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HIGHLY TENSIONED SUSPENDED PIPELINES

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ABSTRACT

In 1996, ARCO Technology and Operations Support (ARCO TOS) began considering Highly Tensioned Suspended Pipelines (HTSPs) as a promising concept for above ground, cross-country pipelines in Arctic regions. HTSPs resemble high voltage, cross-country power lines. Similar construction methods and support towers are used. The primary differences are that the pipelines are larger in diameter and are supported against out-of-plane wind loads. Three years of development work are summarized in this paper. This work includes analytical modeling, pipeline code compliance, conceptual design of components, and construction studies. Fatigue resistance under North Slope Alaska wind conditions is estimated. HTSPs are judged to be technically feasible and a cost effective alternative to traditional elevated pipelines.

1. INTRODUCTION

1.1 HTSP Concept

This paper reviews the concept of a High Tension Suspended Pipeline (HTSP), in which a pipeline is suspended between supports, much like an electrical power line. The essential features of an HTSP line are shown in Figure 1. An HTSP span is radically different from a conventional above ground pipe span in that the weight of the pipe is carried mainly by axial tension force in the pipe (i.e., cable action) instead of by beam action. This allows HTSPs to span several hundred feet, compared with about 40 to 60 feet for conventional spans. HTSPs have the potential to reduce costs substantially compared with conventional elevated pipelines, and also to be more benign environmentally. This can make it more feasible to develop remote oil discoveries, particularly on the Alaskan North Slope. Because an HTSP is radically different from a conventional pipeline, there are special considerations for the design, analysis, erection, monitoring, operation and maintenance of HTSP systems. Some of these considerations are as follows.

(1) Design Criteria. As with a conventional pipeline, the stress and strain criteria used for design must insure that; (a) the system will not collapse under sustained loads during erection, hydro-testing or operating conditions, (b) the system will not undergo fatigue failure due to thermal cycling (or other cyclic loads), and (c) the system will not experience progressive collapse under combined stresses due to sustained and cyclic loads. However, since the structural behavior of an HTSP system is different from that of a conventional system, the specific criteria may also be different.

(2) Analysis Methods. The behavior of an HTSP system is dominated by cable action, whereas the behavior of a conventional system is dominated by beam action. In the analysis of cables, nonlinear large-displacement effects must be considered. HTSP analysis must account both for the cable nonlinearity and for the interaction between beam and cable effects.

(3) Erection Methods. For cross-country applications the erection process involves laying out a long string of pipe covering several spans between two anchor points. The support saddles are clamped to the pipe at precisely calculated locations along the pipe string, so that when it is lifted onto the towers the desired sags, tension and ground clearances are obtained. The pipe is anchored at one end, and jacked against the anchor at the other end to apply a tension force. The pipe is then lifted onto the tower supports, one by one, and finally attached to the other anchor. The tension force must be carefully controlled during the lifting process, to ensure that the erected pipe rests correctly on its support points, and to avoid overstressing the pipe. This requires close coordination between teams of jacking crews and lifting crews. The tension force at tie-in must be carefully controlled and precise locations of support points and anchor points along the pipe must be used to obtain desired sags and slopes.

(4) Load Cases. The basic operating loads are pipe and contents weight, pressure and thermal expansion. Other cases that must be considered include erection loads, hydro-test, wind (including vortex shedding), earthquake, unbalanced contents weight (some spans full and some empty), ice loads, maintenance loads and multi-phase flow.

(5) Bearing Design. In a cross country HTSP system, there are relatively few supports, and hence the bearing force per support is larger than in a conventional pipeline. Also, the pipe must bend as it passes over each support. Since the pipe must be laid out straight prior to erection, it is not feasible to pre-bend the pipe at the support locations, and hence the pipe may yield locally during the erection process. The support hardware must be designed to limit the amount of yielding and to transmit large local bearing forces to the pipe without compromising its integrity. The supports may also have to accommodate two or more parallel pipelines.

(6) Support Towers. The support towers must be stiff laterally in the direction transverse to the pipeline, and strong enough to resist wind and earthquake loads. Except for temporary bracing during erection, it is likely that the towers can be (and should be) allowed to flex longitudinally, or to pivot about the base. The tower foundations must be designed to remain stable in permafrost conditions.

(7) Maintenance. There are many inspection and repair issues to be considered. For example, a repair method may be needed to allow a damaged tower or section of pipe to be repaired without laying down the entire pipeline between anchors, which may be more than a mile apart.

(8) Regulatory Acceptance. HTSPs represent a significant departure from conventional pipelines, and there may be some reluctance to accept the new technology. Questions that might be raised include visual impact, potential hazard to birds and aircraft, and spill isolation in the event of a pipe rupture.

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2. OVERVIEW OF CONCEPT AND WORK TO DATE

2.1 General Features of HTSP Systems

In a conventional above ground pipeline, gravity loads on the pipe are supported by bending and shear (i.e., beam action). The structural behavior of a highly tensioned pipe span is fundamentally different in that the gravity loads are supported mainly by axial tension in the pipe (i.e., cable action). A pipe differs from a simple cable, however, because it has substantial bending stiffness, especially for larger pipe diameters. Hence, the pipe behaves like both a beam and a cable, and HTSP spans resist loads with a combination of cable and beam action. Changes in the temperature of the pipeline cause the sag within the span to increase or decrease, with only small changes in stress, and hence expansion loops are not needed. The flexibility of the system also tends to make it resilient under earthquake loads. However, bracing and/or damping may be needed to control displacements and stresses under wind loads. Pipe diameters ranging from 3 inches to 16 inches have been considered in the work conducted to date. For cross-country pipelines, span lengths of up to 700 feet have been considered. Longer spans should be feasible for locations such as river or canyon crossings.

Figure 2 (a) shows a cross-country HTSP configuration within an anchor-to-anchor section containing two interior full spans and two exterior half spans. Cross-country configurations with up to 10 spans between anchors are envisioned. Figure 2 (b) shows a possible configuration for an HTSP river crossing, with a long interior span and two exterior half spans. Figure 2 (c) shows a possible multi-span configuration over irregular terrain. When the pipeline crosses sloping terrain, the pipe is supported vertically at each tower, not in the direction normal to the slope. An important feature of a multi-span configuration is that the horizontal component of the pipe tension is balanced at each interior support. It is not necessary for the span lengths to be equal for this requirement to be satisfied. The pipe tension can change at the anchor points, if desired. Since unbalanced forces can occur during construction and repair, anchors must be designed to resist the full tension force on either side of the anchor. Each time the pipeline changes direction, a horizontal force must be resisted because of the change in direction of the pipe tension. The optimal proportions for an HTSP line, in terms of number of spans, span length, tower height, ground clearance, etc. are not currently known. Some aspects to be considered are as follows.

(1) The pipe tension stress is an important parameter.
(2) A minimum ground clearance must be provided.
(3) The tower height must be kept to a reasonable minimum, to reduce cost, to lessen visual impact, and to reduce the height requirement for construction, inspection and repair equipment.
(4) If the span length changes, the sag must be adjusted to keep a constant value for the horizontal component of pipe tension. This may require varying the tower heights.
(5) The anchors must be designed for the full pipe tension. The height of the anchors above the ground is an important parameter that can affect the cost. The pipe does not have to be horizontal as it enters the anchor, but if it is sloping the anchor must be designed to resist uplift forces.
(6) Changes in horizontal alignment should normally be made at anchors, not at towers.
(7) To avoid large lateral displacements of the pipe under wind loading, some form of lateral sway bracing will probably be needed.

2.2 Design and Technical Studies

Although no complete designs have been prepared for HTSP applications, ARCO TOS has performed four preliminary design studies. Extensive analytical studies have been undertaken on a 16-inch diameter oil pipeline. Preliminary design work has been undertaken on a 3-inch gas line for a cross-country pipeline using existing VSMs. A number of design alternatives were considered in pilot studies on a 4-inch HTSP system for a gas pipeline including a cross-country configuration and a crossing of a river channel with a span of 1350 feet. Preliminary design work has been performed for a 4-inch water pipeline across another river channel with a main span length of up to 600 feet.

To provide a background for future design efforts, ARCO TOS commissioned a study on the technical feasibility of HTSPs for applications on the Alaskan North Slope which was completed in December 1997 [1]. The report concludes that the HTSP concept is technically feasible, especially for smaller diameter pipelines. In 1998, ARCO TOS commissioned an independent peer review of the feasibility report [2]. The principal conclusion of the review is that there are no apparent reasons to doubt the feasibility of the HTSP concept. ARCO TOS recently prepared a patent application for the HTSP concept [3] and commissioned a summary report documenting the HTSP development through October 1999 [4].

3. ERECTION

3.1 Overview

This section outlines the erection process and reviews the analysis tools that can be used to calculate displacements, forces, stresses and strains during erection. The procedure for erecting a multi-span HTSP system is shown schematically in Figure 3. The steps are as follows.

(1) Construct the anchors at the beginning and end of anchor-to-anchor run.
(2) Install the support towers at surveyed locations between the anchors. The towers must be temporarily guyed in the longitudinal direction.
(3) Lay out and inspect a length of pipe from anchor-to-anchor. Mark the pipe where the saddles will be clamped to the pipe (or alternatively where the pipe will rest in saddles that are attached to the towers).
(4) Attach the pipe to the left anchor.
(5) By jacking against the right anchor, apply a tension force to the pipe. Since it is necessary to control the axial tension in the pipe, it is important to account for longitudinal friction effects. It may be necessary to support the pipe on low-friction supports at intervals along its length (e.g., roller supports or air bags). Alternatively, it may be possible to lay out the pipe on an ice road without supports, and to account for friction by monitoring the behavior of the pipe. This is a topic that requires additional study.
(6) Starting at the left end, lift the pipe onto the first tower. If the required tension force is maintained in the pipe, and if the bearing points on the pipe have been accurately laid out, the pipe will be correctly positioned on the supporting saddle at the support. If necessary, the guy system for the tower can be adjusted to place the saddle in the correct position along the pipe length before the pipe is lowered. Attach the pipe to the saddle.
(7) Remove the guy system for the first tower. This allows the tower to tilt longitudinally if necessary, to equalize the pipe tension in adjacent spans. Since the pipe is attached to the tower, there is no danger of longitudinal instability (provided the pipe tension is maintained). Guy cable hardware may not be needed for every tower, since it can be moved from tower to tower during the erection process.
(8) Repeat for all towers.
(9) Attach the pipe to the right anchor. Initially, before the pipe is lifted onto the towers, the pipe will extend beyond the right anchor attachment point, possibly by several feet. As the pipe is progressively lifted onto the supports, the end of the pipe will progressively move inwards. If the pipe has been accurately laid out, and if temperature effects have been accounted for, when the pipe is lifted onto the last support, the end point of the pipe should accurately match the anchor attachment point, requiring only minor shimming or other adjustment.

3.2 Analysis Methods

Because the construction of HTSP systems involves long lengths of pipe and tight geometric tolerances, it is important that the erection process be accurately analyzed to insure proper fit. The analysis method must account for both cable action and beam action in the pipe, and must consider the complex nonlinear geometrical relationships. For the HTSP studies to date, the erection analyses have been performed using the PIPLIN computer program [5]. PIPLIN is a widely used program for the stress and deformation analysis of pipelines, including yielding of the pipe and nonlinear geometry. Its main application has been the analysis of buried pipelines, but it is also applicable to above-ground lines, including HTSP systems. The program has a number of unique features that make it effective for simulating complex erection sequences essentially as outlined in the proceeding section.

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4. SUPPORTS, ANCHORS AND OTHER HARDWARE

4.1 Supports and Anchors for Multi-Span Configurations

A schematic of an HTSP interior support is shown in Figure 4. The essential components of the support are (a) a pipe saddle; (b) a support tower; (c) a foundation; (d) a connection between the saddle and the tower; and (e) a connection between the tower and the foundation. Several different support concepts, with various combinations of these components have been studied over the course of this project. The concepts that appear to be the most promising are considered in this section.

4.2 Pipe Saddle

Where the pipe rests on an interior support, the following aspects must be considered.

(1) The slope of the pipe must change from the positive slope at the end of one span to the negative slope at the start of the next. Hence, the pipe must be curved in the support region, possibly enough to cause yield.
(2) A large reaction force must be transmitted from the pipe to the support tower. This can cause large bearing forces on the pipe, possibly causing ovaling and local stress concentrations.
(3) During the erection phase the pipe may yield at the support location. If this occurs, there is a possibility that the pipe wall may wrinkle.
(4) As the pipe temperature changes, the pipe sag changes, and hence also the change in pipe slope across the support. The support must be able to accommodate different changes in pipe slope.
(5) Under unbalanced gravity loads and longitudinal wind loads there may be significant longitudinal displacements at a tower, causing different end slopes in adjacent spans. The support system must be able to accommodate these changes by allowing pivoting of the tower and possibly sliding or swinging of the saddle.
(6) Under gravity, thermal and other loads there may be substantial changes in bending moment at the support location. It may be necessary to account for large numbers of stress cycles (i.e., to consider fatigue life).
(7) The support must allow easy erection and maintenance.
(8) The support must not encourage corrosion of the pipe, and must allow easy inspection.

The most promising support concept makes use of a curved saddle, as shown schematically in Figure 5. A saddle has the following features and behavior.

(1) When the pipe is erected it bends at the saddle, with the same curvature as the saddle. If this curvature is less than the yield curvature of the pipe, the pipe can remain elastic. However, if the yield curvature is small this requires a long saddle. If the saddle curvature is larger than the pipe yield curvature, the pipe yields but the saddle limits the amount of yielding. In effect, the pipe is cold bent during the erection process, as the saddle is lifted into position, or as the pipe is draped over the saddle.
(2) The saddle distributes the support force over a substantial length of pipe, and hence limits the bearing stresses. With proper profiling of the saddle, it should be possible to keep the bearing stresses essentially constant along the saddle length. A cushioning layer between the pipe and the saddle could also help to make the bearing stresses more uniform.
(3) As shown in Figure 5, the saddle can be trough-shaped in cross section, with the radius of the trough equal to the outside radius of the pipe. This type of saddle can restrain ovaling of the pipe, and for modest amounts of yielding it should be able to prevent wrinkling as the pipe yields.
(4) If the basic saddle can not prevent pipe wrinkling, one possibility is to restrain ovaling by surrounding the carrier pipe with reinforcement sleeve that provides ovaling resistance without adding bending stiffness.
(5) The saddle must be designed to accommodate longitudinal movements of the support tower under unbalanced loads. This may mean that the saddle must be allowed to rotate as the pipe moves longitudinally, as indicated in Figure 6.
(6) Energy absorbing devices may be needed to damp out wind-induced vibrations. It may be appropriate to incorporate such devices into the saddle and tower designs.
(7) Not shown in Figure 5 is a clamping device that will lock the pipe and not allow it to move longitudinally relative to the saddle.

4.3 Support Towers

For design of an interior support tower the following aspects should be considered.

(1) The tower must be high enough to provide adequate pipe-to-ground clearance in the maximum sag (hot) condition.
(2) The tower must have adequate lateral and vertical strength and stiffness.
(3) The tower must be able to allow longitudinal movement of the pipe.
(4) The support saddle must be connected to the tower in such a way that it adapts to the pipe when longitudinal movement occurs. To satisfy this requirement the saddle may have to rotate relative to the tower.

For small diameter pipes, a cantilever column tower with a pin connection to the saddle and a fixed condition at the foundation is a possibility. As shown in Figure 7 (a), a rectangular box section with the long axis perpendicular to the pipe axis would be relatively stiff out of plane, to resist transverse wind loads, yet relatively flexible longitudinally. A more likely alternative is a tower that is braced transversely and pinned at the base for longitudinal displacements, as shown in Figure 7 (b). Towers of this type must be temporarily guyed in the longitudinal direction to provide stability during erection.

A variety of details for connecting the pipe-saddle to the tower are possible. These include; a sliding interface between the base of the saddle and the top of the support, a configuration where the pipe is suspended from a trapeze system, and a pinned-pinned assembly. The work conducted to date has considered only single pipe HTSP configurations. Configurations with multiple pipes may be needed, in which case the support design is substantially more complex.

4.4 Anchors

For design of the end anchors the following aspects must be considered.

(1) Each anchor-to-anchor run must be a self-contained structure that is stable independently of the adjacent pipe spans.
(2) The anchor must serve as a reaction block for the jacking operation during erection.
(3) The anchor must resist large axial forces, to account for loads during erection and repair.

A conceptual design for an HTSP anchor is shown in Figure 8. This design uses a pair of anchors, connected by a short segment of conventional (non-tensioned) pipe. This segment allows for direction changes, and also permits a jacking system to be placed between anchors in the erection phase.

4.5 Vibration Dampers

As noted later, wind-induced vibration (WIV) effects can be a concern for HTSP systems. Dramatic reductions in WIV displacements and stresses can be achieved using pipeline vibration dampers (PVDs). PVD design procedures for conventional cross country pipelines are well established, and a number of successful PVD devices are available [6]. The design procedures should also be applicable for HTSP systems. This is an area requiring more study.

4.6 Lateral Wind Bracing

As noted later, under lateral wind load the pipe may swing laterally, like a jump rope. It is probably necessary to provide bracing to control this type of displacement. The following aspects must be considered for design of the bracing system.

(1) The location(s) of the brace(s) in each span. Based on studies completed to date, a single brace point at midspan appears to be sufficient for multi-span HTSP systems
(2) The transverse strength required to restrain the pipe.
(3) Change in the pipe sag between the hot and cold conditions. It is probably necessary for the bracing to allow the pipe to move freely in the vertical direction as the temperature changes, since restraining the pipe vertically may cause excessive stresses. However, it may be possible to use a bracing system that restrains the pipe in both the transverse and vertical directions.
(4) The space occupied by the bracing. The use of guy cables may not be feasible for multi-span HTSP systems where a limited overall footprint is required.

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A possible bracing system is shown Figure 9. This system is in the form of a "goal-post", allowing vertical movement of the pipe while restraining transverse movement. It may be possible to incorporate damping devices into a support of this type

5. STRESS ANALYSIS FOR OPERATING LOADS

5.1 Overview

When a pipe design is checked for structural integrity, decisions are based on comparisons of demand and capacity. Typically, the demand is the stress in the pipe, calculated using accepted procedures, and the capacity is an allowable stress specified by a design code or by project-specific criteria. The allowable stress depends on the type of behavior that is being considered and on the material strength. For fatigue under cyclic loads, the allowable stress may depend on the expected number of load cycles. It may be noted that the actual stress in the pipe (if it were known) might be different from the calculated stress. However, the calculated stress is accepted as a suitable measure for demand-capacity comparisons.

Although stress is the most common demand-capacity measure, a variety of other measures may be used. Demand and capacity values may also be based on force (e.g., the vertical and lateral forces exerted by the pipe on a support tower), on displacement (e.g., the amount of displacement caused by transverse wind load in an HTSP span) and on strain (e.g., the amount of local yielding in the pipe during the erection process).

Forces, displacements, stresses and strains are calculated using computer programs for structural and stress analysis. For typical above-ground pipelines, the analysis is linear, assuming small displacements and linear elastic behavior of the pipe and its supports. For HTSP systems, however, it is necessary to use nonlinear analysis. Because of the large displacements of an HTSP during erection (and possibly during operation), it is necessary to allow for nonlinear geometric effects. This is usually referred to as "geometric nonlinearity". If local yielding is allowed, it is also necessary to allow for nonlinear behavior of the pipe material. This is usually referred to as "material nonlinearity".

As previously noted, structural analyses of HTSP systems must also account for both beam and cable action.

5.2 Overall Analysis for Operating Loads

The PIPLIN computer program can also be used to perform analyses for operating loads, including contents weight, internal pressure and thermal expansion effects. Under these loads the pipe deflects only in-plane, so the behavior is two-dimensional. The analysis sequence is as follows.

(1) At the end of the erection phase, the pipe is supported and anchored, and carries the self weight of the pipe. The pipe is subjected to axial forces and in-plane bending moments, and it may have yielded locally (in the support region) during erection.
(2) Add the weight of the pipe contents.
(3) Add the operating pressure. When the operating pressure is added, the analysis shows that the axial tension force in the pipe increases by the product of the pressure and the pipe bore area (i.e., by the end cap force).
(4) Add a negative temperature change to get the design cold condition (minimum sag).
(5) Add a positive temperature change to get the design hot condition (maximum sag).

Analyses can also be carried out for hydro-test conditions and for unbalanced gravity loads (for example, contents weight in only some spans as the pipe fills, or ice load accumulation in one span). Unbalanced loads cause different amounts of sag in different spans, and also cause longitudinal movements of the support towers.

5.3 General Observations

Based on the analyses of HTSPs that have been conducted to date, the following general observations can be made regarding the behavior under operating loads

(1) The axial stresses corresponding to the tension force in the pipe do not appear to be unreasonable. For a 16-inch diameter HTSP with a 700 foot span and a sag of 17.7 feet, the axial stress due to the tension force is about 16.5 ksi. For a 4-inch diameter HTSP with a 700 foot span and a sag of 17.0 feet, the axial stress due to the tension force is about 19 ksi.
(2) Except near the supports and anchors, the pipe curvature is nearly constant, and depends on the span and the sag-to-span ratio. For example, for a 16-inch diameter HTSP with a span of 700 feet and a sag of 17.7 feet, the curvature of the pipe over most of its length is essentially 0.000322 ft^{-1} (radius of curvature = 3106 feet). For a 4-inch diameter HTSP with a span of 700 feet and a sag of 17.0 feet, the curvature of the pipe over most of its length is essentially 0.000289 ft^{-1} (radius of curvature = 3460 feet). This corresponds to a bending stress of 6.4 ksi for the 16-inch diameter pipe and a bending stress of 1.6 ksi for the 4-inch diameter pipe (i.e., for a given span and sag, the bending stress over most of the span is proportional to the pipe diameter). This is because the pipe behaves like a cable over most of its length.
(3) The relative magnitudes of the stresses due to axial force and bending can be changed by changing the sag-to-span ratio. For larger sag-to-span ratios the bending effect is relatively larger, and for smaller ratios the axial force effect is relatively larger. Since the bending stresses can be larger than the axial stresses, it may appear that it is advantageous to reduce the combined stress by reducing the sag-to-span ratio (i.e., to use a higher tension design). However, as considered later, it can be deceiving to consider only this combined stress. Nevertheless, there are other advantages to using a smaller sag-to-span ratio (e.g., shorter support towers), and it will be important in design to optimize this ratio.
(4) There are substantial bending effects near the supports. One reason is that the pipe must bend sharply at the support (and may yield during erection). A second reason is that beam effects are more important near the supports. For example, for a 700 foot span and a sag of 17.0 feet, the curvature in 4-inch diameter pipe reaches essentially the cable curvature at a distance of 50 feet from the support. That is, the beam effect is significant over about 14% of the span. For a 16-inch diameter pipe however, the beam effect is significant over about 33% of the span.
(5) There can be a significant change in sag between the hot and cold conditions (up to 0.5 inches of sag change per degree F temperature differential for the cases considered to date).
(6) Under thermal cycling from the hot to the cold condition, the stress range over most of the pipe is small. However, there can be significant stress ranges at the supports and at the end anchors.
(7) As the pipe sag changes between the hot and cold conditions, the slope of the pipe changes at the supports, and hence there is a change in the length of pipe that is in contact with the support saddle. This causes local changes in the bending stresses in the pipe, and also local effects due to changes in the bearing force distribution along the saddle. These effects must be considered in the design of the saddle. If the pipe is restrained rotationally at the end anchors, there can be a substantial bending stress range at this location between the hot and cold condition. The stress range is reduced significantly if the anchor allows the pipe to rotate (see Figure 8).
(8) An important aspect in HTSP design is that one-time pipe yield can be permitted as the pipe is draped over a saddle during erection. Additional yielding may occur as gravity and pressure loads are applied. For subsequent changes in load, the stress changes are much smaller, and the pipe can be designed to shake down to elastic behavior.

6. ANALYSIS FOR WIND AND EARTHQUAKE LOADS

6.1 3D vs. 2D Analysis

The analyses for erection and operating loads can be two dimensional. For wind and earthquake effects, however, it is necessary to consider three-dimensional effects. As with wind and earthquake analyses of most conventional pipelines, the analyses can assume elastic behavior of the pipe steel. Also, provided the pipe is restrained so that wind and earthquake loads

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do not cause large displacements of the pipe, the analyses do not have to consider geometric nonlinearities. However, the analyses are not the same as conventional linear analyses. This is because the pipe has a large axial force, due to the gravity and pressure loads, and hence has additional stiffness. This additional stiffness is termed "initial stress" stiffness, and its magnitude depends on the amount of tension in the pipe. A similar effect occurs in a guitar string, where the vibration frequency of the string (which is related to its transverse stiffness) increases as the string tension increases. The initial stress stiffness is present in addition to the basic axial, bending and torsional stiffnesses of the pipe.

If the displacements of the pipe do not change much when wind or earthquake forces are applied (i.e., if there is negligible geometric nonlinearity), if the axial forces in the pipe do not change much (i.e., if the initial stress stiffness is essentially constant) and if the pipe remains essentially elastic (i.e., if there is no significant material nonlinearity), then a linear structural analysis can be performed. (The analysis is actually "linearized", rather than truly linear, because of the initial stress stiffness.) This greatly simplifies the computations, since nonlinear dynamic analyses for wind and earthquake loads can be very difficult to perform. In the analyses conducted to date, the DRAIN-3DX computer program [7] has been used.

In a typical linearized structural analysis, the axial force effect is included by first applying static gravity and pressure loads, and then performing other analyses about this loaded state. The axial forces caused by the gravity loads are the initial stresses that affect the subsequent stiffness. For the DRAIN-3DX analyses a different procedure is used, as follows. In the present case, the axial forces due to gravity and pressure loads are obtained from the results of the PIPLIN analyses, and these forces are specified in the DRAIN-3DX model as initial forces in the elements. The procedure is as follows.

(1) The shape of the pipe and the pipe axial forces are obtained from a PIPLIN analysis.
(2) The unloaded shape of the DRAIN-3DX model is this PIPLIN shape, and the pipe elements in the model are assigned initial axial forces calculated by PIPLIN. Gravity and pressure loads are not applied to the DRAIN-3DX model.
(3) Static and dynamic analyses are carried out for wind and earthquake loads. The analyses are linearized, with initial stress stiffnesses based on the specified initial axial forces.

6.2 Wind Loads

A fundamental concern for long above ground pipeline spans is how they will respond to wind loading. When subject to strong, steady transverse winds and wind gusts, the relatively flexible span will tend to respond by swaying essentially like a "jump rope". Using static analysis for design wind loads, the maximum pipe stresses and reactions can be estimated for evaluating the span, the supports and wind brace design. A separate concern, for relatively low speed transverse winds, is wind-induced vibration of the span due to vortex shedding. This response is dominated by oscillations transverse to the wind direction. Based on these considerations, HTSP design evaluations should consider the in-plane and out-of-plane responses due to strong static winds and dynamic vortex shedding.

6.2.1 Static Response to Steady Winds

The main concern for static wind loading is the out-of-plane response. There are two key steps, namely (1) estimate the wind load, and (2) calculate the stresses and deformations. A number of methods are available to calculate design wind loads. In the HTSP studies conducted to date, the procedures outlined in [8] were used to develop these loads. Lateral wind bracing can be modeled as transverse springs.

6.2.2 General Observations on Static Response

Based on a number of analyses for static wind loads on HTSP systems that have been completed to date, the following observations can be made.

(1) The maximum deflections and stresses are caused by transverse wind loads. If there is no transverse bracing, the out-of-plane displacements in an HTSP span can be large, because the structure is very flexible in the transverse direction.
(2) For multi-span HTSP systems, a single goal-post brace at the middle of each span should provide sufficient transverse restraint.
(3) The interior towers, wind braces and anchors must be designed for transverse wind loads based on tributary lengths. The anchors in multi-span HTSP systems with pivoting towers must resist the entire longitudinal wind load, since the interior supports provide no longitudinal resistance.

6.2.3 Dynamic Response to Vortex Shedding

The vibration of above ground pipelines due to vortex shedding has been studied extensively [9, 10]. The effect is described briefly as follows. As the wind blows transversely across the pipe, vortices can be shed successively from above and below the pipe. This vortex shedding exerts periodic vertical lift forces on the pipe. The input energy per cycle is small, but under steady winds, vortices can lock into resonance with a lightly damped pipe, causing substantial vibrations to develop. The effect depends on the Reynolds and Strouhal numbers, and on whether the wind flow is laminar or turbulent. It does not necessarily increase as the wind speed increases.

Based on wind-induced vibration experience for above ground arctic pipelines, SSD has developed a proprietary aerodynamic model to estimate the steady-state dynamic response of pipelines due to vortex shedding. The model is based on a range of published information (see [11, 12, 13]) and is qualitatively similar to model presented in [14] and [15]. It has been widely used on North Slope pipeline projects for ARCO and BP-Amoco. It has been implemented as a post-processor program that operates directly on the mode shapes and frequencies calculated by DRAIN-3DX. The model computes the response for each mode of the span as if it were excited individually (uni-modally) in resonant conditions. In order to bound the expected behavior, two levels of response are calculated, namely the response due to laminar and turbulent wind conditions. The response is computed by scaling the mode shape by a factored laminar or turbulent lift coefficient that is a function of the Reynolds number of the wind flow. For each mode, the perpendicular wind speed, the estimated maximum (zero-to-peak) displacement amplitude, the estimated maximum longitudinal stress range, and the Reynolds number of the wind flow are calculated. The dynamic stresses are nominal longitudinal beam bending stresses ($\pm M_Z/Z$ and $\pm M_Y/Z$) and potential changes in the axial force ($\pm T/A$). At any location in the span, the stresses can be intensified to account for stress intensification effects

6.2.4 Fatigue Evaluation

A method for evaluating fatigue damage due to wind-induced has been implemented for the HTSP studies to date. The approach accounts for the damping in the HTSP system, site specific wind speed and direction data (e.g., a wind rosette), an assumed annual variation of air temperature (which affects air density and viscosity), wind turbulence conditions, and an assumed fatigue design (S-N) curve.

6.2.5 General Observations on WIV Response

Based on a number of analyses of WIV response that have been completed to date, the following observations can be made.

(1) The HTSP displacement and stress response to vortex shedding appears to be of the same order of magnitude as that of conventional, above ground cross-country pipeline configurations. However, there is some uncertainty regarding the range of wind speeds or vibration modes over which this narrow-banded, uni-modal vibration model can be applied. It would be desirable to gather WIV data on a prototype HTSP system to help investigate the existence of a "cut-off" Reynolds number or wind speed analogous to that observed in conventional pipeline systems.
(2) The fatigue life calculations performed to date show long fatigue lives, especially if base metal fatigue design curves are used (as opposed to fatigue curves for field welded joints). Since the largest cyclic stresses tend to be concentrated at the support locations, it is important to locate field welds away from the supports.
(3) The fatigue damage calculations due to WIV indicate that a 4-inch diameter multi-span HTSP is likely to experience relatively more fatigue

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damage than a 16-inch diameter HTSP. This is consistent with field observations on conventional Arctic pipeline systems where WIV and fatigue failures tend to occur most frequently in smaller diameter lines. One contributing factor to this behavior is that with all other things being equal, the smaller diameter lines tend to have smaller Reynolds numbers, and hence larger fluctuating lift coefficients.

(4) The estimated fatigue life is sensitive to the assumed level of damping, with a shorter fatigue life for smaller amounts of damping. Hence, an accurate estimate of the actual damping ratio can be important for assessing WIV performance. To date, the WIV analyses performed on HTSP systems have assumed a damping ratio of 0.5% of critical. This assumption is based on previous experience on conventional pipeline spans supported on steel vertical support members. It is recommended that the actual damping ratio be established by field testing.

6.3 Earthquake Loads

The main concerns for earthquake effects on HTSP systems are the dynamic vibration response of the pipeline, response when there are different ground motions at different supports, which is possible because of the long length of an HTSP system and possibly earthquake induced landslides. The work to date has considered only the conventional dynamic response. Because an HTSP system is very flexible, the stresses caused by earthquake loads can be expected to be relatively small.

6.3.1 Methods of Analysis for Earthquake Loads

There are three methods that can be used to assess the earthquake response of a structure. In order of increasing complexity these are equivalent static load analysis, response spectrum analysis, and time history analysis. Response spectrum analysis appears to be the best choice for design purposes in most cases. This method accounts for the dynamic properties of the structure, and although it can not provide as much detailed information as time history analysis, the results are usually adequate for making design decisions. The method has the major advantage that the earthquake is represented by a response spectrum, not as a detailed time history. For design purposes, a response spectrum can be developed that envelopes the response spectra for several actual earthquakes, eliminating the need to perform analyses for several earthquakes. The response spectrum method is a linear method, however, and it does not apply if the structure is significantly nonlinear. In the work conducted to date, only the response spectrum method has been used to evaluate HTSPs. The analyses have been carried out using the DRAIN-3DX program with linearized dynamic properties for the HTSP structure. The analysis using response spectra gives the maximum response in each natural mode. Since it is unlikely that all modes will reach their maximum responses at the same time, statistical methods are used to combine the modal maxima. In the work to date, simple square-root-of-sum-of-squares (SRSS) combination has been used. To obtain more accurate values of the stresses, it would be better to use the complete quadratic combination (CQC) method [16].

7. STRUCTURAL INTEGRITY AND CODE EQUATIONS

7.1 Goals

As noted earlier, when a pipe is checked for structural integrity, design decisions are based on comparisons of demand and capacity. Although stress is the most common demand-capacity measure, a variety of other measures may be used. Demand and capacity values may also be based on force, displacement or strain. The preceding sections have considered methods for calculating demand values for stresses, forces, displacements and strains. This section considers capacity values and demand-capacity comparisons. The emphasis is on integrity of the pipe, based on stress and strain demands and capacities.

7.2 Differences Between Conventional and HTSP Systems

A structural integrity evaluation for the pipe involves structural analysis to calculate pipe stresses (demands), followed by comparison with code allowable stresses (capacities) using design code equations. The following sections review the design code equations for conventional pipelines, and indicate how these equations must be modified for HTSP systems. The equations are not directly applicable because in a conventional pipeline, gravity loads are supported almost entirely by bending in the pipe. Hence, bending stresses due to gravity and other sustained loads are "primary" stresses, and they must be limited to ensure safety against plastic collapse. In an HTSP system, however, the gravity loads are supported almost entirely by axial force in the pipe, and bending stresses are relatively unimportant. In particular, during the erection process the pipe is bent over the support saddles, and there are large bending stresses. It is not necessary, however, to include these stresses in the code equation for sustained loads, because the loads are supported by tension, not bending. In a conventional pipeline, if the pipe yields in bending it may collapse. In an HTSP system, if the pipe yields in bending the cable action takes over, and the pipe does not collapse. The important consideration for integrity of the pipe is not bending stress but bending strain. During erection and subsequent operation the pipe can be allowed to yield in bending, but the amount of yielding (the strain) must be limited to acceptable levels.

7.3 Sustained Loads

Sustained loads include gravity, internal pressure and static wind. Earthquake loads are also usually included, although they are dynamic loads and not strictly sustained. The allowable stress is often increased for load combinations that include earthquake. Thermal expansion is a self-limiting effect, not a sustained load. Wind-inducted vibration (WIV) effects should not be considered as sustained loads. B31.4 [17] Sections 402.3.2(d) and 419.6.4(c) and B31.8 [18] Section 833.4 consider collapse under sustained loads using an equation of the form:

$$S_P + S_L \le \beta \cdot SMYS \tag{7.1}$$

where:

S_P = the longitudinal pressure stress;
S_L = longitudinal bending stress.

The codes do not explicitly provide an equation for S_P. For an unrestrained pipe the longitudinal pressure force is the end cap force, and S_P is this force divided by the pipe area. This is essentially S_P=PD/4t, where P is the internal pressure, D is the pipe outside diameter and t is the pipe wall thickness. The codes do not explicitly provide an equation for S_L for unrestrained pipe but most pipe stress analysis computer programs [19] assume that S_L is given by:

$$S_L = \frac{\sqrt{(i_i \cdot M_i)^2 + (i_o \cdot M_o)^2}}{Z} \tag{7.2}$$

where;

M_i = in-plane bending moment;
i_i = in-plane bending stress intensification factor;
M_o = out-of-plane bending moment;
i_o = out-of-plane bending stress intensification factor.

Equation (7.1) is not applicable to HTSP systems. A new equation covering collapse is required that considers (1) the axial force due to combined gravity load and pressure (but not the bending moment), and (2) the axial force and bending moment due to wind and earthquake. An equation is also needed to limit the amount of yield as the pipe is bent over the saddle. A possible procedure is to apply the cold bend limits specified by the ASME B31.4 and B31.8 codes.

7.4 Cyclic Loads

The main concern for cyclic loads is fatigue. Cyclic stresses can be caused by thermal expansion and contraction, multi-phase flow and by WIV effects. B31.4 Sections 402.3.2(c) and 419.6.4(c) and B31.8 Sections 833.2 and 833.3 consider cyclic stresses. An equation of the following form must be satisfied for an unrestrained pipe:

$$S_E = (S_b{}^2 + 4 \cdot S_t{}^2)^{1/2} \le 0.72 \cdot SMYS \tag{7.3}$$

where:

S_E = expansion stress range (from the hot to cold);
S_t = torsional stress = M_t/2Z;
Z = pipe section modulus;
M_t = torsional moment;
S_b = resultant bending stress, with stress intensification effects:

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$$S_b = \frac{\sqrt{(i_i \cdot M_i)^2 + (i_o \cdot M_o)^2}}{Z} \qquad (7.4)$$

Since thermal expansion is usually the dominant cause of cyclic stresses, and since the number of thermal expansion cycles is typically small, this equation does not explicitly consider the number of stress cycles. Stress intensification effects are important for cyclic stresses, since fatigue crack initiation is related to peak local stresses. Equation (7.3) is also applicable to HTSP systems. Stress intensification must be considered at the saddle supports. To account for large numbers of stress cycles for WIV effects, the allowable stress should be specified to depend on the number of cycles. Since there can be different numbers of cycles at different stress levels, a cumulative damage calculation should also be required. Miner's linear damage theory [20] is commonly used.

7.5 Combined Sustained and Cyclic Loads

The stresses due to combined sustained and cyclic loads (e.g., combined gravity and thermal) may exceed yield. However, yielding will typically occur only in the first one or two load cycles, and the behavior for subsequent cycles will be elastic (i.e., the pipe will shake down to elastic behavior). If the sustained and cyclic stresses are both large, however, the pipe may not shake down. In this case, yield continues to occur in each load cycle, and the accumulated effect can cause progressive collapse of the pipe. To guard against this, some codes consider combined stresses using an equation of the following form:

$$S_E + S_P + S_L \leq SMYS \qquad (7.5)$$

Equation (7.5) is also applicable to HTSP systems.

7.6 Additional Criteria

It is worth mentioning that the B31.8 code committee is considering a proposed revision to Section 833 on longitudinal stresses [21]. The proposed revision provides clearer definitions of the individual components of longitudinal stress, and it distinguishes between stress intensification factors for cyclic loads and those appropriate for sustained loads. It is also worth mentioning that both the B31.4 and B31.8 codes contain an offshore chapter (B31.4 Chapter IX and B31.8 Chapter VIII). Considering some of the major differences between highly tensioned and conventional pipe spans, it may be appropriate to consider the sections of the offshore chapters on strength criteria during operation for HTSP systems. In addition to limits on hoop and longitudinal stress for pipelines and risers, the offshore chapters place limits on combined stresses (using either the Tresca or von Mises stress equations). In many of the HTSP analyses performed to date, we have included an additional check against excessive pipe yielding, based on limiting the von Mises effective stress to 90% of the pipe SMYS.

8. OVERALL ASSESSMENT OF THE HTSP CONCEPT

The work presented in this paper has identified important aspects related to the feasibility of HTSP systems, considering erection, gravity loads, thermal loads and wind and earthquake loads. Based on these studies, the Authors believe that the HTSP concept is not only a technically feasible solution, but an attractive one economically, especially for smaller diameter pipelines. Some of the desirable features of the HTSP concept are as follows.

(1) It allows for long spans, and hence has a small "footprint".
(2) It makes efficient use of material.
(3) It is inherently flexible for thermal expansion, eliminating the need for expansion loops.
(4) It is resilient for earthquake loading.

Analysis tools are available to perform most of the calculations that are needed for analysis and design of HTSP systems, including erection loads, normal operating loads, wind loads and earthquake loads. However, since the HTSP concept is new, experimental validation is desirable to confirm the modeling and analysis assumptions.

9. RECOMMENDED FUTURE WORK

9.1 Prototype Designs

An important step toward eventual implementation of an HTSP system is the development of a prototype design. It is recommended that an experienced pipeline design group and/or construction contractor be commissioned to develop one or more prototype HTSP designs, building on the work completed to date. A detailed erection plan will be an integral part of the prototype design. PIPLIN appears to be a useful analysis tool for planning the erection process. However, it should be tested in a practical context. It is recommended that a contractor with extensive pipeline experience be hired to develop a detailed erection plan, and to determine whether the PIPLIN program has the features needed to support the erection process. A particular concern is the control of friction forces. In the evaluations conducted to date, the supports, saddles, anchors, etc. have been considered only conceptually, based on functional requirements. Sketches and diagrams have been developed, but these are largely conceptual. Detailed designs for support saddles, towers, anchors, transverse braces and other components should be developed.

9.2 Cost Estimate

Preliminary cost evaluations of HTSP systems relative to conventional elevated pipelines indicate that HTSPs have the potential to reduce cost by 5 to 25%. Based on the prototype design(s) described above, it is recommended that an experienced Arctic contractor be commissioned to develop detailed cost estimates for several HTSPs on the Alaskan North Slope, and compare the costs with conventional pipeline configurations.

9.3 Component Testing

The proper performance of a number of components, in particular the saddles, is critical to the success of an HTSP system. It is recommended that full-scale tests of critical components be performed to refine their designs. Two effects that should receive careful study are the behavior of the pipe as it is cold bent across a saddle and possible stress concentration effects in the pipe near the saddle ends.

9.4 Prototype Testing

Since an HTSP system is different from a conventional pipeline in many respects, it is recommended that one or more full-scale tests be performed to confirm the erection scheme, test the design details and check the overall structural behavior. The tests should be on a length of pipeline consisting of several spans, under arctic conditions. Measurements of deflections and strains should be taken during erection, under operating loads and under wind loads. Free-vibration tests should be performed to confirm the mode shape and frequency calculations and to measure the amount of damping that is present in the system. The amount of damping is an important parameter for wind-induced vibration and the fatigue life of the pipe. If the amount of damping that is inherent to an HTSP system is low, it may be necessary to add damping devices.

10. ACKNOWLEDGEMENTS

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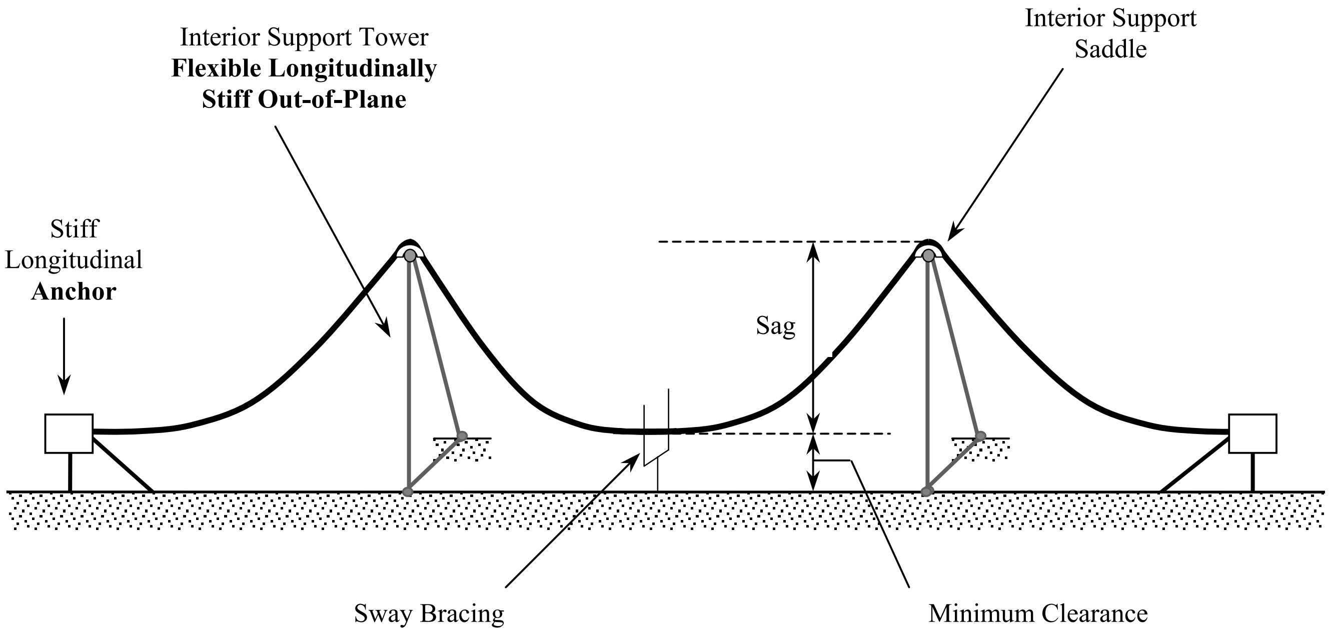


Figure 1 Essential Features of a Multi-Span HTSP

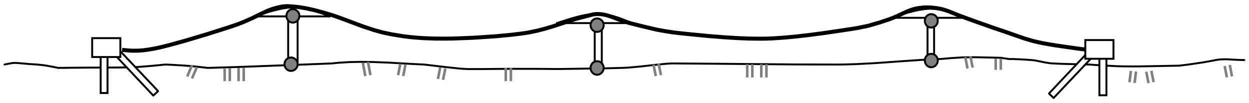


Figure 2 (a) Cross-Country Configuration

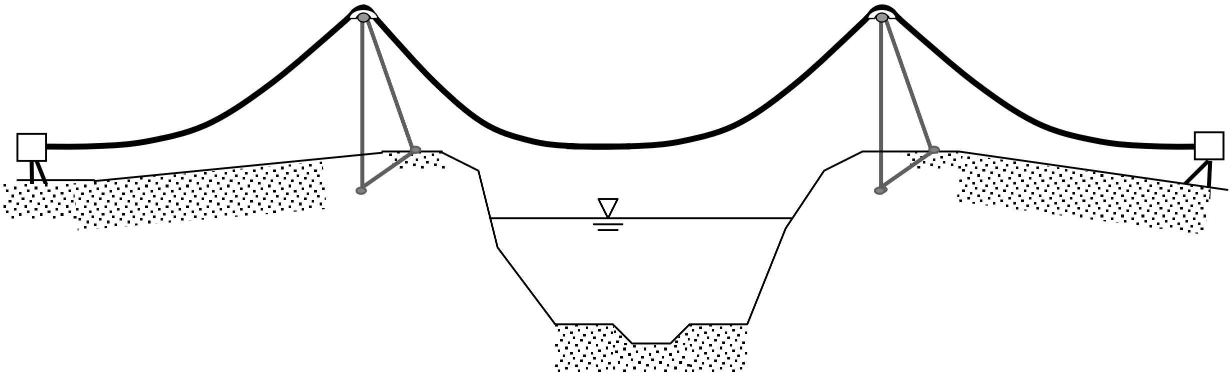


Figure 2 (b) River Channel Crossing Configuration

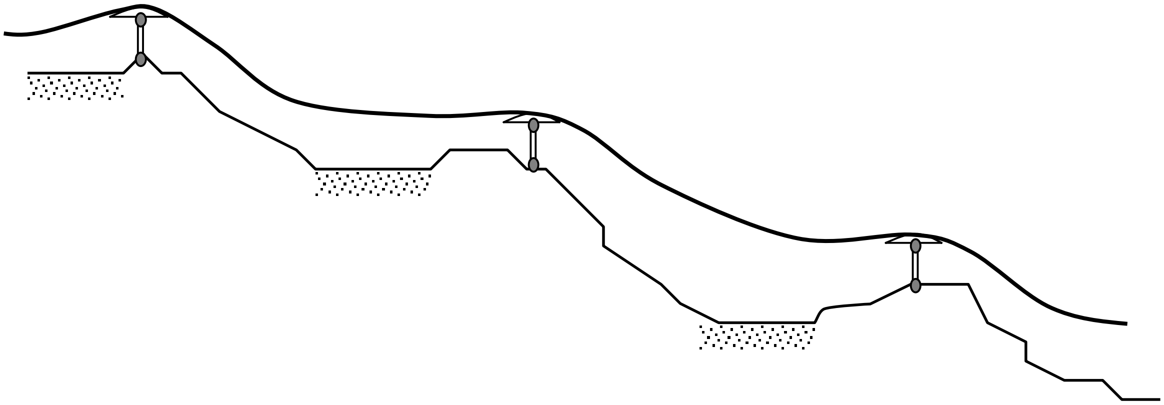


Figure 2 (c) Steeply Sloped and Irregular Terrain

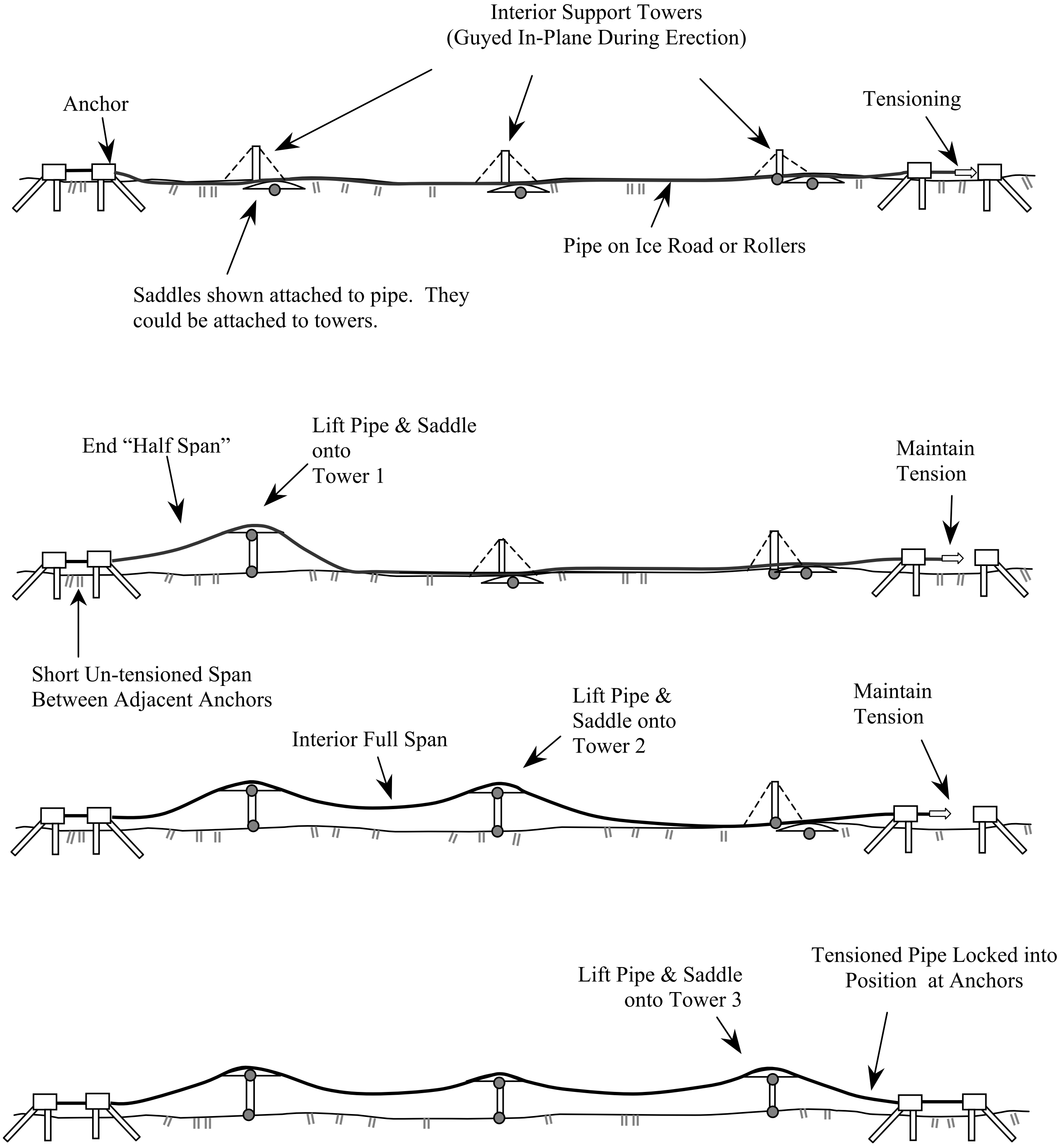


Figure 3 Multi-Span HTSP Erection Method

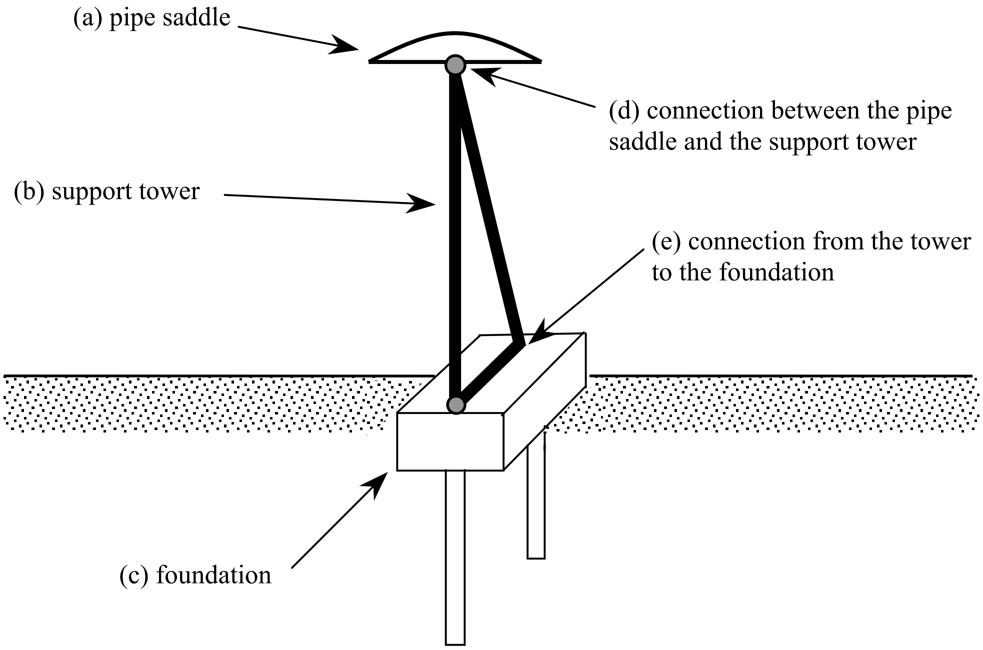
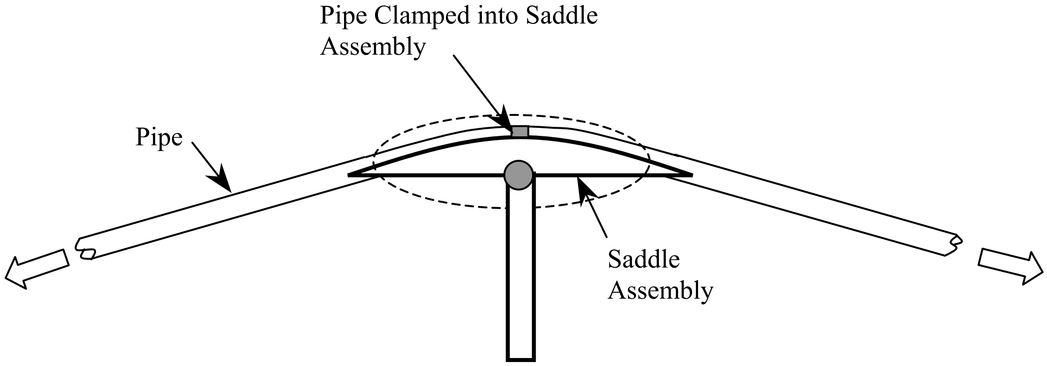
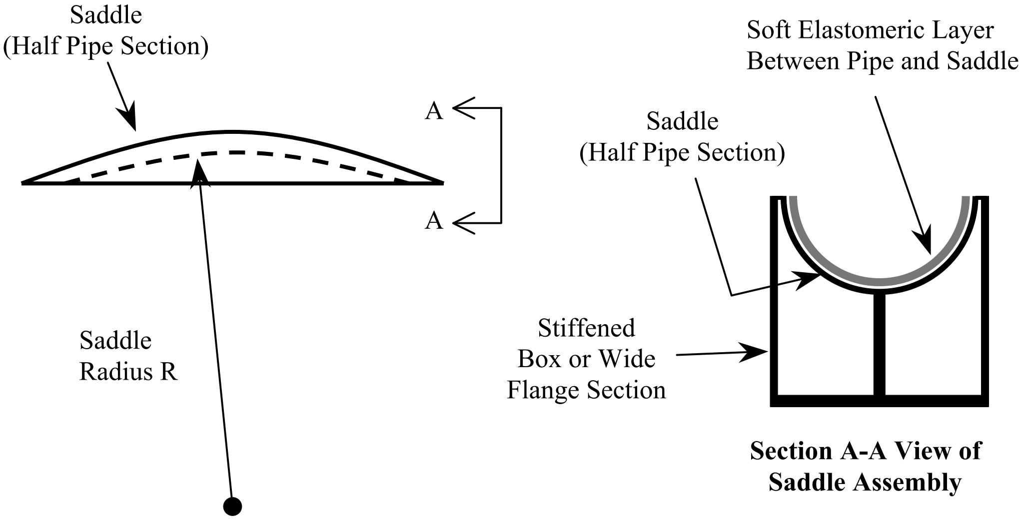


Figure 4 Schematic of Interior HTSP Support Tower



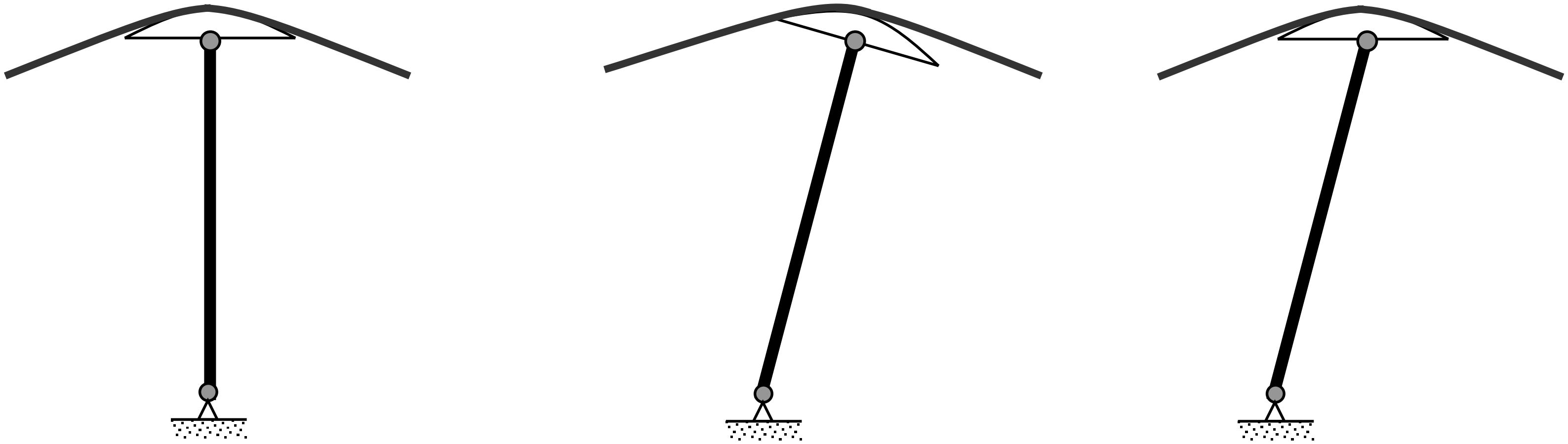
Overall View of Saddle Support



Side View of Saddle Assembly

Section A-A View of Saddle Assembly

Figure 5 Schematic Pipe Saddle Details

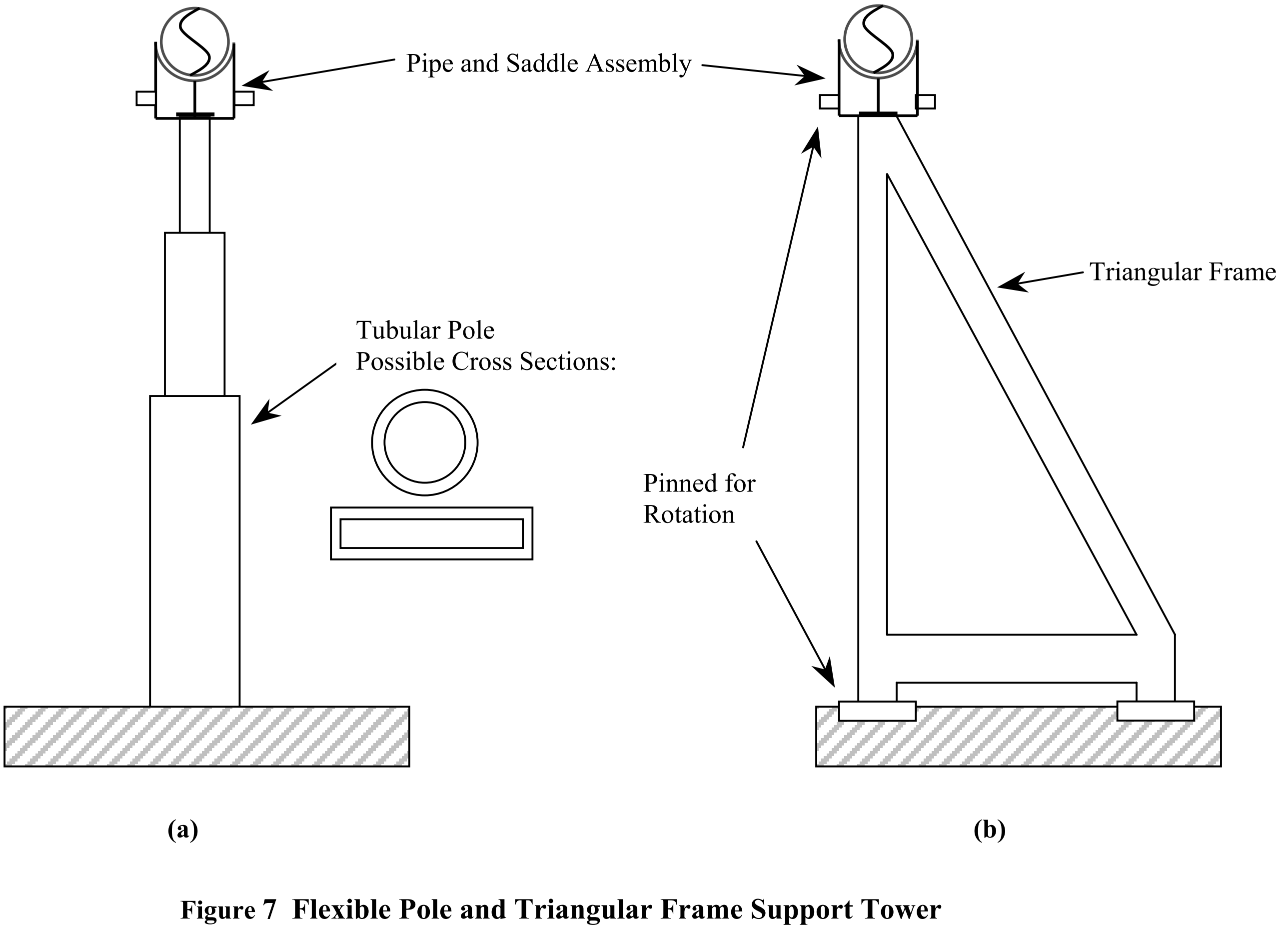


(a) Vertical Tower

(b) Tower Inclined, Fixed Saddle
(Undesirable Behavior)

(c) Tower Inclined, Rotating Saddle
(Desirable Behavior)

Figure 6 Pivoting Tower Configurations



(a)

(b)

Figure 7 Flexible Pole and Triangular Frame Support Tower

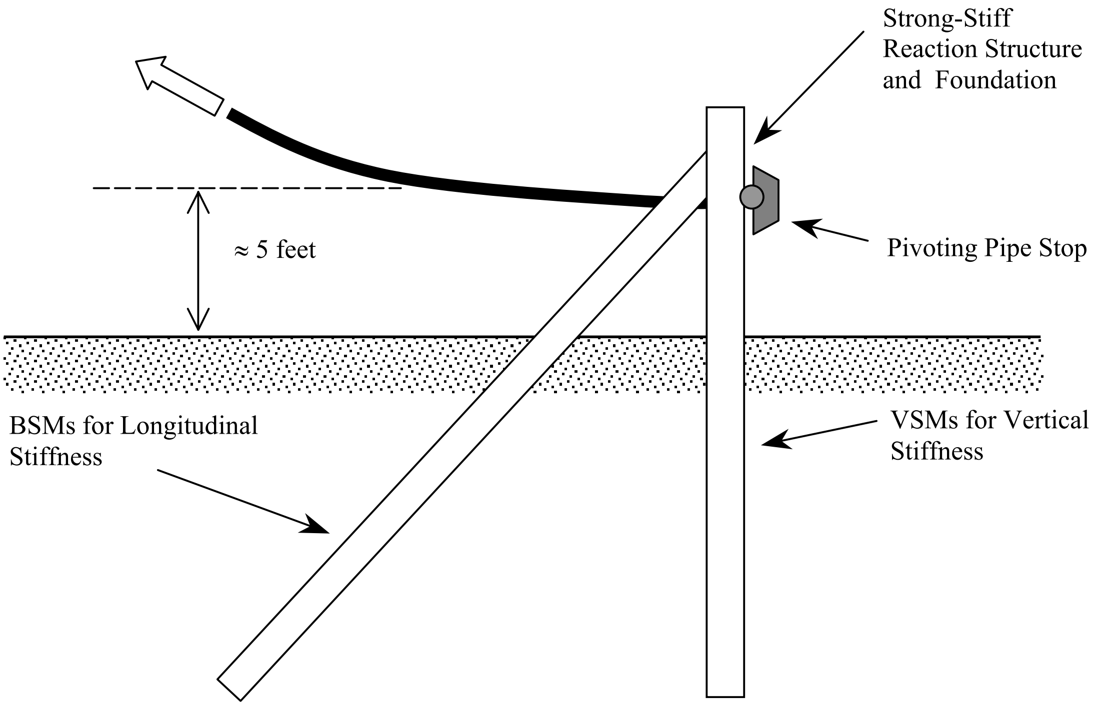


Figure 8 (a) Schematic of End Anchor Configuration

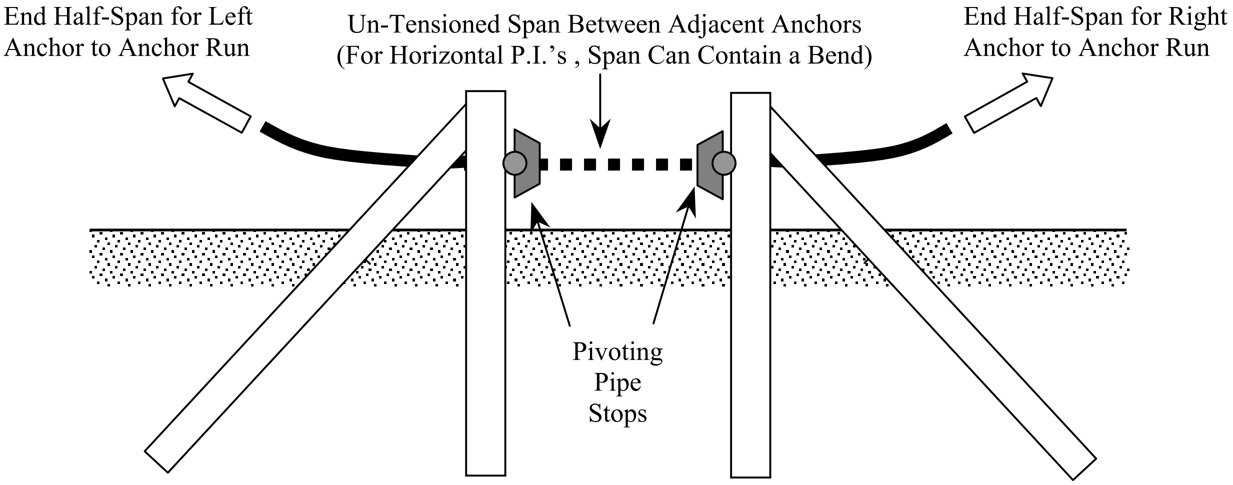
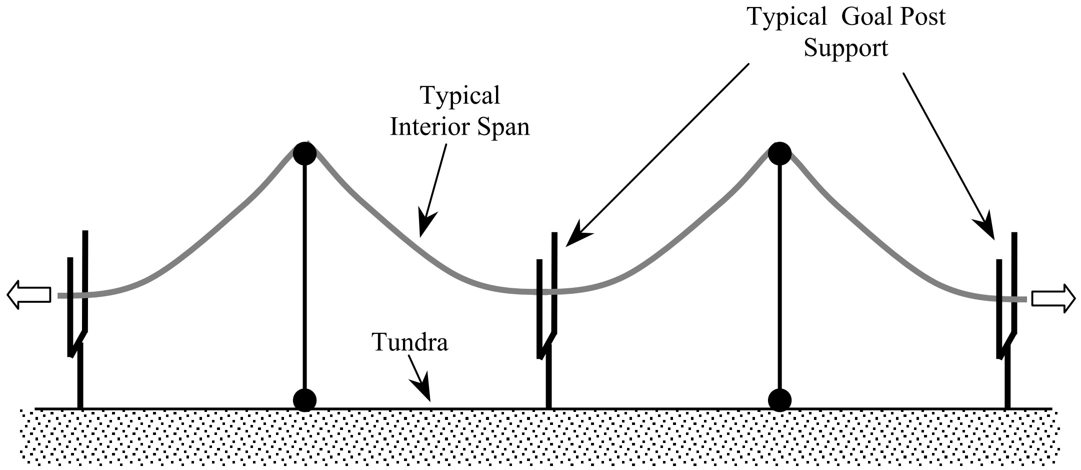
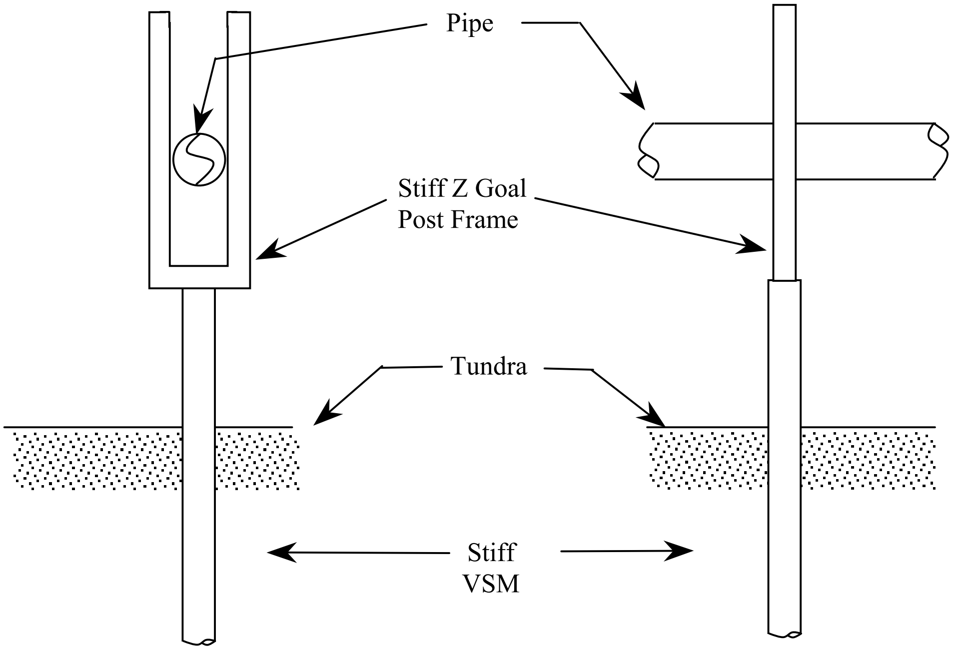


Figure 8 (b) Schematic of Two Adjacent Anchors



Typical Spans with One Restraint at Midspan



End View of Typical Goal Post Frame

Side View of Typical Goal Post Frame

Figure 9 Schematic of Goal Post Out-of-Plane Restraints