Analysis of Aboveground Pipeline Insulation in Contact with Vertical Support Members

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Abstract

The aboveground support system of the Trans Alaska Pipeline System was extensively analyzed during the initial design phase of the pipeline to ensure integrity during operational and contingency loading conditions. These analyses assumed the position of the pipeline on the beam supported by the Vertical Support Members (VSM) were within defined operational bounds. The original design analyses did not include an analysis of the pipe when the pipe position on the support beam during operational conditions placed the insulation of the pipe in contact with a VSM. During an audit of the pipeline, the pipeline insulation was identified to be in contact with a VSM at a number of locations, and identified as a potential risk to the pipeline integrity during a seismic event. This paper describes the series of analyses performed to address this operational situation, as well as the relatively small, remedial construction required as a result of these analyses and the recommended continued monitoring program.

Introduction

In 1993, the US Department of the Interior, Bureau of Land Management (BLM) conducted an audit of the Trans Alaska Pipeline System (TAPS) operated by Alyeska Pipeline Service Company (APSC). Concerns were raised with regard to pipeline integrity during a seismic event in view of the identified contacts between the pipeline insulation modules and the Vertical Support Members (VSM). A series of structural and dynamic analyses were conducted to evaluate the pipeline system under this condition. This paper discusses these analyses and presents the findings.

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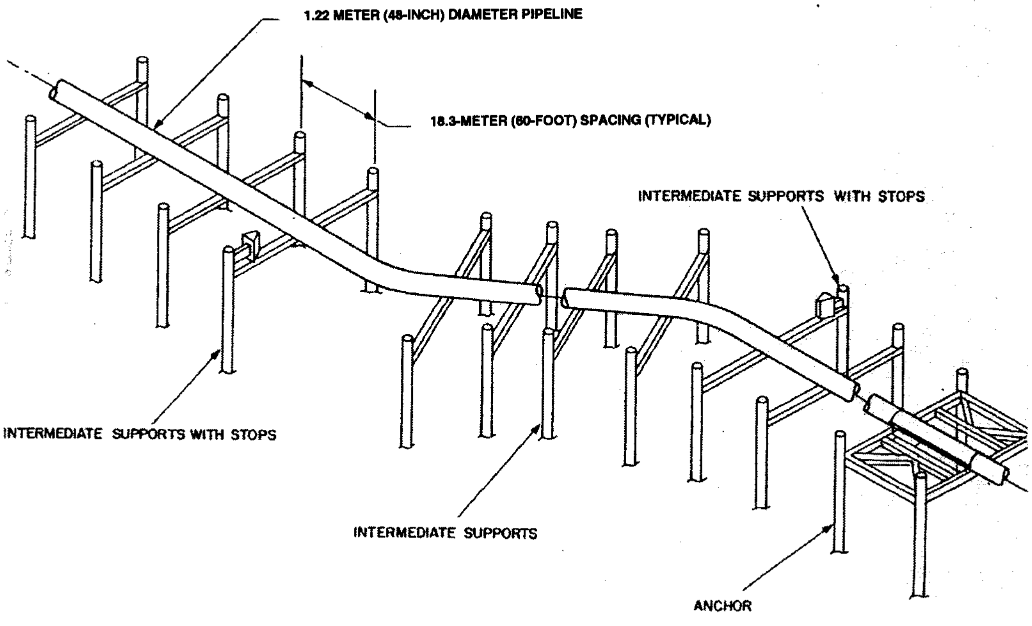
Pipeline Description

TAPS is a 1.22-meter (48-inch) diameter crude oil pipeline that has transported over 13 billion barrels of oil from the oil fields in and around Prudhoe Bay, Alaska to the Valdez Marine Terminal, where the oil is loaded on ocean-going tankers for delivery to refineries. The pipeline was constructed in the mid-1970's with the first oil reaching Valdez, Alaska in July 1977. The pipeline is approximately 1,280 kilometers (800 miles) in length, crosses three major mountain ranges, several major rivers (including the Yukon River), and three fault zones. The subsurface conditions range from continuous permafrost for the first 448 kilometers (280 miles) to discontinuous permafrost for the next 736 kilometers (460 miles) across the interior of Alaska to sporadic permafrost through the Chugach Mountain Range as the pipeline traverses the last 96 kilometers (60 miles) to its terminus. The pipeline was generally buried wherever thawed or thaw-stable soils were encountered. Where this criterion could not be met, the pipeline was constructed on specially designed aboveground supports (APSC 1997).

This aboveground mode is built in a zigzag configuration to allow for expansion or contraction of the pipe due to temperature changes by converting changes in pipeline length into lateral (sideways) movements. To permit lateral motion, the pipe is mounted on a structure that can slide on crossbeams installed between VSM (piles). This design also allows for motions caused by an earthquake. Slightly more than half of the entire pipeline is built aboveground.



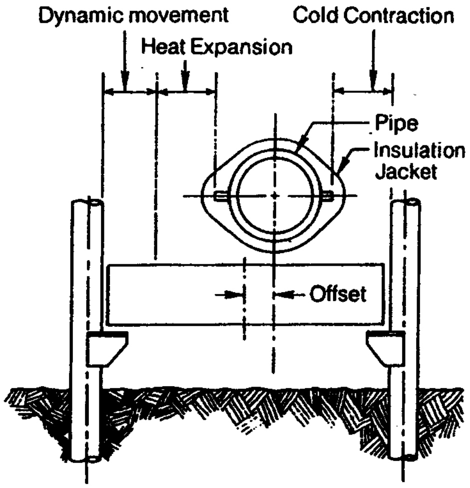
(Courtesy of Alyeska Pipeline Service Company)

Figure 1. Schematic of Standard Zee Configuration

The aboveground system is broken into short lengths (244 to 549 meters or 800 to 1,800 feet) which are traversed by one of five types of "configurations"

(APSC 1997). The standard zee configuration (Figure 1) is the most common and the analyses presented in this paper are for this type configuration. At each end of a typical configuration, the pipe is restrained by the installation of an anchor support. The anchor supports consist of four VSM, a structural steel platform and a friction slide plate assembly. The friction slide assembly is design to resist an initial differential force in the longitudinal direction (along the pipe) before sliding and damping dynamic forces.

At approximately 18.3-meter (60-foot) spacing in between the anchors, the pipe rests on intermediate supports (Figure 2). Intermediate supports typically consist of two VSM and a structural steel crossbeam. In a relatively few cases, a third VSM was installed to increase resistance to lateral loads.



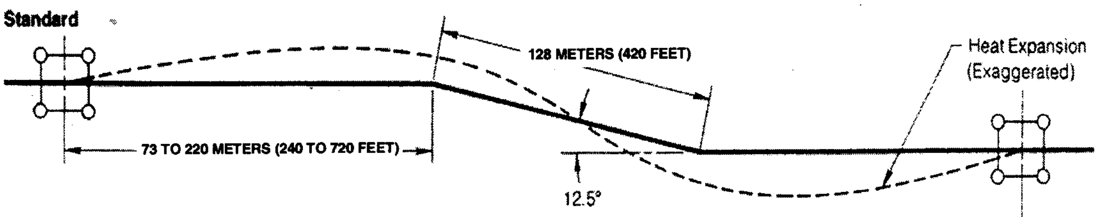
(Courtesy of Alyeska Pipeline Service Company

Figure 2. Cross Section of Intermediate Support VSM

Original Design Analysis

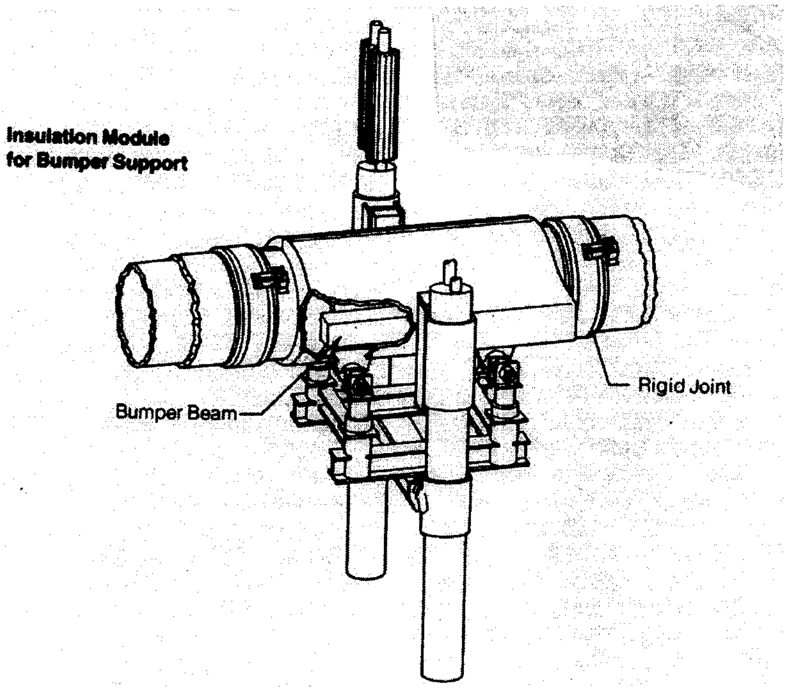
In the original design, all aboveground configurations for TAPS were analyzed under static conditions (gravity, design pressure and design temperature differential; Figure 3). In addition, dynamic analyses were conducted to determine the movement of the pipe on the supports during a seismic event. The results of these analyses were used to size the support hardware. Crossbeams of varying length were installed to accommodate the predicted lateral movements of the pipeline. The beams were positioned off center with respect to the pipe centerline to allow for thermal expansion as the pipe heated up to the design temperature. The side to which the pipe was expected to move when heated was called the "hot" side, while the opposite side was the "cold" side. Seismic bumpers were designed for selected locations to control seismic movement of the pipeline (Figure 4).

The original design was based on a bare pipe scenario. Clearances were designed without consideration of the insulation modules, which were assumed to be sacrificial during a contingency seismic event. There are 40.6 centimeters (16 inches) from the outside surface of the shoe insulation module to the pipe surface. Similarly, there are 16.5 centimeters (9.5 inches) from the outside edge of the insulation to the face of the pipe clamp flange.



(Courtesy of Alyeska Pipeline Service Company)

Figure 3. Movement of Pipeline in a Standard Zee Configuration



(Courtesy of Alyeska Pipeline Service Company)

Figure 4. Intermediate Support with Bumper Beam

Statement of Concern

During an audit conducted by the BLM in 1993, the pipeline location within several aboveground configurations was observed to differ from the original design. In particular, the pipeline insulation at several intermediate bents was seen to be very close, and in some cases in contact, with the VSM. This raised concern as to whether earthquake induced motion and forces might exceed those motions and forces computed by the original design analyses. A study was initiated to determine the integrity of the pipeline under the observed conditions.

Analytical Approach

The analysis focused on developing a computer modeling procedure that would reasonably replicate the conditions for the majority of contacts. The best apparent method is to model the pipe in the least energy position by using the deflected shape, from changes in pressure and temperature as modeled by assuming zero friction, between the shoes and the crossbeam, as a basis for analysis. This differed from the original design analysis, which analyzed the movement of the pipeline under static conditions (e.g. dead weight, pressure, and temperature differential) for a 10% friction interface. The original design assumption of 5% coefficient of friction provides a conservative upper bound for the evaluation of displacements for short-term loads when modeling a 10% friction interface. (The value of 10% coefficient of friction was also analyzed to produce the bounding force values for the static load cases). The deflected shape for the case of a zero coefficient of friction was demonstrated to be significantly different from the 5% friction case used in the original design. The main differences encountered are the switching of the "hot" and "cold" sides for several supports and significant amplification of deflections in the vicinity of some seismic bumpers. The first difference becomes especially significant in conjunction with the fact that the centerlines of the beams were originally offset toward the design "hot" side determined from the 5% friction assumption. The seismic bumpers generally negate effects of the second difference (amplified deflections). Using the zero friction model as basis for analysis produces good results when compared with actual field conditions. This is consistent with "shakedown" effects for structural systems where elements involving frictional constraints tend to migrate over time to a lower energy state.

Once these deflected shapes of the models were calculated and calibrated to observed pipe locations, the dynamic effect is then imposed on these deflected shapes to find the additional movement due to seismic excitation. The dynamic analyses themselves retained the assumption of 10% friction coefficient, consistent with the original design submittal, since the friction coefficient is considered fully applicable for short duration loadings.

Seismic Analysis

The pipeline alignment is divided into five distinct seismic zones. The northern part of the line is designated as a relatively low, 5.5 Richter Magnitude (RM) zone, while the two highest (8.0 and 8.5 RM zones) are located in the southern end of the line and near the fault crossing zones close to the Alaska Mountain Range, respectively. These two RM zones were assigned the same design ground accelerations and displacements and are, therefore, normally analyzed together.

The design spectrum is the basic descriptive technique for dynamic excitation for structures. It is much more descriptive of excitation than a single "g" level since it is well known that response acceleration levels vary with frequency. There are two basic spectra for the TAPS project, developed during the original design, which correspond to the "Operational" and "Contingency" loading. Operational loading defines the excitation level which the project structure must withstand and remain fully operating, while the contingency loading is the excitation level which the structure must withstand without catastrophic failure. At the contingency level, it is recognized that some damage may occur, and that a safe shutdown of the structure may be required for inspection and repair. Often, the operating level is used to compare structure excitation so that members remain within stress allowables consistent with wind loading and other occasional loads, while contingency allowables are increased to the yield value.

There are several specific techniques to approach the analysis of structures subjected to dynamic loading, but they can all be loosely categorized into three main approaches: Equivalent Static techniques, Response Spectrum/Modal techniques, and Time History techniques. The Equivalent Static Procedure and Response Spectrum Procedure, which are the easiest to apply and also the most commonly used procedure, have implicit assumptions which make it inapplicable to the TAPS pipeline. First, these techniques assume the structure is to have a linear response, or at least linear about a defined equilibrium position. The presence of friction and nonlinear stops and gaps violates this assumption. Also, these common techniques assume that the excitation at the base of the structure is uniformly applied in time, i.e. all supports are excited in phase by the same time loading function. However, ground excitation is best characterized by a traveling wave, which imparts motion to the surface as it travels at a seismic wave velocity. This wave velocity (typically 1000 m/sec or 3283 ft/sec) imparts a lag to excitation for structures which have a considerable length relative to the wave velocity. For these reasons, only the Time History Techniques are suitable for the analysis of TAPS aboveground configurations.

Unfortunately, the Time History Technique is also the most demanding dynamic analysis procedure since it imparts the excitation as a prescribed function of excitation versus time to the structure, and the structure is monitored over the duration of excitation for response. This requires a discretization of the excitation input with time, an analysis of all structural response during each discrete time interval, and then evaluation of the new state of the structure which forms the initial basis for the next excitation discrete interval. This technique has the advantage that nonlinear events can be incorporated, and commercial computer programs are available for this. Because of the small axis of most structures, however, it is unusual to find an analysis program that will readily analyze the lagged excitation for long axes structures, such as the aboveground pipeline configurations of TAPS.

The analytical technique requires a time history of the motion and subsequent integration of the response. The design spectra for the project form the basis for the aboveground seismic loading. Earthquake time history motions were artificially generated using random generation routines governed by statistical procedures so as to replicate the overall frequency-response characteristics of the basis spectra. In order to ensure that the response is bounded by the analysis, it is standard practice to generate an ensemble of these histories each of which have slightly different frequency characteristics. Five such earthquake time histories were generated. Each record is an acceleration time history with accelerations recorded at a constant time interval of 0.03 seconds. There are a total of 1,664 accelerations for each record, so each record simulates an earthquake history with duration of 49.89 seconds. The seismic motion input required is the same used by the original design, generated by Dames and Moore at that time.

The analytical technique is to either run all five earthquake records for each direction of motion (while running another one of the five histories in the orthogonal direction) or to identify which combination produces the response envelope for the structure class under consideration. The original design studies concluded that a combination of the earthquake record #3 applied parallel to the seismic wave travel direction and the earthquake record #2 applied normal to the seismic wave travel direction (the “3x2 combination”) produced the maximum response. This study also found that the “3x5 combination” could produce the maximum response for some configurations for the new set of initial condition, so all analyses were subjected to both earthquake combinations.

In addition, it is recognized that the "attack angle" of the earthquake (the angle between the seismic wave front and the structure axes) should be specified so as to produce the maximum response. This procedure was evaluated during the design phase where it was determined that an attack along the longitudinal axes of the configuration was most conservative.

Analysis Tools

During the original design, the TAPS project recognized that time history analysis was applicable to the analysis and design of the TAPS pipeline. Lacking an applicable computer analytical tool, the unique program called DrainPIPE was developed specifically for the TAPS project by Graham Powell, Ph.D., former Professor at the University of California, Berkeley. This program allows friction, gaps, and stops at supports for the pipeline, as well as proper consideration of the traveling wave excitation. The DrainPIPE program was originally written in FORTRAN to run on a CDC 6600 mainframe computer. The original card deck of the program source code was translated to DOS and recompiled using the Lahey FORTRAN compiler for use on the personal computer.

Output DrainPIPE files from the original design and new input decks for the PC version were prepared to ensure that the results for the analyses would be comparable. The DrainPIPE program is a complex numerical simulation program, and every analysis involves hundreds of time integration steps. Thus, only a small number of comparable results that use all options and element types of the program is required to instill confidence that the DOS program version is operational. The DrainPIPE PC version of the program was validated by comparing analytical results on the PC program with available original design output files.

The same input earthquake records were used for all RM zones, and for both the Operational and Contingency loadings, but scaled so as to recognize the different excitation levels while still preserving the frequency content of the records.

The following scale factors are applied to acceleration.

8.0/8.5 RM, Contingency	Unscaled (i.e. scaling factor = 1.0)
7.5 RM, Contingency	Scale factor = 0.67
7.0 RM, Contingency	Scale factor = 0.44
5.5 RM, Contingency	Scale factor = 0.30

The Operational loading is found by taking 50% of the corresponding contingency scale factors for acceleration.

Viscous damping values for typical structural analyses use estimates of 2% to 5% for analysis. However, the DrainPIPE analyses explicitly models energy dissipation, using frictional elements and stop elements with slip after yield. Therefore, only a nominal value of 0.5% damping is input to DrainPIPE so as to control the numerical integration procedure.

Structural elements were modeled to incorporate not only their initial elastic resistance, but also their yield points and resistance after yield. Successive yield points were input so as to simulate successive failures of the component systems – for example insulation crushing then followed by bending failure of the VSM and then ovallization of the pipe.

Results

The 7-4-7 Zee configuration is the most prevalent used in the design of the pipeline and therefore was chosen as the "Base Case" for the analyses. This configuration consists of three straight segments joined by two 12.5-degree 36.6-meter (120-foot) radius field bends (See Figure 3). The first segment from the anchor is twelve 18.3-meter (60-foot) nominal spans with a horizontal 12.5-degree field bend at the end of the segment. Next is a 128-meter (420-foot) diagonal segment consisting of seven 18.3-meter (60-foot) nominal spans and another 12.5-degree bend in the opposite direction from the first bend. The final 219.5-meter (720-foot) segment is parallel to the beginning segment, offset 27.7 meters (91 feet), and ends at another anchor. Adjacent to this "target" configuration, a further configuration was added beyond each anchor to replicate the influence of these adjacent "boundary" configurations on the target configuration.

The base case scenario includes the following model parameters:

1. Initial gaps between the insulation module and the VSMs at the pipe centerline level at all supports are based on static analysis results for a frictionless case.

2. No friction preload on intermediate supports. DrainPIPE has a provision to preload the frictional supports, using the results of previous static analyses. This preload was not used, which is consistent with the results of the frictionless static analysis case.
3. Anchor preload forces of 333.6 kN (75 kips) directed inward toward the target configuration were imposed on the anchors at the ends of the target configuration, with no preload forces imposed on the anchors at the ends of the boundary configurations. This is consistent with the original design analysis.

The DrainPIPE analysis results are examined for nodal and elemental responses on the target configuration. Responses on the boundary configurations, though reported by DrainPIPE, are ignored since the boundary configurations are only modeled to provide boundary conditions to the target configuration, i.e. their response is incidental to the focus of the analytical investigation.

The analysis results for this example configuration is shown in Table 1. The different results correspond to global (X and Y) displacements. The long legs of the 7-4-7 configurations were modeled as parallel to the X global direction, and the Y global direction is perpendicular to these legs. The maximum X displacement for the 8.5 RM case is shown as 17.0 centimeters (6.7 inches) which is a combination of elastic deformation and slip. This occurred at the first anchor of the configuration. The minimum X displacement is given as –10.2 centimeters (-4.0 inches), but this occurred at the last bend of the configuration. The maximum Y displacement was 48.5 centimeters (19.1 inches) and occurred at the last support before the first of the configuration, while the minimum Y displacement of –49.0 centimeters (-19.3 inches) occurred at the last bend of the configuration. For all analytical results, the DrainPIPE analyses were scanned to find the minimum and maximum values regardless of their location in the target configuration.

The anchor slip at the first anchor in these example results of the target configuration is noted as 16.3 centimeters (6.4 inches). This value indicates that the anchor has overcome its initial frictional resistance and has slipped. At the other end of the configuration, the anchor shows a displacement of –7.2 centimeters (-2.8 inches), with a slip of –6.3 centimeters (-2.5 inches). The same modeling was used, so it can be concluded that this anchor has also overcome its initial frictional resistance.

The analyses indicate that all four bumpers will be impacted with the maximum bumper force approximately 97.9 kN (22 kips) occurring at the bends nearest the transverse leg. Note that for the bumper and intermediate reactions, the frictional force is not added to the stop reactions. Contact at other points is also noted at the center of the 219.5-meter (720-foot) leg, and at the support next to the bumper, for a total of four intermediate contacts. The maximum reaction at these points is approximately 89.0 kN (20 kips) located at the support next to the bumper.

This type of table was completed for the hundreds of DrainPIPE analyses concluded. To expedite the analyses and ensure consistent quality, additional digital procedures were developed to extract summary tables from the DrainPIPE results for comparison and evaluation. In addition to the example Zee configuration, the analysis considered other types of standard configurations such as transitions from belowground to aboveground moding. Finally, special analyses were conducted for configurations that required site specific evaluation such as the TAPS configurations containing bridges and mainline valves.

A review of all configurations analyzed indicates that the pipe stress does not exceed the design criteria as presented in DB-180 (APSC 1997). The highest intermediate contact forces are reported from the analysis of the Zee at just less than 89 kN (20 kips) near the center of the longitudinal leg where a zero initial gap was specified from static analysis. The 720 Vee configuration (two straight segments connected by 12.5-degree bends to effect a change in alignment direction) produces the highest bumper force of 360.3 kN (81 kips). This is in good agreement with the original analysis results for the design of TAPS, which also indicated that the 720 Vee case controlled the bumper forces.

Table 1 – Analysis Summary

Case	Nodal Displacements (cm)				Anchor Slip (cm)		Intermediate Bents		Bumper Bents	
	Max X	Min X	Max Y	Min Y	Pos	Neg	Contacts	Max Force (kN)	Contacts	Max Force (kN)
8.5/8-C	17.0	-10.2	48.5	-49.0	16.3	-6.4	4	88.1	4	95.6
8.5/8-O	9.9	-8.1	35.6	-31.8	9.1	-5.1	3	28.9	2	59.2
7.5-C	7.6	-6.6	29.5	-25.4	9.4	-3.8	2	24.5	2	30.7
7.5-O	4.1	-4.1	14.7	-13.7	2.5	-1.5	2	17.8	2	28.0
7.0-C	3.0	-3.3	10.4	-7.4	1.3	-1.0	2	17.3	2	25.8
7.0-O	1.8	-1.8	4.8	-5.6	0.3	-0.3	2	15.1	2	16.5
5.5-C	1.5	-1.5	4.1	-5.3	0.0	0.0	2	13.3	2	14.7
5.5-O	0.8	-1.0	2.0	-3.8	0.0	0.0	2	6.7	2	9.3

Future Evaluation Procedure

Based on the results of the analyses, a decision tree was developed to guide further assessment of VSM contact. The decision tree is considered a conservative procedure for screening contacts so as to determine the need for additional analyses and/or remedial measures. The decision tree calls for site specific analysis of the contacts, and appropriate remedial action whenever the insulation module of an intermediate bent is indented more than 3.8 centimeters (1.5 Inches). Intermediate bent contacts with up to 3.8 centimeters (1.5 inches) of indentation go through several screening steps before they can be considered acceptable. Contacts in the 5.5 or 7.0 RM zone with up to 3.8 centimeters (1.5 inches) of indentation are considered acceptable, based on the results of dynamic analyses for those areas. Dynamic analyses show that maximum expected lateral movements, due to seismic excitation, including the restraining effect of the insulation module, are approximately 5.1 centimeters (2 inches) and 12.7 centimeters (5 inches) in the 5.5 and 7.0 RM zones, respectively. These values would be expected to increase if the restraining effect of the insulation was removed. These values are the maximum anticipated movements anywhere in the configuration and actual movements at contact locations could be much less. The maximum values are well below the actual clearance of 20.3 centimeters (8 inches). This is calculated from 24.1 centimeters (9.5 inches) between the module and the pipe clamp flange minus the maximum 3.8 centimeters (1.5 inches) of indentation.

In the 7.5, 8.0 and 8.5 RM zones, the maximum expected movements without the restraint afforded by the insulation module could be greater than 20.3 centimeters (8 inches), and so cannot be immediately eliminated as acceptable under contingency seismic loading. For these locations, the expected displacement at the contact location must be identified by including the effects of the restraint afforded by undamaged insulation modules in further bounding dynamic analyses.

Conclusion

In conclusion, the contact situation at transitions can be forecast reliably with assuming zero friction in static analyses with operating loads corresponding to the current operating condition. Starting with these initial conditions, time history dynamic analysis is then used to predict expected motion and forces during the design earthquake events. For this analysis, the specially formulated DrainPIPE program, which incorporates the needed elements of friction, successive yielding of structural components, and time-lagged excitation corresponding to the traveling wave velocity, is the best available tool for use in the calculations. A project procedure for utilizing the tool was developed to expedite the hundreds of analyses performed, as well as to ensure consistent quality of the analysis.

The results confirmed that the TAPS aboveground configurations are generally able to resist expected seismic forces. In those few cases where TAPS criteria could have been exceeded during seismic events, field retrofits of additional seismic bumpers were completed. In addition, a monitoring tool, based on a flow chart developed in concert with the analysis was developed for continued monitoring of the configuration.

References

Alyeska Pipeline Service Company (1997), "Design Basis Update, DB-180, Third Edition, Revision 0," Anchorage, Alaska.