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EFFECT OF THE DENALI FAULT RUPTURE ON THE TRANS-ALASKA PIPELINE

Steve P. Sorensen[1] and Keith J. Meyer[2]

Abstract

The Trans-Alaska Pipeline winds its way south from the Alaskan North Slope, transecting the state for a distance of 1,287 km (800 miles), to the Marine Terminal at Valdez. At peak throughput, the 1,219-mm (48-inch) diameter pipeline transported 2.1 million barrels of warm North Slope crude oil per day, and currently delivers about 1.0 million barrels per day. Alyeska Pipeline Service Company has operated the pipeline for its owner companies since startup in 1977.

On November 3, 2002 the Denali Fault, which intersects the pipeline route near Milepost 589 in central Alaska, ruptured over a distance of 336 km, producing the largest earthquake from a continental strike slip fault in North America since the 1906 San Francisco earthquake. This paper describes the design of the special above-ground pipeline segment in the Denali Fault zone and its response to violent, near fault shaking and displacement during the November 3rd, magnitude 7.9 Denali Fault event.

Introduction

Prior to construction of the Trans-Alaska Pipeline System (TAPS), a geologic study and field survey was conducted to identify active surface faults crossing the proposed route of the pipeline. Three potentially active fault zones were identified: Denali, McGinnis Glacier, and Donnelly Dome. In addition, over half of the route traverses areas of thaw unstable permafrost necessitating an above-ground mode on piling supports. A special design utilizing long grade beam supports was utilized within the Denali Fault zone.

The magnitude 7.9 Denali Fault earthquake produced ground motions that slightly exceeded the TAPS seismic criteria at periods longer than about 1.0 second and generally approached design criteria at shorter periods. The duration of shaking was approximately 100 seconds, with violent shaking in the near fault region of the pipeline. In near proximity to the Denali Fault crossing, large fault movements occurred.

The long period nature of the ground motion, produced a maximum ground velocity of approximately 114 cm/sec (45 in/sec)[3] coupled with violent near fault movement

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[1] Engineering Coordinator, Alyeska Pipeline Service Company, Fairbanks, AK, M. ASCE.

[2] Vice President, Michael Baker Jr., Inc., Anchorage, AK, M. ASCE.

[3] 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.

in the above-ground segments. The event tested the ability of the fault crossing design to withstand fault rupture displacements approaching design level with respect to pipe movement on the at-grade sliding supports and pipe stress. There was no evidence of damage to the pipeline in the form of wrinkling or buckling of the pipe, but there was some support damage as described later in this paper. Realignment of a limited number of supports in the fault zone was required following the event to restore the fault movement response capacity of the pipeline to an additional 1.7 m of strike slip. This allowance accounts for early estimates of further fault displacements that may reasonably be expected if additional faulting occurs in the short term. The standard above-ground pipeline segments immediately north and south of the fault crossing zone were also inspected and support damage was repaired as described in Sorensen et al. (2003). Subsequent smart pig runs verified this observation.

This paper provides an overview of the field reconnaissance conducted in proximity to the Denali Fault, observations of movement and damage resulting from the violent lurching motion induced by the earthquake, and a discussion of the methodology used during early adjustments to the special grade beam design for the Denali Fault.

TAPS Design Background

Seventy five percent of the TAPS route was originally underlain by permafrost, necessitating a unique above-ground design that accommodates potentially unstable, ice-rich permafrost conditions. The below-ground pipeline is a conventional buried design used in thawed soils and in permafrost soils that are defined as thaw stable. A deep burial mode (below unstable surficial soils) and a refrigerated insulated burial mode (thick non-thaw stable soils) are used in some areas. Over half the pipeline (676 km) is constructed above ground and the remainder (611 km) is buried.

Both above and below-ground designs are affected by the extreme seismic activity of Alaska. (The magnitude 9.2 Prince William Sound subduction zone earthquake of 1964 is the second largest earthquake ever recorded.) TAPS traverses a wide range of geotechnical conditions that directly affect design and operation of the pipeline and related facilities. The goal of the original geotechnical design was to provide a stable foundation for pipeline elements, both statically and dynamically, so that the system can operate for the long term in an effective and safe manner without undesirable consequences to the public or environment. Alyeska Pipeline Service Company (Alyeska) conducted extensive seismological and engineering studies during the design of the pipeline to develop seismic structural design criteria, characterize active faults crossing the pipeline, and mitigate the potential affects of geohazards such as soil liquefaction and landslides.

Faulting that results in surface rupture is an important consideration for pipelines because pipelines crossing fault zones must deform or move longitudinally in response to axial compression or tension forces and laterally in response to bending and shear forces to accommodate ground surface offsets. Three potentially active faults were identified that crossed the pipeline in central Alaska. Alyeska carried out fault studies to characterize fault length, expected rupture slip, fault zone width, and slip recurrence interval (Cluff et al., 2003). Estimated ground displacements associated with these faults are shown in Table 1.

Table 1. Design Displacements at Active Fault Crossings.

Fault	Milepost	Max Credible Slip (m)		Design Slip Value (m)	
		Strike Slip	Dip Slip	Strike Slip	Dip Slip
Donnelly Dome	556	9.1	2.1	6.1	1.5
McGinnis Glacier	587	4.0	3.0	2.4	1.8
Denali	589	1.5	4.6	0.9	10.0
Note: Displacements were originally specified in units of integer feet.					

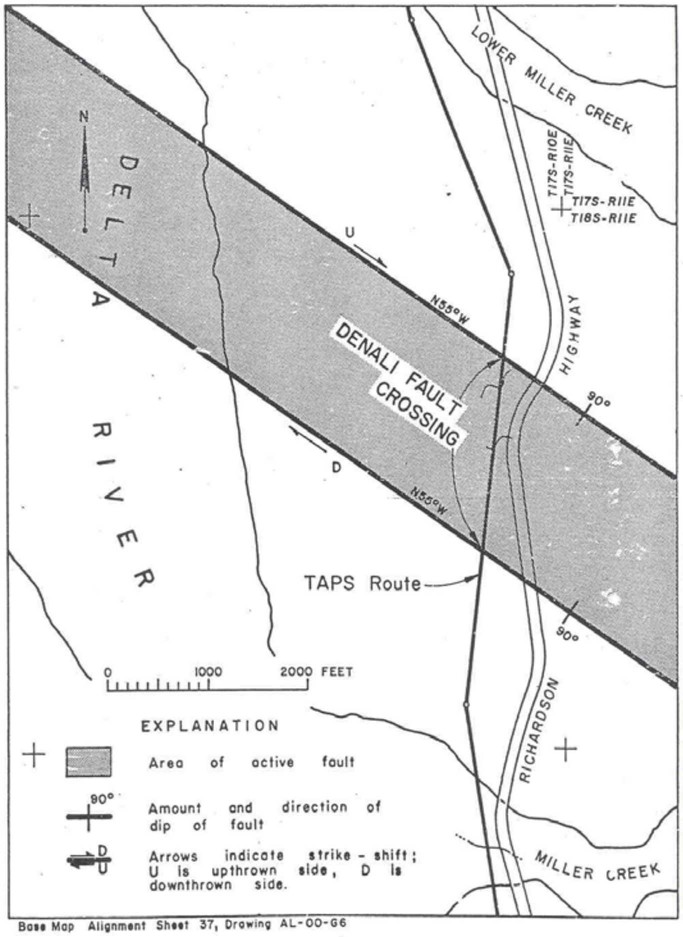
During the November 3, 2002 magnitude 7.9 event, the Denali Fault ruptured over a distance of 336 km. The epicenter occurred near the newly discovered Susitna Glacier thrust fault, approximately 90 km to the west of the pipeline. The fault intersects TAPS at Milepost 589 in central Alaska. Average slip on the fault is estimated to be 5.5 m near the pipeline crossing with maximum slip of almost 9 m occurring 120 km to the east of the pipeline crossing.

Special Above-Ground Configuration at Denali Fault Crossing

The Denali Fault extends east to west more than 650 km through the Alaska Range. It is a right-lateral strike-slip fault with a normal-slip component. The fault plane is nearly vertical, and the up-block is to the north. The pipeline crosses the Denali Fault zone between Lower Miller Creek and Miller Creek near MP 589. The width of the fault zone used in design was 579 m, which implies that a surface rupture was possible anywhere within this zone. The limits of the fault zone were established between pipeline as-built Stations 31082+00 and 31101+00 (feet). The fault strike at the pipeline crossing is N55°W. Since the pipeline bearing is N6°32′E at the fault crossing, the fault crossing intersection angle is 61°32′ counterclockwise with respect to the pipe survey centerline as shown in Figure 1.

The area is predominately a level outwash plain composed of thawed fluvial gravels and glacial till material overlaying bedrock at an undetermined depth. However, the northern 61 m of the fault zone is a relatively steep hill composed of silty gravelly glacial till and granite bedrock.

During the course of pipeline design, it was determined that the warm crude oil pipeline would be above-ground in the Denali Fault area because of the presence of thaw unstable permafrost soil. Due to the magnitude of the design fault displacements, conventional above-ground construction was judged impractical at the Denali Fault crossing. Instead, at-grade beam construction on which the pipe is free to slide was selected to provide support for the pipeline across the fault zone because it can accommodate relatively large displacements without significant pipe deformation. This low-to-the-ground construction mode has the added benefit of limiting damage to the pipeline if, for any reason, the pipe unexpectedly slips off the



Base Map Alignment Sheet 37, Drawing AL-00-G6

Figure 1. Pipeline crossing of Denali Fault.

support beam during a seismic event. The pipeline was designed to accommodate a right lateral strike slip of 6 m and a vertical slip of 1.5 m with the north block up. The dip plane was assumed to be vertical. The three-dimensional displacement components relative to the pipeline orientation (i.e., parallel to the pipeline bearing of N 6°32′ E) are 2.9 m longitudinal 5.4 m transverse, and 1.5 m vertical.

At the Denali Fault crossing, the pipeline is supported on 33 steel box beams and concrete beams set on-grade, at approximately 18-m intervals over a distance of 579 m. The beams are approximately 12 m long. The location of some of these beams is shown as Grade Beam Numbers 5 through 12 (Figure 2) in the immediate vicinity of the fault. These beams were sized and arranged to accommodate a fault slip. Anchors in the typical above-ground configuration bound the special Denali Fault above-ground segment north and south of the fault crossing area.

The pipeline shoes were lengthened in the fault zone to accommodate the large longitudinal and lateral pipeline movements anticipated by the largest projected fault displacement and magnitude as shown in Figure 3. Close attention was paid to the sliding surface of the crossbeam and the material lining the bottom of the pipe shoe. The pipe shoe base consisted of a 0.63-cm thick steel plate to which was bonded a

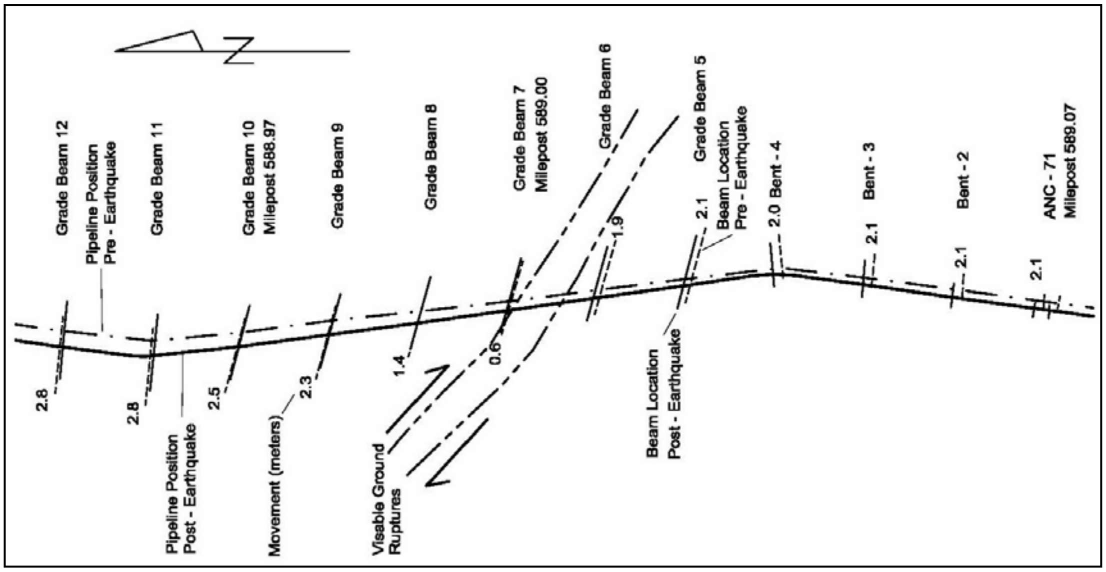


Figure 2. Denali Fault pipeline crossing schematic

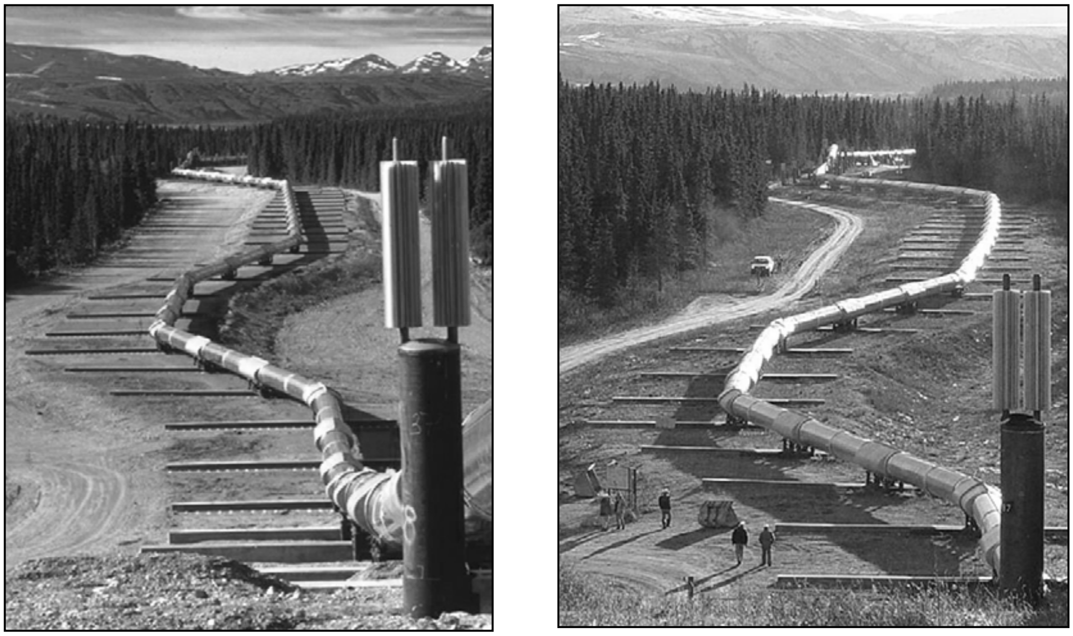
Teflon pad. The crossbeam surface was sand blasted and painted with zinc rich epoxy paint. The coefficients of friction values of 0.10 static and 0.05 dynamic were specified by design and confirmed through testing.

Performance of Special Fault Crossing Configuration

As expected, significant pipeline and pipeline support movements occurred during the November 3, 2002 fault rupture. The trace of the rupture was clearly visible between grade beam supports 6 and 7 near the southern end of the special

Figure 3. Typical special configuration bent on a concrete grade beam: Note offset shoe position by design to accommodate pipe movement in this case to the left.

configuration shown schematically in Figure 2. A range of potential locations of fault surface rupture was analyzed during design. From these design studies, the most severe effect on the pipeline was determined to be when surface rupture was postulated at grade beam 7, which is only one bent away from the observed fault trace. Therefore, this event actually represented the near maximum expected movement for the design, as was indeed the observed result. The relative locations between pre-event and post-event pipeline and beam positions are shown in Figure 4.



(a) before (b) after

Figure 4. 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.

Anchors are designed to control longitudinal movement of the pipeline through frictional resistance. Anchors begin slipping at an instantaneous force of 475 kN (105 kips). The anchors north and south of the fault crossing slipped longitudinally and experienced further movement through slippage between the anchor frame and support brackets on the VSMs. Some deformation of the anchor frames was observed via yielding of the slotted bolted connection on the frame itself, but not at the support bracket. During repair operations on the first anchor south of the Denali Fault, the pipe clamps connecting the anchor assembly to the pipeline were released. There was no observed movement of the pipe through the anchor clamps demonstrating that there was no residual compressive stress in the pipeline.

The pipeline support shoe at the first VSM bent (immediately south of the last grade beam configuration) was severely damaged (see Figure 5). This was probably due to the vertical faulting and concurrent violent dynamic shaking both vertically and horizontally. The shoe was replaced during the field repairs after the event, and the pipe was thoroughly inspected. Based on documented inspection reports, the pipe itself had no observable damage in this region.

Figure 5. Post-event shoe damage (left) and pre-startup repair (right) on the seismic bent immediately south of the Denali Fault. Note the temporary shoring beneath the pipe used during repairs (right side of picture), the bumper beam on the pipe clamp (center), and the impact absorber on the VSM (far left side of picture).

At special configuration locations, ground movement at the grade beams was evident, although no damage to the grade beams, pipe support shoes or the pipe itself was observed (see Figure 6). Slip marks caused by the pipeline shoe sliding across the crossbeams and grade beams during faulting and associated shaking were observed throughout the fault crossing. Some of the grade beams in the near fault area exhibited evidence of minor ground plowing, probably through inertial forces in the beam and/or as a result of sliding friction resistance between the shoe and beam. Pipe shoe movement was often more than the estimated ground fault displacement, and occurred well back from the rupture trace line due to compression and pipe flexure. The final "set" of the pipeline results from friction resistance between the shoe and the cross beam, producing the illusion of residual compression. The observed movement was expected and predicted by the design analysis.

Figure 6. Post-earthquake shoe location on grade beam prior to re-centering.

Post Earthquake Assessment and Repairs

Surveillance of the pipeline in the first hours after the event clearly established that surface rupture of the Denali Fault had occurred near the south end of the fault crossing zone and that sliding pipe shoes had experienced large movements. Within hours of the event, a response coordinator was mobilized in the field to initiate damage assessments and mobilize repair crews. The fieldwork was aided by unseasonably warm (near freezing) temperatures, but hampered somewhat by short daylight hours. By early the next day, engineering assessment crews were fully engaged, and repair crews and equipment were on site.

Initial field estimates of the ground faulting at the fault scarp indicated displacements of approximately 2.3 m strike slip and 0.8 m vertical. GPS and geodetic surveys initiated within one week after the earthquake determined the fault displacements to be larger: 5.5 m horizontal and 1.5 m vertical distributed over a zone of approximately 200 m.

Several of the shoes in both the typical VSM-supported configuration and the special Denali Fault grade beam configuration were reported to be near the edge of the crossbeams. An analysis was performed to determine which pipe shoe locations needed to be adjusted to ensure the shoes would remain on the beams should additional fault displacement occur.

The Alyeska survey group collected post-earthquake longitudinal shoe position data on November 13th. Because of the onslaught of winter, a decision was made during the early repair period to try to accommodate any further short-term fault movement by leaving the support beams in place and relocating the shoes on the pipe where necessary. This would allow additional longitudinal and lateral movement capacity. By consensus among geologists it was decided that this was a major event, and that it had released most if not all of the locked-in strain energy. The geologists expected no more than a 1.7 m displacement potential in the short term. This was believed to be an upper bound limit.

The allowable extents of future longitudinal shoe movements were estimated based on the least remaining amount of lateral shoe movement available on the grade beams. This shoe position was then compared to the early estimates of a maximum near term lateral fault shift, 1.7 m. The additional expected longitudinal pipeline movement was found by multiplying the predicted full design movements at each bent by the ratio of the anticipated fault shift (1.7 m) and the design fault shift (6.25 m).

The final location of the shoes were then determined by adding the expected longitudinal movements to the post-earthquake locations for each shoe and verifying whether or not the shoe could still rest on the beam. A safety buffer of 150 mm was used; meaning that at least 150 mm of shoe had to remain overhanging the crossbeam at the shortest shoe location, or the shoe location on the pipe would require adjustment.

A total of ten shoes were estimated to have less than 150 mm of remaining overhang after calculating the projected additional fault displacement. One shoe had less than 150 mm of overhang in its post-event position. All eleven of the target shoes were re-centered on the pipeline.

Conclusion

The design of the Denali Fault crossing for TAPS was the first specially designed crossing of an active fault by a crude oil pipeline. The innovative above-ground crossing design was developed over 30 years ago when "lifeline earthquake engineering" was in its infancy. The 2002 Denali Fault earthquake provided a full-scale test of this crossing concept, and the pipeline and support system performed as expected, without damage to the pipeline or leakage of oil. It is worthwhile to note that had the pipeline had been buried in a special fault crossing trench (loose backfill and sloped sides), it would have required much heavier wall pipe and local buckling likely would have occurred, hence requiring pipe repair and more extended downtime.

Additional studies are in progress to characterize the potential for future displacement on the Denali Fault during the remaining life of the pipeline. The pipe and supports in the fault crossing zone will be further realigned if required.

Acknowledgment

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