

PERFORMANCE OF THE TRANS-ALASKA PIPELINE IN THE NOVEMBER 3, 2002 DENALI FAULT EARTHQUAKE

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Abstract

The magnitude 7.9 earthquake that occurred in south-central Alaska on November 3, 2002 ruptured a 336-km long segment of the Denali Fault. The epicenter was located about 88 km west of the Trans-Alaska Pipeline, and the rupture propagated to the east across the pipeline right-of-way. The above-ground segments of the pipeline were subjected to violent near-fault ground shaking approaching or exceeding design criteria, and liquefaction was observed at a number of locations along the pipeline, including a remote gate valve location. The performance of the pipeline was in line with original project design requirements, and there was no oil leakage. The paper presents a high-level overview of the seismic design of the Trans-Alaska Pipeline, performance of the pipeline system during the magnitude 7.9 event, and a brief commentary on post-event emergency response.

Introduction

The Atlantic Richfield Company discovered oil at Prudhoe Bay, on the Alaskan North Slope, in 1968. Construction of the Trans-Alaska Pipeline System (TAPS) was proposed in early 1969, but controversies over Alaska native land claims and environmental issues delayed pipeline construction until 1974 (Roscow, 1977). On June 20, 1977, after three years of construction by 70,000 men and women and an investment of eight billion dollars, oil began flowing through the pipeline. Since then, this pipeline system has safely transported over 14 billion barrels of oil from Alaska's North Slope to the Port of Valdez. Currently the pipeline transports approximately 17 percent of the crude oil produced in the United States. In 2003, the pipeline owners received state and federal right-of-way approval for another 30 years of operation. The pipeline is operated by Alyeska Pipeline Service Co (Alyeska) for its owners.

Over its 1,287-km (800-mile) route from Prudhoe Bay to a marine tanker terminal at the port of Valdez, the 1,219-mm (48-inch) diameter Trans-Alaska Pipeline passes through areas with high potential for significant seismic activity. To safeguard the fragile arctic environment, major seismic design requirements were imposed on the TAPS, namely that the entire pipeline system should be capable of withstanding all reasonably anticipated effects of earthquakes without impairing the structural integrity of the oil pipeline or the associated pressure containing system components.

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With the exception of nuclear power plants, the attention given to the seismic design of TAPS rivals that for any other critical facility in the United States.

For many aspects of TAPS design, just as in the case of nuclear power plants, no seismic criteria, standards or codes existed at the time of design. Alyeska's adoption of seismic criteria for pipeline design was the first major action of this kind in the pipeline industry. Even so, during that time period, TAPS design and construction was benefited immensely by the research and development under way for seismic design of nuclear power plant facilities. Consequently, the design of TAPS was state-of-the-art for its time and has remained remarkably consistent with current practice in earthquake engineering.

The attention given to seismic design paid off on November 3, 2002, with the occurrence of the magnitude 7.9 Denali Fault earthquake. Ground motions approached the seismic design criteria for the section of the Trans-Alaska Pipeline passing through the Alaska Mountain Range in the vicinity of Pump Station 10 and the Denali fault. The surface rupture passed across the Trans-Alaska pipeline right-of-way, producing approximately 5.5 m of right-lateral offset and 0.6 m of up-to-the-north vertical displacement. There was no damage to the pipeline or release of crude oil; but there was incidental damage to the above-ground pipeline support hardware where violent pipe shaking and ground motion apparently took place. Limited displacement of the below-ground pipeline occurred in liquefaction areas, but no damage to the pipe occurred as verified by an in-line inspection device (“smart pig”).

Seismic Hazard along the TAPS Route

The pipeline route begins in a region of low seismicity on the North Slope of Alaska and terminates at Valdez, which is one of the most seismically active regions of the world owing to its location along the Pacific Rim. In 1964 one of the largest earthquakes ever recorded in North America, with a moment magnitude of 9.2, occurred in Prince William Sound, Alaska. The epicenter of this earthquake was about 65 km west of the yet-to-be-built Valdez Marine Terminal (VMT). The city of Valdez and its harbor facilities, at that time at the eastern end of the Valdez Arm, were severely damaged by wave run-up caused by a massive submarine landslide. The city of Valdez was subsequently relocated to a site on the north shore of the Valdez Arm that offers natural protection against a similar occurrence. Prior to the November 3, 2002 Denali Fault earthquake, the largest earthquakes near the pipeline corridor were of modest magnitude and at significant distances from the TAPS route. There had been no reports of earthquake damage to TAPS facilities prior to the Denali Fault event.

The seismic design criteria for the Trans-Alaska Pipeline System (TAPS) were defined as stipulated design earthquakes for five seismic zones along the 1,287-km route as shown in Figure 1. The delineation of seismic zones was based on studies by the U.S. Geological Survey (Page, et al., 1972) and independent assessments performed by consultants to the pipeline project. A Design Contingency Earthquake (DCE), with an estimated return period of 300 years or more, was established for

each of the five seismic zones according to Richter magnitude. The areas along the pipeline route of principal interest are the magnitude 8.5 Richter zone at the southern end of the pipeline (Valdez) and the magnitude 8.0 Richter zone in the Alaska Range in the vicinity of the Denali Fault and Pump Station 10 (about 5 km north of the pipeline fault crossing).

The seismic design ground motion criteria employed at the time of original design are shown in Table 1 as a function of earthquake magnitude (Newmark and Hall, 1974). By way of example, for the magnitude 8.5 seismic region, the criteria called for 0.60 g Zero Period Acceleration (ZPA) for free field ground motion and 0.33 g ZPA for structural design. Both values were selected on the basis of the concept of “effective acceleration” in conjunction with discussions with the USGS. Based on the ZPA values of Table 1, design spectra were constructed for each magnitude and for different soil conditions.

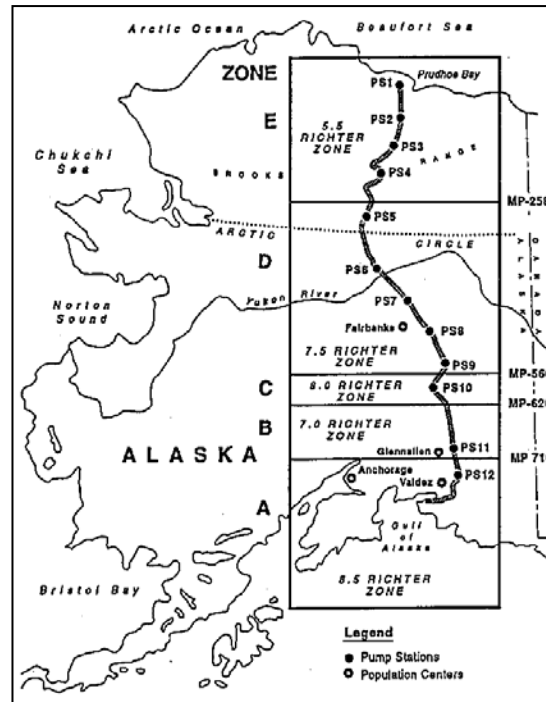


Figure 1. Seismic Zones along the Trans-Alaska Pipeline

Based on the ZPA values of Table 1, design spectra were constructed for each magnitude and for different soil conditions.

Table 1. Design Ground Motions for TAPS Seismic Zones

Richter Magnitude	Acceleration (g)		Velocity (in/sec)	
	Free Field	Structures	Free Field	Structures
8.5	0.60	0.33	29	16
8.0	0.60	0.33	29	16
7.5	0.45	0.22	22	11
7.0	0.30	0.15	14	7
5.5	0.12	0.10	6	5

A structural geologic and engineering geologic study and field survey to identify and locate possible active surface faults that may affect the trans-Alaska pipeline system was carried out by Woodward-Lundgren Associates in 1973-74 (Cluff et al., 2003). Three potentially active fault zones that cross the TAPS route were identified in the fault study: Denali, McGinnis Glacier, and Donnelly Dome faults. The McGinnis Glacier and Denali fault crossings are located within 5 km to the south of Pump Station 10. The Donnelly Dome fault crossing is located on the pipeline alignment where it passes to the east side of Donnelly Dome, about 24 km south of Pump Station 9. The design displacements were taken as approximately two-thirds of the maximum credible displacement, as shown in Table 2.

Table 2. Design Displacements at Fault Crossings

Fault	Maximum Credible, m		Design Value, m	
	Right Shift	Dip Shift	Right Shift	Dip Shift
Denali	9.1	2.1	6.1	1.5
McGinnis Glacier	4.0	3.0	2.4	1.8
Donnelly Dome	1.5	4.6	0.9	10.0

Note: Displacements were originally specified in units of integer feet.

Seismic Design and Observations on Earthquake Performance

During design, it was recognized that the major seismic hazards that could potentially affect TAPS were fault movement, liquefaction, landslides, ground motion (shaking), seismic wave propagation and tsunami. Of these, the first three hazards, faulting, liquefaction, and landslides, were the most serious concerns for the buried portion of the pipeline (about 612 km). Ground shaking was a major concern for the above-ground pipeline (about 675 km)⁵, buildings, structures, vessels, and similar components. Seismic wave propagation was also considered, but resulting pipe strains are normally not high enough to cause damage if the pipeline is constructed of ductile steel with good quality girth welds (which was the case for TAPS). At the Valdez Marine Terminal, in addition to ground shaking, slope and rock instability and the potential effects of tsunami were important considerations.

The philosophy underlying the original design of TAPS was that for a high-level earthquake with a recurrence interval of about 300 to 500 years, referred to as the “Design Contingency Earthquake” (DCE), considerable inelastic behavior and limited damage would be permitted, but that there would no structural collapse, loss of function of essential facilities, or release of crude oil or hazardous substances. The amount of permissible damage varies according to the type of structure or component and its function. The functionality of essential control, communications and emergency systems was specified to be maintained without interruption during and after a DCE. For a lower level earthquake having ground motions one-half the DCE, referred to as the “Design Operating Earthquake” (DOE), the pipeline and facilities were to be capable of withstanding the prescribed seismic motions without damage, significant deformation, or interruption in operation.

Fortunately, the timing of the development of the seismic criteria for the TAPS project and design-related analyses was coincidental with the early, formative stages of the ATC-3-6 effort (Newmark, 1975; Applied Technology Council ATC-3-6, 1978). As such, not only the seismic loading criteria employed in the TAPS design and analysis approaches were “modern,” but equally important, the design and construction employed high quality materials and construction practices that were at the forefront of practice at that time, and almost identical to that which would be employed today.

⁵ The pipeline was constructed above ground in areas of unstable and/or ice-rich permafrost.

The November 3, 2002 Denali Fault Earthquake, magnitude 7.9, was the largest strike-slip earthquake in North America since the 1906 San Francisco earthquake. Surface rupture on the Denali, Totschunda, and Susitna Glacier faults extended 336 km (USGS, 2003). The rupture passed beneath the Trans-Alaska pipeline producing approximately 5.5 m of right lateral offset and 0.6 m of up-to-the-north vertical displacement, as confirmed by geodetic and GPS surveys. The fault displacement was distributed over a zone approximately 200 m in width, with approximately 50 to 70 percent of this displacement occurring as an abrupt offset. The largest maximum measured offset along the fault was 8.8 m. Peak recorded free-field acceleration at Pump Station 10, about 5 km north of the Denali fault, was 0.34 g, with a significant velocity component of about 114 cm/sec (45 in/sec). Strong ground motions lasted about 90 seconds.

Above-Ground Pipeline. To accommodate the effects of thermal expansion and contraction, the above-ground portion of the pipeline is configured in a trapezoidal or “zigzag” configuration on sliding pipe supports spaced at 18-m (60-ft) intervals as shown in Figure 2. The 18-m support spacing was selected to provide adequate support for the pipeline in the event of a loss-of-support condition at any two adjacent supports. A typical above-ground support is shown in Figure 3. The pipe supports are “H-type” supports consisting of a cross-beam supported by two 457-mm (18-inch) diameter pipe piles (actually drilled piles) referred to as vertical support members, or VSMS. At each support a sliding shoe assembly is clamped to the 1,219-mm pipeline, and is allowed to slide on the support cross-beam to accommodate thermal expansion or seismic movement. The bearing surface between the pipe and the beam is a low-friction Teflon interface. Thermal transmission protection from the pipeline to the VSMS is accomplished through use of Micarta bearings in the assembly.

The above-ground pipeline is anchored against movement at intervals of 200 to 600 m by anchor assemblies supported by four VSMS (see Figure 4). The dynamic response



Figure 2. Trapezoidal or “zigzag” above-ground pipeline configuration.



Figure 3. Sliding shoe support, used at 18-m intervals.

of the pipeline is limited at the anchors by a pretensioned longitudinal slipping mechanism and crushable sacrificial honeycomb energy absorber and by specially designed bumpers placed at selected H-type supports (see Figure 5) to limit lateral movement of the pipeline within the configuration.

The dynamic response of the above-ground pipeline to earthquake motions is highly non-linear and the design requires a non-linear transient dynamic analysis to simulate the interaction at the soil-VSM interface, support stiffness, frictional sliding of the pipe shoes, bumpers that stop pipe movement, non-linear reaction characteristics at the anchors, and the spatial variation of ground motion inputs due to seismic wave propagation. The insulation modules, provided to retain heat, also provide some degree of damping to the system.

The magnitude 7.9 Denali Fault earthquake produced ground motions near the fault rupture that generally approach design criteria in the low to mid-frequency range of the design spectrum and exceed the TAPS seismic criteria at frequencies shorter than about 1.0 Hz as can be observed in Figure 6. Considering that the natural frequency of the above-ground pipeline system generally lies in a range from about 0.5 Hz to 2.0 Hz, this level of ground shaking provided a full-scale test of the pipeline design for ground motions essentially equivalent to those considered in the original design analyses.

Most importantly, and consistent with the original design premise, pressure integrity of the pipeline system was maintained. There was no damage to pipeline, i.e., no wrinkling, buckling, or excessive curvature (strain) conditions resulting from earthquake ground shaking. There was



Figure 4. Anchor support for above-ground pipeline. Longitudinal capacity of 667 kN (150 kips). Frictional slipping occurs at 467 kN (105 kips).



Figure 5. Bumper restraint to control lateral seismic movement.

incidental damage to the above-ground support system within about one km either side of the Denali Fault crossing. This consisted of structural damage to eight above-ground supports and separation⁶ of eight support shoes from the pipe. The worst of this damage is illustrated in Figure 7. The frictional slipping mechanisms at nine anchors “tripped” to absorb excess energy from seismic motion. The segment of TAPS that experienced support damage is generally considered to be the zone over which near-fault violent motion exceeded design criteria.

All things considered, the above-ground pipeline performed as required by the design. However, the damage to the supports was more extensive than expected, mainly due to the effects of near-fault violent motion. Studies are in progress to evaluate this behavior in detail and to determine if any retrofits are advisable.

Buried Pipeline. Nearly one-half of the 1,287-km Trans-Alaska Pipeline System (TAPS) is buried in a standard pipeline trench with a minimum depth of cover of 0.9 m. The buried pipeline (Figure 8) must be able to deform axially and in bending in order to accommodate ground strain and curvature associated with seismic wave propagation and permanent ground deformation related to liquefaction, slope movements, surface fault effects, and normal settlement. In the buried mode it was

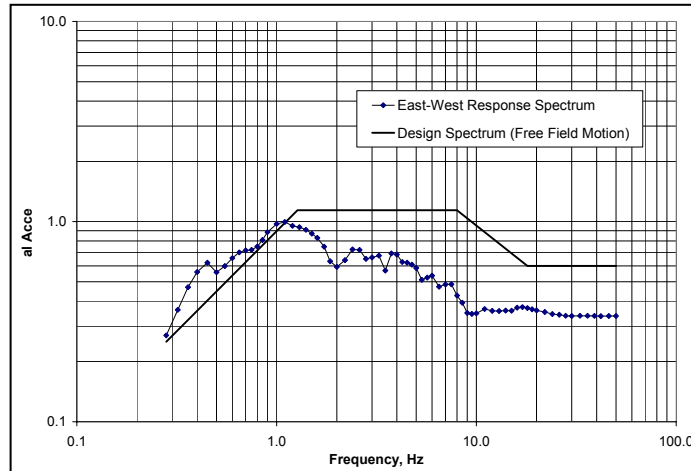


Figure 6. Spectra for ground motion recorded at Pump Station 10, 5 km north of Denali Fault, N39°E. Note that the free-field design spectrum has been exceeded below 1.0 Hz.



Figure 7. Loss of two adjacent supports on above-ground pipeline near Denali Fault. The possible loss of two adjacent supports was a fundamental design assumption.

⁶ Separation of a pipeline support shoe means that the support dropped away from the pipe when the shoe slid longitudinally off the cross-beam. This is an intentional design feature that precludes pounding of the support against the cross-beam.

assumed that the pipeline would interact axially and in bending so as to be fully compliant with the ground deformation, i.e., the pipeline will deform axially and in bending to have the same curvature and longitudinal strain as the ground.

The duration of strong shaking was approximately 90 seconds, and this undoubtedly contributed to widespread liquefaction of subsurface deposits along the pipeline, as evident from numerous sand blows.

In some areas in proximity to the Denali Fault crossing, moderate lateral spread movements were observed. Landsliding did not occur along or across the pipeline right-of-way, although there a number of landslides and rockfalls that occurred along the highways in the area.

The long period nature of the ground motion, a relatively high ground velocity of approximately 114 cm/sec (45 in/sec)⁷, and soil liquefaction along the TAPS route provided significant opportunity for developing large bending and axial strain in the buried pipeline. The pipeline was excavated at a remote gate valve location where surface ground movement was apparent (see Figure 9), but there was no evidence of damage in the form of wrinkling or buckling of the pipe wall or significant displacement of the pipe. Approximately one month after the earthquake, an instrumented pig (“smart pig”) was run through the pipeline. The pig data indicated that the pipeline had moved in some of the liquefaction areas, but the resulting pipe curvatures were well within acceptable limits. In fact, curvatures were reduced in some cases, apparently due to some redistribution of the bedding and padding material within the pipe trench (Johnson et al., 2003). Liquefaction also occurred around the VSM foundation of the RGV equipment shelter (see Figure 10), resulting in minor structural damage.



Figure 8. Buried TAPS pipeline section being lowered into trench during original construction in 1976.



Figure 9. Pipeline and remote gate valve excavated at liquefaction zone. There was no evidence of damage or movements were well within tolerable limits.

⁷ The maximum computed velocity is affected by high-pass filtering at 0.1 Hz. Based on preliminary results from in-progress studies by the USGS, it is believed that the actual peak velocity could have been about 50 percent higher than the calculated value of 114 cm/sec, i.e., about 170 cm/sec.

Fault Crossings. Fault crossings are handled by various modes, namely elevated on pipe supports, laid at the ground surface on “sleeper” supports, or buried (Newmark and Hall, 1975; ASCE, 1984). At the Denali Fault crossing, the pipeline is supported in a special above-ground configuration. Support beams were placed on grade on gravel berms for approximately 600 m, with the ability to slide to accommodate thermal movement and surface fault rupture to prevent excessive pipeline strain. The crossing was designed to accommodate a fault displacement offset of approximately 6 m right-lateral strike-slip and 1.5 m vertical slip, without exceeding permissible strain limits.



Figure 10. Evidence of liquefaction at remote gate valve equipment shelter. Some structural damage occurred.

The magnitude 7.9 earthquake that occurred in south central Alaska on November 3, 2002 ruptured a 350-km long segment of the Denali Fault. The epicenter was located about 88 km west of the pipeline, and the rupture propagated to the east. The fault displacement at the pipeline crossing was about 5.5 m, and reached a maximum of nearly 9 m about 120 km southeast of the pipeline.

The pipeline withstood the Denali Fault rupture without damage. Since the fault trends generally northwest and crosses the pipeline at an angle of approximately 60° , right-lateral movement will place the pipeline in compression. The zigzag configuration in the fault zone compresses like a coiled spring. This can be observed by comparing the two photographs in Figure 11. The photograph on the left in Figure 11 was taken prior to fault movement, and the photo to the right was taken after the occurrence of the 5.5-m fault displacement. The net compressive displacement applied to the pipeline in the fault zone (due to the 55° crossing angle) was approximately 3.5 m. Not only did the pipeline slide laterally toward the outside of the bends to accommodate the compressive displacement, but the initially straight segments of the pipeline took on a bowed shape.

Following the earthquake, it was necessary to re-center eleven support shoes in the fault crossing that had reached the end of their travel tolerance (see Figure 12) to restore fault displacement capacity to an additional 2 m of strike slip, which enveloped geologists' estimates of further short term fault displacements that could reasonably be expected. An evaluation of permanent design retrofit alternatives is in



(a) before



(b) after

Figure 11. TAPS crossing of Denali Fault before and after fault slip, looking south. Note movement and bowed segment after fault displacement, which acts to compress the pipeline crossing segment.

progress, and a final determination of a suitable retrofit will be made after the completion of a post-event field geologic investigation of the Denali Fault.

Piping and Equipment. The DOI Stipulations and U.S. DOT requirements through Title 49 of the Code of Federal Regulations, Part 195, and thereby ANSI Standard B31.4, provide regulations for the design, construction and operation of crude oil pipelines. However, the regulations at that time were essentially “quiet” as to specific requirements for seismic design. As a result Alyeska undertook major effort to adopt applicable American Society of Mechanical Engineers loading and code provisions, with seismic and faulting input added in much the same way as was occurring in the nuclear power industry, the offshore pipeline industry, and the military establishment. Software such as DRAIN-2D was then under development and was employed, to the extent possible, as part of the design and analysis process to validate the behavior of large diameter piping on sliding supports. Equipment qualification was carried out in accordance with recognized procedures of the period



Figure 12. Pipe shoe at Denali Fault crossing perched at edge of grade beam support following fault displacement.

(Hall et al., 1975; Anderson and Nyman, 1979). The same general philosophy was undertaken for tankage and the other many ancillary portions of the system.

Although Pump Station 10 was near the Denali Fault, it had been taken out of service over six years prior to the event. The “mothballed” process and control facilities withstood the earthquake ground shaking with no significant damage, but design seismic loading was not attained during the earthquake, because the piping, vessels and tanks were empty of fluid, and there were no snow loads on the building roofs. Certain critical communications and control systems (including electronic components, cabinets, battery racks, inverters, cable trays, etc.) were in operation at Pump Station 10 during the earthquake and performed as intended without damage or malfunction.

Post-Earthquake Response. The Denali Earthquake in November 2002 provided a “live” test of the TAPS' earthquake emergency response plan. An Oil Spill Contingency Plan coupled with a general emergency management system known as ICS (Incident Command System) provides an emergency management structure for responding to pipeline system emergencies, road and highway closures, commercial power outage, loss of communications, and general disruption including oil spills. During the earthquake, particular emphasis was afforded to the reconnaissance of fault displacements, liquefaction and landslide areas, including the evaluation of the pipeline for excessive strain conditions and/or wrinkling.

An earthquake monitoring system (EMS) serves as a cornerstone for planning and guiding field reconnaissance. The EMS has been included as part of the pipeline control system since the start-up in 1977 (Nyman et al., 1981; Nyman et al., 1999). It was developed pursuant to stipulated Federal and State governmental requirements, and consists of eleven remote digital strong motion accelerograph stations distributed over the 1,287-km pipeline route. Six of the eleven stations triggered into an alarm status when the Denali earthquake occurred. The EMS automatically processed ground motion data immediately after the event, which helped system operators evaluate the severity of the earthquake ground shaking and, in turn, to make a general assessment of the potential for damage to the pipeline and supporting facilities. A key function of the EMS was that it delineated inspection requirements (via detailed checklists) for the affected portion of the route. The use of a comprehensive and focused field inspection effort based on estimates of ground motion shaking severity permitted the pipeline operation to resume after a 66-hour shutdown (Nyman et al., 2003).

Conclusion

This is the first case, known to the authors, where a large-diameter crude oil pipeline system, specifically designed for major earthquake hazards, has been subjected to design level earthquake shaking and fault displacement. The magnitude 7.9 Denali Fault earthquake that occurred on November 3, 2002 approached design criteria for the section of the pipeline passing through the Alaska Mountain Range in the vicinity of Pump Station 10 and the Denali Fault crossing. There was no damage to the

pipeline or release of crude oil, although there was incidental damage to the above-ground support hardware and some movement of the below-ground pipeline in liquefaction areas. The pipeline system withstood the earthquake in a manner consistent with the original design premise.

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