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ASSESSMENT OF THE BELOW-GROUND TRANS-ALASKA PIPELINE FOLLOWING THE MAGNITUDE 7.9 DENALI FAULT EARTHQUAKE

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Abstract

Nearly half of the 800-mile (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 (3 feet). The magnitude 7.9 Denali Fault earthquake produced peak ground motions of 0.34 g at a location 5 km from the fault. The duration of shaking was approximately 90 seconds, contributing to liquefaction of subsurface deposits along the pipeline as evident from numerous sand boils. In some areas in proximity to the Denali Fault crossing, moderate lateral spread movements occurred. Landsliding did not occur along or across the pipeline right-of-way itself, although there were a number of landslides and rock falls that occurred proximate to the Denali Fault zone several tens of kilometers west of the pipeline.

The near-source violent motions coupled with soil liquefaction provided the opportunity for developing significant bending and axial strain in the buried pipeline. The pipeline was excavated at a location where evidence suggested lateral spreading or subsidence due to liquefaction, but no damage to the pipe was observed. Approximately one month after the earthquake, the pipeline was inspected using an instrumented in-line monitoring device ("smart pig") capable of detecting pipeline curvature and deformation. No evidence of pipe deformation, strain increases, or curvature changes in excess of acceptable limits were observed.

This paper provides an overview of the field reconnaissance of the below-ground pipeline segments in proximity to the Denali Fault, observations of liquefaction and ground failure, and a discussion of the use of an instrumented pig to validate pipeline structural integrity.

Introduction

The Trans Alaska Pipeline System (TAPS) zigzags off the North Slope in its unique above-ground configuration, transecting the State of Alaska 1,287 km (800 miles), south to its marine terminal in Valdez (Figure 1). At peak throughput, the 1,219-mm (48-inch) diameter pipeline transported 2.1 million barrels[4] per day (mbpd) of warm North Slope crude oil. Due to declining North Slope production, it currently delivers about 1.0 mbpd, or about 16 percent of America's domestic supply. The pipeline has

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[4] One barrel equals 42 gallons.

been operated by Alyeska Pipeline Service Company (Alyeska) for its owners since startup in 1977.

On November 3, 2002 the Denali Fault, which intersects the pipeline route at Milepost 588 in central Alaska, ruptured over a distance of 336 km, producing the largest earthquake from a continental strike-slip fault in the United States since the 1906 San Francisco earthquake. This paper describes the design and performance of buried portions of TAPS near the fault during the magnitude 7.9 Denali Fault event. The above-ground pipeline design and its performance during the Denali Earthquake are described in a paper by Sorensen, et al. (2003).

TAPS Design

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 under both static and dynamic conditions. The pipeline design was affected by the extreme seismicity of Alaska, acknowledging that the magnitude 9.2 Prince William Sound subduction zone earthquake of 1964 remains the second largest earthquake ever recorded worldwide. Prior to construction, Alyeska conducted extensive seismological and engineering studies (Cluff et al 2003) to characterize active subduction zone and continental faults crossing the pipeline, develop ground motion design criteria, and mitigate the potential affects of geohazards such as soil liquefaction and landslides.

Three potentially active faults that crossed the pipeline in central Alaska were identified and fault studies were carried out to characterize fault length, expected rupture slip, fault zone width, and slip recurrence interval. Large rupture displacements up to 6m/1.5m (strike/dip) were anticipated on the Denali Fault, with 4m/3m on the McGinnis Glacier, and 2m/5m on the Donnelly Dome Fault.

Approximately 75 percent of the 1,287 km TAPS route was originally underlain by permafrost, necessitating a unique above-ground design in many places to accommodate potentially unstable, ice-rich permafrost conditions. Over one-half the pipeline (676 km) is constructed above ground, with the remainder (611 km) buried. The below-ground pipeline is, for the most part, a conventional buried design used in thawed soils and in permafrost that is defined as thaw stable (less than 6 percent fine grained soil). However, TAPS unique terrain and seismicity conditions required two additional options – a deep burial mode for use below unstable surficial soils, and a refrigerated insulated burial mode for use in thick non-thaw stable soils. As expected, the warm buried pipeline has thawed most permafrost along the right-of-way (where permafrost was initially present within 35-50 m below pipe), except for a relatively short (6-km) portion of the buried pipeline where a specially insulated and refrigerated system keeps the foundation frozen.

During the development of the design concept for TAPS, it was presumed that a buried construction mode would be incapable of withstanding the large ground ruptures that might occur at the three identified active fault crossings. Hence, all known active faults were crossed above-ground (Sorensen et al., 2003; Hall et al., 2003). As an additional design safeguard, the standard trench design was validated for a generic condition of 0.6 m (2 ft) of differential movement due to ground rupture.

Seismic design ground motions for the Trans-Alaska Pipeline System are based on stipulated design earthquakes for five seismic zones along the route as delineated by the U.S. Geological Survey (USGS) (Cluff et al., 2003). A maximum credible earthquake, with an estimated return period of 300 years or more, was specified for each of the five seismic zones and defined in terms of Richter magnitude (used at the time of pipeline design) as depicted in Figure 1. Alyeska established design ground motions for earthquakes in each seismic zone as delineated in Table 1.

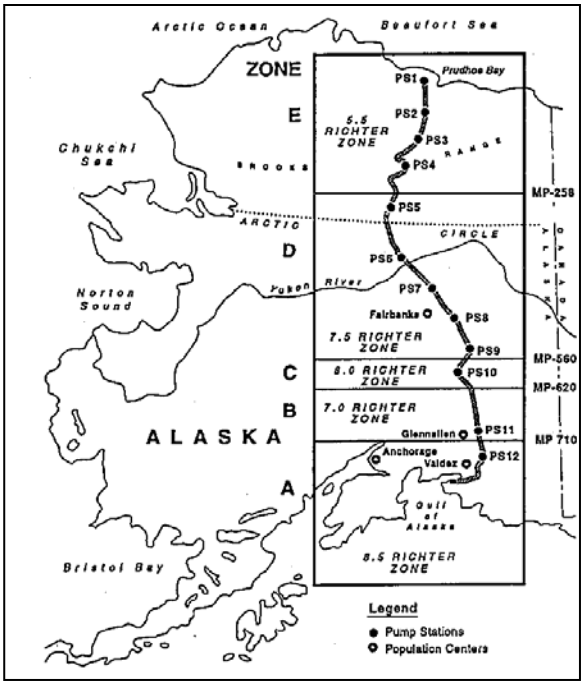

Figure 1. Seismic zones along the Trans-Alaska Pipeline

Table 1. Free Field Design Ground Motions

Seismic Zone according to Pipeline Milepost	Acceleration (g)	Velocity (cm/sec)
0 – 258	.12	15
258 – 560	.45	56
560 – 620	.60	74
620 – 710	.30	36
710 – 800	.60	74

November 3, 2002 Magnitude 7.9 Event

The Denali Fault ruptured over a distance of nearly 350 km. The epicenter occurred near the newly discovered Susitna Glacier thrust fault, approximately 90 km to the west of the pipeline. The fault intersects the TAPS route at Milepost 588 in central Alaska. Slip on the fault was measured at 5.5 m near the pipeline crossing with maximum slip of almost 9 m occurring 120 km to the east of the pipeline crossing.

Ground Motion during the Nov 3 event was recorded by Digital Strong Motion Accelerograph (DSMA) units maintained by Alyeska at Pump Stations 7, 8, 9, 10, 11, and 12 as part of its Earthquake Monitoring System (EMS). Peak ground acceleration measured at these stations is given in Table 2. The highest ground motions were recorded at Pump Station 10, 5 km north of the Denali Fault. Maximum measured peak ground acceleration was 0.34 g, and a maximum ground velocity of 114 cm/sec (45 in/sec) was computed from the acceleration record. Considering that the acceleration signal was high-pass filtered at 0.1 Hz, the maximum ground velocity actually may have been about 50 percent higher than the value computed from the accelerograms[5].

At Pump Station 11, 155 km south of the Denali Fault pipeline crossing, measured peak ground acceleration was about 0.1 g whereas at Pump Station 9, 64 km to the north, the measured peak ground acceleration was about 0.08 g. Measured horizontal and vertical ground accelerations were less than design ground accelerations at all measurement stations, but the peak ground velocity was three to five times higher than would normally be associated with this level of acceleration due to the near-source violent ground motions associated with fault rupture.

Table 2. Peak Ground Accelerations vs. Design Accelerations

Pump Station	Pipeline Milepost	Measured Peak Accel.		Design Accel.	
		Horiz	Vert	Horiz	Vert
PS 07	414	0.018	0.010	0.450	0.300
PS 08	489	0.046	0.024	0.450	0.300
PS 09	549	0.074	0.053	0.450	0.300
PS 10	586	0.337	0.238	0.600	0.400
PS 11	686	0.087	0.033	0.300	0.200
PS 12	735	0.039	0.024	0.600	0.400

Below-ground Pipeline Design and Performance

The below-ground pipeline design and operation considers the affects of a number of geohazards including thaw induced subsidence, landslides, soil liquefaction, fault movement, and axial strain associated with seismic wave propagation. Subsidence caused by thawing permafrost was the key factor influencing the TAPS below-ground design, and while not directly related to seismic aspects of design per se, it precipitated the development and use of in-line inspection technology that proved very effective in post-earthquake damage assessment of the buried pipeline.

Since 1992 Alyeska has used an inertial navigation inline inspection device ("smart pig") to obtain measurements that can be used to detect pipe deformation and other conditions that approach operational tolerance limits (Figure 2). The pig uses three-axis gyroscopes and accelerometers to determine the position of the pig in three-

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[5] The maximum computed velocity is affected by high-pass filtering at 0.1 Hz. Based on preliminary results from in-progress studies conducted 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.

dimensional space, and thus the pipe at 5-cm intervals along the pipeline. This position data is post-processed to calculate bending radius and bending strain. The pig also uses 64 radius-measuring fingers to determine circumferential deformation.

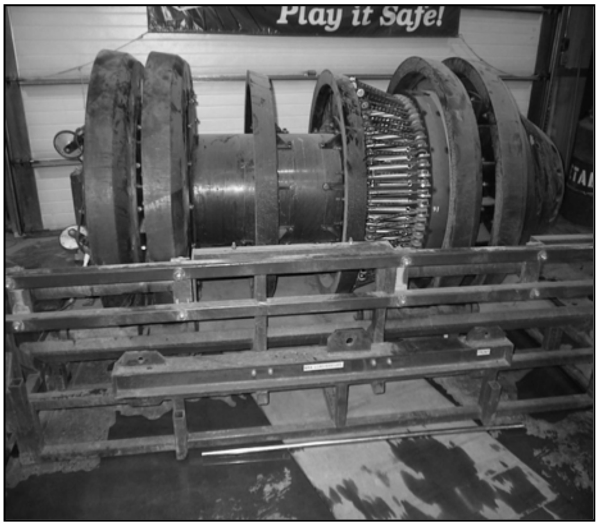

Figure 2. Inertial navigation tool used to determine pipeline curvature and deformation

Slope Stability

The federal and state Right of Way Agreements stipulated that unstable slopes shall be avoided, or where not possible, the design shall mitigate "harmful effects". Alyeska slope stability evaluations considered all types of soil mass movement including liquefaction. Near the Denali Fault, the pipeline design avoids potentially unstable slopes. Field surveillance was initiated immediately following the November 3rd earthquake. No evidence of slope instability affecting the pipeline was observed. Shallow soil detachments on ridge crests and rockfall and raveling on talus slopes was noted in the vicinity of the pipeline corridor, but these were too distant from the pipeline to constitute a threat. Significant (massive) landslides were noted by USGS observers where the fault zone parallels the Black Rapids Glacier, but these areas were several tens of kilometers to the west of the pipeline route.

Soil Liquefaction

Seismic liquefaction describes the behavior of certain cohesionless soils which, under saturated conditions, may lose a large portion of their shear strength as a result of earthquake shaking and may acquire characteristics of a viscous liquid mass with flow capabilities. The potential for soil liquefaction during a seismic event was one of the most important considerations in the design of the pipeline. Approximately 160 km (100 miles) of the below-ground pipeline is located in areas that were judged to be potentially liquefiable.

A pipeline buried in level ground subjected to liquefaction will tend to "float" or "sink" depending on buoyancy considerations. Lost ground associated with sand boils can also contribute to subsidence. When liquefaction occurs in a soil mass not confined by adjoining stable soil strata, lateral sliding or motion in the unconfined direction may occur.

For potential liquefaction areas that could not be avoided in construction, design mitigation measures were employed to assure long-term integrity for the pipeline. For below-ground sections of the pipeline, the most common mitigation is burial below the potentially liquefiable soils. Other buried pipeline mitigations include grading of slopes to less than 2 percent, removal and replacement of potentially liquefiable soils and, special design with insulated pipe and heat pipes (thermo-siphons). On flat ground (less than 2 percent grade) no protective measures were required, but buoyancy of buried pipe sections was considered in the design.

Field inspection after the November 3 earthquake showed liquefaction events in high groundwater areas of floodplains, especially in the Delta River and Phelan Creek areas up to 30 km south of the Denali Fault. All of the observed liquefaction events are in relatively flat areas (less than two percent grade) with shallow groundwater conditions. Four locations were observed with a length totaling about 2 km (Table 3).

Table 3. Areas of Observed Soil Liquefaction

Location (Milepost)	Length, m	Slope
590.7 – 591.1	640	<2 percent
592.7 – 592.9	320	<2 percent
599.4 – 599.6	320	<2 percent
606.4 – 606.8	640	<2 percent

Observed liquefaction events resulted in sand boils, surface cracking with liquefied soil flow, and surface cracking resulting from lateral spreading of surface fill. Figures 3 and 4 show typical liquefaction sites in the Delta River floodplain south of the Denali Fault.

Ground cracking occurred parallel to the sides of the original pipeline ditch where select clean backfill surrounds the pipe. No ground cracking was observed over the pipe. Liquefied soils are thought to have used these parallel cracks as an avenue for escape, causing sand boils at the ground surface (Figure 5).

Figure 3. Surface evidence of liquefaction near Remote Gate Valve 91. south of Denali Fault.

Figure 4. Surface evidence of liquefaction in the Delta River floodplain.

Fault Movement

As mentioned earlier, the Denali Fault was crossed in an above-ground mode. Thus, the Denali Fault rupture did not affect the buried pipeline in a direct sense, i.e., due to abrupt surface offset and localized ground deformation in close proximity (100 m) to the rupture. The response of the above-ground fault crossing is discussed by Sorensen and Meyer (2003).

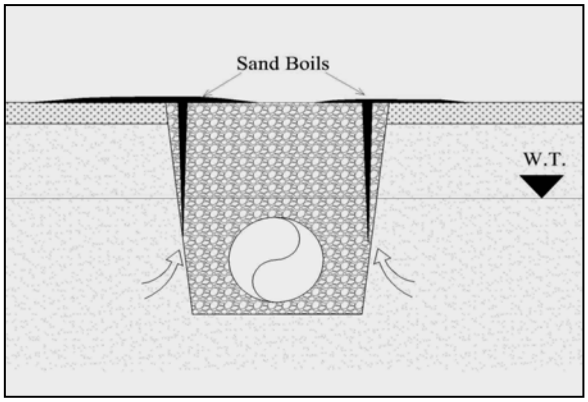

Figure 5. Diagram of typical liquefaction event

Surface Wave Propagation

A pipeline buried in soil that is subject to the passage of seismic waves (compression, shear and surface waves) will incur longitudinal and bending strains as it conforms to the associated ground strains. In most cases, these strains are relatively small, and welded pipelines in good condition, which is the case with TAPS, typically do not incur damage.

A relatively simple method to estimate axial ground strain from wave propagation is based on an approach developed by Newmark (1968) can be used to obtain an upper-bound estimate of ground strain due to a propagating seismic wave with a constant shape (sine wave). The maximum axial ground strain, ε_g, is given by:

$$\varepsilon_g = \frac{V_{\max}}{\alpha_\varepsilon c} \tag{5}$$

where V_{max} is the maximum horizontal ground velocity in the direction of wave propagation, c is the apparent propagation speed of seismic wave, i.e., the component of wave speed parallel to the pipeline under consideration, and α_ε is the ground strain coefficient corresponding to the most critical angle of incidence and type of seismic wave and ranges from 1.0 for compression and Raleigh waves to 2.0 for shear waves (ASCE, 1984). Estimates of wave travel speeds have not been made for the Denali Fault area, at least not by the authors; however, an apparent propagation velocity of 900 m/sec can generally be taken as a lower bound estimate (ASCE, 1984) to provide a maximum estimate of ground strain from body waves.

Assuming a maximum ground velocity of 170 cm/sec, a propagation speed of 900 m/sec, and a ground strain coefficient of 1.0, the maximum ground strain, , is 0.187 percent. If there is no slippage of the pipeline relative to the surrounding soil, then the maximum axial strain in the pipeline can be taken equal to maximum ground strain, an upper-bound, conservative assumption. However, if it is assumed that 100 percent of the ground strain is transferred to the buried pipeline, this would relate to a pipe stress of 387 MPa (56 ksi), which is about 85 percent of the specified minimum yield stress for Grade X65 steel pipe, well within elastic limits for buried pipe.

Ground curvature resulting from wave propagation will also induce bending in a buried pipeline, but the resulting pipe strains are generally so small compared to the direct axial strain effect that they can be neglected.

Curvature/Deformation Pig Results

The buried pipeline, located outside the fault zone, is typically less vulnerable to seismic hazards than the above-ground design. Hidden damage to the buried pipeline however, could not be visually inspected and, thus, required use of in-line inspection (ILI) methods (Figure 2).

Immediately after the occurrence of the Earthquake, planning began for the running of a smart pig. Before the pig could be run, it was necessary to run five cleaning pigs through the line to assure it was clear of wax accumulation which could affect the instrumented pig readings. Two of these cleaning pigs had a greater hard diameter thereby assuring clear passage for the smart pig. Following the smart pig run, the measurement data acquired between Pump Stations 9 and 11 was processed and reviewed to assess pipeline integrity. This covered a pipeline distance of approximately 220 km (137 miles).

If the pipe were to change position as a result of the earthquake, the change would first be apparent in the strain or curvature data. The software allows data from one year to be subtracted another and thus differences in values other than zero indicate a change. Example output from the smart pig run is shown in Figure 6. Changes were noted in the below-ground pipe in the area of Remote Gate Valve 91 (RGV91) and other areas with observed surface disturbance. Interestingly, in each case the change

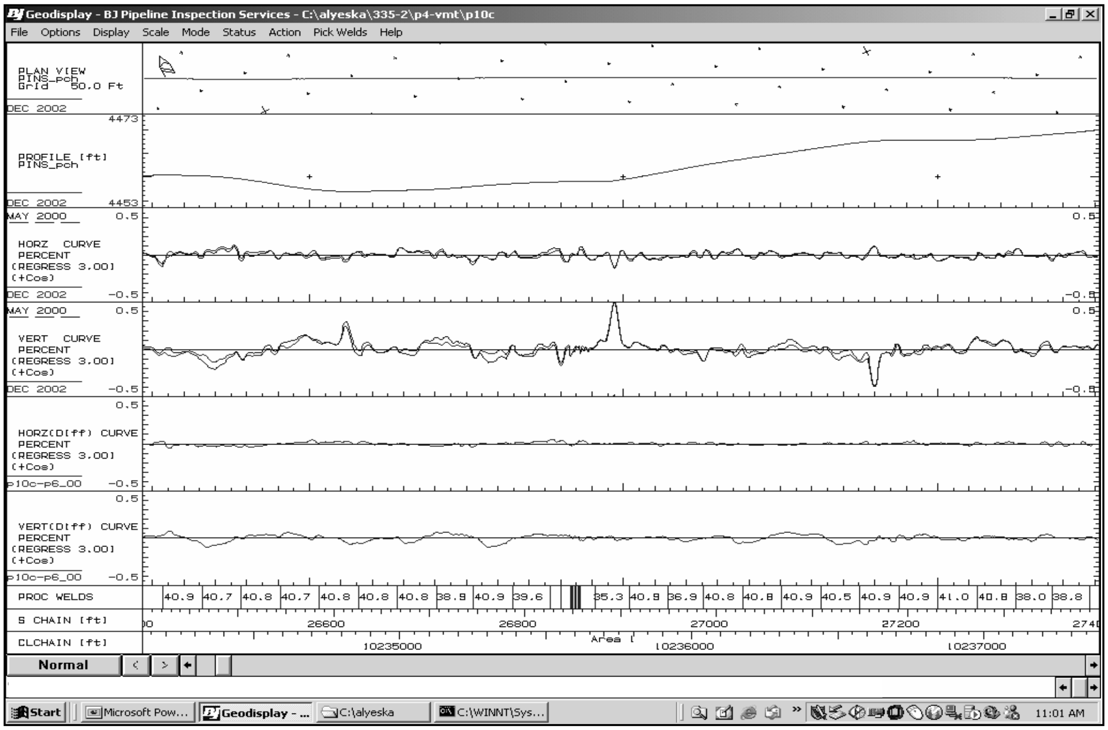

Figure 6. Smart pig data

was to a lower strain level. For example, one area north of RGV91 experienced a curvature change from 60 to 41 percent of critical bending curvature. Another area south of RGV91 experienced a curvature change from 56 to 34 percent of critical bending curvature. Both these areas demonstrated some indication of liquefaction, which apparently allowed the pipe to relax in the ditch during the shaking. Between Pump Station 9 and Pump Station 11 there are 15 dents and 18 other target areas of known bending curvature. Each of these locations were checked and found not to have changed as a result of the earthquake.

Summary of Observations and Findings

The buried pipeline met all performance expectations associated with the magnitude 7.9 earthquake of Nov 3, 2002. This section summarizes some of the key observations and findings.

1. Ground motions of 0.34 g maximum acceleration, velocities perhaps as much as 170 cm/sec, and a ground shaking duration of 90 seconds caused liquefaction to occur in loose, saturated cohesionless soils. A design strategy of crossing potentially liquefiable areas either on essentially flat terrain (less than 2 percent slope), or buried below liquefaction depth successfully avoided harmful effects of subsidence or spreading.

2. Avoidance of unstable slopes in the vicinity of the Denali Fault proved to be an effective slope stability design strategy. Actual earthquake ground motions (0.34g), however, were less than ground motions used to assess potential geohazards (0.60g).

3. As has been observed worldwide for buried steel pipelines with good quality welds, seismic wave propagation did not damage or permanently deform the below-ground pipeline. Estimated maximum pipe strain was less than the specified minimum yield strength of the pipeline.

4. Post-event inspection of the pipeline using the instrumented curvature/deformation monitoring pig was an effective and conclusive technique for verifying pipeline integrity. The pig data provided a continuous record of pipe displacement and curvature through the area affected by the earthquake.

5. The usual design approach for pipeline fault crossings is to construct the pipeline in shallow, sloped-wall trench with loose backfill while permitting large strains and permanent deformation to occur, provided pipe rupture is prevented. In other words, the risk of damage to the pipe requiring repair is generally acceptable, so long as leakage is prevented. Had this concept been used on TAPS, an extensive pipe repair operation would have been required. However, since the pipeline crosses the Denali Fault above grade on sliding shoe supports, the pipeline was not subjected to the large bending strains and local buckling that would have resulted in a shallow buried pipeline. While

fault rupture is a rare event, it certainly happened in the case of TAPS, and as planned, the above-ground crossing mode prevented damage that would have resulted in a more significant interruption in throughput.

Acknowledgment

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