Oil and Water System Performance – Denali M 7.9 Earthquake of November 3, 2002

By John Eidinger[1] and Mark Yashinsky[2]

1.0 Introduction

The November 3, 2002, magnitude 7.9 Denali, Alaska earthquake struck through rural Alaska. Fortunately, no one was seriously injured, due to the small population located within 30 miles either side of the fault.

The Denali earthquake provides an opportunity to study how lifelines perform in an area of the world where the typical design is often governed by mitigation for frost heave. Of particular interest is the performance of the Trans-Alaska Pipeline System (TAPS). The TAPS 1973-vintage steel pipe was exposed to 14 feet of right lateral fault offset (18 feet by one survey), coupled with high levels of inertial forces, a high velocity pulse, and liquefaction-induced lateral spreads. This earthquake-engineered pipeline survived the earthquake with no rupture of its pressure boundary and no oil spill, although some pipe supports suffered repairable damage. The most serious damage was to roads and airports. Water systems were modestly affected. This report summarizes the performance of the TAPS and water systems in this earthquake.

A more comprehensive report, covering the locally severe damage to highways, bridges, airports and other lifelines is available from Mark Yashinsky (Caltrans). Hardcopy published versions of this material may also be available from EERI and ASCE. Electronic copies with photos and maps of this limited report or the more comprehensive report may be obtained by contacting the authors.

Alaskans living in the vicinity of this earthquake tend to be self-sufficient. They get water from privately-owned wells, get heat from fuel-oil furnaces, cook their meals on propane-fired stoves, and deposit their waste into individual septic systems. Fortunately, just one person was injured by the main shock (a broken arm).

In remote and low-density population areas of the world, the cost of high-quality construction is usually not justified. However, when protecting the environment and a high value product (such as for the TAPS oil pipeline), then the higher expense for those lifelines is justified, and this earthquake proved this point.

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The region of strong ground shaking from this earthquake is populated by towns (Tok, Glenallen, Delta Junction) of a few thousand people each, Athabascan villages (Mentasta, Slana, Tetlin) of several hundred people each, and by widely-disbursed, single-family homesteads.

1.1 Key Findings

The November 3, 2002 Denali, Alaska earthquake was of keen interest to geologists, glaciologists, and seismologists. The earthquake ruptured on three faults, one of which was unknown. There were large surface fault offsets through land as well as across the surface of glaciers. Our current concepts about fault rupture propagation, surface faulting, and rupture directivity were enhanced by this earthquake.

One most important finding for engineers was that by careful planning and continual maintenance, an important lifeline like the Alyeska pipeline could be designed to survive a 14 foot (18 feet by one survey) fault offset. This has practical applications to owners of pipelines whose facilities must cross over active faults.

There was also information gained about earthquakes striking cold regions. An earthquake occurring in winter can result in additional damage in the spring. Landslides can redirect frozen rivers causing flooding with warmer weather. Frozen soils can settle in the spring, toppling structures. Facilities located at sites with good resistance to frost heave can experience liquefaction-induced damage in earthquakes.

1.2 Acknowledgements

The editors of this report would like to thank the many Alaskans for their support during site visits and for data that was collected. We would like to thank all the contributors, a few of whom include Elden Johnson of the Alyeska Pipeline Services Company who provided photographs and data for the section on the pipeline. Many other Alaskans contributed their time, recollections and photographs, and we sincerely thank them. We also wish to thank the American Society of Civil Engineers, which has generously supported this investigation as well as the many other investigations conducted by the Technical Council on Lifeline Earthquake Engineering. In this way, we hope to advance the state-of-the-practice for lifeline engineering.

Many of the figures and tables in this report include acknowledgements to the agencies that provided the information. Those figures or tables without a specific reference were developed by Mark Yashinsky or John Eidinger.

1.3 Abbreviations

ASCE	American Society of Civil Engineers
g	acceleration of gravity (1g = 32.2 feet / second / second)
MP	Mile Post

PGA	Peak Ground Acceleration
TAPS	Trans-Alaska Pipeline System
USGS	United States Geological Survey
VSM	Vertical Support Member

1.4 Approach to Investigation

The findings presented in this report are based on a field reconnaissance effort byMark Yashinsky and John Eidinger, as well as from numerous accounts provided by various Alaska agencies.

The team arrived in Fairbanks on December 16, 2002. Meetings were held in Fairbanks with the Alyeska pipeline service company and the Fairbanks-based water, wastewater and electric power agencies. The team visited the epicentral region, driving along all the major roadways, and meeting with various highway, airport, telecommunications, electric power, and emergency response officials in the area.

2.0 Seismology and Geotechnical Issues

The chief geologic feature in the earthquake-affected region is the Alaska Mountain Range formed by the movement of the Wrangle Subplate against the North American Plate (Figure 2.1). The resulting stresses from this plate movement produced the southeast trending Denali and Toschunda right-lateral faults.

The Alaska Range is slowly being eroded by glaciers that deposit silts and gravel onto the mountains' flanks. This material is further eroded by rivers and streams. Wind-blown loess blankets the hills in these river basins. Much of the silt is carried to valley bottoms, incorporated with organic debris, and subsequently frozen and occasionally thawed.

Soil typically becomes warmer with depth. However, in cold regions a layer of soil (called permafrost) may remain frozen throughout the year. Where permafrost exists, the top several meters of soil may experience considerable temperature variation.

In the late Quaternary, more loess was deposited on the hills and valleys of the upland. Organic silts accumulated in valley bottoms, became frozen and large ground-ice masses formed. About 5,000 to 6,000 years ago a slight warming of the climate caused a small amount of the permafrost to thaw. Since then, additional loess and organic silt have been deposited and the cooling of the climate has caused the organic silt in valley bottoms to become perennially frozen. Above this permafrost is the more recently deposited sands and gravels.

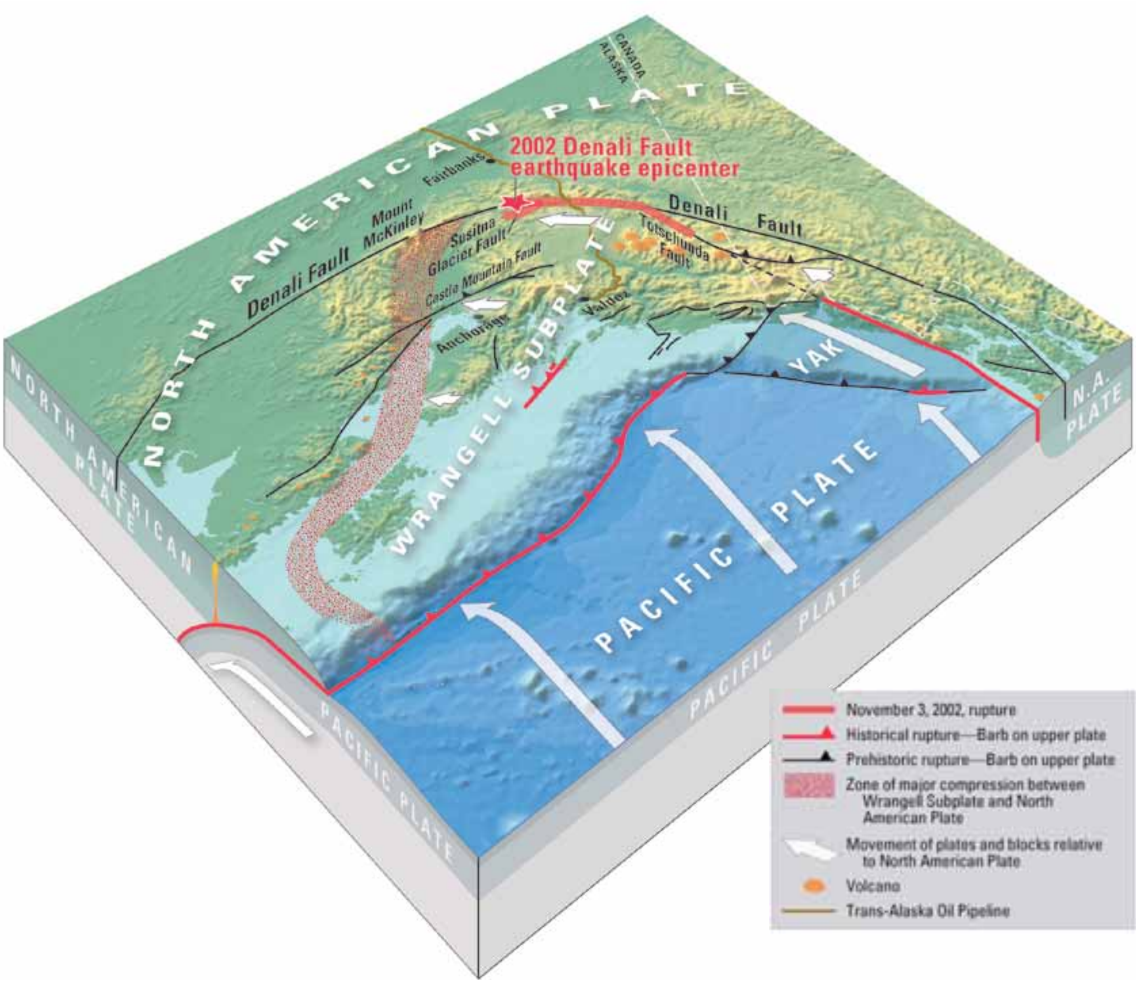

Figure 2.1. Plate Movement in Southern Alaska (Drawing Courtesy of the USGS).

In most cold regions with alluvial soils, the most common geologic hazard is the effect of frost heave. Silts and clays are the most susceptible soils to frost heave, and heaves of piles driven into such soils have sometimes reached more than 10 feet. The subsequent spring thaw causes loss of strength of these soils and excessive settlements. Given the difficult nature of such soils to frost heave, Alaskans have found that building on sands and gravels to be a better way to deal with cold weather issues. Since earthquakes are rare, the implications as to earthquake-induced liquefaction are often not fully addressed.

At the time of the earthquake, the top foot (or so) of soil was frozen, while the underlying several feet (up to a few meters) of alluvial material remained thawed due to the unseasonably late onset of cold winter weather. This left sandy soil highly vulnerable to ground shaking induced liquefaction.

A magnitude 7.9 earthquake occurred at 1:13 P.M. local time on Sunday, November 3, 2002 in south-central Alaska. This was a complex earthquake consisting of at least two sub-events. The initial rupture occurred at latitude 63.520N, longitude 147.530W, and at a depth of 5 km on the previously unknown Sustima Glacier (thrust) Fault (Figure 2.2). The rupture continued to the southeast for 300 km along the Denali Fault and continued onto the Toschunda Fault. The rupture broke the ground surface west of the Richardson Highway with a right lateral offset of about 3 m and increasing to a maximum offset of almost 9 m. This was the largest earthquake ever recorded in Alaska's interior. The earthquake was preceded 10 days earlier by the magnitude 6.7 Nenana Mountain earthquake.

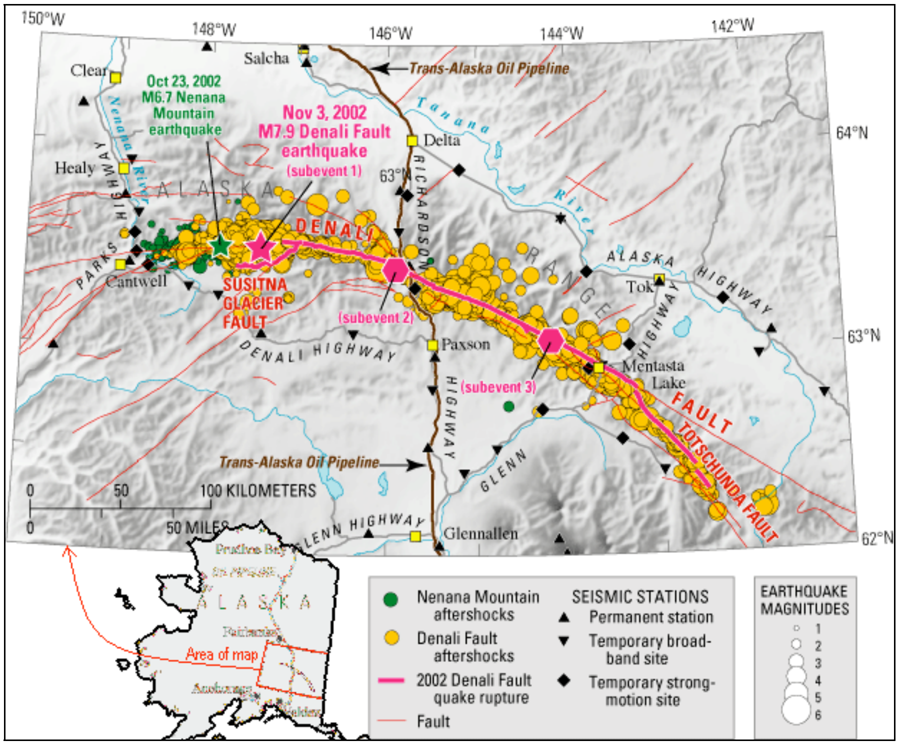

Figure 2.2. Map showing fault rupture and other significant features of two earthquakes (USGS)

A ShakeMap was created based on recordings (Table 2.1) and also using the Modified Mercalli Intensity Scale (Figure 2.3). The PGA contour lines form an ellipse with the fault rupture as the principal axis.

The ground motion data in Table 2.1 is based on available information as of December 2002. The latitude and longitude data is for the location of the instrument. The distance, in kilometers, is between the earthquake epicenter and the instrument. Further information about the types of sensors and the style of data processing for Table 2.1 is available from http://nsmp.wr.usgs.gov/recent_events/20021103_2212_peaks.html.

Soon after the earthquake, there was quite a bit of speculation that the ground motions appeared to be stronger at perpendicular distance from the fault rupture to the east of the epicenter than to the west of the epicenter. This speculation could not be verified by the damage observed to lifelines.

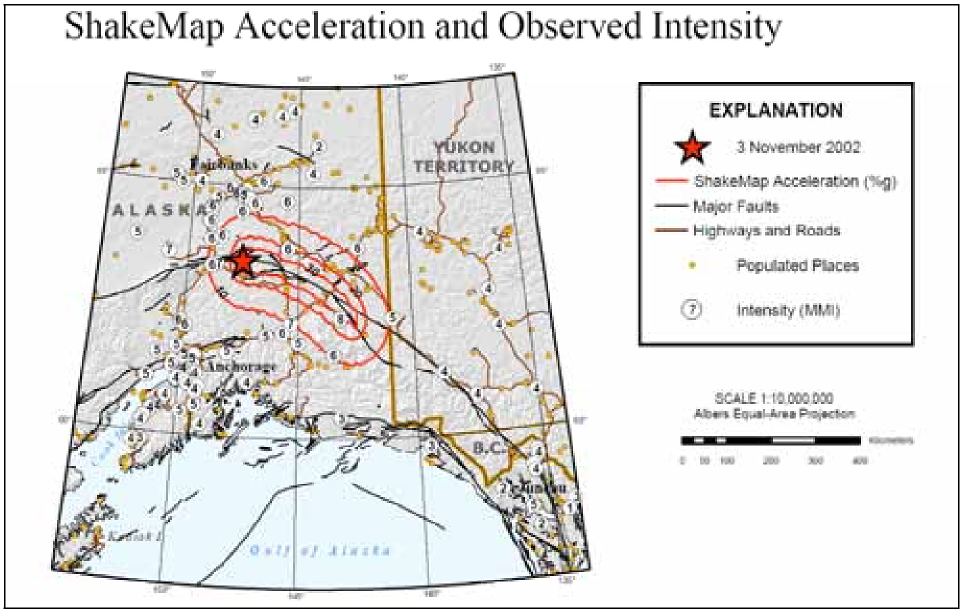

Figure 2.3. ShakeMap of the November 3, 2002 Denali Earthquake (USGS).

Table 2.1. Recorded ground motion from the November 3, 2002 Denali earthquake (part 1)

Sta	Inst	Recorder Location	Owner	Lat	Lon	Dist	Orient	PGA	PGV
Code	**S/N**			**deg**	**deg**	**km**	**deg**	**cm/s/s**	**cm/s**
R109	5596	AK: R109 (temp)	ANSS/UA	63.3953	-148.6468	57.6	360	107.3	12.95
							90	58.57	-6.15
							UP	48.49	5.72
Carlo	5595	AK: Carlo (temp)	ANSS/UA	63.5514	-148.8093	64	360	-86.14	10.38
							90	-98.01	7.56
							UP	-70.21	-8.51
2767	4005	AK: Moose Creek Dam; Upper Gallery	ACOE	64.792	-147.18	143.1	30	-29.75	4.21
							UP	15.35	2.69
							300	42.33	5.46
FA02	5609	AK: Fairbanks; Ester Fire Station	ANSS/GI	64.8455	-148.0089	150	360	-40.02	2.95
							90	-46.76	-5.37
							UP	-24.24	3.75
2797	2178	AK: Fairbanks; Univ of Alaska; Elvey Building	USGS	64.86	-147.848	150.5	360	62.94	-5.3
							UP	-40.24	3.4
							270	108	-8.89
8022	593	AK: Fairbanks; Geophysical Observatory, CIGO	USGS	64.8735	-147.8614	152.1	360	-69.27	6.28
							UP	47.15	-3.66
							90	-84.51	-7.07
8019	528	AK: Eagle River; Alaska Geologic Materials	USGS	61.3493	-149.5411	263	360	-5.96	-1.17
							UP	-4.25	1.14
							90	-5.47	1.86

Table 2.1. Recorded ground motion from the November 3, 2002 Denali earthquake (part 2)

Sta	Inst	Recorder Location	Owner	Lat	Lon	Dist	Orient	PGA	PGV
Code	S/N			deg	deg	km	deg	cm/s/s	cm/s
2784	1728	AK: Valdez; Valdez City Hall	USGS	61.1302	-146.3547	272.8	90	-26.03	4.61
							360	-21.36	3.05
							UP	-12.22	-2.25
2723	1727	AK: Valdez; Valdez Dock Company	USGS	61.1276	-146.3605	273	90	8.54	-2.68
							360	-9.42	2.06
							UP	5.85	-2.04
8034	1713	AK: Valdez; Valdez Civic Center	USGS	61.1263	-146.3567	273.2	90	-5.86	-2.74
							360	6.26	2.24
							UP	-5.75	-2.08
K2-03	142	AK: Anchorage; K2-03	UA/ANSS	61.219	-149.718	280.1	360	9.09	1.86
							UP	-5.32	1.15
							90	-8.47	2.45
K2-02	137	AK: Anchorage; K2-02	UA/ANSS	61.224	-149.822	281.8	360	-11.53	2.92
							UP	6.59	-1.33
							90	-10.59	2.79
8038	1737	AK: Anchorage; New Fire Station # 1	USGS	61.2184	-149.8829	283.7	90	-17.04	3.08
							360	18.05	-4.19
							UP	-8.13	-1.55
K2-06	136	AK: Anchorage; K2-06	UA/ANSS	61.191	-149.822	285.2	360	10.7	2.27
							UP	4.99	1.3
							90	-9.57	-2.23
8036	1731	AK: Anchorage; DOI Office of Aircraft Services	USGS	61.1779	-149.9657	289.7	90	-12.42	-3.4
							360	22.38	-3.96
							UP	-7.54	-1.5
8027	1744	AK: Anchorage; State Fish & Game	ANSS	61.1609	-149.8892	289.7	90	-13.4	2.66
							360	-11.91	2.53
							UP	6.47	1.84
K2-04	132	AK: Anchorage; K2-04	UA/ANSS	61.177	-150.01	290.8	360	-11.15	3.37
							UP	-6.99	1.69
							90	13.27	4.64
8037	1397	AK: Anchorage; NOAA Weather Facility	USGS	61.1562	-149.9845	292.3	360	19.25	-4.26
							UP	-7.3	1.13
							90	-13.51	3.57
8039	1734	AK: Anchorage; New Fire Station # 7	USGS	61.1416	-149.9512	293	90	-20.15	-3.85
							360	20.26	-3.24
							UP	-7.79	1.27

Table 2.1. Recorded ground motion from the November 3, 2002 Denali earthquake (part 3)

Sta	Inst	Recorder Location	Owner	Lat	Lon	Dist	Orient	PGA	PGV
Code	S/N			deg	deg	km	deg	cm/s/s	cm/s
8016	1356	AK; Anchorage; BP Building	USGS	61.1922	-149.8645	286			
		14th Floor, NE					270	-26.33	-8.42
		14th Floor, SW					270	-23.68	8.03
		8th Floor, NE (noisy sensor)					270		
		8th Floor, SW					270	-18.21	-5.33
		14th Floor, Center					360	27.69	10.87
		8th Floor, Center					180	26.33	-6.37
		Basement, NW					UP	-5.81	1.51
		Basement, SE					UP	-6.15	1.54
		Basement, SE					270	15.57	-2.91
		Adjacent Hole, 2'					90	-20.77	3
		Adjacent Hole, 2'					360	-16.14	2.47
		Adjacent Hole, 2'					UP	-6.19	1.52
8030	1741	AK: Anchorage; Police Headquarters	ANSS	61.1795	-149.8058	286	90	10.09	2.18
							360	8.71	-1.88
							UP	-5.26	1.27
K2-05	144	AK: Anchorage; K2-05	UA/ANSS	61.2	-149.911	286.2	360	14.62	-3.23
							UP	-7.16	1.72
							90	15.7	3.04
8024	1751	AK: Anchorage, Dowl Engineers Warehouse	ANSS	61.1832	-149.8853	287.3	90	10.02	-2.52
							360	-13.91	2.35
							UP	-5.26	-1.12
8017	1736	AK; Anchorage; Aho Residence, Basement	USGS	61.1959	-149.9465	287.4	90	15.62	3.68
							360	-18.31	4.22
							UP	-9.76	-1.77
8036	1731	AK: Anchorage; DOI Office of Aircraft Services	USGS	61.1779	-149.9657	289.7	90	-12.42	-3.4
							360	22.38	-3.96
							UP	-7.54	-1.5

Table 2.1. Recorded ground motion from the November 3, 2002 Denali earthquake (part 4)

Sta	Inst	Recorder Location	Owner	Lat	Lon	Dist	Orient	PGA	PGV
Code	**S/N**			**deg**	**deg**	**km**	**deg**	**cm/s/s**	**cm/s**
ps07*		AK: TAPS Pump Station # 07	Alyeska	65.3111	-148.2786	203.3	309	17.6	-3.3
							UP	9.8	-1.9
							39	-16.9	-3.2
ps08*		AK: TAPS Pump Station # 08	Alyeska	64.5431	-146.8194	119.5	319	-35.1	-4.4
							UP	23.5	3
							49	45.3	-5.3
ps09*		AK: TAPS Pump Station # 09	Alyeska	63.9311	-145.7681	98.3	13	55.2	-11.4
							UP	-54	-8.8
							103	73.1	-12.1
ps10*		AK: TAPS Pump Station # 10	Alyeska	63.4239	-145.7658	88.3	321	-290.1	-64
							UP	-236.1	-52.1
							51	-330.3	113.7
ps11*		AK: TAPS Pump Station # 11	Alyeska	62.0881	-145.4808	190.3	336	-85.2	-15.9
							UP	32.3	8.9
							66	-70.2	-9.7
ps12*		AK: TAPS Pump Station # 12	Alyeska	61.4758	-145.1436	258.4	342	-33.6	4.2
							UP	-23	-3.8
							72	38.5	-5.4

2.1 The Denali Fault

The Denali fault is one of the longest crustal breaks in Alaska. This right-lateral, strike slip fault is topographically expressed as an accurate trough that can be traced without interruption from the southwestern Alaskan Range through the crest of the range into the Shewak Trench, Yukon Territory, and perhaps into Chatham Strait in Southeastern Alaska (Figure 2-1). Some of the largest glaciers in the Alaska Range occupy segments of the Denali fault-line valley, including the Chistochina, Gakona, Canwell, Black Rapids, Susitana and Muldraw Glaciers. The Denali fault includes two strands, called the McKinley and Hines Creek strands, which bifurcate just east of the Richardson Highway and rejoin west of Denali National Park.

Geologic evidence suggests that average rate of displacement along the Denali fault, measured over 10,000 to 65,000,000 year intervals, varies from 1 mm to 35 mm per year. This geologic evidence includes evidence afforded by offsets of glacial ice of Donnelly age, Holocene alluvial fans, and at least 5 to 60 m of right-lateral movement and 6 to 10 m of vertical movement (through 1990) have occurred in the past 10,000 years. The

November 3, 2002 earthquake adds about 4 to 8 m of right lateral movement to these totals. Prior to the November 3, 2002 event, there had been no documentation of historic offsets along this fault.

2.2 Surface Rupture

The fault rupture moved to the east at a speed of 7000 miles per hour, taking about 90 seconds to travel 184 miles along the southern flank of the Alaska Range. As the rupture propagated eastward, it created huge offsets across roads, streams, glaciers, and under the Alyeska oil pipeline. The offset varied with a maximum horizontal slip of about nine meters (Figure 2.4). Geologists had to use helicopters and small aircraft to get into this remote area and also to see the large-scale effects of the fault rupture (Figure 2.5).

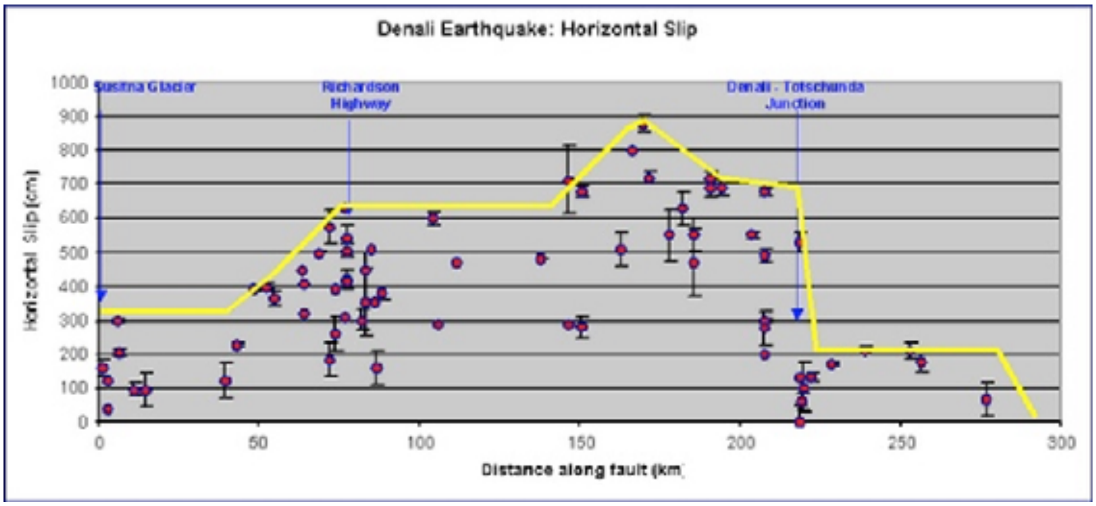

Figure 2.4. Horizontal Slip during the Denali earthquake (USGS)

Figure 2.5. Lateral Offset along Denali Fault (USGS)

The Susitna Glacier Fault had a large variation in its vertical offset with a maximum slip of about 6 meters (Figure 2.6). The behavior of glaciers over faults is a new area of study and the USGS made careful recordings after the Denali earthquake (Figure 2.7).

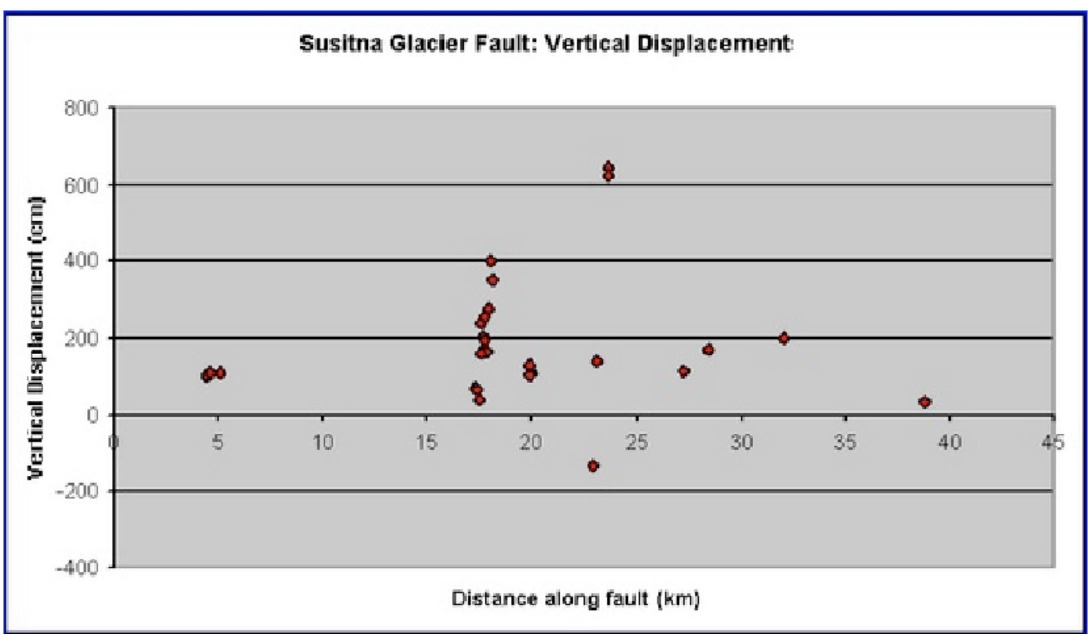

Figure 2.6. Vertical offset along the Susitna Glacier Fault (USGS)

Figure 2.7. Geologists measuring vertical fault offset on top of Susitna Glacier (USGS)

2.3 Landslides

The Denali earthquake caused thousands of landslides along the steep slopes of the Alaska Mountain Range. Fortunately, this was far from any infrastructure and from human habitation (Figure 2.8). The landslides occurred in a narrow band less than 12 miles on either side of the fault rupture and filled the valley with rubble.

Figure 2.8. Landslide from an unnamed 7,000 ft mountain covers the Black Rapids Glacier as well as the Denali Fault surface rupture (USGS)

2.4 Frozen Ground

Our understanding of the earthquake performance of lifelines in Alaska must include the special engineering issues associated with frozen ground. Frost heave refers to the seasonal freezing and thawing of moisture in ground materials and its effect on these materials and related structures. During the winter, ice formation causes an upward displacement of the ground called frost heaving. When the ground thaws in the spring, there is a resultant loss of bearing strength and ability to support structures. Frost heave is particularly prevalent in the region of the earthquake in areas of fine-grained sediments such as silt and clay. This can impact the design for many types of lifeline components, including buried water pipelines, pile supported bridges, surface level roadways and the pile supported elevated oil pipeline. To understand the performance of these lifelines in this earthquake, one should consider what role frost heave had in the original design of these lifeline components, and hence how these components performed in the earthquake.

2.4.1 Cause of Frost Heave

As mentioned above, frost heave is most prevalent in fine-grained soils such as silts and clays. In warmer regions, silts and clays can provide good support for lifeline components such as buried pipes, given that these types of soils are not susceptible to liquefaction. In much of Alaska, soils with sand and gravel are considered not particularly susceptible to frost heave and thus are preferred soils. For example, the growth of seasonal ice in pore spaces between coarse-grained sediments causes limited volume expansion and therefore slight ground distortion. Such volume changes in coarse grained sediments is generally due to expansion of interstitial water when it changes from a liquid to a solid with a resultant volume increase of about 9%. In contrast, volume expansions of up to 140 percent have been recorded during seasonal freezing of fine grained materials when excess water is drawn into the freezing soil. The intensity of this activity varies according to temperature, soil texture and soil moisture.

Areas most intensely affected by frost action include organic silt lowlands. Many highway bridges in Alaska, especially smaller ones, are distorted and even destroyed by seasonal frost heaving of piles. Wood, steel, and concrete piles and concrete piers can be affected by frost heave.

2.4.2 Frost Heave Impacts on Piles

A 20-foot long pile may be driven in the summer time into the ground with the top 10 feet unfrozen, and the bottom 10 feet frozen. During driving, the bottom 10 feet of the pile offers good support with a high skin friction (adhesion) force between the pile and the permafrost. During the following winter, the top five feet of this soil profile (composed of silty sediments) may freeze. This top five feet expands upwards. The skin friction between the frozen top five feet of soil and the pile results in a net upward force on the pile. The upward force increases as the top layer of frozen soil thickens. If this upward force exceeds the resistance offered by the bottom 10 feet in frozen permafrost, plus the pile's own dead weight, plus whatever load it might be supporting, then the pile will uplift, or heave upward. Consequently, most heaving occurs during the late winter.

2.4.3 Frost Heave Impacts on Railroad Systems

The Alaska Railroad roadbed and bridges have been significantly affected by frost-heave action. Portions of the Alaska Railroad, including about 35 miles from Fairbanks west to Dunbar, are underlain by fine-grained poorly-drained sediments in Goldstream Valley. These locations have promoted annual frost heaving of the track and of many wood-pile railroad bridges. The frost heave has resulted in misalignment of track gage that require speed reductions of trains.

To maintain a uniform track elevation during the winter and early spring, wedges are inserted under the rails near the ends of bridges. Up to 8 inches of cumulative shimming have sometimes been necessary to maintain a uniform height between the ends of bridges and the elevated portion, which often rests on frost-heaved piles. During the summer, several inches are trimmed from bridge beams of the tops of the supporting frost-heaved piles and shims removed to lower the disturbed rails.

2.4.4 Frost Heave Impacts on TAPS Piles

A large portion of the original $8 billion project cost was devoted to overcoming permafrost and seasonal frost related problems. Because the crude oil is warmer than 32°F, frozen ground will thaw in areas of pipeline burial, To prevent thawing in ice-rich zones, 382 miles of the 798-mile pipeline were elevated. These portions of the pipeline were supported on 132,000 piles. These piles are called Vertical Support Members (VSMs). Each VSM is a 18-inch diameter steel pipe. Elevated portions of the pipeline are supported at 60-foot intervals using two VSMs with a horizontal crossbeam. About every 1,800 feet there is a 4-VSM "anchor" support that provides restraint for vertical dead weight, pipeline transverse and pipeline longitudinal directions.

Mechanical refrigeration of piles is very expensive. Thermal piles were successfully deployed on the Trans-Alaska Pipeline to eliminate frost heaving of its Vertical Support Members (VSMs). The supports were frozen firmly into permafrost, filled with hydrous ammonia gas, and equipped with heat-radiating fins. Each winter the ammonia gas rises to the tope of the VSM, cools, liquefies, and sinks to the bottom where it warms, boils, and again rises to the top, thereby chilling the ground whenever the ground temperature is warmer than the air temperature. The devices are non-mechanical and self-operating, and require no external power source. The pipe is insulated with 4 inches of resin-impregnated fiberglass jacketed by galvanized steel. The VSMs were installed generally as follows. First, a dry auger holes was drilled into the ice-rich permafrost. The piles were then surrounded by a cold mud slurry (water and silt) and allowed to freeze firmly into the permafrost before any stresses were applied.

2.4.5 Frost Heave Impacts on Highway Systems

Highways can be subject to intense seasonal frost action in flood plains where they cross meander scars, swales and intermittent drainage channels filled with organic silt.

2.5 Distantly Felt Impacts

The earthquake created a ripple effect thousands of miles away. The passing seismic waves triggered a series of micro-earthquakes (M < 3) at the Geysers geothermal area in northern California and at Yellowstone National Park in Wyoming (Figures 2.9 and 2.10).

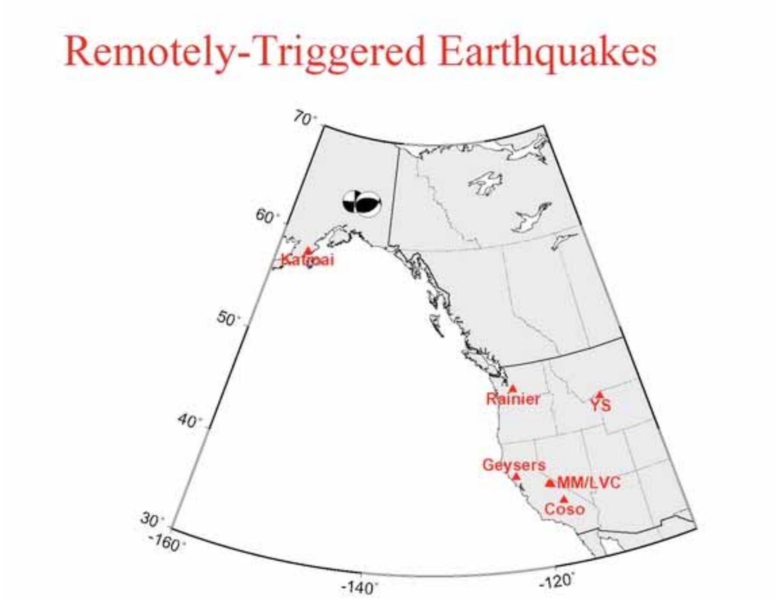

Figure 2.9. Remotely-Triggered Earthquakes (USGS)

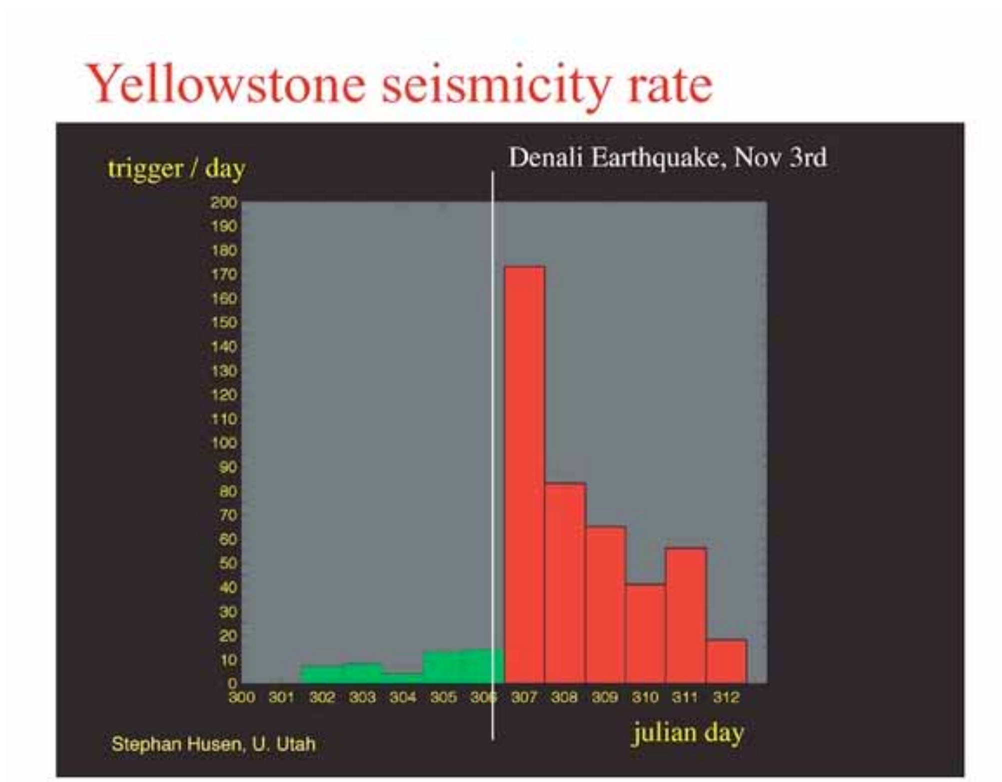

Figure 210. Higher seismicity in Yellowstone following Denali Earthquake (USGS)

In the New Orleans area (over 3,000 miles away) residents saw water in Lake Ponchetrain slosh about as a result of the quake's power. Similar observations were recorded in Seattle, Minnesota, Texas and Louisiana. As far east as Pennsylvania and Georgia, USGS instruments recorded significant changes in ground-water level immediately following the earthquake. Seismic waves effected other distant areas as well. Some houseboats were shaken from their moorings and Minnesota and Wisconsin residents reported water wells became turbid (dirty). In Louisiana, water sloshed from swimming pools, ponds and embossments to the amazement of local observers. However, the reported sloshing times may not match the occurrence of the seismic waves.

3.0 Trans-Alaska Pipeline System (TAPS)

3.1 Introduction

Oil was discovered at Prudhoe Bay in 1968. To transport the warm crude oil from the North Slope of Alaska to a ice-free port, a 48 inch diameter pipeline was built traversing Alaska from Prudhoe Bay to Valdez.

The Trans-Alaska Pipeline System (TAPS) was built from April 29, 1974 to June 20, 1977 by the Alyeska Pipeline Service Company, which was (then) owned by eight (now six) oil companies. At the peak of construction in October 1975, 21,600 contractors (28,072 including Alyeska and contractor employees) were employed in the effort. The cost of constructing TAPS was about $8 billion. Over the past 25 years, the pipeline has often transported about 1,200,000 barrels of crude oil daily to Valdez; the pipeline was originally designed to transport as many as 2 million barrels per day. Most recently, throughput was 30.4 million barrels in August 2002, or an average of 0.98 million barrels per day; the daily average for the first 8 months of 2002 was 1.021 million barrels per day. It takes about 9 days for oil from Prudhoe Bay to reach Valdez.

About 300 miles of this 798 mile long pipeline traverses through permafrost terrain between Fairbanks and Valdez (Figure 3.1). Probably about $1 billion of the original construction cost was necessary to learn about, combat, accommodate and otherwise work with the perennially and seasonally frozen ground.

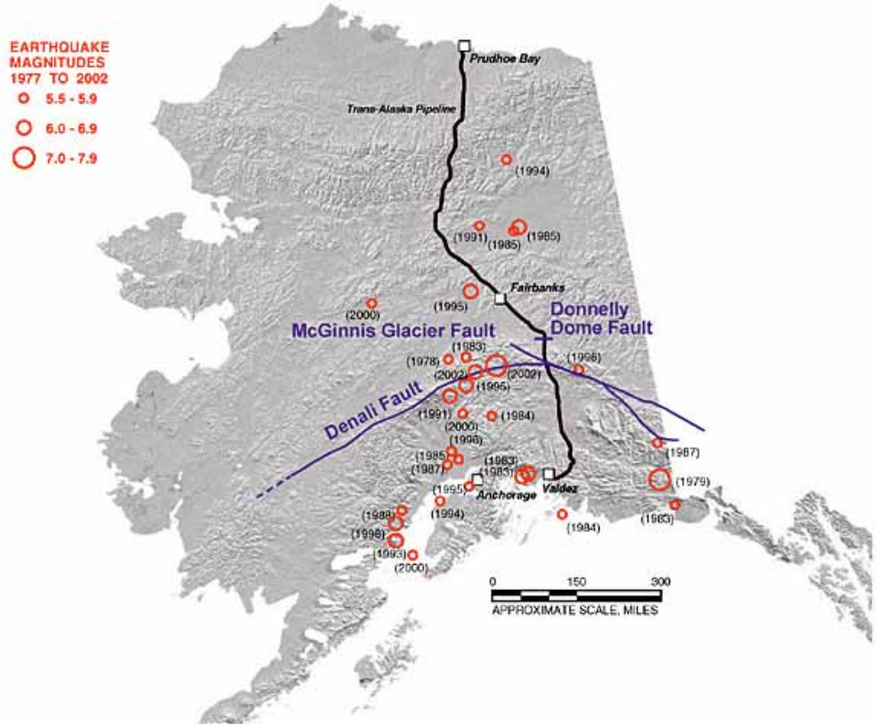

Figure 3.1. Map of the Trans-Alaska Pipeline System (Alyeska)

The pipeline was originally considered for design using burial in permafrost along most of the route. At full production rate, oil temperatures in the pipeline would have been in the range of 158 to 176°F. Such an installation could have thawed the surrounding permafrost.

Thawing of the widespread ice-rich permafrost by a buried warm-oil pipeline could cause liquefaction, loss of bearing strength, and soil flow. Such loss of strength in the soil would lead to differential movement of the pipeline, with attendant increase in longitudinal tension and compressive stresses in the steel pipe wall. High tensile stresses could lead to rupture of the pipe; high compressive stresses could lead to local buckling (wrinkling) of the pipe. The greatest differential settlement could occur in areas of ice wedges, where troughs could form and deflect surface water into the trenches, causing erosion and more thawing.

Given these concerns, several trial design installations were tried for the pipeline before selecting the final design. Ultimately, the pipeline was constructed in three modes, depending on environment, terrain and permafrost conditions. Oil is pumped along the route using 10 currently operating pump stations. The oil reaches temperatures up to 145°F, depending on production rates and how the oil is handled before delivery to the pipeline from the wells in the Prudhoe Bay field. Because of the heat generated by pumping and friction with the pipe, oil moving through the system at the design rate of 2 million barrels per day ranges in temperature from 130 to 140°F. Potential effects of the heat on frozen ground along the route determined the mode of pipeline installation.

The pipeline currently provides about $4 million into the Alaska State treasury, every day that the pipeline is in operation.

3.1.1. Pipeline Specifics

The pipeline is a 48-inch diameter welded steel pipe with a wall thickness of either 7/16 or 9/16 inches (9/16 inches through the Denali fault crossing zone). Shop-made longitudinal welds were either longitudinal seam welds or helical welds. The pipeline steel is highly ductile steel, with yield strength of about 60 to 65 ksi. Once installed, the pipeline was hydrostatically tested to a maximum 96% of the specified minimum yield strength, or a minimum of 125% of the operating pressure or 750 psi, whichever was greater. There are about 66,000 field girth welds. These welds were made in 6 passes for the 7/16th inch wall, or 7 passes for the 9/16th wall. Shop girth welds (called double joint welds) are two pipe segments welded into a single length before transport to the field for placement. There were 42,000 of these welds. The pipeline includes 177 valves. These include 71 gate-valves, 24 block-valves, 1 ball-valve and 81 check-valves.

3.1.2. Conventional Burial

In areas where the ice content of permafrost is very low or absent or where no permafrost exists (thaw stable), the pipe is buried in a conventional manner, as are similar pipelines in most areas of the world. About 376 miles of the pipeline were installed using this method. The pipe is underlain by fine bedding material and covered with prepared gravel padding and soil fill material in a trench 8 feet to 16 feet deep in most locations, and up to 49 feet deep at one location. Zinc ribbons, which serve as sacrificial anodes to inhibit corrosion of the pipe are buried alongside the pipeline. The Atigun pipe replacement section, 8.5 miles long, uses four magnesium ribbon sacrificial anodes. The typical trench size during construction was 8 feet wide by 8 feet deep. The actual overburden for the buried pipeline ranges from 3 to 35 feet. The maximum thermal stresses are 25,000 psi for fully restrained below ground pipelines, from tie-in temperature to maximum operating temperature.

3.1.3. Special Burial

In seven short sections of the pipeline (totaling 7 miles), the pipe was buried and then frozen into the ground (Figure 3.2). Some of these sections are for crossings for caribou and other animals and include both ice-poor and ice-rich permafrost environments. In these locations, the pipe is covered with 3.2 inches of polyurethane foam insulation and then covered with a resin-reinforced fiberglass jacket. The temperature of the permafrost in which the pipe is buried is maintained by pumping refrigerated brine through 6-inch diameter pipes buried beneath the pipeline. The refrigeration units are powered by electric motors.

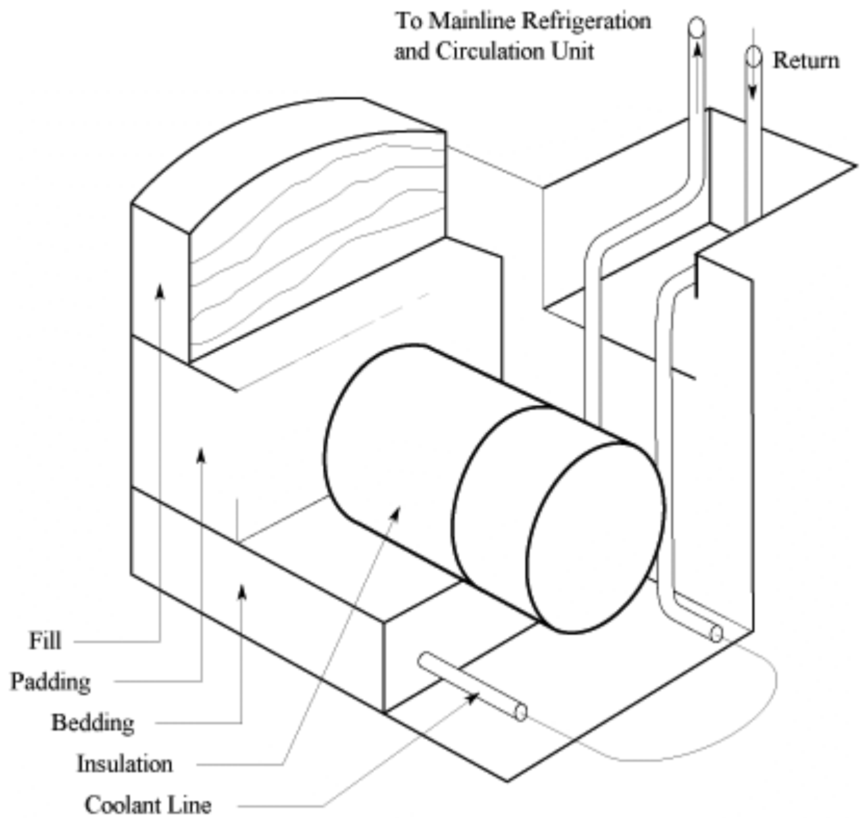

Figure 3.2. Special burial of Alyeska oil pipeline (Alyeska).

3.1.4. Conventional Elevated and Anchor Support

About 420 miles of the pipeline is built above ground due to the presence of ice-rich permafrost (thaw unstable) (Figure 3.3). In the above ground configuration, the pipeline successfully discharges its heat (from the warm oil) directly into the air, without affecting the permafrost below. Except at the Denali fault crossing location, the above ground installation is made with two styles of supports: two-legged supports spaced about every 60 feet long the pipeline, and four-legged supports spaced about every 1,800 feet (some as close as 800 feet) along the pipeline. The two-legged supports provide vertical support along with limited transverse and longitudinal restraint. The four-legged support provides an "anchor" for the pipeline, with higher longitudinal and transverse restraint capacity. Figure 3.4 shows a model of a typical four-legged anchor support.

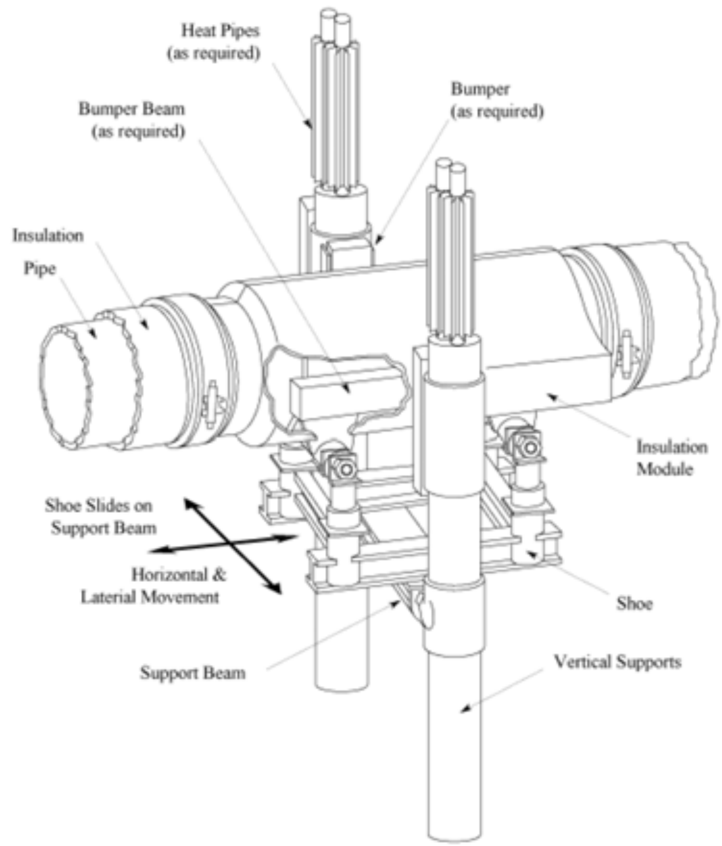

Figure 3.3. Two-legged pipe support (Alyeska)

The vertical support members (VSMs) (either two- or four-legged supports) are subject to potential frost heave. VSMs are typically 18-inch diameter steel pipes, driven or placed into holes about 15 to 70 feet into the ground. There are about 78,000 VSMs along the entire pipeline route. There are 16 types of VSMs to accommodate a variety of soil and permafrost conditions. To eliminate frost heave, each VSM is frozen firmly into the permafrost using a thermal device that is installed in the steel pipe. The devices consist of two 2-inch diameter metal tubes filled with ammonia, which becomes a gas in winter and rises to the top of the tubes. In the cold atmosphere (commonly –20 to –40°F in winter), the ammonia liquefies, running down the pipe and thereby chilling the ground whenever the ground temperature exceeds the air temperature. The devices are non-mechanical and self operating. Aluminum fins on top of the VSMs permit rapid dispersion of heat (Figure 3.5). 61,000 of the VSMs have heat pipes installed[3].

[3] www.alyeska-pipe.com/Pipelinefacts/PipelineEngineering.html

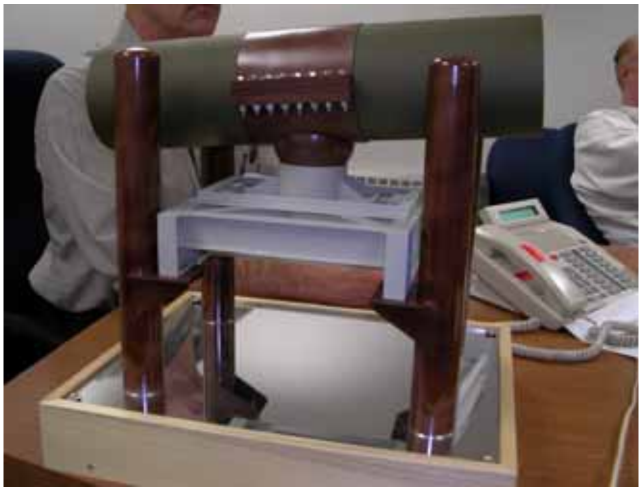

Figure 3.4. Model of four-legged pipe support

The above ground pipeline is subject to thermal growth due to the warm oil and contraction due to cold air temperature. There are no slip joints along the length of the pipe. To accommodate thermal growth and contraction, the pipeline is laid out in a zig zag fashion. As the pipe heats up due to warm oil, the increase in pipe length is accommodated by lateral outward movement over the supports. As the pipe cools down due to cold air, the decrease in pipe length is accommodated by lateral inward movement over the supports. The four-legged anchor supports are located at the end of each zigzag, usually at about 1,800 foot intervals (Figure 3.5).

Figure 3.5. Four-legged anchor support.

The above ground pipe is insulated with a 3.75-inch thick layer of resin-impregnated fiberglass that is jacketed with galvanized steel. This insulation keeps the oil warm and pumpable for a sufficient period of time to complete any unexpected maintenance, should oil movement stop for any reason. Under original design, the oil is kept moving through the pipeline by a series of 12 pump stations; currently (2002), pump station 10 is no longer needed and has been taken out of service.

The pipeline at each 2-leg VSM support is attached to the support cross beam via a "shoe". The shoe includes a set of adjustable steel assemblies and a horizontal cross beam, on the bottom of which is a Teflon pad. The Teflon pad of the "shoe" rests on the horizontal cross arm of the VSM support. There are about 39,000 shoes along the length of the pipeline. The nominal coefficient of friction between the Teflon pad and the steel cross arm is about 0.1; the apparent coefficient of friction during the earthquake was back-calculated to be 0.01, although some of this might be explained by the likely vertical uplift of the pipeline off the cross arm for at least some of the time during the earthquake.

Two extreme locations of the pipeline are defined for thermal expansion. The "Hot" position is the position of the pipeline when it is at 145° F (maximum oil temperature). The "Cold" position is the position of the pipeline when it is at –60° F (pre-start-up). The longitudinal expansion of a typical 720 foot-long straight run is 9 inches from tie-in temperature to maximum operating temperature. The maximum lateral movement is 8 feet from tie-in to hot position, or 4 feet from tie-in to cold position.

The start-up process for TAPS began on June 20, 1977 when oil was introduced into the pipeline at Pump Station 1 at Prudhoe Bay. The first oil reached Valdez Terminal on July 28, 1977.

3.1.5. Special Crossings

Figure 3.6 shows the TAPS where it crosses the Richardson Highway at milepost 243.5. The pipeline is buried at least 6 feet under the roadway in a corrugated metal casing that is 115 feet long. Permafrost is protected from the warm oil in the pipeline by 12 inches of polystyrene insulation throughout the length of burial. At this location, the perennial frozen ground consists of sandy gravel that is frozen to depths of more than 43 feet. Several thermal piles either side of the road crossing, the same as those used in the elevated section, are used to keep the ground frozen. Similar burial was used at a few thaw-unstable locations, where above-ground installation was impractical, such as at locations prone to rockfalls or avalanches. There are 46 road crossings along the length of the pipeline, one of which is refrigerated.

Figure 3.6. Pipeline crossing under Richardson Highway.

At seen in Figure 3.7 (Richardson Highway milepost 242.2), there are occasional arches in the pipeline to provide for animal (and truck) crossings. There are 554 elevated animal crossings along the length of the pipeline. There are 23 buried animal crossings, two crossings of which are refrigerated.

Figure 3.7. Raised pipeline to allow work pad to cross underneath.

There are major 13 bridge crossings, including 1 orthotropic box girder, 9 plate girder, 2 suspension and 1 tied arch bridges.

3.1.6. Denali Fault Crossing

The McKinley segment of the Denali fault intersects the Alyeska Pipeline near pipeline milepost 589 between upper and lower Miller Creeks and approximately 5 km south of Pump Station 10. This 48 inch diameter pipe is supported through this fault crossing zone on 47-foot long concrete "sleepers" that are spaced approximately 60 feet apart for a distance of 1,960 feet (Figure 3.8). The concept behind this design is to allow adequate lateral movement of the pipeline to accommodate up to a maximum lateral fault offset of 20 feet in conjunction with a vertical fault offset of 6 feet. A computer-based seismic monitoring system provides instantaneous detection, evaluation and automatic reporting of earthquake activity to the Valdez Operations Center. Seismic strong motion instruments are located at Pump Stations 1, 4 through 12 and at the Valdez Terminal.

Figure 3.8. Concrete 'sleepers' supporting pipeline in fault crossing zone (post-earthquake)

3.2 Original Seismic Design

The original ground motion values used for the design of the Trans-Alaska Pipeline came from a study done by the USGS in late 1960's (Page, et al 1972). The pipeline was designed to accommodate a magnitude 8.0 earthquake in the vicinity of the Denali Fault (Figure 3.9). This translated to design ground motions of PGA = 0.6g (in the free field), or PGA = 0.33g (for structural design), with peak ground velocities of 29 inches / second and 16 inches per second, respectively. It was recognized that even higher PGAs might be possible due to high frequency motions, but that these might not be damaging. Structural analyses of the pipelines were conducted under the direction of Ed Keith in the 1970s, using PISOL, a predecessor of SUPERPIPE and other piping programs developed by Professor Graham Powell.

In the 1990's, the design criteria were updated to include performance for two earthquakes with the Design Contingency Event near the Denali Fault remaining a magnitude 8 earthquake. A 1,900 ft wide fault crossing zone was identified (Figure 3.10) with a 20 ft of lateral and 5 ft of vertical offset. During such an earthquake there should be limited damage, but no spills, no structural damage or loss of function. However, flow may be interrupted.

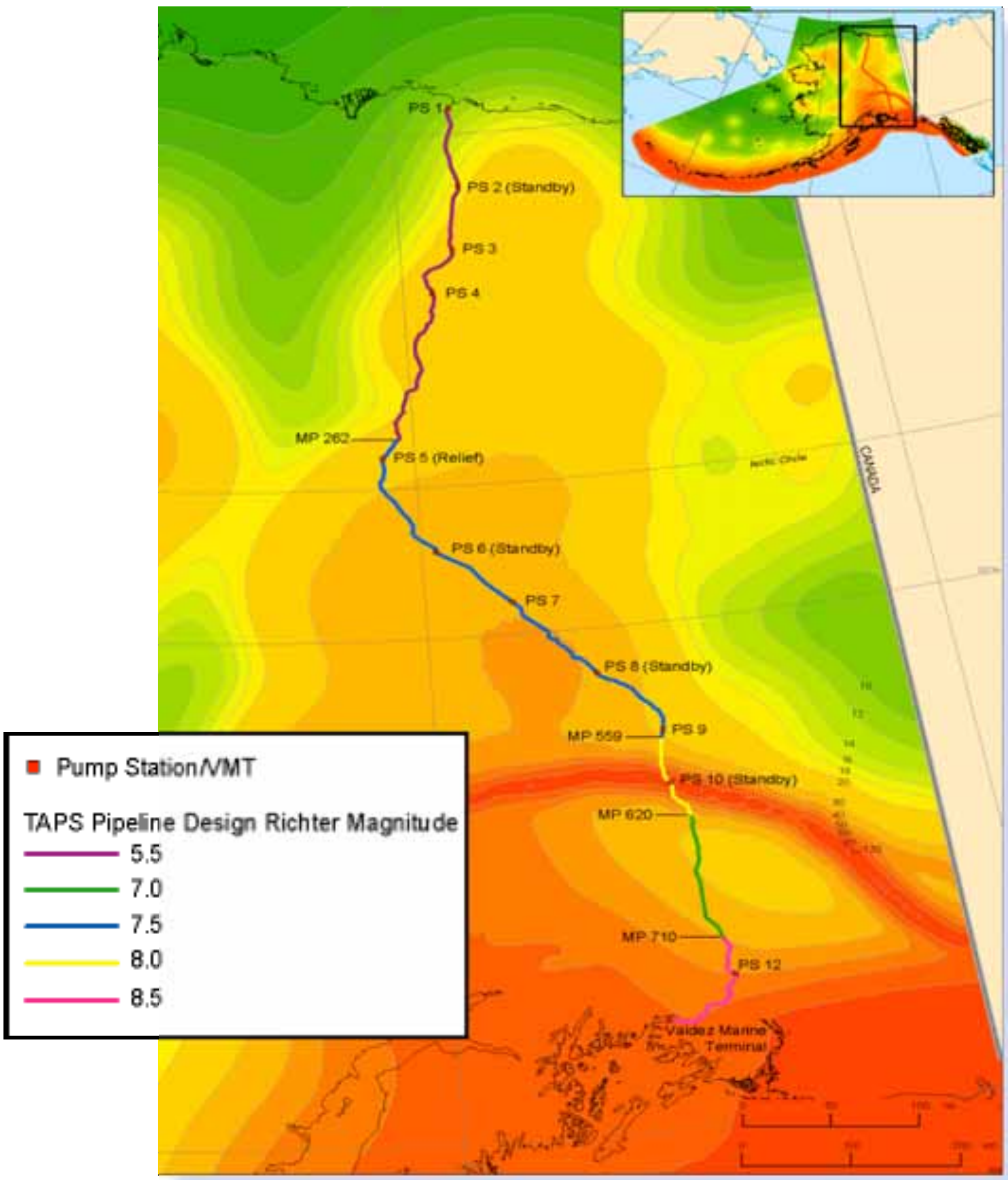

Figure 3.9. Hazard Map (Alyeska)

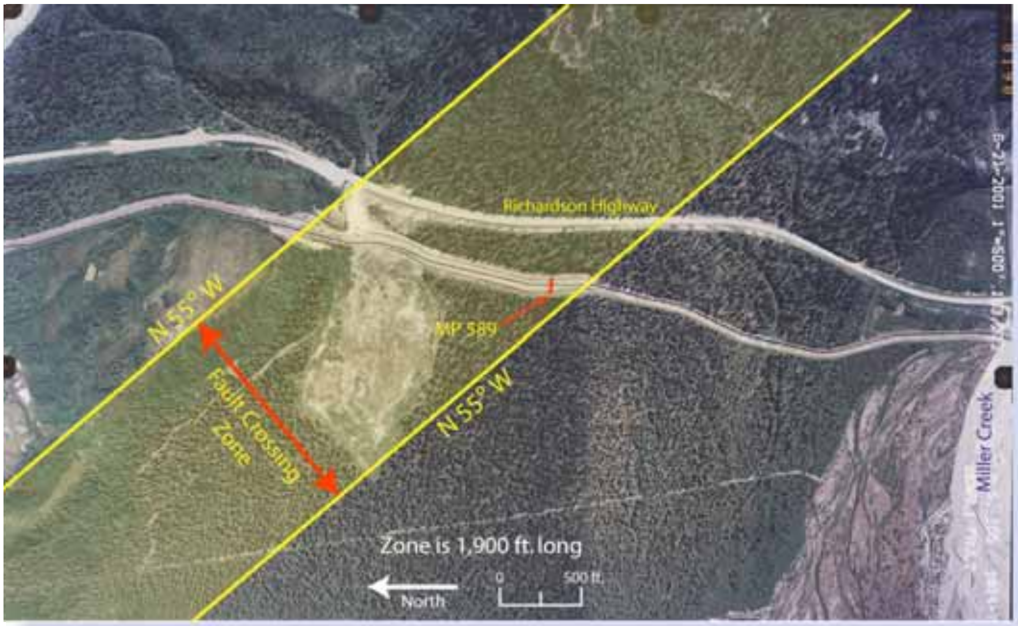

Figure 3.10. Denali Fault Crossing Zone (Alyeska)

3.3 Performance of the Pipeline during the Earthquake

The earthquake occurred at 1:13 PM Alaska Standard Time on 11/3/2002. During the earthquake, the fault caused a surface offset (near the south end of the fault rupture zone) of about 18 feet (5.5 meter) horizontal and 2 feet (0.8 meter) vertical, distributed over a zone of about 600 feet (Figure 3.11). There was an automatic shutdown switch (with an acceleration trigger) that closes the pipeline valves 10 minutes after an earthquake. However, this type of shutdown is extremely undesirable since it can cause hydraulic surges and it disables the leak detection system. After it was determined that there was no leakage, the switch was manually over-ridden to have a more controlled (and safer) shutdown. One it became known that there had been some damage to some pipe supports, at 2:00 PM the pipeline was manually shutdown for precautionary purposes. At 8:00 AM on 11/6/2002, the pipeline was restored to service. By "shutdown", it is meant that a series of valves were consecutively closed along the length of the pipeline. Once shut down, the oil remained in the pipeline, without moving. During the shutdown, oil production on the North Slope continued, with excess oil being stored locally.

Recorded ground motions at pump station 10 were about 0.36g (horizontal PGA) and 114 cm/sec (horizontal peak ground velocity). Pump stations with accelerometers that "alarmed" are listed in Tables 2.1 and 3.1 (the data in Tables 2.1 and 3.1 somewhat differ due to different data processing techniques).

Five vertical support members (VSMs) were damaged, although none fell or were so severely damaged that they had to be replaced. In 8 locations, the "shoes" that connect the pipeline to the horizontal cross members were on the ground, leaving the pipeline unsupported for one or two spans. During the 66 hours that the pipeline was shut down, repairs were made to the few VSMs that were damaged as the pipe moved laterally, axially and vertically during the earthquake. At one support, wooden sleepers were temporarily installed to provide additional support under the pipeline to prevent a drop if there was a substantial aftershock. Figure 3.12 to 3.16 shows the typical damage.

Table 3.1 Recorded ground motions along TAPS Pipeline

Station	Start Time	Max Accel, g	Max. Velocity, inch/sec	Peak Spectral Acceleration , g	Peak Spectral Velocity, inches/sec
7	13:13:25	0.02	1.4	0.05	4.3
8	13:12:47	0.05	2.1	0.12	5.7
9	13:12:45	0.08	3.7	0.25	8.7
10	13:12:47	0.36	32.5	0.94	79.2
11	13:12:50	0.10	3.9	0.31	6.0
12	13:12:20	0.04	1.6	0.1	5.7

After these repairs were completed, the pipeline was unfastened at the anchorage on each side of the fault and moved about a foot to relieve the stress. A pig was then run through the pipeline to check for curvature and the pipeline was found to be okay. It was determined that the pipeline in its present configuration can handle another few feet of fault movement. Studies are currently being done to determine what future repairs and mitigation efforts need to be done. For instance, it may be decided to lift up the pipeline and to move the supports so they are re-centered under the pipeline in its current configuration to handle the next earthquake.

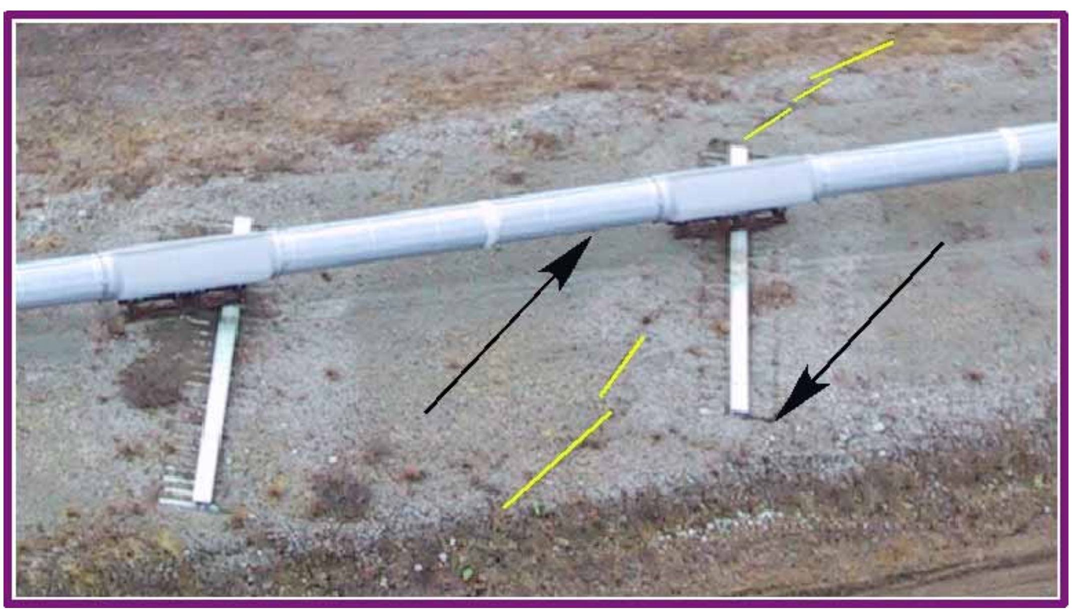

Figure 3.11. Location of Surface Fault Rupture (Alyeska)

Figure 3.12. Damage to vertical and horizontal members and to teflon shoe supports (Alyeska)

Figure 3.13. Dropped Shoe on elevated portion at north end of Fault Crossing Zone (Alyeska)

Figure 3.14. Consecutive fallen beams leaving pipeline unsupported for three spans (Alyeska)

Figure 3.15. Perched Shoe at end of 'sleeper.'

Figure 3.16 (left side) shows the pipeline at the Denali fault crossing in its pre-earthquake configuration. Figure 3.16 (right side) shows the same pipeline in its immediate post-earthquake distorted configuration. Note that the straight legs of the pipeline (pre-earthquake) have a modest bow outwards in the post-earthquake condition, demonstrating that the pipeline has moved outwards from its original centerline position, in order to accommodate the (about) net-axial shortening between the two anchors either side of the fault, as well as the net lateral offset caused by the fault offset. Figure 3.17 shows the snow-covered in-service pipeline about six weeks after the earthquake – the residual displacement of the pipe is still apparent; 9 months after the earthquake some more of the residual displacement had "dissipated".

Figure 3.16. TAPS pipeline, before (left image) and after (right image) earthquake

Figure 3.17. TAPS pipeline, six weeks after the earthquake

Portions of the pipeline near the fault-crossing zone that are not underlain by frost-heave susceptible soils are buried. Liquefaction of sandy soils occurred at and near some of these sections of buried pipeline (about 2 kilometers of pipe alignment liquefied, cumulatively at 4 locations). Lateral spreads dragged one section of buried pipeline laterally a number of feet, causing visible distortion and torsional tilting (3 degrees) of a gate valve, but the pipe did not leak. Inspection after the earthquake showed that the stress was within acceptable tolerances (Figure 3.18).

Figure 3.18. Inspection at site of liquefied soil (Alyeska)

Strong ground shaking also caused some relatively minor damage at Pump Station 10, located about 3 km north of the fault offset. A ground motion instrument at this site recorded peak horizontal accelerations of about 0.36g and velocities of 45 inches/second. The damage included falling of the overhead suspended ceiling and failure of some fluorescent lamp fixtures, but none of this damage was life threatening or particularly significant to post-earthquake operations. The work pad (roadway) that runs parallel to the pipeline suffered lateral spreads and grabens along its embankment, but the roadway was still serviceable.

Economic impacts to the TAPS system from the earthquake included direct damage repair costs, post-earthquake evaluation costs, and temporary loss of revenue due to the safety shutdown for inspection. The pipeline normally delivers about $30 million worth of oil each day to Valdez. Had the pipeline not been designed for the fault offset, it would have leaked, with a longer shutdown period, clean-up costs, and environmental damage. It is possible that a leak could have resulted in a many months-long or even multi-year long shutdown to address the engineering and environmental problems that would have been caused by a spill.

3.4 Further Activities by Alyeska

After the earthquake, Alyeska did a careful inspection of the pipeline and ran analyses to see how much stress the pipeline was under and how much more it could take (see for example Sorenson and Meyer 2003, and Johnson Metz and Hackney 2003). Decisions about any further repairs and retrofits are still being discussed and are related to ongoing research. Trenching of the Denali fault may be conducted to establish the recurrence interval for this fault. Alyeska, as it has done in the past, will continue to rely on data and technical expertise from the USGS and from consultants to ensure that the pipeline is designed to meet its performance criteria.

4.0 Water and Wastewater

The only civilian water and wastewater utility systems near the epicentral area are located in Fairbanks. The Golden Heart Utilities operates both these systems, which serve about 80,000 people. There is one water treatment plant and one wastewater treatment plant. There are about 200 miles of water distribution and 140 miles of wastewater collection pipes. In one part of the system, water mains are either ductile iron pipe (38 miles) or steel (93 miles), mostly 4" to 18" diameter. There are about 1,800 fire hydrants, 8,000 services, 26 water pump stations, 82 sewer lift stations. Average day water demand is about 3.8 million gallons per day. The only earthquake impact was water sloshing out of clarifiers at both the water and wastewater plants; there were no leaking pipes. Ground motions in the Fairbanks area were 0.04g to 0.05g, so the lack of pipeline damage would not be unexpected; however, much of the soil underlying Fairbanks is sandy and gravelly by nature, and a closer earthquake event would no doubt have caused pipeline damage. Most water pipelines are steel (with push on gasketed joints). Most collection pipelines are ductile iron. Most modern pipeline installations have four feet of cover although a few older pipelines may have eight feet.

Nearer the epicentral area, there is a population of about 10,000 people in rural locations with PGA > 0.10g to 0.15g. In essentially every instance, these people rely upon private wells for their water supply, and septic systems for waste; some people rely upon trucked-in water. It was reported that all wells use submersible pumps. In Tok, one well casing was reportedly ejected out of the ground by about 3 feet. In Slana, a similar well ejection was reported. The cause of these well casing failures might be attributed to accumulated frost heave forces on casing pipe that lost its soil resistance temporarily due to ground shaking and/or liquefaction; coupled with thin wall / weak welds in the casing pipe. There were intermittent reports of sanding for a few minutes (or hours) at wells. There were reports of "improved" water quality after the earthquake in a few locations and reports of "reduced" water quality after the earthquake at other locations. In Mentasta, there was a broken buried septic pipeline.

Figure 4.1. Damaged well casing at Fort Richardson in Anchorage

On the military bases there are drilled wells, water treatment facilities, but no sewage treatment plants. The only reported damage was to a water well casing at Fort Richardson many miles away. Figure 4.1 shows the spider bushing inside the broken 8-inch pump casing. The damage occurred 80 feet below the ground surface. The many reports of increased turbidity of well water, changes in the level of water tables, and damaged well casings suggests that aquifers are particularly sensitive to even weak ground motion.

5.0 Other Pipeline-Related Lifeline Systems

5.1 Fire Suppression

There were no reported fire ignitions caused by the earthquake. The Tok Fire Chief, Tony Conrad reported a fire on December 5th caused by an aftershock. An illegally buried propane tank had a line break pouring propane into a home and a nearby pilot light was apparently the source of ignition. The house burned to the ground and urethane insulation sent six firefighters to the hospital from inhaling toxic fumes (Tok provides fire fighting for most of the region with six vehicles with water or foam tanks).

5.2 Oil and Gas Distribution Systems

The typical heating system used in the towns in the epicentral area is a furnace powered by oil. Oil is distributed to each building via tanker truck, with oil being stored in above ground tanks. At Mentasta (PGA ~ 0.4g or higher), about half of the oil tanks at homes toppled; small diameter buried pipelines from oil tanks to homes were damaged in a few spots.

At the Northway Airport (PGA ~ 0.2 to 0.35g), the unleaded gasoline in three horizontal oil tanks is delivered to small pumps at the runway apron via underground small diameter pipes. These pipes broke due to the earthquake-induced liquefaction. There was little spill, as the system is normally pumped.

In Mentasta, there was a broken buried fuel line from gasoline storage tanks to a gasoline service bay.

6.0 References

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