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AN INTEGRATED APPROACH TO PIPELINE BUOYANCY CONTROL AND IMPLEMENTATION

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ABSTRACT

A case study approach clearly demonstrates how to integrate various investigative methods with design, procurement, contracting and construction strategies to significantly reduce life cycle costs for a recently constructed operating pipeline. Emergent strategies based on lessons learned throughout the process are presented based on an after construction review.

KEY WORDS

Buoyancy control, bolt-on weight, deep ditch, screw anchor, ground penetrating radar, fixed frequency electromagnetics.

INTRODUCTION

Frequently, pipeline design must be carried out with a less than desirable volume of information. This paper uses a case history to illustrate an integrated approach to pipeline design and construction. The design/construction problem was an NPS 24 x 83 km long natural gas pipeline in a remote location of northeastern British Columbia (Figure 1). Routing and preliminary assessment began during the winter of 2002-2003, with construction scheduled for the following winter. With a dearth of project-specific right-of-way data, high costs were anticipated for the following elements:

- Buoyancy control
- Permafrost protection
- River crossing construction

Usually such a pipeline design exercise involves air-photogrammetry and a detailed winter/summer borehole

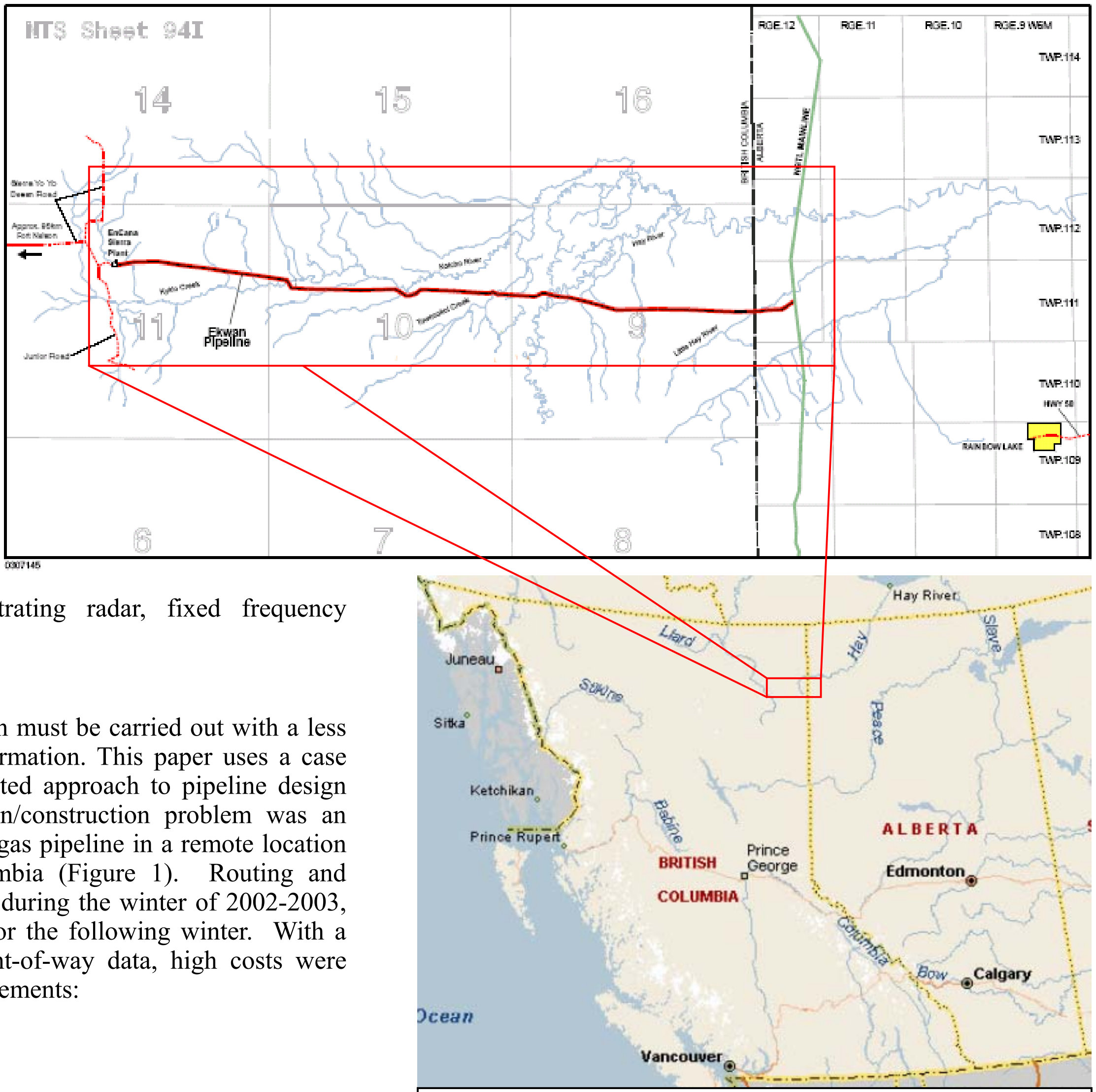


Figure 1: Project Location

program. However, the technical requirements for permit acquisition and the construction time frame did not readily allow for cost-effective implementation of such an approach. Instead, the project team adopted a suite of geophysical methods:

- Air photo interpretation
- Borehole investigation
- Ground-penetrating radar (GPR)
- Fixed frequency electromagnetics (FEM)
- Seismic refraction

These methods were originally intended to merely supplement the investigative approach and accelerate the design/permit acquisition process. Examined individually, each of the above methods yielded limited data. However, when integrated effectively with each other and with other project elements (listed below), the combined data were found to potentiate each other, yielding a body of project-specific information greater than the sum of the individual investigative parts, and dramatically reducing construction costs. Taking full advantage of this body of information, entailed formulating and executing effective strategies to integrate it with:

- Assessment
- Design
- Procurement,
- Construction

EKWAN PIPELINE DESIGN/CONSTRUCTION ISSUES

As shown on Figure 1, the EnCana Ekwan Pipeline starts at EnCana's Sierra Gas Plant (A-26-K, 94-I-11) approximately 81 km east of Fort Nelson, B.C. The Pipeline proceeds for 83 km in a generally eastward direction to an existing NOVA Gas Transmission Ltd. (NGTL) pipeline (SE 15-111-12-W6M). Air photo interpretation and aerial route reconnaissance confirmed that the route traverses significant areas (up to 60%) of muskeg terrain, discontinuous permafrost and four major water crossings.

Major Water Crossings

The pipeline route crossed four major rivers, with the preferred method being horizontal directional drilling. At each crossing, accurate subsurface information was critical for permit aquisition, design and construction. Because the directionally drilled crossings required a thorough assessment and design for permitting, a traditional assessment-design-procure-construct sequence was employed, using boreholes and seismic refraction. Further work should entail more innovation to this approach, for discussion in a future paper.

Discontinuous Permafrost

Early in the design process, it was recognized that the pipeline route traversed areas of discontinous permafrost. An assessment method, fixed frequency electromagnetics (FEM), was used to accurately catalogue all permafrost encountered along the route. In addition, appropriate design and construction strategies were developed to install a servicable pipeline while minimizing disturbance to sensitive surface vegetation. While this paper is focussed on buoyancy control innovation, it should be pointed out that the FEM results, when combined with the results of the ground penetrating radar (used for buoyancy control assessment), produced a better defined muskeg-soil interface. This, in turn, enabled a more accurate estimation of the number of weights, required early in the project cycle.

Buoyancy Control

With up to 60% of the route overlain by muskeg, buoyancy control had the potential to cost up to 18% of the overall project budget. Accurate near-surface data were critical to optimizing buoyancy control design and construction. However, retrieving high quality data during the design phase of the project at first appeared impossible. Without accurate data to rely upon, the project team initially developed conservative buoyancy control strategies to compensate for the worst-possible case. Without further investigation and design refinement, up to 9000 indiviual bolt-on weights would have been installed to control buoyancy with the degree of certainty necessary for reliable pipeline operation. The high cost of this conservatism provided the incentive to seek alternative investigation methods and more closely examine the interrelationship between assessment, design, procurement and construction.

TRADITIONAL DESIGN AND CONSTRUCTION MODEL

When addressing the above design/construction issues, it is common to begin by analysing air-photos and then acquire the necessary surface and subsurface information with a detailed winter/summer borehole program. After assessment is completed, design is finished. This approach reduces uncertainty during procurement by ending the design optimization phase before completing the procurement phase and beginning construction. However, the schedule did not allow for such thorough investigation to finish before procurement began. In fact, access to the right-of-way for final buoyancy control assessment was not available until after the initial phase of construction began.

For the Ekwan Pipeline, the problem with the traditional design-construct approach stemmed from keeping each of the four main elements (assessment, design, procurement and construction) separate and completing each one before proceeding with the next one, when:

- Assessment must provide information when required, but the highest quality information is not available until after construction begins,
- Design must rationally apply buoyancy control principles, but the most optimum design relies on the highest quality of assessment,
- Procurement must get the best price available to install the design solution(s), but remain open-ended enough to take advantage of savings realized during construction,
- Construction must take advantage of assembly line efficiencies, yet allow for and be prepared to respond to changes resulting from field assessment.

This approach can be illustrated with the simple circular model shown in Figure 2.

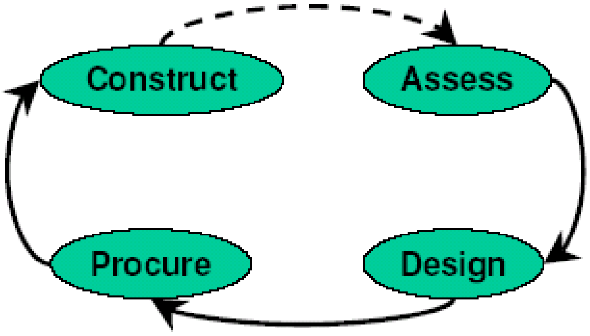


Figure 2: Traditional Approach to Engineering, Procurement and Construction

Experience has shown that opportunities for more accurate ground condition assessement occur after construction begins. Most of the time, however, further design refinement, material ordering and response to changes in design by the pipeline contractor are not practical. As a result, the owner, engineer and contractor are all compelled to design, procure and install overly-conservative buoyancy control. Working backwards through the model in Figure 2, we see that if Construction were flexible enough to efficiently respond to field changes without affecting assembly-line efficiency, then changes to add or delete weights could be made. If the contract, bid on during the Procurement phase, were open-ended enough by providing unit rates for adding/deleting weights, then the engineer could take advantage of a more flexible suite of buoyancy control options. These options, which could include alternatives like deep ditch or screw anchors could be completely developed during the Design phase, to respond to the latest, most accurate ground conditions Assessment. And the most accurate ground conditions data could become available during the earliest part of the construction phase.

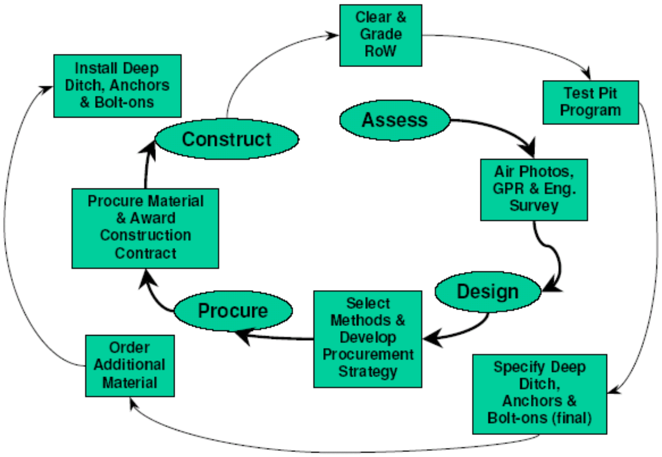


Figure 3: An Iterative Approach to Buoyancy Control

So, by taking the model in Figure 2 and continuing with an additional assessment phase immediately after clearing and grading, buoyancy control design can be further refined, material can be added or deleted (as required) and the contractor can respond and install alternative methods without unnessesary delay. This iterative approach is shown on Figure 3. By running through the model a second time, after construction begins, the most cost-effective buoyancy control system can be installed on a given pipeline. In order to understand how best to implement this iterative approach and take advantage of (rathar than be penalized by) field changes, assessment, design, procurement and construction will now be examined in more detail.

GROUND CONDITION ASSESSMENT METHODS

Several methods were employed to assess ground conditions pertinent to buoyancy control on the Ekwan Pipeline. Most were used before construction began, while site access was extremely limited. Air photo interpretation, Ground Penetrating Radar (GPR) and Fixed Frequency Electromagnetics (FEM) were all used before clearing and grading. As mentioned previously, FEM was used primarily to assess discontinuous permafrost. However, the results from the FEM survey enhanced those from the GPR. After clearing and grading was completed, field assessment, in the form of test pits, was executed.

Air Photo Interpretation

Air photo interpretation remains one of the most effective ground assessment methods for linear projects, such as pipelines, in terms of the amount of useful data collected per dollar expended. Terrain mapping and vegetation identification are well documented products of air photo interpretation. Vegetation type is known to strongly correlate with ground water conditions. However, air photos are poor for assessing depths of organics. Preliminary route selection and muskeg and permafrost mapping were done using air photos for the Ekwan Pipeline. Predictably, while the extent of muskeg traversed by the pipeline route was easily estimated, depth and moisture content of each bog were impossible to ascertain.

GPR and Muskeg Mapping

A common application of GPR is the determination of the depth and spatial extent of muskeg, although it should be noted that the technique has met with mixed success in past surveys. In order for any geophysical survey to be successful, there must be a mappable contrast in physical properties. For the Ekwan investigation, it was anticipated that a substantial contrast in dielectric permittivity would exist between the muskeg and the underlying soil horizon. The dielectric permittivity of subsurface materials is generally controlled by the clay content. As such, the soils underlying muskeg are often clay rich in comparison to the muskeg itself, resulting in large contrasts. When sufficient contrasts exist, the high-resolution data provided by rapid GPR surveys is often less expensive, more representative and more detailed than traditional probes and air photo interpretation alone.

In order to define the location and depth of organic deposits that the pipeline traversed, Associated Mining Consultants Ltd. (AMCL) conducted a geophysical survey using Ground Penetrating Radar (GPR). The survey was conducted during February of 2003, after the final pipeline routing was determined. The survey was undertaken as part of a geotechnical investigation to map muskeg thickness to assist in the design and procurement process for buoyancy control for the Ekwan Pipeline. Air photo interpretation identified approximately 52 km of the 83 km pipeline route to be located in terrain in which buoyancy control may be an issue.

When sufficient contrast in dielectric permittivity exists, the effectiveness of a GPR survey becomes a function of the acquisition parameters selected. For the Ekwan project, a Mala GPR system was employed along with 100 MHz antenna using a recorded trace window length of 250 ns, which, using the estimated radar wave velocity of frozen muskeg of 0.13 m/ns, yields an effective depth penetration range of approximately 20 m. Although the maximum anticipated depth of muskeg was on the order of 4 - 5 m, it is standard survey practice to extend the recording window to allow for unexpected velocity variations. It is noted that surveys were conducted in relatively cold conditions, over a substantial snow base, resulting in the necessity of the longer time window.

Snowmobiles were used for access along the pipeline right-of-way and to tow the GPR antenna. When time and ground conditions allowed, hand augered holes were located in the muskeg to provide ground truth for the GPR interpretation. Due to the significant thickness of seasonal ice, it was not always possible to hand auger holes. It was also the case that detailed notes were recorded during the construction of the pipeline to enable a thorough review of the results of the GPR and their influence on buoyancy control during the design, procurement and implementation phases of the project.

CONSTRUCTION FIELD VERIFICATION

Although data collection had taken place to aid in the preliminary buoyancy control design, the best indicator for choosing which buoyancy control method to use was the condition (soil types and depths, stability, moisture content) of the ditch during construction. Ditch conditions were predicted by a qualified technician by digging a series of test pits along ditchline immediately after clearing and grading (Figure 4). Test pits were dug wherever vegetation and/or GPR records indicated muskeg.

Figure 4: Construct Field Verification (test pits)

By digging the test pits, the technician could readily ascertain organic depth, underlying mineral soil type and available free water (the latter condition was important in determining the need for bolt-on weights). Using the test pit data, the field technician, in consultation with the design engineer, made a final determination of how many weights and/or anchors to install and precisely where they were required. Opportunities to bury the pipe deeper were also identified at this time. The same technician was also present on site during ditching to assess final ditch conditions. Based on ditch conditions and criteria provided by the design engineer, the technician decided whether to use screw anchors, bolt-on weights or deep ditch to control buoyancy. Weight and anchor quantities required (versus specified and ordered) were assessed on an on-going basis and adjusted as appropriate. Information regarding installed buoyancy control was collected and included as part of as-built project data.

Other Methods of Field Verification (Summer Drilling)

Field reconnaissance during the summer could have provided additional information on soil type, depths and wetness through probing, drilling or a combination of both. Although some valuable data could be obtained from a summer program, it was recognized that the most definitive information would be collectable during the construction field verification phase, using test pits. In addition, a summer field program would have incurred significant extra summer mobilization and access costs. Therefore, a summer field program was not employed for the Ekwan Pipeline, because the proposed Procurement Strategy and Construction Field Verification Program was deemed capable of ensuring timely and economical supply of buoyancy control material to most accurately fulfil the design requirements.

PIPELINE BUOYANCY CONTROL DESIGN

Pipeline buoyancy poses a problem wherever buoyant forces succeed in causing a buried pipeline to float to the ground surface. The buoyant force on a pipeline (or any other object) is equal to the weight of the fluid displaced and, with thanks to Archimedes, can be expressed as Equation 1.

Equation 1: Archimedes Principle

$$F_{buoy} = Vol_{pipe}\gamma_{water}g$$

Where:

F_{buoy} = Buoyant force (kN)

Vol_{pipe} = Volume of pipe (m^3)

γ_{water} = Density of water (kg/m^3)

g = Force of gravity ($9.81 m/s^2$)

The buoyant force acting on an NPS 24 buried gas line is significant. When Equation 1 is solved on a per-metre basis for an NPS 24 pipeline submerged in water, we get:

$$F_{buoy} = \pi\left(\frac{0.610m}{2}\right)^2\left(\frac{1000kg}{m^3}\right)\left(\frac{9.81kN}{1000kg}\right)$$

$$F_{buoy} = 2.87 kN/m$$

This force is shown acting on a buried pipe in Figure 5.

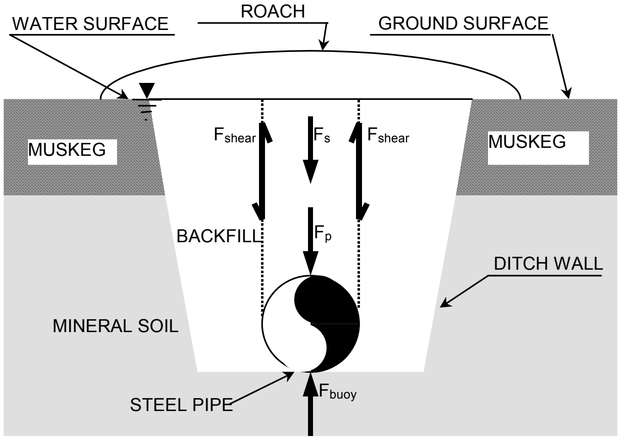


Figure 5: Forces Acting on a Submerged Pipeline

Where:
F_{buoy} = buoyant force on the pipe
F_p = downward force of pipe and coating
F_s = downward force of soil mass on pipe
F_{shear} = backfill shear stress on pipe

Various methods are employed by the pipeline industry to offset buoyancy. The significant cost that buoyancy control could have contributed to the Ekwan Pipeline (up to 18% of project total) called for a rigorous, integrated assessment, design, procurement and construction strategy to be implemented to optimize safety, integrity and cost.

Backfill

Typically, backfill weight and shear resistance combine to successfully resist pipeline buoyancy, even in saturated conditions. If the in situ backfill material is not competent enough to resist this uplift force, then the designer has the option to use stronger or denser soil, or increase the burial depth. Often the organic layer overlying the wet areas where buoyancy may be a problem is not that thick and there is ample mineral soil underlying it. Mixing a sufficiently high proportion of this underlying mineral soil with the organic soil in the backfill has been shown to provide adequate design resistance to buoyancy uplift (Simmons and Thomas, 1998).

Deep Ditch

The term “deep ditch” refers to the method of trenching deeper than would normally be required in order to provide the pipeline with a greater resistance to buoyant forces. The greater resistance is provided by a combination of the self-weight of the soil overlying the pipe and the shear forces generated between the column of soil and the surrounding backfill.

This approach is viable only where the soils encountered within the deeper ditch have a greater mineral (versus organic) content, which in turn provide resistance when backfilled in the ditch. Using deep ditch can reduce the requirement for extra materials and installation crews, resulting in cost savings, depending on the terms and conditions of the construction contract. Disadvantages of this approach include the extra spoil generated (during trenching) and its reliance on fairly ideal ditch and soil conditions. If water cannot be removed from the ditch before the pipe could be lowered in, for example, it is not likely that deep ditch would be a viable option. Hence, the best time to decide whether or not to employ deep ditch is immediately after after the ditch is open. A further disadvantage is that buoyancy resistance is lost if a wash-out of ditch material occurs (similar to any other area where weights or anchors are not used).

For the Ekwan Pipeline, use of deep ditch was evaluated based on field verification of ditch and soil conditions and economic considerations. Unit rates for extra depth were included in the contract.

Set-on Weights

Set-on or saddle weights are single piece concrete weights that sit on top of the pipe in the ditch. They are installed after the pipe is lowered into the ditch before backfilling. As a result, ditch conditions need to be relatively firm and dry, not only to prevent the pipe from floating up and out of the trench during installation, but also to prevent the set-on weight from overturning and releasing the pipe.

These weights are frequently used whenever buoyancy control is needed for operating conditions, that is, whenever it is anticipated that the local water table will rise and the soil overlying the pipe will be incapable of restraining the pipe from floating.

The contractor can install small quantities of set-on weights quickly, after the pipe has been lowered into the ditch, using equipment that is already at the construction site. Easy installation employing equipment already on-site translates to a relatively low installation cost for set-on weights. However, ditch conditions must be optimal and the weights’ high mass and need for pre-casting off-site contribute to a relatively high transportation cost and overall cost, particularly when installing large numbers.

Early in the design cycle, preliminary calculations indicated that a significant quantity of concrete weights (upwards of 9000) would be necessary for the Ekwan Pipeline. Hence, it was assumed that wherever conditions were suitable for set-on weights, screw anchors could be used instead. As screw anchors are more economical wherever significant quantities are required, no set-on weights were used for this pipeline.

Bolt-on Weights

Bolt-on weights are two-piece concrete weights that encircle the pipe with the pieces “bolted” together to prevent detachment from the pipe. They are primarily used for water crossings or where ditches are very wet and/or have no firm bottom (Figure 6). Their main advantage is the certainty they provide that the weight will stay with the pipe to perform its intended purpose. However, their transportation costs tend to be high, because of the need to fabricate off-site and their large mass (NPS 24 bolt-on weights typically weigh 2540 kg each). In addition, handling costs are high, because the contractor must bolt them onto the pipe outside of the ditch and then lower-in the pipe piecemeal (rather than stringing), which takes extra equipment and time. Based on the given mass and volume of an NPS 24 bolt-on weight, the required spacing is 5.5 m, from centre to centre (similar to a set-on weight).

Figure 6: An NPS 24 Bolt-on Weighted Section of Pipe is Lowered into the Ditch

With the high cost of bolt-on weights for the Ekwan Pipeline, much effort was taken in limiting their use to areas identified with deeper muskeg After preliminary design and procurement, field verification was used to confirm actual conditions and adjust requirements to provide optimum, cost effective buoyancy control.

Concrete Coating

A thin layer of concrete applied continuously to the required length of pipeline can provide weight for buoyancy resistance. The concrete may be applied on site at ditch side, or remotely. The advantages of this system are that trucking costs may be reduced when local sources of concrete are available and mechanical protection is provided to the pipe in cases where installation damage is a concern. The disadvantages of the system are that extra equipment and care are required to handle the pipe, due to the extra weight. If coating off-site, transporting the heavier coated pipe is also more costly.

For the Ekwan Pipeline, an easily accessible source of aggregate was not available near the right-of-way, so onsite concrete coating was not an option. As the cost to transport concrete bolt-on weights and concrete coated pipe was comparable, and handling of concrete coated pipe would have been more onerous, bolt-on weights were used instead of concrete coating.

Heavy Wall Pipe

By increasing the wall thickness of the pipe, the extra weight provided by the steel may provide sufficient resistance to buoyant forces. While such an approach may impose minimal impact on construction cost, the disadvantage is the extra cost associated with the pipe and welding. Generally, opting for heavy wall pipe only proves economical on small diameter pipelines.

For the Ekwan Pipeline, the NPS 24 diameter was too large to make use of heavy wall for buoyancy control, because of the relatively high cost.

Pipe Sacks

Pipe sacks are woven textile bags that hold aggregate (sand or gravel) and are draped over the pipe to resist buoyant forces, much like a set-on weight. The advantages of pipe sacks are that trucking costs are reduced and installation is relatively easy. The disadvantages of this system are that sufficient quantities of aggregate must be available nearby and ditch conditions must be suitable for installation.

For the Ekwan Pipeline, an easily accessible source of aggregate was not available along the right-of way. Therefore, pipe sacks were not used for this project.

Screw Anchors

Screw anchors (Figure 7) are pairs of steel helixes (screws), with one screw installed on either side of the pipeline, providing an "anchor" into the ground. A polyester strap crosses over the pipe and connects to each of the screws. The advantages of this system are that the materials are relatively light and transportable, anchor spacing is much greater than with conventional set-on weights and overall costs are low where significant quantities are involved. An additional advantage of screw anchors is that they only engage if the pipe attempts to move upwards. As a result, they don't contribute to any settlement loading on the pipe in poor soil conditions. Disadvantages of this system are that ditch conditions must be suitable and a special installation crew is required. Screw anchors, while usually less expensive to procure, transport and install than concrete weights, must be limited to those areas where the pipe can be successfully placed in the bottom of the ditch prior to backfilling.

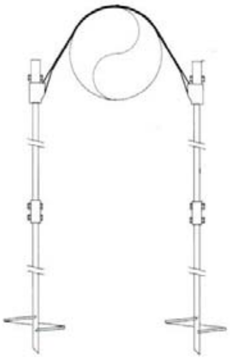


Figure 7: Screw Anchor

Figure 8: Screw Anchor Installed in a Dry Ditch

Screw anchors and extra depth are not effective if, during lowering-in, the open ditch is filled with water. However, if the organic layer is too deep to allow "deep ditch" to be used, and the ditch is relatively dry (Figure 8), screw anchors can be cost effective. For the Ekwan Pipeline, screw anchors were used wherever buoyancy control was required and ditch conditions permitted.

Buoyancy Control Decision Matrix

Deep ditch was intended for use wherever optimal ditch conditions (dry and stable) and sufficient mineral soil (shallow muskeg upper layer) was anticipated. It was recognized that actual ditch condtions could not be known until after excavation. However, unit prices for varying depths of cover were sought during the procurement phase, so that the use of deep ditch could be optimized with the other methods during construction. If practicable, deep ditch was the most cost effective means of buoyancy control for the Ekwan Pipeline.

The next more costly method of buoyancy control chosen for use on the Ekwan Pipeline was screw anchors. Anchors were intended for use wherever optimal ditch conditions (dry and stable) occured in muskeg laden areas, but deep ditch had to be ruled out because of excessive depth and or high installation cost. Screw anchors were also chosen over set-on weights and pipe-sacs because the anchors were the lowest cost of those three options quoted during the bid process. This made screw anchors the least expensive "middle" option.

The final (and most conservative) option selected for Ekwan's buoyancy control was bolt-on weights. They too, proved less costly than pipe-sacks during the bid process (it is likely that pipe-sacks were higher cost because of the dearth of readily available aggregate near the site). Bolt-on weights were intended for use wherever water-filled ditch was anticipated.

In summary, the three buoyancy control methods chosen for the Ekwan Pipeline were:

1. Deep ditch
2. Screw anchors
3. Bolt-on weights

In order to choose which of the three buoyancy control alternatives to apply at a given location on the pipeline, the designer and field technician used the decision matrix illustrated below in Table 1. It combines the soil and groundwater conditions, assessed by digging test pits, with the depth of organics. If, for example, a test pit indicates that the open ditch should be dry or pumpable and the depth of organics falls within an allowable range, then that particular section of pipeline would be installed with a deeper than standard ditch. The depth required would be calculated and recommended by the engineer.

Table 1: Buoyancy Control Decision Matrix

	Shallow organic layer	Organic depth within an allowable range	Organic depth too great for extra depth of cover
Open ditch dry or pumpable	Standard depth of cover	Deep ditch	Screw anchors
Open ditch too wet to pump out	Concrete weights	Concrete weights	Concrete weights

PROCUREMENT

The traditional approach to pipeline procurement is to make single requisitions for large quantities of material, in order to (hopefully) take advantage of economies of scale. Usually all of the pipe and weights are ordered at one time after the design phase is completed. Schedule risk is mitigated by ensuring that all long-lead items, such as bolt-on weights, and screw anchors, are ordered in sufficient quantities ahead of time. Along the same vein, lump-sum construction contracts are frequently employed to minimize owner exposure to cost overruns.

Ekwan Pipeline Procurement

For the Ekwan Pipeline, the goal of the procurement strategy was to provide for the appropriate buoyancy control methods employed during construction, while driving the overall cost of buoyancy control down. It could be characterized as a "just in time" approach, with bolt-on weights, screw anchors and deeper burial used wherever appropriate.

Deep Ditch

Deep ditch pricing was included in the pipeline contract as a unit rate for increasing depth. As a result, wherever economical to do so and conditions determined by construction field verification dictated, deeper ditch was employed in lieu of weights or anchors.

Screw Anchors

It was recognized that screw anchors are more economical than bolt-on weights, however, they cannot be applied in all situations. It was anticipated that abundant quantities of screw anchors would be readily available and restocking charges would not be onerous. Based on this assumption, the quantity of screw anchor sets estimated during the preliminary design phase was ordered. A cost and delivery of an initial allotment of anchors was determined, along with a restocking charge for return of unused sets. The exact number of anchors required was subject to results of the construction field verification.

Bolt-on Weights

Bolt-on weights are manufactured primarily from concrete, weighing in the order of 2540 kg each. Weights are unique to a specific pipe diameter. NPS 24 pipelines, especially those of significant length in muskeg areas, are not common. Given the above factors, carrying inventory or restocking were not practical options for bolt-on weight procurement.

Initially, the required number of bolt-on weights were conservatively estimated during the preliminary design phase. As part of the bid process, vendors were required to specify their production rate for provision of additional incremental quantities of weights on short notice. The initial number of bolt-on weights ordered was determined by optimizing the supply of incremental quantities of weights (based upon supplier production rates), together with the refined weight requirement estimate (based upon the geophysical survey), and expressed as a certain percentage of the number required by preliminary design. After that, construction field verification results were used to determine whether additional allotments of bolt-on weights were necessary. Due to the cost of transportation, all the bolt-on weights produced and delivered to site were to be used on the pipeline, and any surplus anchors were returned for credit.

PIPELINE CONSTRUCTION: A LINEAR PROCESS

As with roads and power lines, pipeline construction's nature is essentially linear, with the work itself organized as an assembly line. In contrast to a conventional assembly line, however, when building a pipeline, the 'assembly line' moves along the final product, while the product itself (the pipeline) remains stationary. To take advantage of assembly line efficiency, the pipeline contractor splits the work up into individual phases and optimizes each phase. When running at peak efficiency, pipeline construction resembles a well-organized parade, with each step closely following the one ahead. Moreover, upsetting or delaying any individual phase of a pipeline constructing sequence leads to delay of subsequent phases and extra cost. However, for the Ekwan Pipeline, there was sufficient time available immediately after clearing and grading for the field assessment phase to occur without udue delay to stringing and welding.

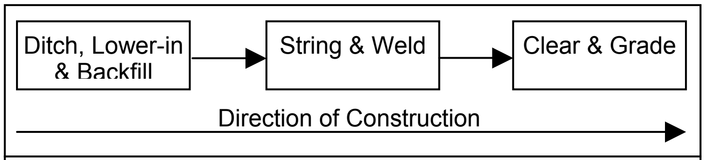


Figure 9: Construction Spread

A complete pipeline construction sequence is normally confined to one or more "spreads", with each construction spread capable of performing the three major phases shown in Figure 9.

Clear and Grade

Clearing and grading the new pipeline right-of-way sets the stage for all subsequent phases of pipeline construction. During this phase, the pipeline contractor follows the surveyed right-of-way, removes tree cover, provides enough work-space to store ditch spoil and builds a temporary road along ditchline. Construction over large wet organic areas is usually scheduled for winter, so that the contractor can take advantage of frozen ground conditions to build the working side road.

Figure 10: Clearing Timber from the RoW

String & Weld

Once the right-of-way is cleared and the working-side road is in place, the pipeline contractor can begin distributing (stringing) individual joints of pipe near ditch-line. Bending selected joints of pipe at the appropriate locations accommodates changes in alignment, such as horizontal turns, hilltops and valleys. Welding, x-ray and joint coating proceed immediately behind stringing. Before the trench is excavated and the pipe is lowered in, the contractor must install any bolt-on weights called for on the construction plans.

Figure 11: Stringing

Ditch, Lower-in and Backfill

After the individual joints of pipe are joined, x-rayed and coated, the contractor excavates the ditch using track-hoes and/or wheel ditchers. This is the final time at which weights can be bolted onto the pipeline, if necessary. If deeper ditching can be employed rather than weights or anchors, then it would be done at this stage.

Figure 12: Backfilling After Lowering-in

For the Ekwan Pipeline, the contractor elected to use a series of hoes. rather than a wheel ditcher, to excavate the ditch. Once the ditch was excavated to the specified depth, the assembled pipe was lowered in and the ditch was backfilled (Figure 12). Additional material (resulting from bulking up during excavation) was left crowned over the top of the pipeline in a 'roach'. The roach left over the top of the pipeline is expected to eventually settle back to near-grade elevation. Wherever anchors were specified for a given section of line, the ditch was left open at intervals appropriate for subsequent anchor installation.

LESSONS LEARNED ABOUT GPR AND FEM

This paper discussed various methods of buoyancy control and their applicability to the NPS 24 EnCana Ekwan Pipeline. Early in the project, (before detailed design) GPR data were combined with air-photo interpretation and FEM data to determine the location, length and likely winter ditch conditions for every span of muskeg along the route. Subsequently, bolt-on concrete weights were specified for pipeline through areas anticipated to have deeper/wetter muskeg. Screw anchors were specified for areas anticipated to have shallower/frozen muskeg.

Upon completion of construction, the project team reviewed the GPR/FEM interpretation and buoyancy control measures implemented. The results were generally favourable in that areas of thick muskeg were identified. The actual lengths of thick muskeg differed between the geophysical interpretation and actual observed zones. There are many possible explanations for the differences, including increased thickness of seasonal frost, moisture content, soil content, etc. The important aspect of the review is that the refined GPR data provided an estimate, which proved to be uncannily accurate, of the number of river weights required for buoyancy control. The review also indicated a means of refining acquisition parameters for future surveys to improve the accuracy of the results.

Although GPR commonly has the ability to image multiple horizons in muskeg environments, the data recorded were processed to highlight only the base of muskeg in accordance with the primary project objectives. Also interpretable in the GPR data was the thickness of overlaying snow and ice.

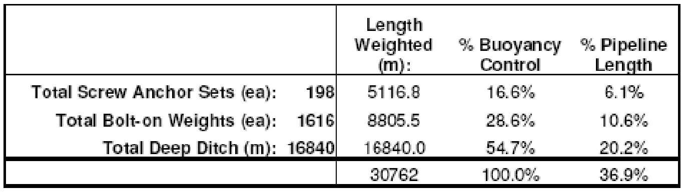
The GPR data did not provide an indication of moisture content of the muskeg. To acquire this information, test pits were dug immediately after clearing and grading the pipeline right-of-way. In addition, there was no indication in the GPR data of changes in stratigraphy underlying the muskeg for the entire survey area.

The geophysical investigations provided an accurate profile of the muskeg thickness beneath a 51 km segment of the proposed Ekwan Pipeline. In general, the data indicated the muskeg thickness to be relatively consistent to gently undulating. Declivities in the interpreted base of muskeg profiles correlated to the spatial extents of each muskeg region as identified by air photo interpretation.

RESULTS OF USING AN INTEGRATED APPROACH

A brief summary of the final results is provided on Table 2.

Table 2: Ekwan Pipeline Buoyancy Control Summary



		Length Weighted (m):	% Buoyancy Control	% Pipeline Length
Total Screw Anchor Sets (ea):	198	5116.8	16.6%	6.1%
Total Bolt-on Weights (ea):	1616	8805.5	28.6%	10.6%
Total Deep Ditch (m):	16840	16840.0	54.7%	20.2%
		30762	100.0%	36.9%

As stated previously, the earliest buoyancy control assessment, based upon air photo analysis alone, provided the least certainty and lead to a design calling for approximately 9000 bolt-on weights. The subsequent GPR survey and analysis reduced the number of weights specified 6000. After the FEM survey was completed (for the permafrost assessment), the GPR data were refined further and weighting requirements were re-analysed, resulting a further reduction of bolt-on weights specified to approximtely 3700.

After this preliminary assessment was completed and design options were identified and reviewed, prices for the various buoyancy control options were obtained. Then, the procurment strategy was developed, to allow for final additions or deletions resulting from the field assessement program. Prices and lead times were established for bolt-on weights, screw anchors and deep ditch. Initial quantities of the first two were ordered, with options to order further amounts later on during construction, as required.

During construction, the test pit program successfully verified (or modified) the numbers of bolt-on weights ordered, earmarked opportunities for using deep ditch and set the final numbers and locations for screw anchors. This crucial step was completed immediately after the clearing and grading phase, but far enough ahead of the stringing phase to allow the distribution of pipe and bolt-on weights to proceed unencumbered. Overall, buoyancy control for the Ekwan Pipeline was optimized from a preliminary specification of 9000 bolt-on weights to a final as-built installation of

- 16840 m of deep ditch (average depth of 0.3m)
- 198 sets of screw anchors
- 1616 bolt-on weights

The total amount spent for buoyancy control on the Ekwan Pipeline was reduced from a potential 18% of capital cost to an installed cost of less than 5% of the project total, including all labour, material, and data collection methods used. This significant cost saving was the direct result of the effective use of geophysical methods (primarily GPR) for preliminary assessment and conducting a more detailed assessment during construction, after access was available. Integrating this phased assessment program with design, procurement and construction optimized buoyancy control for the EnCana Ekwan Pipeline.

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