Analytic Model for the Evaluation of Inclined Piling in Permafrost

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Abstract

There are approximately 78,000 Vertical Support Members (VSM) on the Trans-Alaska Pipeline System (TAPS). A small fraction of VSM have tilted over time, primarily as a result of frost heave. Corrective maintenance to address this situation, which can include VSM replacement, is very expensive. As an alternative, a model was developed to determine if, and when, VSM integrity would be compromised beyond acceptable factors of safety to the point where the pipeline foundation would be jeopardized. The model was finite element based, using non-linear soil elements to simulate the subsurface resistance. This paper reports on the model and a summary of the results.

Introduction

The 1290-km Trans-Alaska Pipeline System (TAPS) traverses Alaska from Prudhoe Bay on the North Slope to its southern terminus, the Port of Valdez. Approximately 680 kilometers of the pipeline was built aboveground to avoid burying a warm oil pipeline in areas of thaw unstable permafrost. A typical pipeline support bent is comprised of two 46-cm diameter pipe pilings, referred to as Vertical Support Members (VSM), that support a cross beam and shoe assembly which in turn support the pipeline, see Figure 1. The shoe assembly can slide laterally and longitudinally on the cross beam with a static coefficient of friction of 0.1. Bents are spaced approximately 18 meters apart along the elevated portion of the pipeline.

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The construction specifications for TAPS allowed a one-percent deviation from vertical for installation of the VSM. Three-percent tilt is allowed as an operational constraint prior to mandatory reporting. Over the 22 years of operation, a small fraction, 250 out of 78,000 VSM have tilted from vertical between three and eighteen percent. The majority of tilting VSM are associated with areas of fine grained soils, high moisture content active layer, and thawing of the deeper regions of marginally frozen or warm permafrost. The general mechanism of tilting begins with warming of the marginal permafrost soils and loss of adfreeze bond between the VSM and surrounding soils. Frost heave during late winter pushes the VSM upward. Because of eccentricities in the VSM to cross beam connection, or longitudinal and lateral forces from pipeline gravitational forces on slopes, the VSM tends to tilt slightly as it is heaved upwards. As freeze thaw cycles continue from year to year, tilting becomes more pronounced.

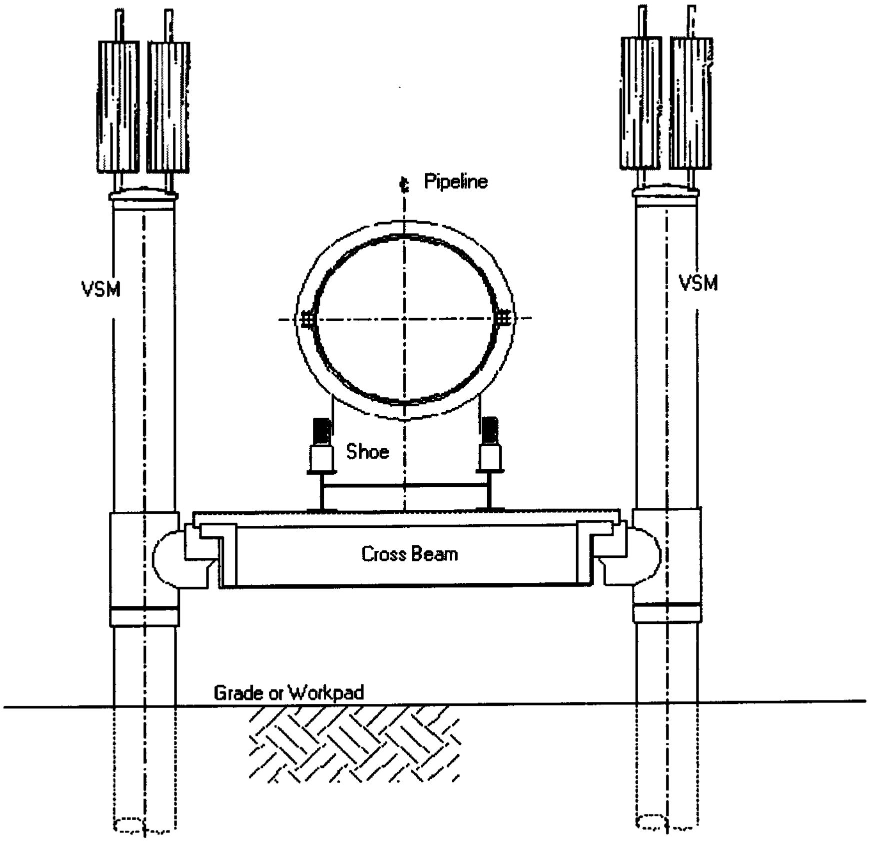

Figure 1. An Aboveground VSM Support Assembly

Route surveillance has recorded several VSM that have continued to tilt over time. Some VSM have been replaced because of appearance, however no VSM ever failed from tilting. The cost of replacing VSM is very high because of the remote nature of the pipeline and because so few VSM are affected over a wide area, reducing construction efficiencies. As an alternative, an analytic tool has been developed to determine if, and when, VSM integrity would be compromised beyond acceptable factors of safety to the point where pipeline foundation would be jeopardized. The model was finite element based, using non-linear soil elements to simulate the subsurface resistance.

Problem

VSM performance became a concern at several locations along the pipeline when surveillance over many years showed an increasing trend in both the number and in the degree of tilt greater than three percent.

As a function of the original design, loss of two consecutive supports could be tolerated without significant risk to pipeline integrity (ref. 1). Additional analysis of the pipeline under loss of support scenarios effectively demonstrated that under normal operational conditions, loss of several supports could be tolerated in the short term (ref. 3). A review of the lateral load criteria for VSM design, using conservative allowable soil strengths, demonstrated that the original support system design was conservative and robust (ref. 2). However, the ability of tilting VSM to support loads was not well defined. Some VSM were replaced because of appearance and without clear understanding of their load carrying capacity.

In an effort to define operational performance of tilting VSM with respect to the load requirements established in the original Alyeska Pipeline Service Company (APSC) design basis, a more definitive model of VSM behavior in four typical soil types was needed. "Pile-PC®" is a digital analysis program utilizing large-deflection concepts and non-linear soil resistance functions for the analysis of single piles. It utilizes Microsoft® Excel® as the user interface for both the input and output. The user inputs the required information into the Microsoft Excel input sheet, and then the analysis is initiated based on these values. The analytical program is written in Visual Basic for Applications (VBA) and the code itself is appended to the Microsoft Excel workbook – i.e., no separate code application installation is required.

Analytical Approach

There are two aspects of this problem that require advanced structural considerations. The first is the effect of the compressive load "P" on the pile acting through the lateral displacement "Δ". This "P-Δ" effect causes an additional moment on the pile in addition to the lateral load acting through the pile stick-up. For small displacements, this can often be ignored, but for this problem which examines the structural state to relatively large tilt angles, it is required. The second effect is the non-linear resistance of the soil, especially the lateral soil resistance. To examine these effects for the large number of cases involved, an easy-to-use analytical program that incorporates both these effects was required. The finite element approach was selected as the analytical basis. It was decided to implement this approach fully in Microsoft Excel to avoid the development of a new user interface and to facilitate its use by engineers.

In the Finite Element approach to structural analysis, the structure is idealized into an assembly of structural elements. The elements are attached to adjacent elements at node points, which may be actual joints or fictitious points obtained by subdividing a structural member into a number of smaller members. To determine the structural characteristics of the entire assemblage of elements, first it is required to ascertain the stiffness of each individual element, i.e. the response of the unassembled elements to the various types of loadings the individual element will or could resist.

There are a variety of well-known techniques for deriving the relationships between the force applied to an individual, unassembled member and the deflection of the member resulting from the application of the force. Of these methods, the simplest is the unit-displacement method wherein a displacement equal to unity (units are implied by the type of deformation) is applied to the individual element and the resulting force response is found. This procedure leads directly to the required matrix equations relating element forces to their corresponding displacements (ref. 4).

Two-Dimensional Elastic Small-Deflection Beam Formulation

The relationship between the forces and displacements on a two-dimensional (planar) beam can be fairly easily derived from elementary beam mechanics, based on small deflection theory. In this formulation, there is a linear relationship between the applied forces **P** and the displacements **U**, i.e., $\mathbf{P}=\mathbf{K_E}\mathbf{U}$, where $\mathbf{K_E}$ is a matrix of constants relating the forces to the displacements under the assumptions of elasticity and small deflection theory.

The final structural matrix formulation for the two-dimensional beam is given below, while Figure 2 shows all the implied structural actions.

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{Bmatrix} = \begin{pmatrix} AE/L & & & & & \\ 0 & 12EI/L^3 & & \text{(Symmetrical)} & & \\ 0 & 6EI/L^2 & 4EI/L & & & \\ -AE/L & 0 & 0 & AE/L & & \\ 0 & -12EI/L^3 & -6EI/L^2 & 0 & 12EI/L^3 & \\ 0 & 6EI/L^2 & 2EI/L & 0 & -6EI/L^2 & 4EI/L \end{pmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{Bmatrix}$$

$$\mathbf{P} = \mathbf{K_E} \quad \mathbf{U}$$

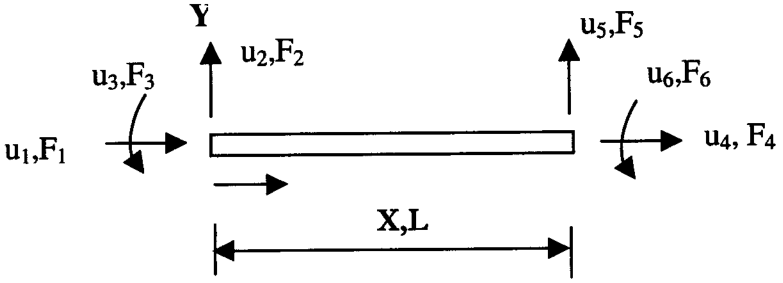

Figure 2. General Beam Force-Displacement Relations

Extension of Beam Formulation for Large Deflections

When large deflections are considered, the linear relationship of $P=K_EU$ discussed in the previous section can no longer be used. To treat the effects of large displacements, the solutions for U are obtained in steps, with the relationship between the forces and displacements updated in preparation for further steps. In addition to the K_E matrix that relates P and U, we add the effects of large deflections with the matrix K_G so:

$$P = (K_E + K_G)U$$

K_G is known as the "geometric stiffness" matrix. K_G is initially set to the null matrix.

The values for the geometric stiffness are derived by considering higher-order terms in the relationship between the strains induced in the member and the displacements of the member. The small-deflection strain-displacement relation for the axial stress is:

$$\varepsilon_{xx} = \partial u_x/\partial x$$

When the next term in the expansion for this strain is added the relation is:

$$\varepsilon_{xx} = \partial u_x/\partial x + \tfrac{1}{2}(\partial u_y/\partial x)^2$$

Note that, as expected, when the displacement u_y is small with respect to the length of the structure under consideration, the second term does not contribute a significant amount. For example, if the displacements are on the order of 1% of the length, then we can approximate the effect of the second term as on the order of $(0.01)^2 / 0.01$, or about one-hundredth, the effect of the first term. This relatively small influence can be, and is, often neglected in structural evaluations. Using this strain-displacement relation in the development of the beam force-displacement relations results in the following extra terms:

$$\mathbf{K_G} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & T/L & 0 & 0 & -T/L & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -T/L & 0 & 0 & T/L & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

where T is the tension in the beam element. This formulation for $\mathbf{K_G}$ is known as the "string stiffness." Even higher-order formulations are possible, although this addition often suffices for most structural calculations.

If the beam is in tension, the term has the effect of "stiffening" the beam in response to lateral forces. Thus, this formulation is required for the analysis of cable systems, which develop resistance to lateral loads by tensioning the cable members. Conversely, if the tension in the beam is negative, the term has the effect of weakening the system. The consideration of this term is required for a P-Δ analysis for beams, which considers the effect of the axial load acting through the lateral beam displacement, causing increased moment.

To use this formulation, note that the value of T is not initially known. Therefore, the analysis first completes the initial structural evaluation assuming that $\mathbf{K_G=0}$. The first evaluation thus uses only the elastic, small deflection, formulation. Once complete, an initial estimate of the value of T is known, and can be used to form the first estimate of $\mathbf{K_G}$. This new $\mathbf{K_G}$ is added to the elastic matrix (which itself is constant), and the analysis re-run to form an updated estimate of T and thus an updated estimate of $\mathbf{K_G}$. This process is continued until convergence, i.e., until the value of T used to form $\mathbf{K_G}$ is equal to, or within some specified tolerance of, the value of T that results from the analysis. Alternatively, small steps can be taken in the loading so that $\mathbf{K_G}$ can be evaluated at the end of each load step and used as the starting point for the next load step. Another solution strategy is to combine both techniques and execute small load steps and iterate until convergence at the end of each of these incremental steps. This latter strategy is the solution method used by Pile-PC.

Soil Springs Formulation

The soil spring formulation is easily derived from elementary mechanics. For the soil spring elements in Pile-PC, it is assumed that one end of the spring is fixed and the other is attached to a node on the beam. As the beam deflects, the soil reacts through a spring constant "k" as shown in Figure 3.

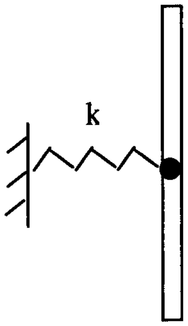

Figure 3. Soil-Springs

Thus, the matrix form is identical to the simple one-dimensional equation:

$F_s = ku$

Where

F_s = Soil Resistance to the beam deflection

k = Effective stiffness of the soil

u = Beam deflection

Note that the figure depicts lateral soil springs, but that the same formulation holds for axial soil springs. Both lateral and axial soil springs can be modeled in Pile-PC.

The value of "k" is not required to be constant throughout the analysis, i.e., the soil stiffness may be assumed non-linear. In particular, a value of "yield" is input denoting the end of the initial linear soil response of $F_s = k_1u$. Thereafter, the soil is assumed to follow another different linear path $F_s = k_2u$, which simulates the drop-off in soil strength following yield as shown in Figure 4.

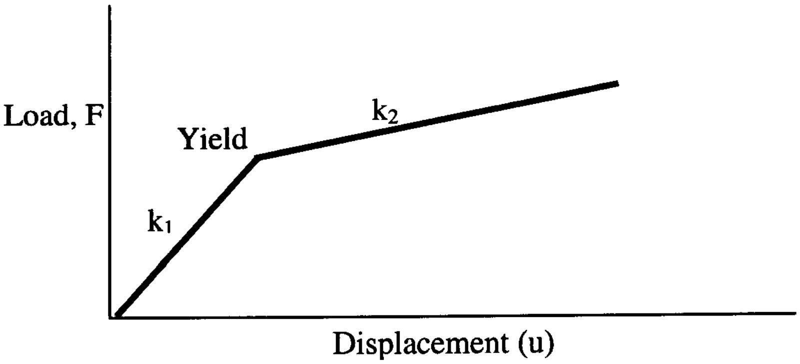

Figure 4. Soil-Spring Load Deflection Relation

In the Pile-PC formulation, the load-deflection equations for the soil springs are elastic even though they are bilinear. That is, the soil is assumed to unload along the same path that it loads. This formulation is appropriate for increasing loading situations, although should be used with care where the load history is assumed to reverse.

Global Formulation

Once the stiffness properties of the elements are formulated, the individual element matrices must be assembled to represent the overall structural matrix. This is done by uniquely assigning node numbers to all joints or divisions of the elements that make up the structure and then using proper matrix addition to add the effects of the individual elements to the overall or "global" matrix. The solution is given by $\mathbf{U} = \mathbf{K}^{-1}\,\mathbf{F}$, where $\mathbf{K}^{-1}$ is the inverse matrix of $\mathbf{K}$. In Finite Element practice, the inverse of a matrix is rarely found since the computations are extensive. Alternatively, the system of equations are solved simultaneously by first decomposing the N by N structural matrix into an equivalent system composed of an upper and lower matrix product, which can then be easily solved.

The matrix evaluation results in the initial estimate for all of the displacements of the structure. Using these displacements, the individual elements are reassessed using the new information. For the beams, the initial estimate of the axial force, if any, can be found and used to formulate each beam element geometric stiffness which, when added to the beam elastic stiffness matrix, forms the estimate of the element combined stiffness for the next iteration. Similarly, the displacements in the soil springs are evaluated to see if the soil stiffness is beyond the yield value and, if so, the new value of the soil stiffness is substituted for the next load step. Using these new individual element matrices, the global stiffness matrix is reassembled and the analysis continued until convergence to a specified tolerance is achieved.

Implementation

The VBA program reads all the data from the input sheet, and automatically divides the structure into a number of smaller elements. Once the data is further checked, the more formal finite element part of the program activates to formulate the individual member stiffnesses, assemble the global equations, and steps through the loading. Once complete, a new output worksheet is made in the same Microsoft Excel workbook, and all displacements, member forces, stresses, and soil resistances are output. A plot of the deformed pile shape is automatically inserted on the output worksheet, before the program terminates and control is transferred back to the user. At this time, the user can perform any further Microsoft Excel functions to investigate this case, or use the results from a number of output worksheets to plot trends.

As an example of the utility of this program, a further Microsoft Excel worksheet was developed which stepped through a series of initial tilt angles, each case automatically filling out the input sheet and producing a separate output worksheet until all cases were completed. The trend of increasing the tilt angle was then automatically plotted.

Although many analytical programs accept Microsoft Excel worksheets as input for their programs, the idea of developing an advanced analytical tool for finite element analysis working completely within Microsoft Excel is novel. It avoids the need for specialized user-interfaces and installation techniques. More importantly, it places an advanced tool within a widely distributed and used program, and makes the powerful Microsoft Excel functions available to more easily analyze and work with results. A further step in the implementation will be the development of a plasticity module to allow full inelastic analysis.

Results

A series of structural analyses were conducted using the finite-element program. The analyses were initially conducted using plumb VSM with a six-meter embedment in each of the four soil types described in the APSC Design Basis. The analyses consisted of placing a vertical and lateral load on a VSM as shown in Figure 5 with an initial Top of Beam to Top of Pad (TOB-TOP) height. The loading is ramped until either the soil around the VSM failed or the stress in the steel exceeded AISC allowable stresses. This was completed for TOB-TOP heights of 0.6 to seven meters in increments of 0.9 meters and the deflections calculated at the completion of load or at "failure" for each combination. These deflection values were converted to percent tilt and used to create a series of graphs defining the maximum anticipated VSM tilt at various TOB-TOP heights based solely on a "load-driven" mechanism. After completing the initial analyses, two things became apparent:

1. The three- percent value being used to flag tilting VSM is justified. This is approximately the lower limit of tilt calculated for all combinations of load and TOB-TOP height that resulted in stresses less than the AISC allowable level (i.e., tilt at the maximum AISC allowable stress were as low as three percent for some combinations analyzed).
2. The analyses show that the magnitude of actual field observations of tilting VSM cannot be attained for reasonable combination of loads (i.e., the analyses show that the loads required to produce higher percent tilts are of such a magnitude that other aboveground hardware components would have already probably failed). This led to the conclusion that the majority of the field observations must be a result of geotechnical movement rather than bending deflection.

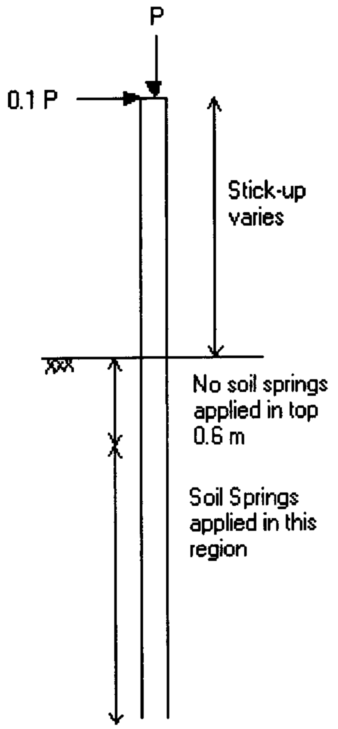

Figure 5. Pile Geometry Analyzed

The second series of analysis was completed assuming an initial tilt angle. This is more representative of actual field conditions. The final product was a series of curves, illustrated in Figure 6, for each soil type and embedment depth combination analyzed. These curves define the percent tilt and TOB-TOP height combinations at which "failure" is reached for a set VSM load. "Failure" is defined as reaching the soil resistance limits or an overstress condition in the steel based on AISC allowables.

Typically, the operational criteria for maintenance at three percent tilt is conservative to ensure against VSM overstress or soil failure. To determine if corrective maintenance on VSM exhibiting tilts greater than three percent is necessary, an evaluation is required. VSM may be evaluated initially using the graphs produced from the second series of analyses described above. If VSM do not pass this initial evaluation, more intensive assessment is required and site-specific information must be obtained that includes current soils information and temperature data. The VSM can then be re-evaluated using the finite element analysis model with the site-specific information. Based on the results of this re-evaluation further maintenance and/or monitoring action can be initiated.

The weak thawed soil charts for the nearest corresponding embedment length were used for initial evaluations on 92 tilting VSM. By plotting the intersection of the tilt and TOB-TOP on the appropriate chart, a comparison of the recorded load to the allowable load was made. This initial evaluation determined 83 of these VSM to be adequate based on the information gathered. Additional information is being gathered for the remaining tilting VSM as of printing of this paper.

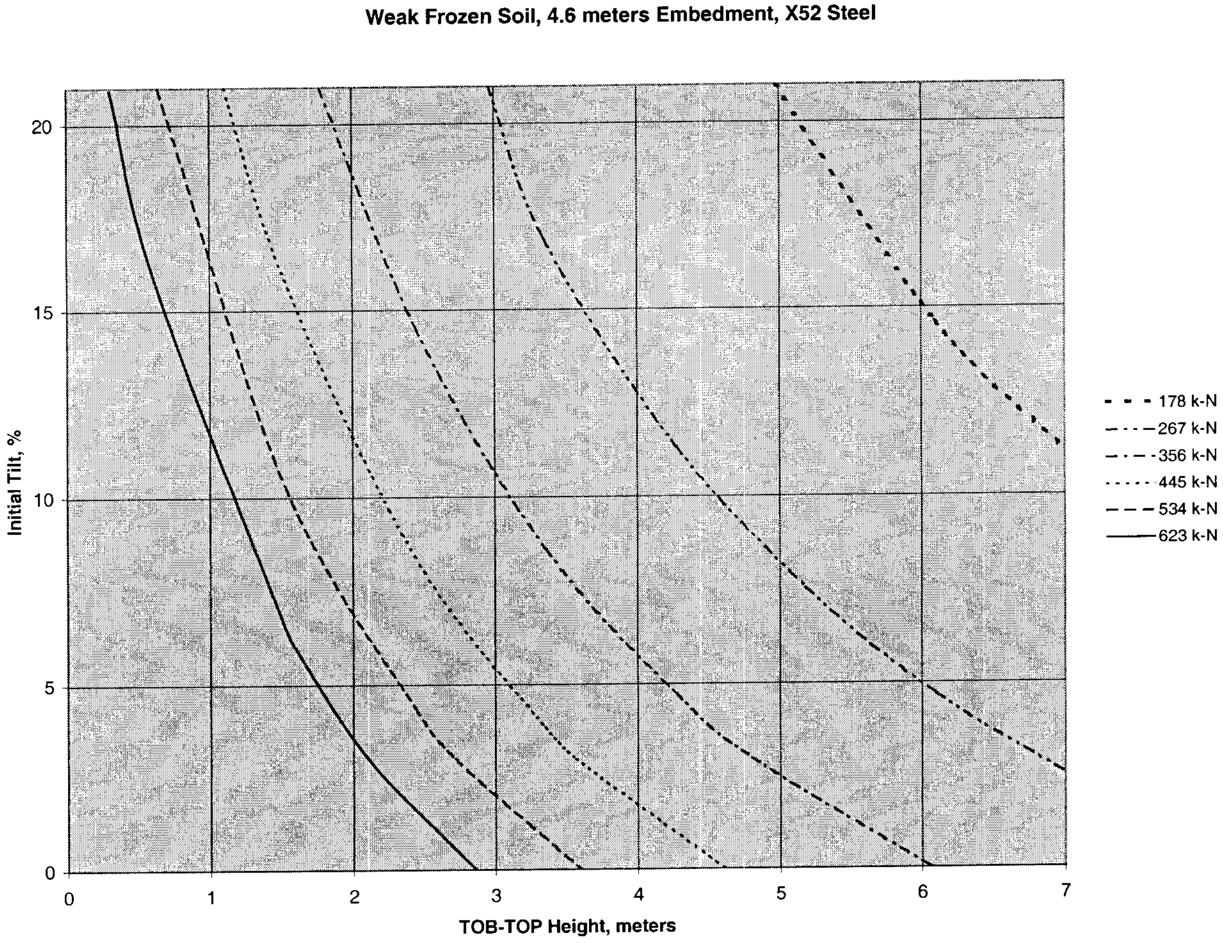

Figure 6. Example Results plot

Conclusions

The finite element model has allowed APSC to perform an initial assessment of tilting VSM based on information from as-built data and the tilt angle. If the VSM fails this initial screening evaluation, an additional assessment can be initiated using the finite element model and current geotechnical information gathered from the field. Since the majority of tilting VSM are found in weak frozen or weak thawed areas, the failure mode is overturning and not overstress of the pile. Of the 78,000 VSM installed, 250 exhibit tilt in excess of three percent. Of the tilting VSM studied to date, approximately ten need further evaluation using current site-specific data.

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Useful Life of the Trans-Alaska Pipeline

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Abstract

Useful life is defined as a combination of *design life, physical life,* and *economic life.* The useful life of TAPS can be described as the period during which the pipeline provides a safe, environmentally sound, economically viable transportation link to get Alaska North Slope crude oil to market. Useful life is also one of the three primary elements for establishing the duration of the federal and state rights-of-way for TAPS, the others being serving a public purpose or benefit, and the ongoing facility costs.

This paper addresses the following issues with special emphasis on facility aging and life-cycle issues associated with operating a warm crude oil pipeline in cold regions:

- TAPS design life is based on the incorporation of robust components coupled with system monitoring programs designed to detect and counteract aging and facility use factors.
- TAPS physical life can be virtually unlimited given the execution of appropriate maintenance, repair and replacement programs.
- TAPS economic life is governed by the extent of recoverable North Slope crude oil reserves. Predictions show these reserves being produced in quantities sufficient to support the continued operation of the pipeline well into the 21st century.

Introduction

The Trans Alaska Pipeline System (TAPS) has transported over 13 billion barrels of Alaska North Slope crude oil since start-up in 1977. The pipeline currently carries nearly 20 percent of all crude oil produced in the U.S., and it can continue for decades to provide a critical link in the supply of a significant share of the nation's crude oil.

In its 800-mile (1288 km) length from the North Slope oil fields to the port of Valdez, the pipeline crosses hundreds of miles of state and federal land. Before constructing and operating the pipeline on those lands, the TAPS Owner companies were required to obtain long-term, renewable rights-of-way from the government land

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management agencies. These rights-of-way, issued in 1974 for 30-year terms, expire in 2004. The TAPS Owners' application for renewal of these federal and state rights-of-way seeks the maximum terms for the renewals.

In considering the length of a renewal term, federal and state right-of-way laws invoke several criteria — the useful life of the pipeline, its public purpose, and its cost. The focus of this paper is the useful life of the pipeline, which comprises both physical and economic utility. The physical life span of a pipeline is determined primarily by both the quality of its original design and its upkeep. The economic life of a crude oil pipeline is determined by how long it can provide its owners with a reasonable economic return and attract shippers.

Useful Life

While the term "useful life" is not defined in the applicable laws or regulations, the useful life of TAPS seems clearly meant to describe the remaining life of the pipeline, which is a function both of its physical life span and its economic utility. The physical life of the pipeline is determined principally by the nature of its original design and subsequent maintenance, repair, and replacement activities. The economic life of the pipeline is determined by how long it provides reasonable economic return, considering original investment and operating costs.

For purposes of this document, *useful life* is defined as a combination of *design life, physical life,* and *economic life.* The useful life of TAPS can be described as the period during which the pipeline provides a safe, environmentally sound, economically viable transportation link for Alaska North Slope crude oil.

TAPS useful life can continue well beyond the maximum allowable 30-year right-of-way renewal because:

- TAPS design life is based on the incorporation of robust components coupled with system monitoring programs designed to detect and counteract aging and facility use factors.
- TAPS physical life is considered virtually unlimited given the execution of appropriate maintenance, repair, and replacement programs.
- TAPS economic life is governed by the extent of recoverable North Slope crude oil reserves. Predictions show these reserves being produced in quantities sufficient to support the continued operation of the pipeline, with tariff rates that attract shippers, well into the 21st century.

The succeeding sections discuss, in turn, design life, economic life and physical life in more detail.

Design Life

Engineers developed design criteria for TAPS based on assumptions that protection of the Alaska environment was paramount and that, as the only oil transportation link to Alaska's North Slope, the pipeline had to function reliably and safely, with sufficient structural integrity to resist arctic conditions over an indeterminate period. These significant technical challenges resulted in a design that incorporates many redundancies and safety factors to account for known and unpredictable future conditions. The pipeline design was intentionally robust, and 25 years of operation have provided the opportunity for a critical evaluation of the design assumptions and features (TAPS Owners, 2001b). That evaluation has confirmed that the design decisions were correct.

Key TAPS design features addressed technical challenges such as support of a warm-oil pipeline in permafrost and seismic risks to pipeline integrity.

Design elements included assumptions and features that anticipated the effects of aging, such as:

- Estimates of thaw settlement allowances for buried pipeline segments,
- Pipe movement allowances in the above-ground design to provide for crude-oil temperature changes over time, and
- Analysis of soil creep or frost jacking at aboveground pipe supports.

TAPS performance is evidence that the design tolerances and protective features have been more than adequate to meet the challenges. Pipeline integrity has been stable, and age-dependent issues have been manageable over time. Buttressing the design features are surveillance and monitoring programs that continually assess the viability and functioning of the system and gauge the status of the pipeline system against the original design standards. Maintenance and repair programs keep TAPS in a safe, reliable state that protects the surrounding environment from adverse impacts from TAPS operations.

The design life of TAPS is a concept used by engineers to provide a basis for time-dependent economic analysis of alternative materials and techniques for the original pipeline design. For continued operations, the performance of design features that mitigate the effect of cold region operation or seismic risk is continually evaluated and upgrades and modifications are made whenever appropriate.

While some early statements regarding the intended service life of the pipeline estimated 30 years, in fact the pipeline design was not based on retirement or cessation of operations 30 years from the start of operations in 1977. These statements are derived from original estimates of the life of the proven Prudhoe Bay field reserves (Norman, 1971), which were used to justify the field owners' decision to proceed with TAPS construction. However, given the size of the Prudhoe Bay field, the possibility of further North Slope discoveries, and the consequences of a design failure, the pipeline was designed and built so that it could be physically operated indefinitely while meeting all safety and environmental criteria. Of course, Prudhoe Bay has produced far more reserves and has a far longer life span than originally predicted. Moreover, other significant North Slope fields have been, and still are, being developed. The original design goal — to incorporate features which would facilitate a virtually unlimited useful life of the system — was well selected.

In fact, the initial duration of the Federal Grant and State Lease was set at 30 years because that was the maximum period allowed by law, not because of any concern that the pipeline system would not last longer than 30 years.

Economic Life

The economic life of TAPS is essentially determined by whether there is sufficient North Slope crude oil economically available to justify continued operation of TAPS.

U.S. government and State of Alaska predictions of North Slope oil production show that, although production from current fields will continue to decline, by 2020 production will level off in the range of 500,000 barrels per day until the end of the period in 2034. These conservative estimates are based principally on well-established decline curves for existing fields and on a small increment in future production to be supplied by increased production from existing fields and by production from very modest discoveries. The estimates do not include the assumption that any oil will be produced from new major discoveries or from areas that are currently closed to exploration and production. More than sufficient economically recoverable oil is available to support the operation of the pipeline.

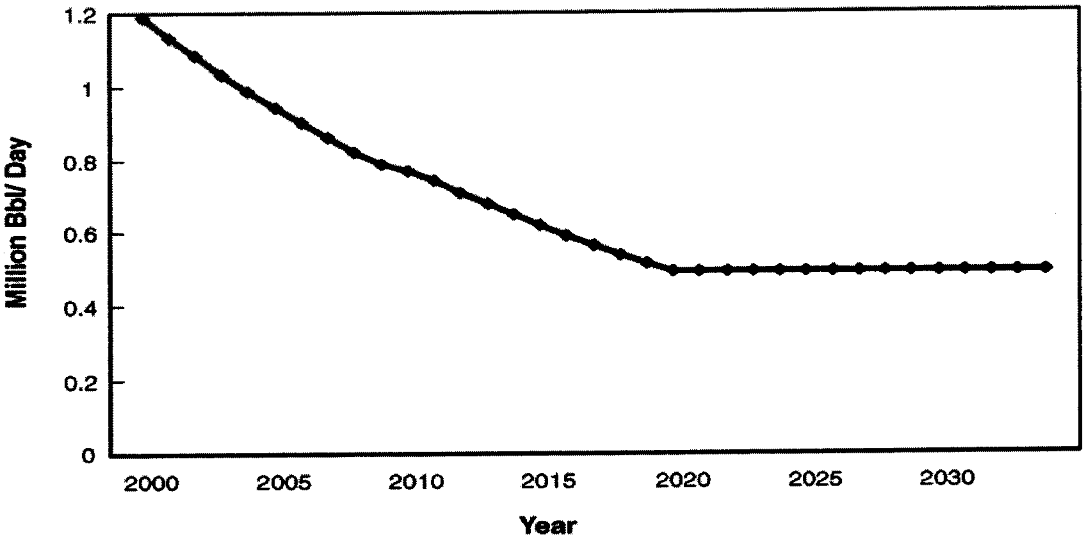

Figure 1 - Projected Throughput to 2034 (Source: TAPS Owners 2001a)

Currently, TAPS throughput is about 1 million barrels per day (bbl/day). Throughput projections indicate that throughput will continue to decline and then stabilize at about 500,000 bbl/day (TAPS Owners, 2001a) (Figure 1). At pipeline startup in 1977, throughput was about 300,000 bbl/day, and at peak operation in 1988, throughput was over 2 million bbl/day (Figure 2). Two conclusions can be drawn from this operating experience:

1) TAPS has already operated in the throughput ranges expected to occur in the next 30 years, and
2) Since throughput has decreased by over one million bbl/day in 12 years, dealing with an additional decline of 500,000 bbl/day in the next 30 years is well within technical and operating abilities.

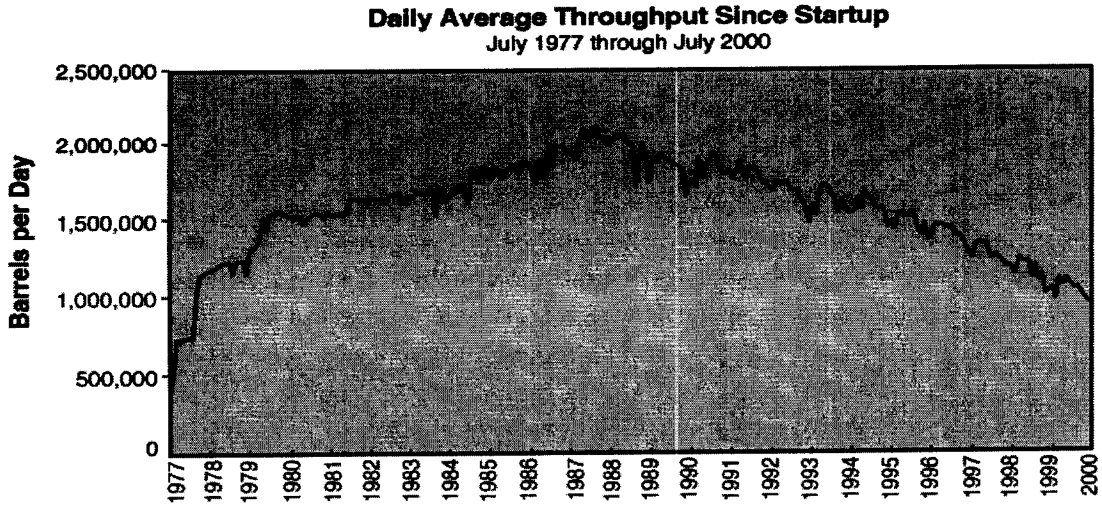

Figure 2 - Daily Throughput

Physical Life

TAPS physical life will last as long as the integrity of the pipeline and facilities is maintained adequately to allow continued safe and environmentally sound transport of crude oil. Alyeska possesses one of the industry's most rigorous maintenance programs, key aspects of which are continual monitoring and replacement of TAPS components, where advisable, either to ensure system integrity or to take advantage of technological improvements and efficiencies. Just one indication of the massive nature of that program is the approximate $25 million to $50 million spent each year to detect and control corrosion.

TAPS is proven to be reliable — from July 28, 1977, through December 31, 2000, the pipeline operated for over 204,000 hours and was shut down for a total of only 852 hours, giving it a reliability rate of 99.6 percent. The pipeline also has an excellent performance record with respect to leaks. Since startup, over 13 billion barrels of crude have been transported, with only 6 major leaks (i.e., greater than 1,000 barrels) on the mainline pipeline totaling approximately 31,600 barrels, one-half of which occurred through a sabotage incident at Steele Creek. The expectation is that these results will be improved on in the future, given diligent upkeep and further developments in such areas as in-line inspection and leak detection technology which Alyeska has pioneered in past years.

Since startup of TAPS in 1977, Alyeska has continued to improve and expand its initially comprehensive programs to detect and repair potential problems that might threaten the integrity of the pipeline system. Alyeska has developed innovative, state-of-the-art methods to monitor the condition of the pipeline and associated facilities. Where corrosion, settling, or other problems have been detected, prompt repairs — including the replacement of several sections of mainline pipe — have been made. These programs verify that the initial design specifications and construction methods were robust and lasting even in harsh arctic conditions.

Pipeline Longevity/Performance Studies

In addressing TAPS longevity, it is useful to compare the TAPS operating period with that of other pipelines. Some pipelines have been in good operating condition for more than 50 years (Muhlbauer, 1996).

A study of Cook Inlet, Alaska, oil pipeline performance performed by Alaska Department of Environmental Conservation (ADEC) noted:

> "The fact that the pipelines have reached their original design life does not imply that the lines have become inadequate or unsafe. The integrity of an older pipeline is a function of how well the line has been maintained, the type of throughput, and how the current operating conditions compare with the original design conditions. With proper maintenance the remaining life of a pipeline can be several multiples of the original design life." (Visser et al., 1993)

Several studies have examined the effect of aging on pipelines. In one recent study, a European pipeline consortium collected data over a 25-year period on the performance of cross-country oil pipelines in Western Europe (Lyons, 1998). The data were analyzed to record the pipeline system development over time, quantify environmental performances, and reveal trends in causes of spills. The following summarizes the findings of the study:

- In 1971, 70 percent of the pipelines inventoried were 10 years old or less, but by 1995 only 8 percent were 10 years old or less and 30 percent were over 35 years old.
- Pipeline spills averaged fewer than 14 per year and most were very small. Less than 5 percent of the spills were responsible for 50 percent of the gross volume spilled.
- Over the 25 years, the frequency of spills improved from 1.2 spills per 1,000 kilometers (620 miles) of pipeline to 0.4 spills per 1,000 kilometers.
- The two most important causes of spills are third-party accidents and mechanical failure, with corrosion in third place, and operational and natural hazards making minor contributions.

The study concluded that there is no evidence that the aging of a pipeline system increases risk. The development and implementation of new techniques, such as internal inspection using smart pigs, hold out the prospect that pipelines can continue reliable operations for the foreseeable future.

In assessing TAPS longevity versus performance, it is useful to review oil spill statistics over time. If aging of TAPS increased risk, an upward trend in oil spills would be noted. Such an analysis was done for the draft *Environmental Report for Trans-Alaska Pipeline System Right-of-Way Renewal* (TAPS Owners, 2001) (Figure 3) presents volumetric spill rates by year for the pipeline. There is substantial variability, but also evidence of a downward trend in volumetric spill rates in later years. Except for a sabotage incident near Livengood, all large pipeline spills occurred during the first five years of operation of TAPS.

A linear regression line (the dashed line in Figure 3) has a negative slope, indicating decreasing volumes spilled. Nonetheless, the predictive power of the linear trend model is not high, indicating that year-to-year variability is large relative to any time trend. For this reason, it is conservatively assumed that the volumetric spill rate is constant over time. Consequently, oil spill statistics do not indicate a pipeline nearing the end of its useful life.

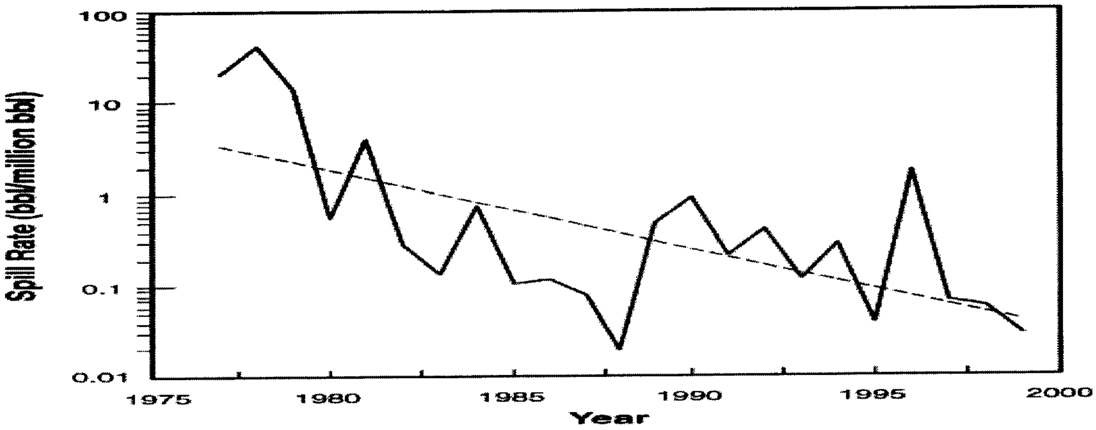

Figure 3 - Volumetric Spill Rates by Year

Age-Related Effects on Pipelines

Pipeline age itself has no metallurgical effect on the microcrystalline structure of steel that would cause the strength and ductility of the pipe to degrade over time. However, there are several ways that the age of a pipeline can influence the potential for failures, including corrosion, fatigue, and manufacturing and construction methods (Muhlbauer, 1996; Crocket and Maguire, 1999). An indirect effect of age is the increased time when a pipeline is exposed to the threat of "outside-force damage" (damage caused by accidental impact from an external force such as a vehicle or heavy equipment).

The following discussion highlights these effects on pipelines in general. Following this discussion is a section describing techniques and programs used specifically on TAPS to mitigate the threat of these age-related effects.

- **Corrosion** is related to the environmental conditions surrounding the pipe. It is reasonable to assume that with the passage of time, the opportunity for undetected (and hence, uncontrolled) corrosion and/or fatigue effects increases. Pipe-coating systems are susceptible to deterioration over time from mechanical abrasion and chemical reactions from absorbing gases and liquids in the surrounding environment. Pipeline operators use corrosion-control programs to counter the threat from corrosion.
- **Fatigue stresses** that result in cracks are a potential effect of age in metal pipelines. Fatigue cracks, if unchecked over time, can lead to pipe failure. Pressure fluctuations during pipeline operation over long periods can lead to fatigue. Common practices used to detect fatigue are fatigue monitoring, hydrostatic testing, and in-line inspection with crack detection tools.
- **Manufacturing and construction methods** can affect physical life. Poor field welds, incomplete fusion of longitudinal pipe seams, and defects in the steel manufacturing process could contribute to pipe failure over time. Although most defects of these types are detected before initial pipeline operation, some defects could manifest themselves over time as pressure cycles, fatigue stresses, and external impacts affect pipeline performance. Radiographic examinations of

welds, construction and manufacturing inspections, hydrostatic testing, and in-line inspections are methods by which this threat to pipeline integrity is detected.

- **Outside-force damage** is an indirect age-related effect on physical life simply by the increased time of exposure to potential incidents. Damage caused by outside forces is usually localized and is minimized by information dissemination (e.g., posted notices, public awareness campaigns), surveillance, and monitoring.

Mitigating the Effects of Age on TAPS

Potential effects of age discussed above are countered on TAPS through surveillance and maintenance programs to identify flaws in coatings, provide adequate cathodic protection and monitor pipe condition through in-line inspection. Pumps, turbines and other components of the pipeline are repaired and replaced as required. If the potential age-related effects are properly controlled, the physical life of the steel pipe is considered essentially unlimited. On TAPS, potential age-related threats are mitigated as described below.

Corrosion. Monitoring of corrosion protection is accomplished in several ways. Cathodic protection monitoring of mainline pipeline takes place annually. Data are gathered from test stations, buried corrosion coupons, cased road crossings, and the fuel gas pipeline. Cathodic protection data also are gathered at buried propane tanks, pump stations, and the Valdez Marine Terminal. Rectifiers are checked six times a year.

Inhibitors are used to control corrosion in isolated and low-flow or seldom-flow piping in pump stations and in road-crossing casings. Internal coupons, which verify the effectiveness of the inhibitors, are removed and analyzed twice yearly. In-line inspection tools ("smart pigs") are used to monitor corrosion and curvature on the mainline pipeline. Data are collected, stored, evaluated, and trended.

Fatigue. Cracks from fatigue stresses can affect the physical life of metal pipelines. On TAPS, two potential fatigue-stress scenarios exist: structural resonance of the piping and pipeline pressure-cycling.

Structural resonance of piping occurs in the piping manifolds of mainline pumps when the pump impeller spins at a rate that can excite the piping or its appurtenances at their natural structural frequency, resulting in high vibration and stress levels. Structural resonance manifests itself only in piping and appurtenances adjacent to the mainline pumps. To mitigate the effects, operators routinely check for fatigue damage to piping near the mainline pumps and implement corrective measures as required to maintain system reliability.

Pressure-cycling is a concern only in areas on the mainline pipe where dents, sleeves, or similar anomalies can result in localized pipe-wall bending stresses as the pipe goes through changes of pressure. The degree of potential fatigue damage depends on the number of cycles and the stress magnitude for each cycle. For dents, sleeves, and other pipeline anomalies, the potential fatigue stresses can be high during shutdowns and restarts, but the number of cycles is low. In areas where the cycles may be high, such as at the base of slackline areas, the pressure deviations and resultant stresses are low. These slackline and dent areas, such as Thompson Pass, have been studied, and either fatigue life has been determined to be unlimited or corrective actions have been implemented. (Baskurt et al., 1998; Hart et al, 1998; Norton et al., 1998; Stevick et al, 1998; Tart and Hughes, 1998; Tonkins et al., 1998)

Manufacturing and Construction Methods. Manufacturing defects or poor construction methods could have a deleterious effect on the longevity of a pipeline. However, TAPS was built under the most stringent criteria available and was closely inspected, tested, and monitored. The following examples of pipe materials, welding, and valves indicate the level of mitigating measures employed.

Mainline Pipe. TAPS pipe is carbon steel (API 5LX and 5LS) with five different pressure capabilities. There are two wall thickness 0.462-inch (11.7 mm) and 0.562-inch (14.3 mm) and three specified minimum yield strengths 60,000; 65,000; and 70,000 psi (413,400; 447,850; and 482,300 kPa).

The design basis criteria for allowable curvature were based on pre-construction mainline pipe testing at the University of California at Berkeley (Bouwkamp and Stephen, 1974). In order to study the potential behavior of the pipeline prior to construction, test specimens were subjected to a number of different load conditions. The basic parameters in these studies were the internal pressure and the temperature differential between tie-in or installation temperature and operating temperature. To evaluate these phenomena under increasing lateral loads, a total of seven specimens under different pressure and simulated temperature conditions were investigated. These tests continued until the pipe wall buckled. For five specimens, tests continued until the pipe wall ruptured. Furthermore, one test specimen was used to study the effect of a pressure drop on pipe-wall stability.

Recent advances in analytical techniques have led Alyeska to develop tools to evaluate the below-ground pipe at specific locations on the basis of the demand on the pipe and the pipe's particular capacity to resist bending. These studies and tools allow Alyeska to confirm that, in light of current technical knowledge, TAPS pipe continues to retain original throughput performance capabilities.

Welding. Welding on the pipeline, whether during construction or repair, must:

- Be performed by qualified welders in accordance with approved procedures;
- Be protected from weather conditions such as precipitation;
- Be performed in a manner to prevent, repair, or remove defects; and
- Undergo nondestructive testing (radiography and hydrotesting).

All mainline pipe was hydrotested and all welds inspected by radiography before TAPS was commissioned. In the event that pipeline repairs require relocation or replacement, all replacement components undergo hydrostatic testing, and all mainline welds are inspected to ensure the integrity of the relocated or replacement pipe. Alyeska does not use any replacement pipe or component that has not been hydrostatically tested in conformance with Department of Transportation standards or that fails to meet hydrostatic testing standards.

Valves. Alyeska specifications for the design of mainline valves require conformance to American Petroleum Institute standard API 6D, as well as several other requirements. Department of Transportation regulations under 49 CFR 195 also require that new valves meet the test requirements of API 6D, which covers valves of 2-inch nominal pipe diameter and larger.

The Department of Transportation regulations also require pipeline operators to maintain those valves "required for safe operation" in good working order. Alyeska maintains its valves in good working order and demonstrates the functionality of the valves through partial closure of the valves twice a year. In addition to the regulatory requirements, Alyeska implemented the TAPS Valve Program in 1997 to validate the condition of these valves and to perform testing to determine if the valves performed in accordance with sealing criteria developed by Alyeska. Valves that do not meet performance criteria are repaired or replaced. (Aus et al., 2000; Jackson and White, 2000; Pomeroy and Norton, 2000; Weber and Malvick, 2000)

Outside-Force Damage. Approximately half of the 800-mile (1288 km) pipeline is above ground and, therefore, potentially subject to damage caused by accidental impact from an external force such as a vehicle or heavy equipment. Access to most of the right-of-way is determined by the federal (Bureau of Land Management) and state (Alaska Department of Natural Resources) landowners. In addition, Alyeska limits access to the pipeline through signs and with locked gates on access roads to the right-of-way. For locations where access roads pass under the pipeline, "headache" bars have been installed to ensure that vehicles have enough clearance under the pipe.

For below-ground pipe, all excavation within the right-of-way must be authorized by Alyeska. Warning signs along the pipeline contain a 24-hour telephone number to contact the Controllers at the Operations Control Center (OCC). Callers with excavation requests are connected with the appropriate personnel to coordinate excavation requirements. In addition, Alyeska conducts an educational program to help the public, government organizations, and people engaged in excavation-related activities to recognize a crude-oil pipeline emergency and to report it to Alyeska and/or other emergency response organizations.

Alyeska's pigging program monitors the pipeline for external damage using state of the art ultrasonic technology to detect pipe-wall thinning from gouges and scrapes. Other curvature pigs detect dents and ovalities. Leak detection systems monitor for leak loss from any source, including outside-force damage.

Conclusion

The useful life of TAPS is the period during which an economic benefit is derived from continuing operations and during which the pipeline can be operated safely and without harm to the environment. The useful life of TAPS will continue well beyond 30 years for at least three key reasons.

1) The physical life of TAPS is virtually unlimited assuming continued appropriate maintenance and surveillance. In-line inspection tools (smart pigs) for pipeline corrosion, deformation and settlement are run on rolling three-year

cycles. If corrosion or other damage is found that would reduce the capacity or pressure capability of TAPS, repairs are made. Pumps, turbines and other components of the pipeline are repaired and replaced as required.

2) The economic life of TAPS will continue for the foreseeable future based on pipeline throughput estimates from a variety of public sources.
3) The design life of TAPS is a concept used by engineers to provide a basis for time-dependent economic analysis of alternative materials and techniques for the original pipeline design. For continued operations, the performance of design features that mitigate the effect of cold region operation or seismic risk is continually evaluated and upgrades and modifications are made whenever appropriate.

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