC 463-42-265)

The following section describes natural hazards which may impact the proposed project and briefly describes environmental design measures included in the project to mitigate these potential impacts.

0.1.1 POTENTIAL GEOLOGIC AND NATURAL HAZARD MAPS

Appendix B contains a series of maps that identify the potential natural hazards along the pipeline corridor and alignment alternatives. These maps are referred to throughout this section specifically to identify potential areas of moderate and high mass wasting and liquefaction susceptibility.

0.1.2 EARTHQUAKE HAZARD

Earthquakes can cause fault rupture and induce ground motions which could, if not mitigated through design features or construction practices, adversely impact the construction and operation of the proposed pipeline. The level of this impact would be a direct result of the distance from and magnitude of the earthquake event, coupled with the soils upon which the pipeline is built. Fault rupture and liquefaction are specific impacts that are addressed in this subsection.

Fault rupture can cause an abrupt displacement, creating a crack in the ground surface that could sever the pipeline. Liquefaction is a process whereby loose saturated granular soil loses strength due to earthquake induced ground motion, and becomes similar to quicksand. The impacts which can be reasonably expected and the level of protection recommended are based on the evaluation of the geology and potential seismic activity along the alignment. Section 3.1 of the application contains a comprehensive geologic survey of the pipeline corridor and an assessment of potential seismic activities.

Subsurface fault movement accompanying earthquakes of M6 or greater often results in differential horizontal lateral (strike-slip) and/or vertical (dip-slip) displacement of the land surface straddling the fault. Differential movement on the order of 10 to 20 feet has occurred historically during earthquakes in the western U.S. and other seismically active areas of the world. Differential land movement would affect the pipeline only if the pipeline were to cross an active fault. As is described below, the proposed pipeline route does not cross any known active faults. Seismic damage to steel pipelines is usually limited to bending or buckling of the pipe wall in the immediate area of the sharp ground movement.

Possible impacts to pump station and terminal facilities from fault rupture and liquefaction include shearing of foundation and wall junctures, support cracking or shearing, loss of bearing pressure, and roof collapse. To protect against and minimize these impacts, strength and ductility requirements to resist the earthquake ground motions have been incorporated into the design of the pipeline and facilities. The design loads for the pipeline will meet or exceed the most recent requirements of the Uniform Building Code (UBC) for the particular seismic zone in which each facility lies.

Figures 2.15-1a through 2.15-1f identify the known and suspected faults within a thirty-mile area surrounding the proposed pipeline corridor. The figures also include the contours of peak ground acceleration (PGA) that were developed to quantify the groundshaking hazard within the pipeline corridor. The PGA contours represent earthquake ground motions having a 10 percent probability of being exceeded within a 50 year period. An earthquake that generates ground motions having a 10 percent probability of exceedence in 50 years is defined as a AContingency Design Earthquake,@ or CDE, by the ASCE Technical Council on Lifeline Earthquake Engineering. The PGA along the pipeline alignment ranges from 0.29g at the western terminal near Woodinville to 0.08g at the eastern terminal near Pasco.

FIGURE 2.15-1A - QUATERNARY FAULTS AND MAJOR ANTICLINES

Figure 2.15-1b - QUATERNARY FAULTS AND MAJOR ANTICLINES

FIGURE 2.15-1C - QUATERNARY FAULTS AND MAJOR ANTICLINES

FIGURE 2.15-1D - QUATERNARY FAULTS AND MAJOR ANTICLINES

FIGURE 2.15-1E - QUATERNARY FAULTS AND MAJOR ANTICLINES

FIGURE 2.15-1F - QUATERNARY FAULTS AND MAJOR ANTICLINES

The source of the ground motion data was the USGS National Seismic Hazard Mapping Project or NSHMP, which produced maps of earthquake groundshaking hazard for the United States (USGS Open-File Report 96-532). The methodology incorporated both seismic activity and geologic data in defining a national model of seismogenic sources. The maps have been the subject of extensive review and were incorporated into the 1997 NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.

The USGS maps were developed by computing four ground motion parameters (PGA and 5 percent damped pseudo-spectral acceleration at oscillator periods of 0.2, 0.3, and 1.0 seconds) at three probability-of-exceedence levels (10 percent, 5 percent, and 2`percent in 50 years) on a dense grid of locations that covered the 48 contiguous states. Electronic versions of the maps and the gridded ground motion are available on the Internet and can be downloaded from the Internet World Wide Web site http://gldage.cr.usgs.gov/eq/.

0.1.2.1 Potential Impacts Due To Fault Rupture

The faults and folds shown in Figures 2.15-1a through 2.15-1f are located within approximately 30 miles of the pipeline corridor, and are known or inferred to exhibit deformation of geologic strata during the Quaternary Period (from the present to approximately 1.6 million years ago). Table 2.15-1 presents a list of these Quaternary faults and folds and was principally compiled from maps prepared by Geomatrix (1988, 1990) and Gower et al. (1985) as well as more recent published literature. It should be noted that many of the faults shown on the Columbia Plateau on these figures have associated Quaternary folds adjacent and sub-parallel to the faults; but these folds were not depicted except where they extend laterally beyond the mapped fault traces. These regional Quaternary faults are considered to be the most pertinent relative to potential natural seismic hazards for the corridor. Other more distant Quaternary faults would be expected to generate earthquakes of similar size and recurrence to the faults shown on Figures 2.15-1a through 2.15-1f. Consequently ground motions within the pipeline corridor from earthquakes on these more distant faults (e.g., Toppenish Ridge, Antanum Creek) would be expected to be similar to or less than those generated by the faults closer to the pipeline.

The majority of Quaternary faults in the vicinity of the pipeline corridor are a series of approximate east-west trending reverse and thrust faults mapped on the Columbia Plateau (e.g. the Frenchman Hills, Saddle Mountains, Manastash Ridge, and Umtanum Ridge-Gable Mountain faults). These faults are associated with anticlinal folding in the Yakima Fold Belt. The Manastash, Umtanum, Rattlesnake Mountain and Wallula faults are part of a postulated geologic lineament known as the Olympic-Wallowa Lineament (Raisz, 1945). This lineament was believed by some to represent a crustal boundary between crustal and oceanic rocks but this interpretation has been discounted by geophysical evidence (Campbell, 1989).

The Saddle Mountains area is one of the most seismically active regions in central Washington (Geomatrix

1990, 1996). The Saddle Mountains fault exhibits evidence of late Quaternary surface faulting (West et al., 1996) and is the closest Quaternary fault to the pipeline route. The easternmost extent of this fault feature has been mapped to terminate approximately 1-1/2 miles from the nearest segment of the proposed alignment. All other faults crossed by the pipeline alignment considered inactive because they occur in Tertiary or older rocks, are buried by Quaternary deposits, and lack the tectonic geomorphic expression indicative of late Quaternary surface displacement.

Another prominent fault situated in the general area of the proposed pipeline alignment is the Seattle Fault. The Seattle Fault is located east of the city of Seattle and is known to have experienced movement within the past 1,000 years. The eastern limit of the fault has been mapped approximately 8 miles to the west of nearest segment of the proposed alignment.

Many of the mapped faults shown in Figures 2.15-1a through 2.15-1f are spatially associated with the epicenters of historical and instrumented earthquakes. However, there has been no documented historical surface fault rupture on any of these faults and no historical instrumented earthquakes of greater than M 5.0 associated with these faults (Noson et al., 1988; Geomatrix, 1988, 1990), with the possible exception that 1936 M 6.1 Milton-Freewater earthquake. This earthquake may have been associated with the Wallula fault zone which exhibits displacement of Holocene age (i.e., last 10,000-11,000 years before present) deposits (Mann and Meyer, 1993).

TABLE 2.15-1

SUMMARY OF QUATERNARY FAULTS WITHIN 30 MILES OF THE CROSS CASCADE PIPELINE

Fault Name	Closest Distance to Pipeline in Miles	Type of Displacement	Strike/Dip	Recurrence Interval or Slip Rate
South Whidbey Fault (3 splays)	3 mi. N of Thrasher Pump Station	Right-lateral SS, R	N50EW/65E-vertical;	$0.6 mm/yr vertical
Unnamed (H)[a]	2 mi. NW of Thrasher Pump Station	East plunging anticlinal fold	E-W/?	Unknown
Seattle Fault (main trace)	7.5 mi. W	R	E-W/70E S	5m-9m/13,500-14,000 yrs; 11m-14m/ 15,000-18,000 yrs, vertical
Unnamed (I)[a], Major splay of Seattle fault zone	7.5 mi. W	R	E-W/65E S	Unknown (included in main trace)
Manastash Ridge Fault Zone	6 mi. SW Kittitas Terminal	R	N70EW/?ES	ND
Gable Butte-Gable Mountain	12 mi. W	R	N55EE/?ES;	0.03-0.09 mm/yr
Umtanum Ridge	9.5 mi. S Kittitas Terminal	R	E-W/?ES	0.02 - 0.21 mm/yr
Saddle Mtns. Fault Zone	3 mi. S	R	EW/?ES	0.13 - 0.18 mm/yr; 0.16 - 0.65 mm/yr
Frenchman Hills Fault Zone	3 mi. N	R	EW/30-40ES	0.02 - 0.07 mm/yr
Wallula Fault Zone	9 mi. S of Terminus	Right lateral SS	N70EW/55E- vertical	0.47 mm/yr 0.02 - 0.03 mm/yr, vertical
Rattlesnake Fault	6 mi. SW of Terminus	Reverse or Reverse Oblique SS	NW/?ES	0.04 - 0.12 mm/yr
Kennewick lineament	5 mi. SW of Terminus	Right lateral SS	NW/vertical (?)	ND

SS=Strike Slip ?=value presented is uncertain R =Reverse ybp=years before present m=meters
cm=centimeters ND=no data is available

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2. Seismotectonic Map of Puget Sound Region, Washington; H.D. Gower, J.C. Yount, and R.S. Crosson: U.S. Geological Survey, Miscellaneous Investigations Series Ma
3. Origin and evolution of the Seattle fault and Seattle basin, Washington; S.Y. Johnson and C.J. Potter: Geology, v.22, p. 71-74, 1994.
4. Postglacial Offset Along the Seattle Fault; R.M. Thorson: Science, v.260, May 7, 1993.
5. Abrupt uplift within the past 1700 years at southern Puget Sound, Washington; R.C. Bucknam, E. Hemphill-Haley, Leopold, E.B.: Science, v.258, p. 1611-1614, 1992
6. Earthquake recurrence and glacial loading, western Washington; R. M. Thorson: Geological Society of America Bulletin, v.108, p. 1182-1199, 1996.
7. Seismotectonic evaluation Northern Cascade Mountains Geomorphic Province, U.S. Department of the Interior Bureau of Reclamation, report prepared by Geomatrix C
8. Seismotectonic Evaluation, Walla Walla Section of the Columbia Plateau Geomorphic Province, US Department of the Interior Bureau of Reclamation, prepared by Ge
9. A Pilot Study of Late Quaternary Surface Deformation, Saddle Mountains Anticline, Northern Pasco Basin: M.W. West,A.J. Busacca, G.W. Berger, M.E. Shaffer, Open-File Report No. 95-210, v.2, p. 817-827.
10. Late Quaternary deformation, Saddle Mountains anticlinal, south-central Washington: M.W. West, F.X. Ashland, A.J. Busacca, G.W. Berger, and M.E. Shaffer: Geolo
11. Late Cenozoic structure and correlations to seismicity along the Olympic-Wallowa Lineament, northwest United States; G.M. Mann and C.E. Meyer: Geological So 1993.
12. Late Cenozoic structure and correlations to seismicity along the Olympic-Wallowa Lineament, northwest United States: Discussion and Reply; S.P. Reidel, T.L. To America Bulletin, v.106, p.1634-1641, 1994.
13. Probabilistic Seismic Hazard Analysis, DOE Hanford Site, Washington: Geomatrix Consultants, report prepared for Westinghouse Hanford Company, February, 1996.

0.1.2.2 Protection Measures Against Fault Rupture

Faults cannot be precluded from rupturing the ground surface in the event of a large earthquake. Impacts are minimized by avoiding areas where indications of recent (surface displacement in the Holocene or multiple pre-Holocene late Quaternary surface displacements) activity are present. The proposed pipeline does not cross the known surface trace of faults known or inferred to have been active during the late Quaternary (approximately 700,000 years ago to the present). Inactive faults which are crossed by the proposed route are present in Tertiary or older rocks, are locally covered by Quaternary deposits and lack the tectonic geomorphology indicative of late Quaternary surface displacement.

As noted above, avoidance has been selected as the most effective mitigation measure against damage due to fault rupture. As a standard practice, the pipeline will be constructed of welded high-grade steel which allows a significant amount of movement of the pipeline during ground displacement without rupturing the pipeline. Welded steel pipe has the ability to deform in tension and conform to ground movement and therefore can accommodate large displacements.

To further take advantage of the ductile capacity of the pipe, the trench geometry can be altered if necessary. For example, the trench can be over-excavated and backfilled with a medium dense sand. Depending of the length of pipe impacted, a soil-pipe interaction analysis can be used to evaluate induced stresses and strains for various backfill configurations. Based on the analysis results, combinations of pipe wall thickness, backfill compaction and trench geometry can be evaluated that will accommodate the expected displacement thereby protecting the pipe from damage. Alternatively, an active mitigation measure is to place block valves on both sides of the fault.

The pipeline corridor has been located to avoid the portion of the Saddle Mountains fault with documented recent activity. However, the pipeline alignment may cross the buried eastern extension of the Saddle Mountains fault which is inferred to be present beneath the anticline crossed by the route (See Appendix B, pages 80 - 82). During trenching for construction of this portion of the pipeline, the trench will be inspected for evidence of the fault or deformed soils by a qualified geologist. If necessary trench alterations as described above will be implemented.

0.1.2.3 Potential Impacts Due To Liquefaction

Potential impacts to the pipeline associated with liquefaction include lateral spreading, flow failure and a loss of bearing capacity. Numerous studies of pipeline performance during earthquakes indicate that modern steel pipelines with arc-welded joints have very low vulnerability to ground shaking and gradual lateral and vertical displacement. The few pipeline failures that have occurred have all been associated with abrupt ground failure such as fault rupture, slope failures, or lateral spreading of liquefied soils. The following impacts are associated with liquefaction and lateral spreading:

- A pipeline containing petroleum products is buoyant in liquefied soil, allowing it to float up toward the ground surface while the soil is in a liquefied state. Although the pipe itself typically tolerates this relatively gradual displacement, it may float to a level of inadequate cover and require replacement at an adequate depth.

- Lateral spreading can cause large transverse displacements where the pipe runs across the spreading direction. If pipe failure occurs, it would likely be caused by bending at the edge of the liquefied zone (Youd, 1973 and O'Rourke and Tawfik, 1983). Also, lateral spreading can cause compressive buckling where the pipe runs down a slope comprised of liquefied soil.

*In determining areas along the proposed pipeline route that may be susceptible to liquefaction, a review was first made of the soil types that were present in the corridor. Loose sandy soils saturated by a shallow groundwater table are the most susceptible to liquefaction. Clayey or cemented soils are less susceptible to liquefaction. Similarly, non-saturated soils regardless of composition or cementation are not susceptible to liquefaction.

Estimated ground motion parameters, such as peak ground acceleration (PGA), are important components in assessing liquefaction potential. The estimated peak ground acceleration (PGA) levels as a percentage of gravity that were used in assessing the liquefaction hazard are shown along the planned and alternative pipeline routes on Figure 2.15-1a through 2.15-1f. Areas where the estimated PGA is not capable of inducing liquefaction regardless of material characteristics can be excluded from further assessment. However under the most susceptible soil conditions (i.e., loose, non-cohesive soils with groundwater at the ground surface) liquefaction can occur at PGA as low as 0.05g. Consequently, no portions of the route were excluded based solely on estimated PGA values.

In addition to the estimated PGA, the geologic and hazard maps (Appendix B), supporting geologic maps and reports were reviewed to identify surface deposits along the planned alignment, and each material was classified according to typical liquefaction resistance behavior. This relative liquefaction susceptibility ranking generally accounts for age, relative density, gradation, plasticity, and cementation. The expected or measured groundwater levels along the alignment are summarized in Table 3.3-10 of Section 3.3. The areas where surficial geologic materials are not susceptible to liquefaction (rock and clays) and those areas where near-surface groundwater (e.g., groundwater greater than 40 feet below ground surface) is not known to be present were excluded as potential liquefaction areas and were not assessed further. The remaining areas typically consist of geologically recent alluvial deposits in low-lying drainages and river and stream channels. This general information was used along with visual observations along portions of the route and the geologic materials susceptibility to identify areas of potential liquefaction.

Table 2.15-2 summarizes the site conditions where a liquefaction hazard may exist based on the screening process described above.

TABLE 2.15-2
LIQUEFACTION SUSCEPTIBILITY WHEN SATURATED

Map Symbol	Age	Unit Name	Plasticity	Liquefaction Susceptibility
Avl	Recent	Recent Avalanche deposit	cohesive and non-cohesive	3
6Qa	Quaternary	Alluvium	cohesive and non-cohesive	5
Qoa	Quaternary	Older alluvium on terraces and alluvial fans	non-cohesive	3
Qls	Quaternary	Landslide deposits	cohesive and non-cohesive	3
Ql	Quaternary	Loess	cohesive	2
Qgt	Quaternary	Glacial till	cohesive and non-cohesive	2
Qgo	Quaternary	Glacial outwash	non-cohesive	3
Qgl	Quaternary	Glaciolacustrine deposits	cohesive	1
Qfg	Quaternary	Fluvial gravels	non-cohesive	3
Qpg	Quaternary	Pre-Fraser glacial gravel deposits	non-cohesive	2
Qpf	Quaternary	Pre-Fraser glacial deposits of stratified sand and gravel	non-cohesive	3
Qtb	Quaternary	Fraser and Pre-Fraser non-glacial deposits of clay, silt, and very fine to fine sand	cohesive and non-cohesive	2
Qs	Quaternary	Fluvial and lacustrine sand	non-cohesive	4
Qgi	Quaternary	Ice contact deposits	cohesive and non-cohesive	2
Qag	Quaternary	Alpine glacial deposits	non-cohesive	2
Tal	Tertiary	Alluvium	consolidated	2
T	Tertiary	All others	rock	1
K	Cretaceous	All	rock	1

Key:

1. Non-liquefiable rock or uniform clay
2. Predominantly non-liquefiable with potential for isolated pockets of loose granular soil
3. Typically non-liquefiable with potential for lenses of liquefiable sand and non-plastic silt
4. Predominantly liquefiable with potential for lenses of non-liquefiable clay
5. Liquefiable throughout the deposit

A site visit was conducted at 27 areas identified as having a potential for liquefaction. Twelve areas were selected for field investigation based on the site visits. Areas of low, moderate and high liquefaction susceptibility are shown on the geologic and hazard maps in Appendix B. The sites that were not investigated were sites where access was denied by the landowner (four sites), or where field observations were sufficient to refine the initial assessment (10 sites). One additional site was not investigated as it was an alternative route that was not proposed for the corridor.

Electric cone penetrometer tests (CPT) were conducted at the selected 12 locations along the alignment between July 23 1997 and August 12, 1997. In addition, soil borings were drilled at several stream, canal, and river crossings (Dames & Moore, 1996). The use of the CPT was selected because it has the advantage of being able to accurately delineate site stratigraphy and provide a continuous record of penetration and frictional resistance with depth. This information can then be used to obtain in-situ geotechnical parameters for an analysis of liquefaction potential. The approximate locations of the CPT tests are shown on the geologic and hazard maps in Appendix B. Where possible, the depth of penetration was taken to approximately 50 feet below the ground surface.

The CPT is conducted by pushing an instrumented cone-tipped probe into the ground at a constant rate on the end of a string of steel pipes. The following measurements were made during the cone penetration:

- Tip resistance of the advancing cone tip
- Soil frictional resistance along the cylindrical friction sleeve
- Pore water pressure at the face of the cone tip

Interpretation of the CPT data was conducted to yield information on site stratigraphy and correlate CPT bearing pressures to standard penetration resistance values (SPT-N) for use in the liquefaction analysis. The interpretation of the soil classification was based on the work of Robertson and Campanella (1989).

The seismic input for the liquefaction analysis was based on an event with a magnitude of 7.5 and peak ground accelerations (PGA) ranging from 0.1g to 0.3g. The Seed and Idriss (1971) analysis procedure for level ground was used to assess the liquefaction potential at each test location. The results provided a basis to update the susceptibility of the sites identified in the screening process.

To quantify liquefaction susceptibility a factor of safety (FS) against liquefaction was calculated as the ratio of the cyclic stress ratio (CRS(Q_t) necessary to cause liquefaction to the cyclic stress ratio (CRS(EQ)) caused by the earthquake. The CRS(Q_t) incorporate the site specific geologic data and the magnitude of the earthquake. The CSR(EQ) is calculated using the design PGA, the total and effective overburden stresses, and a depth correction factor. The Tokimatsu and Seed (1987) approach was used to compute the magnitude of the post-liquefaction settlement. Lateral ground displacement was estimated using the simplified empirical procedure developed by Bartlett and Youd (1994). The procedure was developed based on historical data from earthquakes where lateral ground displacements occurred. Table 2.15-3 summarizes the results of the liquefaction analysis.

TABLE 2.15-3
LIQUEFACTION SUSCEPTIBILITY

Liquefaction Area	Geologic and Hazard Map Page Number	Mile marker	Length of effected pipe (in feet)	Site reconaissance (ground or by air)	Field investigation	Liquefaction susceptibility	Lateral Spread	Settlement
1	5	E of 8 to W of 10	5500	Y	Y	4	Y	Y
2	8	16 / N of 17	1000	Y	N	2	N	N
3	14 - 16	32 to E of 38	30600	Y	Y	3	N	N
4	31	Between 72 & 73	2400	Y	N	1	N	N
5	37	E of 87	600	Y	N	2	N	N
6	43	Between 98 & 99	600	Y	NO ACCESS	1	N	N
7	44	Between 101 & 102	900	Y	N	1	N	N
8	45	E of 102	300	Y	N	1	N	N
9	46-47	105 to 107	12500	Y	N	1	N	N
10	47	E of 107	500	Y	N	1	N	N
11	47-48	N of 109 to N of 110	3200	Y	N	1	N	N
12	48	110	500	Y	N	1	N	N
13	53	125 to 127	1500	Y	Y	1	N	N
14	55	128 to E of 129 / 128 to W of 131	Primary-2400	Y	Y	1	N	N
15			Alternate-9100			1	N	N
16	78	E of 177	1500	Y	NO ACCESS	1	N	N
17	78	W of 178	1000	Y	NO ACCESS	1	N	N
18	79	W of 179	2000	Y	Y	1	N	N
19	79	E of 179	1500	Y	N	1	N	N
20	83-84	189 to 190	8800	Y	Y	1	N	N
21	84-85	191 to 193	8400	Y	Y	1	N	N
22	86	Between 194 & 195	No pipeline intersect	Y	NO ACCESS	1	N	N
23	88-89	201 to N of 203	8000	Y	Y	1	N	N
24	89-90	S of 203 to S of 204	5100	Y	Y	1	N	N
25	91 - 92	N of 207 to S of 209	15000	Y	Y	1	N	N
26	93 - 96	211 to 218	35000	Y	Y	1	N	N
27	96 -100	219 to 227	40000	Y	Y	1	N	N

Based on the results of the screening analysis and preliminary field investigations, most of the pipeline alignment traverses soil deposits of low susceptibility to liquefaction. The only identified area of potential liquefaction is the Snoqualmie River Valley crossing shown on page 5 of the geologic and hazard maps in Appendix B. At this location a non-liquefiable surface deposit overlies a potentially liquefiable soil layer. However, the surface layer is not thick enough to prevent potential ground level liquefaction damage (Ishihara, 1985). Lateral spreading and post liquefaction settlement are also possible but are estimated to be less than one foot and 5 inches, respectively. The thickness of the overlying non-liquefiable layer in Zone 3 is sufficient to prevent surface damage and therefore damage to the pipeline should liquefaction occur is not likely (Ishihara, 1985).

0.1.2.4 Protection Measures Against Liquefaction

The area the pipeline traverses across the Snoqualmie River Valley is a flood plain and the pipeline will be encased in concrete or weighted with river weights as a mitigation measure to prevent buoyancy of the pipeline should liquefaction occur.

Should site conditions during construction be different from those anticipated, mitigative measures will be implemented according to site specific conditions. For example, mitigation measures will consider the degree of hazard, the soil and groundwater conditions at the site, the topography of the site relative to the pipe orientation, constructability issues, and other factors.

Examples of accepted construction practices that would be considered to mitigate the impact due to liquefaction are provided below.

Buoyancy compensation: Steel pipes filled with petroleum products are typically buoyant in liquefied soil. In areas where liquefaction is possible but lateral spreading is not a significant concern, the pipeline can be weighted with river weights to achieve negative buoyancy. Alternatively, the pipeline can also be encased in concrete, achieving the same effect. Typically, enough weight is added to assure that the pipe will not float if the surrounding soil liquefies.

Deep burial: The pipeline can be installed in non-liquefiable deposits that underlie loose surficial deposits. Increased burial depth will isolate the pipeline from potential displacement of the susceptible overlying layers.

Above-grade support: Where the depth of potential liquefaction exceeds the practical pipe burial depth, it may be feasible to lay the pipe on saddles supported by piles or piers designed to resist lateral loads. Typical pier designs consist of 24 to 36 inch diameter reinforced concrete piers with restraining saddles supporting the pipe. The piers would extend into non-liquefiable soils at depth and would have adequate capacity to resist lateral loads and allow liquefied soils to flow beneath the pipe.

Removal and replacement Liquefiable materials surrounding the pipe can be removed and replaced with compacted fill. The extent of replacement will be determined based on site conditions, but will generally extend several feet to each side of the alignment and down to non-liquefiable soils.

In-situ densification Potentially liquefiable soils can be densified in place where the depth of the susceptible layer exceeds practical excavation depths. In-place densification methods include vibroreplacement (stone columns), heavy tamping, grouting, and other variations. The method, extent, and depth of in-place densification will depend on site topography and soil composition.

0.1.3 VOLCANIC HAZARD

The region contains major composite volcanoes and one area of extensive basaltic shield volcanoes which have been active within the last 2 million years and in some cases, active within the last 10,000 years. The volcanoes are part of the volcanoes of the Cascade Mountains which extend from Mount Garibaldi in British Columbia to Mount Lassen in California (Harris, 1980). Figure 2.15-2 shows the six major volcanoes that could be considered potentially hazardous to public works in Washington and Oregon (Waldron. 1989). Five of the volcanoes have experienced activity within historic time. These are Mount Baker, Mount Rainier, Mount Hood, and Mount St. Helens. Mount Rainier is closest of this group to the project area, lying within 35 miles of the nearest point of the pipeline corridor.

FIGURE 2.15-2 - MAJOR VOLCANOES IN THE CASCADE RANGE

0.1.3.1 Impact of volcanic activity

Impacts to the pipeline, pump stations and terminals from volcanic activity can be either direct or indirect. Direct impacts include the effects of lava flows, blast, ash fall and avalanches of volcanic products (Waldron, 1989). Indirect effects include mudflows, flooding and sedimentation (Waldron, 1989). Figure 2-15-3 shows the hazard zones for the six major volcanoes in the region.

FIGURE 2.15-3 - VOLCANO HAZARD ZONES

With the exception of ash fall, direct effects are localized and confined to the immediate vicinity of the volcano and will not impact the pipeline or the operation of pump stations and terminals. Because the Cascade Range volcanoes are generally covered with snow and ice the most probable impact will be from mudflows and floods created during a volcanic eruption within a defined watershed. For example, in the case of the 1980 eruption of Mount St. Helens, mud flows moved 3 billion cubic yards of material as far as 17 miles down the Toutle River valley (Cummans, 1981).

The greatest potential impact of volcanic activity to the proposed pipeline facilities is the ash carried aloft during the eruption. Data from the eruption of Mount St. Helens in 1980, indicate that up to a 1/4 inch of ash was deposited as far away as Missoula, Montana, a distance of almost 400 miles (Folsom and Quinn, 1980). Contours of ash fall thickness from the Mount St. Helens eruption is shown in Figure 2.15-4.

FIGURE 2.15-4 - DISTRIBUTION AND THICKNESS OF MT. ST. HELENS 5/18/80 TEPHRA

Ash fall from a volcanic eruption will not adversely impact the proposed buried pipeline. However, the abrasive ash can be harmful to machinery, especially engines or any other aspirated equipment, and in severe ash falls can completely bury facilities under many feet of material (Dion and Embrey, 1981). The ash is also relatively inert so chemical impact on watersheds is minimal (Dion, and Embrey, 1981). The prevailing winds of the region are westerly. Therefore, ash fall impacts are most likely to occur east of the Cascade Range and studies show that there will be a pronounced and rapid decrease in ash thickness with increased distance from the source (Crandell and Mullineaux, 1978).

The pipeline route lies within 35 miles of Mount Rainier and so has the potential to be affected by future eruptions of this and other Cascade Range volcanoes. Ash fall would be the most likely hazard to affect the route and based on measurements of past eruption events of Cascade volcanoes, could amount to 6 to 8 inches of ash accumulation. The second most likely effect would be river-borne mud flows and floods. Mud flows from past eruptions of the volcano have not affected the Snoqualmie River or Yakima River, the only major river crossings along the pipeline alignment adjacent to and within the Cascade Range (Crandell, 1976). It is therefore unlikely that mud flows from future eruptions will present a significant hazard to the pipeline.

0.1.3.2 Protection Measures Against Volcanic Activity

Direct or indirect effects of volcanic activity from Cascade Range volcanoes are not anticipated to adversely impact the proposed pipeline, pump stations, and terminals. Therefore no specific protective measures are planned. In the event of a volcanic eruption, protective measures against ash fall would not be necessary during the operation of the pipeline. During the eruptions of Mount St. Helens, fuel deliveries to Portland on the existing OPL mainline in western Washington were not interrupted. As a good engineering practice, the proposed pump station facilities along the pipeline will be equipped with air filtration systems. In the event that ash fallout from a volcanic eruption reaches the pipeline facilities and begins to adversely impact operations, the pipeline system would be shut down until safe operating conditions return. If an eruption occurred during construction, a temporary shut-down would most likely be required to protect equipment and human health.

0.1.4 FLOOD, IMPACTS AND PROTECTIVE MEASURES

Twenty-three of the pipeline crossings have defined floodplain boundaries based on the 100-year flood, which has a 1 percent annual chance of occurring. Most watercourse crossings of the pipeline will be installed below the stream channel, thereby avoiding high water level effects during flooding. The pipeline will also have a protective outer casing to minimize the effect of any streambed erosion that might occur during flooding and to reduce the risk of buoyancy. Increased pipe wall thicknesses will be employed as a good engineering practice to maintain pipeline stability.

The North Bend Station is located within the 100-year floodplain of the Snoqualmie River. Measures will be taken during the design and construction of the facilities to protect the site during flood events by using containment berms, dikes, or other measures. The remaining buildings and other facilities are not located in or adjacent to floodplains.

0.1.5 TSUNAMI, IMPACTS AND PROTECTIVE MEASURES

Tsunamis are exceptional ocean waves that are the result of submarine or nearshore seismic events. Such waves can have a greatly adverse impact on coastal installations. The pipeline origin at the Thrasher Station lies at an elevation of over 400 feet above mean sea level, approximately 7 miles southeast of Puget Sound. As a result, increased water levels due to tsunamis could not reach the site.

Sieches could potentially reach the pipeline corridor in the vicinity of Lake Keechelus and the Columbia River. Sieches are long-period movements of water in lakes and reservoirs produced by earthquakes or strong winds. There are no pump stations or terminals proposed at either the Lake Keechelus and Columbia River locations. It is also extremely unlikely that a sieche event would adversely impact a buried pipeline. Therefore, no mitigation of earthquake-generated waves is warranted.

0.1.6 STORMS, IMPACTS AND PROTECTIVE MEASURES

The Kittitas Terminal buildings and storage tanks will be constructed in accordance with current building codes and designed to withstand wind and rain conditions associated with a 100-year storm event. Erosion and sedimentation control measures will be incorporated in all stages of construction and operation, and will also be designed, when appropriate, for the 100-year event. See Section 2.10 for a description of erosion and sedimentation control measures.

0.1.7 AVALANCHES OR LANDSLIDES (MASS WASTING)

Avalanches are the rapid downward mass movement of accumulated snow and/or ice caused by gravity. In contrast, landslides (shallow and deep) are the downward mass movement of soil and/or rock caused by gravity and can occur rapidly or be ongoing over a period of time. Both avalanches and landslides can be initiated by changing conditions over time, during storm events or by strong ground shaking. Avalanches and landslides will be referred to as mass wasting.

The stability of soil and rock slopes is directly related to the physical characteristics of the soils and underlying bedrock. The mechanics and rate of slope movement are controlled by a variety of factors, including: slope gradient, overburden depth, engineering properties, bedrock properties and groundwater conditions. There are primarily six types of mass movement processes within soils and rock on steep terrain in the Pacific Northwest: falls, creep, slumps and earthflows, debris avalanches and debris flows, debris torrents, and bedrock failures. Falls are the movement of soil and rock through air by free-fall, leaping, bounding, or rolling. Falls are relatively rapid mass movements (e.g., from feet per minute to feet per second). Creep is the slow downslope movement of overburden. Creep rates are relatively slow (e.g., inches per year). Slumps include the rotation of a block of overburden over a generally concave plane. Earthflows are the flow displacement of blocks of overburden. Debris flows or torrents are rapid downslope movements of soil, rock, organic debris, and water. Mass movement susceptible materials are found throughout Washington and are commonly found on relatively steep slopes within drainages.

0.1.7.1 Potential Impacts Due to Mass Wasting

Mass wasting has the potential to adversely impact both the construction and operation of the pipeline. Possible impacts include the movement of soil into excavations during installation, the movement of soil onto the pipeline after installation, and/or the loss of foundation support after installation. Impacts due to mass wasting have been identified for portions of the proposed pipeline route. As a best engineering practice, the proposed route and related facilities generally avoid areas with known potential for mass wasting where possible. However, portions of the pipeline corridor cross slopes which have been mapped as having moderate to high potential for mass wasting and could impact the pipeline. During design and construction, protective measures will be implemented to reduce the risk of pipeline damage in the event of mass wasting. The pipeline pump stations and Kittitas Terminal are not located in areas with mass wasting potential (see geologic and hazard maps in Appendix B).

A screening procedure was used to create an inventory of possible locations along the pipeline corridor for mass wasting potential. The screening procedure consisted of an office study of air photographs, geology, and topography followed by field reconnaissance to selected sites. The potential for slope failure and potential impact on the pipeline was assessed using the angle of the slope, the soils or rock underlying the slope and groundwater conditions.

In general slopes less than 15 percent were considered stable. Slopes of 15 to 30 percent and believed to be stable under normal conditions but with the potential for failure if disturbed without using proper engineering practices were characterized as having a moderate impact potential. High impact potential was assigned to slopes in areas with geologic evidence of slope instability, such as slopes in excess of 30 percent or known areas of inactive slope failures, or have soil/rock types susceptible to failure which require geologic and engineering assessment prior to development. In addition, unstable land as evidenced by recent or active slope failure and generally incapable of accommodating development without increasing stability was also given a high impact potential.

The pipeline will be buried with a minimum depth of cover of 36 inches below the ground surface throughout its length and an average depth of cover of 48 inches. Slope instability affecting less than three feet in depth below the ground surface at the pipeline location will not have a significant impact on the pipeline. For deep-seated sliding pipeline rupture is a possibility. Therefore, a factor in quantifying the impact of mass wasting on the pipeline is to identify the potential depth of slope movement.

The geologic and hazard maps located in Appendix B identify areas of moderate and high mass wasting potential. Table 2.15-4 presents an inventory list of locations that were identified through the initial screening based on slope and geologic units. Subsequent field and aerial reconnaissance aerial photographic interpretation and field investigations were used to refine the inventory to determine the need for protective measures.

TABLE 2.15-4
MASS WASTING INVENTORY

Atlas page	Stream crossing	Slope height (feet)	Slope angle	Pipeline orientation to slope			Geologic Unit[c]	Field visit	Field	Existing Landslides		
				Perpendicular	Parallel	Position on Slope			Investigation	Dormant Deep	Active shallow[a]	Active deep[b]
4	E of 9	100	3H:1V	x			Qgt	yes	soil boring			
5	W of 11	200	5H:1V	x			Qgt	yes	shovel & visual			
5	12&13	150	2.5H:1V	x			Qgo	yes	soil boring			
6	14&15	200	2.5H:1V	x			Qgt	yes	soil boring		x	
8	20	100	3.5H:1V	x			Qgt	yes	soil boring		x	x
8	21	100	3H:1V	x			Qgo	yes	area visual			
11	NW of 26	200	5H:1V	x			Qgo/Qpf	yes	shovel & visual			
11	SW of 27	300	3H:1V	x			Qls	yes	visual			x
12	N of 28	150	3H:1V	x			Qpf/Qgo	yes	soil boring			
12	S of 28	300	3H:1V	x			Qpf/Qgo	yes	soil boring			
14	37	100	8H:1V		x	near toe	Qpf	yes	soil boring			
17	N of 44	150	2.5H:1V		x	mid-height	Qgt	yes	soil boring			
17	S of 44	100	2H:1V	x			Qgi	yes				
18	46 to 49	600	2H:1V		x	mid-height	Tv/Qgo	yes	visual			
18	45&46	150	1.5H:1V		x	mid-height	Tg/Qgo	yes	visual			
19	50 to 56	<600	2H:1V		x	toe	Tg/Qgo	yes	shovel & visual			
20	59 to 61	700	2H:1V		x	lower	Tg/Qls	yes	shovel & visual	x		
21	63	>400	2.5H:1V		x	lower	Qa	yes	visual			
21	67	>400	2.5H:1V		x	lower	Qa	yes	visual			
21	68	<500	2H:1V		x	lower	Qgo	yes	visual			
23	W of 78	>500	2.5H:1V		x	toe/lower	Tg/Qa	yes	hand auger			
23	E of 78	>500	2H:1V		x	lower	Tg/Qa	yes	aerial			
24	E of 83	>500	2H:1V		x	lower	Ts	yes	aerial			

TABLE 2.15-4 (CONTINUED)
MASS WASTING INVENTORY

Atlas page	Stream crossing	Slope height (feet)	Slope angle	Pipeline orientation to slope			Geologic Unit[c]	Field visit	Field	Existing Landslides		
				Perpendicular	Parallel	Position on Slope			Investigation	Dormant Deep	Active shallow[a]	Active deep[b]
25	N of 85	300	1.75H:1V		x	toe	Ts/talus	yes	aerial			
26	92 to 93	<600	3H:1V		x	toe	Ttu/Tv/Avl	yes	aerial			
26	N of 94	<500	2H:1V		x	toe	Ttu	yes	aerial			
30	114	<300	3H:1V		x	toe	Tn/Trh/Qls	yes	aerial	x	x	
31	W of 115	200	3H:1V		x	toe	Qls	yes	aerial & visual	x		
37	E of 134	<200	6H:1V		x	lower	Qf/Qls	yes	hand auger	x		
38	W of 135	>200	5H:1V		x	lower	Qls	yes	hand auger	x		
41	W of 145	250	3H:1V		x	toe	Qls	yes	hand auger	x		
41	W of 147	200	3.5H:1V	x			Qls	yes	soil boring	x		
42	147&148	200	7H:1V	x			Qls	yes	hand auger	x		
42	E of 148	800	2H:1V	x			Tb	yes	aerial & visual		x	
43	W of 151	550	2.5H:1V	x			Tb/Qls	yes	aerial	x		
43	E of 152	650	3H:1V	x			Tb	yes	aerial			
43	152-153	200	3.5H:1V	x			Tb	yes	aerial			
44	E of 156	100	3H:1V	x			Tal	yes	hand auger			
45	157	100	3H:1V	x			Tal	yes	hand auger			
61a/62a	Alt 14	500	5.5H:1V		x	toe	Qls	yes	aerial	x		
82	255	>100	5.5H:1V		x	lower	Tb	yes	aerial			
The following Mass Wasting locations were found on alternative pipeline routes and are not located within the proposed route.												
61	9a	100	10H:1V	x			Qls/Tb	yes	aerial	x		
61	Alt 3	300	7.5H:1V		x	head	Qls/Tb	yes	aerial	x		
61	Alt 13	350	4.5H:1V		x	head	Qls/Tb	yes	aerial	x		
62/62a	Alt 13	550	8H:1V	x			Qls	yes	aerial	x		
62a	16b-16g	300	7.5H:1V		x	mid-height	Qfg	yes	aerial			
62b	N of 16a	400	3H:1V		x	mid-height	Qfg	yes	aerial			
63a	SE of 24e	400	5H:1V	x			Qfg/Tb	yes	aerial			
78a/79	E of 246	>300	2.5H:1V		x	toe	Qls	yes	aerial	x		
80a	250-251	>300	6H:1V		x	mid-height	Ql/Tri	yes	aerial			
86 & 87	S of 261	>100	3H:1V		x	upper	Qls/Qfg/Tb	yes	aerial		x	x

[a] less than 10 feet deep
[b] greater than 10 feet deep
[c] see geologic and hazard map legend for geologic unit definitions
aerial - visual aerial survey via helicopter

Only one avalanche chute has been identified near the pipeline route west of Lake Keechelus (see geologic and hazard maps, page 26, Appendix B). The existing chute terminates above the proposed pipeline route.

However, avalanches are not anticipated to have the potential to adversely impact pipeline operations due to the proposed burying of the pipeline. However, the presence of snow along the alignment would hamper access to the pipeline in the event of a rupture and/or a leak. Open slopes within the Cascade Mountains, where winter-time precipitation in the form of snow can be substantial, are especially susceptible to avalanches and could present an impact to construction operations if the pipeline were to be installed in areas of avalanche hazard during the winter months. Therefore, construction of these segments will be avoided during periods of high avalanche danger or the avalanche hazards will be removed or controlled prior to construction.

The original pipeline alignment crossed the toe of the Corfu Landslide (MP 174 to MP 177, Geologic and Hazard Maps, page 78a - 80a, Appendix B)(Geomatrix, 1990). The feature is believed to represent catastrophic slope failure caused by undercutting and saturation of surface sediments by the Bretz Floods. The majority of the landslide deposits are believed to have been swept away by subsequent flood events, and the clay-rich sediments of the Crab Creek channel may be reworked landslide debris. Later landslides are identifiable in aerial photographs, some of which form debris cones at the present base of the slope.

The proposed pipeline alignment now crosses the Saddle Mountains to the east of the Corfu Landslide where evidence of mass wasting is not present. Geological conditions for this segment are not unlike the Corfu Landslide area. Rapid erosion of downslope areas, resulting in oversteepening of slopes and subsequent mass movement events, is possible along the entire north slope of the Saddle Mountains.

0.1.7.2 Protective Measures Against Avalanche and Landslides

Table 2.15-5 provides a mass wasting hazard assessment and lists specific protective measures for the sites requiring mitigation. To select protective measures to minimize inputs due to mass wasting, categories of impact potential was defined and assigned to each site. The categories of impact potential are defined are as follows:

<u>High Impact Potential</u>

1. Recent landslide activity
2. Active fluvial processes at slope toe
3. Soil slopes steeper than 1H:1V (horizontal:vertical)
4. Incised drainage crossing proposed pipeline route
5. Rock slopes with adversely oriented discontinuities and slope angles
6. Source of concentrated surface water flow above or on slope and shallow groundwater (<5 feet below ground surface)
7. Mapped or inferred geologic fault coincident with other high risk slope conditions

During the final design phase prior to construction, sites identified as having a potential for a high level of impact for future mass wasting due to the above factors will be studied in additional detail. These studies would include a site-specific geotechnical investigation and slope stability analyses to determine the most likely mode of failure and the factor against failure. The results of these investigation may indicate the need for improvements to the site to protect the pipeline from damage due to slope failure. Potential mitigation options could include improving the soil strength properties, adding structural elements to externally retain the slope, changing the geometry of the slope, or rerouting the pipeline. A final decision on the mitigation measures and design will be made prior to construction.

Moderate Impact Potential

1. Pre-historic landslide activity with no evidence of recent movement
2. Soil slopes between 1H:1V and 3H:1V
3. Rock slopes steeper than 1H:1V
4. Shallow groundwater (<5 feet below ground surface)
5. Flat gradient drainage at the slope toe

Sites classified as having a moderate risk for future mass wasting may be studied further, but only if they exhibit factors which are judged to be significant during construction. Additional investigations for sites in this category would include limited characterization of the surface and subsurface conditions and limited slope stability analyses. It is anticipated that these additional studies would confirm that no mitigation of these slopes would be required.

Low Impact Potential

1. No prior history of landslides or pre-historic landslides with all following criteria
2. Soil slopes flatter than 3H:1V
3. Deep groundwater
4. Rock slopes flatter than 1H:1V
5. Absence of fluvial processes on or at toe of slope

Sites classified as having a low risk for future mass wasting will not be studied any further. These sites lack recent landslide activity, steep slopes, or fluvial activity at the slope base associated with higher risk sites. These sites may include pre-historic landslide deposits which currently have shallow to moderate slopes and which are sitting on stable deposits/geomorphic surfaces at the slope toe.

Table 2.15-5 summarizes the results of the mass wasting hazard assessment and the mitigation measures that have been identified at this point. Three sites of particular importance have been identified as having a potential for a high level of impact for future mass wasting due to such factors as steep slopes, evidence of ongoing slope movement, or significant pre-historic landslides which have a high potential for future re-activation. These sites are the south slopes of the Cherry Creek (map page 8, stream crossings 20 and 21) and Tolt River drainages (map page 11, southwest of Stream Crossing #27) and an area west of the

Columbia River (map pages 61a and 62a, Route Segment #14). The Tolt River drainage sites will include a site-specific geotechnical investigation prior to construction when the project is approved. A final decision on the mitigation measures will follow completion of the detailed site investigation.

The site near Cherry Creek and the mass wasting area on the west side of the Columbia River will be mitigated through increasing the depth of burial and installing diversion berms on the slopes.

TABLE 2.15-5
MASS WASTING HAZARD ASSESSMENT

Geologic and Hazard Map Page	Stream crossing or alternative route	Hazard Potential		Mitigation Measures						
		Shallow Failure[a]	Deep Failure[b]	Avoidance	Strain gage pipe	Long Term monitoring	Drainage	Buttress	Increase burial depth	Additional exploration for design
4	E of 9	L	L							
5	W of 11	H	L				x		x	
5	12&13	M	M				x	x		
6	14&15	H	L				x	x	x	
8	20&21	H	L			x	x	x	x/x	
11	NW of 26	M	M							
11	SW of 27	H	H		x	x	x			x
12	N of 28	M	L						x	
12	S of 28	M	L						x	
14	37	H	M				x	x	x	
17	N of 44	M	L						x	
17	S of 44	M	M						x	
18	E of 44	M	L						x	
18	45&46	H	L				x	x	x	
18	46 to 49	M	L						x	
19	50 to 56	L	L				x			
20	59 to 61	L	L							
21	61 to 67	M	L				x			
21	67 to 69	M	L				x			
23	W of 78	L	L							
23	E of 78	M	M							
25	N of 85	M	L							
26	93 to 95	L	L							
30-31	113 to 116	M	M						x	
37-38	133 to 136	M	L				x	x	x	
41	W of 145	M	L				x	x	x	
41	W of 147	H	M				x	x	x	
42	147&148	L	L							
42	E of 148	M	L						x	
43	150 & 151	H	L	x						
43	151 to 153	M	M							
44	E of 156	L	L							
45	157	L	L							
61a/62a	Alt. Segment 14	L	M	x					x	
82	255	L	L	x						

TABLE 2.15-5 (CONTINUED)
MASS WASTING HAZARD ASSESSMENT

The following Mass Wasting locations were found on alternative pipeline routes and are not located within the proposed route.										
61	9a	L	L	x						
61	Alt 3	L	M	x						
61	Alt 13	L	M	x						
62/62a	Alt 13	L	M		x	x		x		
62a	16b-16g	L	L							
62b	N of 16a	L	L							
63a	SE of 24a	L	L							
78a/79	E of 246	alignment	rerouted	x						
80a	250-251	alignment	rerouted	x						
86 & 87	S of 261	alignment	rerouted	x						

[a] less than 10 feet deep
[b] greater than 10 feet deep
WRT = With Respect To: H = High, M = Moderate, L = Low

The mitigation measures recommended in Table 2-15-5 have been selected based on the information available at the time of this application. During design and construction, other alternatives may prove to be better choices depending on site specific conditions. The final mitigation measures implemented will depend on many factors, including the scale of the hazard, the magnitude of the forces required to stabilize the site, ground conditions and constructability considerations. Alternative mitigation measures other than those identified in Table 2-15-5 will be selected only if they provide an equal or greater level of protection to pipeline for the hazard. The following are brief descriptions of the proposed mitigation measures.

Avoidance: Where possible, the pipeline alignment has been moved away from mass wasting locations identified as moderate and high hazards.

Reorientation of Pipeline Against Slope: The pipeline can be oriented from parallel to perpendicular to the fall line (and any intermediate orientation) in either of these two situations:

- Shallow (< 10 feet) movement, either episodic (landslides) or continual (creep); or
- Deep-seated (> 10 feet) episodic movement.

Strain gauge pipe: Monitors induced compression and tension stresses caused by soil movement impacting the pipeline. Serves as an early warning indicator to implement to allow active mitigation measures to be implemented, e.g., closing block valves, trench excavation for stress relief.

Long term monitoring: Installation of instrumentation (e.g., inclinometers, extensometers) to measure ground displacement. Frequency of monitoring to be adjusted according to weather conditions, but will not be greater than one month. Instruments could be read manually or connected to a automated data acquisition system.

Drainage: Diversion of surface and subsurface water. Example of options to improve drainage included; horizontal drains, dewatering wells, trench bedding of with free-draining materials, and rerouting of surface drainage courses. Drainage can be a stand-alone option of used in conjunction with other slope stabilization methods.

Buttress: Increase resistance to slope movement by installing a buttress at the toe of the slope (e.g., retaining wall, rip rap). Buttressing could be used alone or in conjunction with other slope stabilization methods.

Regrade: Flattening slope grades to reduce driving forces tending to cause slope instability. Regrading can be used alone or in conjunction with other slope stabilization methods.

Increase depth of burial: Where potential slope instability is possible to depths of 10 feet or less, increasing the pipe burial depth will place the pipeline below failure surface. The pipeline will be buried approximately five feet below the ground surface across these areas of concern. Slope instability affecting less than five feet in depth below the ground surface at the pipeline location will not have a significant impact on the pipe. Therefore, a key to identifying the relative hazard for the first type of slope instability is to identify the potential depth of slope movement. For the second case, evidence of previous deep-seated sliding would be the key to identifying this type of hazard.

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