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SEISMIC HAZARD EXPOSURE FOR THE TRANS-ALASKA PIPELINE

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Abstract

The discovery of oil on Alaska's North Slope and the construction of a pipeline to transport that oil across Alaska coincided with the National Environmental Policy Act of 1969 and a destructive Southern California earthquake in 1971 to cause stringent stipulations, state-of-the-art investigations, and innovative design for the pipeline. The magnitude 7.9 earthquake on the Denali fault in November 2002 was remarkably consistent with the design earthquake and fault displacement postulated for the Denali crossing of the Trans-Alaska Pipeline route. The pipeline maintained its integrity, and disaster was averted. Recent probabilistic studies to update previous hazard exposure conclusions suggest continuing pipeline integrity.

Introduction

When oil was discovered on the North Slope of Alaska in the late 1960s, the Alyeska Pipeline Service Company, a newly formed consortium of oil companies, envisioned a major pipeline to transport the crude oil from Prudhoe Bay to the ice-free Port of Valdez. The proposed Trans-Alaska Pipeline System (TAPS) would be a 1,219-mm- (48-inch-) diameter pipe that would travel a distance of 1,287 km (800 mi). The pipeline would traverse spectacular wilderness country, cross three mountain ranges, 350 rivers, and numerous faults, some of which are active.

The proposed pipeline route would cross mostly federal lands, requiring a right-of-way permit from the U.S. Department of the Interior. Alyeska requested the permit in June of 1969. The newly enacted National Environmental Policy Act of 1969 required an environmental impact analysis to address the unavoidable and threatened impacts that would result from construction and operation of the TAPS. Thus, public safety and environmental preservation were important issues from the start, and needed to be addressed before the Secretary of the Interior would issue a permit. A Technical Advisory Board was installed by the Secretary to review pipeline design criteria submitted by Alyeska.

U.S. Geological Survey scientists in Menlo Park, California who had expertise in permafrost and Alaskan geology, and independent consultants were selected to study the perceived hazards, including disturbing the thermal equilibrium in permafrost and earthquakes. A temporary seismograph network was installed by the USGS in 1970, centered on the pipeline's proposed intersection with the Denali fault, and USGS

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scientists resurveyed the first-order geodetic triangulation arc established in the Delta River canyon in 1941-1942. Only four of the thirty-three microearthquakes recorded by the network were along the trend of the fault valley (Page, 1971), and the geodetic survey showed no evidence of slip on the Denali fault since the 1942 survey (Page, 1972). Although the Denali fault had geomorphic evidence indicating it was as dangerous as the San Andreas, the last major displacement apparently predated 1800, strongly suggesting significant strain accumulation since the last earthquake.

The Final Environmental Impact Statement was issued by the Department of the Interior in 1972, and included Stipulations governing aspects of the design and operation of the pipeline that were to be attached to the right-of-way permit (U.S. Department of the Interior, 1972). Design earthquakes, considered the maximum likely to occur in 100 to 300 years or more, were established for each of five seismic zones along the pipeline route, and defined in terms of Richter magnitude (the accepted magnitude scale at the time) (Table 1).

Table 1
Stipulated Earthquake Magnitudes along the Trans-Alaska Pipeline Route
(U.S. Department of the Interior, 1972)

Zone	Richter Magnitude
Valdez to Willow Lake	8.5
Willow Lake to Paxson	7.0
Paxson to Donnelly Dome*	8.0
Donnelly Dome to 67 degrees north	7.5
67 degrees north to Prudhoe Bay	5.5

*The Denali earthquake zone.

During the pipeline permitting process, a M_W 6.7 earthquake on February 9, 1971 struck the San Fernando Valley near Los Angeles, California. The fault that released the earthquake, later named the San Fernando fault, had not been recognized previously. Detailed studies along the mountain front, where the fault had ruptured for 16 km, were conducted following the earthquake (Oakeshott, 1975). They revealed abundant geomorphic and stratigraphic evidence that the fault was indeed active, and could have been recognized as active before the earthquake if experienced geologists had looked in the right places. This surface fault rupture eventually led to the creation of the Alquist-Priolo Earthquake Fault Zoning Act of 1972, requiring special studies to accurately locate faults in California, assess their activity, and regulate building within the Alquist-Priolo Zones. The San Fernando earthquake also produced an unusually high peak ground acceleration of 1.25 g, recorded on an abutment of the Pacoima dam on the up-faulted block in the mountains directly north of and near to the causative fault. This acceleration was significantly higher than the 0.5 g many earthquake engineers thought at that time to be the maximum design value; however, up to that time, no strong ground motions had been recorded within 40 km of a magnitude 7 earthquake or within more than 100 km of a magnitude 8 event (Page and others, 1972), and estimates had to be extrapolated from known data. The surface-faulting and strong-ground-motion implications were very controversial, and several large engineering projects, including the TAPS, were put on hold until this and other environmental issues could be accommodated or resolved.

Earthquake Ground Motions

Robert Page and others at the USGS in Menlo Park recognized that high accelerations needed special consideration for important critical engineering projects, including the proposed TAPS. In 1972, the USGS published Circular 672, *Ground Motion Values for Use in the Seismic Design of the Trans-Alaska Pipeline System* (Page and others, 1972). Circular 672 characterized the earthquake ground motions for the stipulated design earthquakes in terms of peak values of near-fault horizontal acceleration, velocity, and displacement, as well as the duration of shaking. They estimated that Pump Station 10, located 4.8 km north of the Denali fault crossing, could experience free-field accelerations as large as 1.2 g in a magnitude 8 earthquake on the Denali fault. Nathan M. Newmark and William J. Hall used the concept of “effective acceleration” (Newmark and Hall, 1975; Hall and others, 2003) to argue for lower accelerations. The agreed-upon acceleration for the magnitude 8.0 earthquake was 0.60 g for the free-field ground motion, considered to affect slope stability, liquefaction, and the below-ground pipe. This value is similar to the 0.7 g estimated by Bolt (1972) for Alyeska. Newmark and Hall (1974) recommended a lower acceleration, 0.33 g, for structural design (considered to affect structures and the above-ground pipe). The same ground motions were recommended for the more distant magnitude 8.5 earthquake in the southernmost seismic zone. The rationale for these ground-motion values was the collective experience of the earthquake engineers.

Surface Fault Displacement

Circular 672 (Page and others, 1972) also pointed out that the proposed pipeline would unavoidably cross active faults as it traversed Alaska. The significance of faults to the design of the pipeline also was called out in the Environmental Impact Statement:

> *The proposed pipeline route intersects several recognized major faults in the active seismic regions; but, except for the Denali fault, which shows evidence of large relatively recent (Holocene) offset, the risk of significant movements on the other faults is essentially unknown.* (U.S. Department of the Interior, 1972, vol. 2, p. xxii-xxiii)

Acknowledging the lack of information at that time, the Stipulations included the requirement that studies be conducted to identify and delineate “all recognizable or reasonably inferred faults or fault zones” along the route. The objective was to assure that the “risk of oil leakage resulting from fault movement and ground deformation has been adequately assessed and provided for in the design of the pipeline.”

A fault evaluation project was developed and undertaken as part of the effort by Alyeska to identify all the factors that had to be considered in developing designs that would ensure the structural integrity of the pipeline at the active fault crossings. The TAPS Fault Evaluation Project was led by Lloyd S. Cluff and David B. "Burt" Slemmons, co-principal investigators. Cluff was Chief Engineering Geologist at Woodward-Lundgren and Associates and also a visiting Associate Professor at the University of Nevada at Reno. Slemmons was Professor of Geology and Geophysics at the Mackay School of Mines, University of Nevada at Reno. They were assisted by George E. Brogan and Marjorie K. Korringa, and fifteen other specially selected Woodward-Lundgren earthquake geologists and geophysicists (Figure 1).

Figure 1. Trans-Alaska Pipeline Fault Study Team (1972-1974). Standing, left to right: Burt Slemmons, Tom McCarthy, Sue McCarthy, Richard Hardyman, Tom Welsh, Marjorie Korringa (deceased), Phil Watson (deceased), Lloyd Cluff, Kerry Sieh, David Schwartz, Cheri Carver, Gary Carver, George Brogan. Seated, left to right: Norma Bigger, Linda Hadley, Dan Collins, Marc Seeley.

The fault study was to satisfy Alyeska's compliance with the Stipulations appended to the Final Environmental Impact Statement issued by the U.S. Department of the Interior; specifically, Stipulation 3.4.2 and its subsections, which dealt with fault displacements (U.S. Department of the Interior, 1972). The fault evaluation project consisted of three phases specifically focused on identifying, delineating, and characterizing active faults crossed by the pipeline route, presenting design values for these faults, and making general recommendations for monitoring at active-fault crossings. The results of the studies are reported in *Summary Report, Basis for Pipeline Design for Active Fault Crossings for the Trans-Alaska Pipeline System* (Cluff and others, 1974).

Active Fault Study. Identification and characterization of active faults was a relatively new field that required first-hand knowledge and experience of how active fault features may be expressed in the topography and their geomorphic expression as they traversed the countryside. Most of the field team members were former students who had been enrolled in Slemmons' geology and Cluff's engineering geology courses at the University of Nevada, at Reno, between 1967 and 1973. An important part of the course work focused on earthquake hazards, including the identification and characterization of active faults. Experience was gained during field trips to observe faults in California and Nevada. The students were exposed to various methods of evaluating fault activity, including interpretation of aerial photographs and special low-sun-angle aerial photographs (Slemmons, 1969; Cluff and Slemmons, 1972) and interpretation of geomorphology. They also learned to interpret historical seismicity and earthquake intensity reports.

Although the members of the TAPS active fault team understood the state-of-the-art principles, methods, and techniques required to evaluate fault activity (Sherard and others, 1974), it was also considered important, at the beginning of the study, for the team to have first-hand experience observing features associated with active faults in Alaska. Therefore, one of the initial work efforts was to observe features representative of active faults in the Alaskan environment to "calibrate the eyeballs" of the fault study team. During the winter months, while preparing for the 1973 field season, aerial photographs were obtained of areas in Alaska traversed by known active faults, and the team studied these photos to gain relevant experience. Faults that were studied included the Fairweather fault, the location of the 1958 magnitude 7.8 earthquake and associated surface fault rupture; the Patton Bay and Hanning Bay faults, which experienced surface rupture on Montague island during the 1964 magnitude 9.2 earthquake in the Prince William Sound region; the Ragged Mountain fault; the Castle Mountain fault; and the Long Glacier fault. Not only were these faults observed and interpreted on aerial photographs, they were studied during reconnaissance flights and ground studies at the beginning of the 1973 field effort.

The field season began in May 1973, and lasted about five months. The "calibration" training prompted insightful evaluations of approximately 8,000 lineaments and faults. Aerial reconnaissance was conducted of the entire pipeline route, especially along the Fairweather, Castle Mountain, Donnelly Dome, McGinnis Glacier, Denali, Totschunda, Stevens Creek, Kobuk, Clearwater Lake, Tintina, and Kaltag fault zones, then considered among the most important potentially active faults. Interpretation of aerial photographs, radar images, and satellite images continued at various scales along the pipeline route. Low-sun-angle aerial photographs were taken along features of interest. Detailed field evaluations using helicopters and fixed-wing aircraft were conducted of all identified lineaments and faults, and hundreds of fault displacements were measured. Along the Denali fault, evaluations at 84 locations along a 277-km length of the fault from near McKinley Park on the west to near the Denali/Totschunda fault juncture on the east included measurement of the width of the most active zone, and the amount of horizontal and vertical surface displacements.

Some geologic materials were dated, and limited trenching and geophysical surveys were conducted; however, these studies were constrained by time and logistics.

From the fall of 1973 until the summary report was completed in January 1974 (Cluff and others, 1974), the team worked on the final collation, evaluation, and interpretation of all the field data. The pipeline route was found to cross three active faults: the Donnelly Dome fault, the McGinnis Glacier fault, and the Denali fault. The locations of these faults were mapped, and their behavioral and other characteristics important to pipeline designers, such as the attitude of the faults and their angle of intersection with the pipeline, were described. Finally, the fault displacement parameters to be used in pipeline design at the active fault crossings were estimated, and the areas potentially influenced by fault displacement were zoned to guide the pipeline designers in designing for fault displacement. Because the Denali fault was considered the most active, and is the fault that released the November 3, 2002 earthquake, we focus, in this paper, on the Denali fault crossing.

Design Fault Displacement. The fault study concluded the 2,150-km-long Denali fault had the potential of releasing an earthquake as large as magnitude 8.0, agreeing with and verifying the Stipulations. The maximum surface displacement along the entire fault zone was estimated to be 9.1 m (30 ft) horizontal and 2.1 m (8 ft) vertical.

The principal investigators' experience during the mid to late 1960s included investigations of large strike-slip faults, such as the San Andreas and related faults in California, the Bocono fault in northwestern Venezuela, the Alpine and related faults in New Zealand, and the North Anatolian fault in Turkey. These investigations and the available literature showed that major strike-slip surface faulting events worldwide could range from 200 to 400 km in length, and the maximum surface displacements could be as large as 9 m. However, the maximum displacement was observed to occur at only a few locations along the total rupture length. The fault study team reasoned it would be unlikely for the maximum Denali fault displacement to occur at the pipeline crossing. An average displacement amount, usually about one-third of the maximum, was considered a more reasonable estimate for random locations along a total rupture segment; however, the team thought 3 m was not sufficiently conservative for the pipeline crossing. The recommended horizontal displacement was double the hypothetical average displacement; a design displacement of 6.1 m (20 ft) horizontal and 1.5 m (5 ft) vertical, up on the north side, were selected for the Denali fault crossing.

Design Displacement Zone. Selecting the location and width of the zone of future fault rupture at the pipeline crossing may sound like a simple task; however, more than 100 m of alluvial deposits overlie the bedrock at the Denali fault crossing. These alluvial deposits are a product of very active post-glacial erosion and deposition, thus evidence of surface faulting at this location has been severely modified or destroyed.

The design displacement zone at the Denali fault crossing had to be located based on projections from confident fault locations to the west and the east. Of the 58 measured data points, the closest to the west was 2.4 km distant. In the glacial valleys to the east of the pipeline, the Denali fault is covered for about 58 km by glacial ice; the closest data point was 64 km distant. Because differential erosion occurs more easily along the sheared rock of a fault zone, the team assumed the glacial valley was fault-controlled and that it delineated the fault zone. Subtle geomorphic features suggestive of faulting in the post-glacial outwash deposits immediately east of the pipeline crossing also helped "connect the dots."

A width of 76.2 m (250 ft) was assigned to the active-fault zone at the pipeline. The zone was extended 152.4 m (500 ft) to the north and to the south to provide a margin of safety. The northern margin was then extended another 198.1 m (650 ft) to include an escarpment that was a natural limit to the zone. The recommended width of the design displacement zone at the Denali fault crossing was 579.1 m (1,900 ft).

Independent Review. John C. Crowell, then Professor of Geology, University of California at Santa Barbara, provided Alyeska an independent review of the fault evaluation report. Alyeska's objective was to ensure high technical quality and compliance with the Stipulations with respect to fault displacements at pipeline fault crossings. Bruce A. Bolt, then Professor of Seismology and Director of Seismographic Stations, University of California at Berkeley, reviewed the report for consistency of the design values for surface fault displacements with the design values for earthquake ground motions.

Innovative Design. The TAPS design team, Nathan M. Newmark, William J. Hall, and James Maple, assisted by Douglas J. Nyman, developed an innovative design to accommodate the expected surface fault displacements at the above-ground sections of the pipeline (Hall and others, 2003). The design consists of a series of 12-m-long Teflon-coated steel beams, which support the pipeline on Teflon-coated shoes. The above-ground pipeline is articulated in a zigzag fashion. This combination of design characteristics allows the pipeline to move freely, horizontally and vertically, in response to fault displacements, without disrupting the integrity of the pipeline.

November 3, 2002 Earthquake

The November 3, 2002, M_W 7.9 earthquake was released due to rupture on three tectonically related faults: the Susitna Glacier thrust fault, the Denali strike-slip fault, and the Totschunda strike-slip fault. The fault rupture began on the Susitna Glacier fault about 72 km east of Cantwell, propagated northeastward along the Susitna Glacier fault for 51 km, joined the Denali fault and continued rupturing southeastward for 216 km, where it branched onto the Totschunda fault, and propagated southeastward for 74 km. (D. P. Schwartz and T. Dawson, personal communication, 2003). The total rupture length along all three faults was about 350 km. Investigations by the U.S. Geological Survey document that vertical fault displacements along the Susitna Glacier thrust fault ranged from 0.5 to 6.2 m. Along the western part of the Denali fault, about 80 km west of the pipeline fault crossing, right-slip displacements ranged from 0.3 to 6.2 m, increasing as the fault ruptured southeastward to maximum right-slip displacement of 8.8 m about 120 km southeast of the pipeline crossing. Right-slip displacements along the Totschunda fault ranged from 1.0 to 2.1 m (D. P. Schwartz and T. Dawson, personal communication, 2003).

At the pipeline crossing, the Denali fault experienced 5.5 m of right-slip displacement, and about 0.8 m of vertical slip, up on the north. The zone of ground disturbance was 200 m wide, and occurred near the southern edge of the design displacement zone, overlapping part of the 76.2-m-width assigned to the active-fault zone at the pipeline.

Comparison of Results

There was minor damage to the pipeline; however, the pipeline performed as designed and not a drop of oil was spilled. This excellent performance was due to accurate and conservative ground motion estimates, accurate and conservative fault displacement parameters, and innovative structural design—all developed 30 years ago. Tests of quantitative estimates of strong ground motions and fault displacements are rare. It is therefore of both historical and methodological interest to compare some of these estimates with the recorded ground motions and fault displacements near the pipeline (Table 2).

Table 2
Comparison of Denali Fault Parameters

Denali Fault Parameters	Estimated		Design	3 November 2002	
Earthquake magnitude	8.0		8.0	7.9	
Horizontal Acceleration at Pump Station 10	Page (1972)	Bolt (1972)	0.6 g	0.34 g	
	1.2 g	0.7 g			
Horizontal Velocity at Pump Station 10	145 cm/s	-	74 cm/s	114 cm/s	
Maximum right slip	9.1 m		6.1 m	Denali rupture	At pipeline
				8.8 m	5.5 m
Maximum vertical slip	2.1 m		1.5 m	Denali rupture	At pipeline
				2.0 m	0.8 m
Displacement zone width	579.1 m		610 m	Rupture within zone	
Fault rupture width	76.2 m		Included	200 m	

The peak horizontal ground acceleration recorded at Pump Station 10 was less than the design value and much less than the USGS estimate, whereas the recorded peak velocity exceeded the design value and was midway between the design value and the USGS estimate. Both seismic source modeling and the observed distribution of shaking-induced ground failure strongly suggest that near-fault shaking was more intense well to the east of the pipeline crossing than that measured at Pump Station 10.

Recent Seismic Hazard Analyses

Alyeska and its consultants conducted a reassessment of the seismic design criteria for the Trans-Alaska Pipeline in the mid 1990s. Following the reassessment, the USGS (Wesson and others, 1999a; 1999b; Frankel and others, 2000) published ground-motion maps for the State of Alaska that have been incorporated into the 2000 National Earthquake Hazard Reduction Program (NEHRP) seismic provisions, and into the 2000 International Building Code (IBC). To update Alyeska's seismic criteria and design procedures to be consistent with the design provisions of the 2000 IBC, a site-specific seismic hazard analysis was conducted. C. B. Crouse directed the analysis of the TAPS route to update the earlier seismic hazard work. The new study provided the ground-motion parameters (S_s and S_1), defined in the IBC. The study also provided IBC Site Class B response spectra for discrete locations along the pipeline route, which included the twelve pump stations (several of which are no longer in operation), selected milepost locations near the Denali fault, and the Valdez Marine Terminal.

A key aspect of the study was the modeling of the Aleutian Interplate Megathrust zone, the source of the magnitude 9.2 Prince William Sound earthquake of 1964. The important issues were the likelihood of a similar size event during the remaining lifetime of the pipeline, and the recurrence model for the intracycle seismicity between the giant megathrust events.

The results of geologic studies for the Copper River delta area (Plafker and others, 1992; Dames & Moore, 1991a) indicate the recurrence time of great megathrust earthquakes in the Prince William Sound region is approximately 720 ±200 years. Analyses of these recurrence data by Donovan, Tang, and Wen and Tang (included in Dames & Moore, 1991b) indicate the likelihood of the repeat of an event similar to the 1964 earthquake is very small (probability significantly less than 10^{-4}/year for the next 100 years). Consequently, this type of event was not included in the hazard analysis for the computation of ground motions.

In contrast, in its seismic hazard analysis, the USGS (Wesson and others, 1999a; 1999b) did include the magnitude 9.2 event, and assigned it an average annual probability of occurrence of 1/700, where the denominator is the USGS estimate of the average recurrence time for this event, in years. Not surprisingly, for the 2-percent-exceedance-in-50-years probability level, the USGS response spectral accelerations at the Valdez Marine Terminal, which is approximately 20 km above the megathrust, were higher than the values computed in the reassessment by roughly 30 to 60 percent.

The Gutenberg-Richter magnitude/frequency relation was selected by Crouse to model the recurrence of the intracycle seismicity associated with the Aleutian

Interplate Megathrust. The maximum intracycle magnitude associated with this model is debatable. Dames & Moore (1991a) argue that magnitude 7.5 to 8.0 is a reasonable range, based on a time-dependent model of strain accumulation on the megathrust since the 1964 event, and comparisons with other strongly coupled subduction zones. On the other hand, in his review of the Dames & Moore (1991a) report, Page (1992) cites the example of intracycle earthquakes in the central Aleutians, southwest of Prince William Sound, where the 1986 magnitude 8.0 earthquake occurred within the rupture zone of the 1957 magnitude 8.6 earthquake. Page (1992) estimates that, by the year 2025, the likely maximum magnitude for the intracycle event for the Aleutian Interplate Megathrust in the Prince William Sound region would be magnitude 8.2. Despite the uncertainty, the reassessment demonstrated that the ground motions computed for the Valdez Marine Terminal were not very sensitive to the maximum intracycle magnitude selected, whether it be 7.75 or 8.25.

An additional update of seismic criteria may be performed in the near future, depending on results from the study of the November 2002 earthquake. Pipeline integrity, public safety, and environmental preservation continue to be important issues in the operation of the Trans-Alaska Pipeline System.

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