# A Geotechnical insight into a pipeline crossing

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ABSTRACT
Pipeline route alignments cross various natural and man-made features which require site specific designs. To select and design the appropriate crossing method for a pipeline alignment that crosses a Canadian Pacific Railway (CPR) right of way (ROW) in Northern Alberta, two boreholes were drilled on both sides of the CPR ROW. Horizontal directional bore (HDB) method was selected as the crossing methodology based on the site conditions, including subsurface information from these two boreholes, and was designed for accordingly. During the activities preceding construction, it was realized that a nearby pipeline crossing the CPR rail had suffered relatively high settlements. This, in turn, initiated the need for additional investigation of the crossing under consideration to gain more insight into the subsurface soil conditions between the borehole points. A geophysical investigation program was proposed and was performed for the area and linked to the existing boreholes. This program included Electrical Resistivity Tomography (ERT), Seismic Refraction (refraction) and Multichannel Analysis of Surface Waves (MASW) techniques. Based on the enhanced subsurface characterization from the combined geotechnical and geophysical investigations a settlement monitoring plan satisfying CPR requirements was designed and implemented for the crossing location. A base survey monitoring was completed for the settlement monitoring devices prior to the HDB construction. Then the settlement monitoring plan was completed during the HDB construction installation activities and few weeks after the completion of the HDB installations until the settlement readings tapered off. This paper summarizes the activities and findings leading into and forming the basis of the monitoring program and provides results of the settlement monitoring plan for the pipeline HDB crossing.

RÉSUMÉ
Les alignements d'itinéraires de pipeline traversent diverses caractéristiques naturelles et artificielles qui nécessitent des conceptions spécifiques au site. Afin de sélectionner et de concevoir la méthode de franchissement appropriée pour un alignement de pipeline traversant l'emprise d'un chemin de fer du Canadien Pacifique (CPR) dans le nord de l'Alberta, deux puits ont été forés des deux côtés de l'emprise CPR. La méthode de forage directionnel horizontal (HDB) a été choisie comme méthode de croisement en fonction des conditions du site, y compris les informations de souterrain de ces deux trous de forage, et a été conçue en conséquence. Au cours des activités qui ont précédé la construction, on s'est rendu compte qu'un pipeline à proximité qui traversait le chemin de fer du CFCP avait subi des règlements relativement élevés. Ceci, à son tour, a déclenché le besoin d'une étude supplémentaire du passage à l'étude afin de mieux comprendre les conditions du sol souterrain entre les points de forage. Un programme d'étude géophysique a été proposé et a été réalisé pour la zone et relié aux forages existants. Ce programme comprenait des techniques de tomographie par résistivité électrique (ERT), de réfraction sismique (réfraction) et d'analyse multicanale des ondes de surface (MASW). En se fondant sur la caractérisation améliorée de souterrain issue des études géotechniques et géophysiques combinées, un plan de surveillance du peuplement satisfaisant aux exigences de réanimation cardiorespiratoire a été conçu et mis en œuvre pour le lieu de franchissement. Une surveillance de base a été effectuée pour les dispositifs de surveillance du tassement avant la construction de la BHD. Ensuite, le plan de surveillance du peuplement a été achevé pendant les activités d'installation de la construction de la BHD et quelques semaines après l'achèvement des installations de la BHD, jusqu'à ce que les lectures du règlement diminuent. Ce document résume les activités et les constatations menant au programme de surveillance et en constitue la base, ainsi que les résultats du plan de surveillance du peuplement pour le passage à niveau de la BHD.

## 1 INTRODUCTION

The authors were engaged in the geotechnical assessment of a pipeline crossing that crosses Railway tracks. This crossing consists of one NPS 8 Condensate (219.1 mm outside diameter, OD) and one NPS 20 Crude Blend (508 mm OD). Horizontal Directional Bore (HDB) was selected and considered to construct this pipeline crossing.

An initial field investigation program was completed which consisted of drilling two boreholes; one on each side of the railway track; only the borehole logs were submitted and no geotechnical report was issued as per client requirement. The intent of the HDB design team was to utilize the borehole data for their needs in the HDB profile finalization. During the pipeline Right-of-Way (ROW) construction, the client informed the HDB design team that a nearby pipeline crossing the CPR rail had suffered relatively high settlements and requested the design team for feedback. The project team was subsequently engaged to:

- Assess the site condition and recommend further site investigations, if needed, and
- Prepare all the documentations required for Canadian Pacific Railway (CPR) approval for the HDB crossing.

This paper addresses these two requirements, summarizes the completed geotechnical activities and provides conclusions and recommendations for similar planned works.

## 2 RAILWAY CROSSING GEOTECHNICAL REQUUIREMENTS

In general, railway companies in Canada, CPR and CN, provide requirements and specifications for pipeline railway crossings. The geotechnical requirements for a railway crossing, generally, follow the same principle or concept of protecting the railway track. However, the geotechnical specifications differ slightly between the CPR and CN requirements. The main difference between the two railway owners is, basically, the specified cutoff for minimum geotechnical requirements. CN requires additional data for a 250 mm (10 inches) diameter pipe or greater (CN 2007), while CPR specifies "*Minimum*" geotechnical process requirements for pipe diameter less than 300 mm (12 inches), (CPR 2017). The main geotechnical requirements for pipeline crossing, as provided by CN and CPR, are presented in the following sections. However, the scope completed and presented in this paper was for a CPR crossing.

### 2.1 CN Railway Crossing Geotechnical Requirements

Generally, all pipelines crossing a CN railroad track is required to conform to the "*current American Railway Engineering Association Specifications"* in addition to the Transport Canada (TC) *Standards.* The CN minimum geotechnical requirements for a pipeline crossing depend largely on two main items, the diameter of the pipe and whether the pipeline is carrying flammable or non-flammable substances, requirements being more stringent and detailed for the flammable substances. Note that "flammable" includes "*oil, gas, gasoline, petroleum products, or other flammable or highly volatile substances under pressure*", CN Pipeline Crossing Specifications, undated document. The main additional geotechnical requirements for the 250 diameter (or greater) pipeline crossing are (CN 2007):

- *Submit a complete copy of Geotechnical Report, including comments and recommendations with respect to construction methodology.*
- *Submit a detailed proposal for in-ground settlement monitoring, developed by a geotechnical Engineer with experience in large diameter pipe installation.*
- *Provide, in writing, the name and number of the qualified site inspector(s) who will be on the job site on a full time basis for the duration of construction.*

The above three main requirements emphasizes that adequate geotechnical engineering review shall be completed, including the following:

- A detailed geotechnical study. This could be a combination of a geotechnical and geophysical field investigations.
- A settlement monitoring plan providing details of the monitoring points types, locations and survey frequency and duration.
- A geotechnical responsible authority for the works, likely to be the Geotechnical Engineer of Record, who "*has determined that there will be no stability issues"* with the pipeline crossing installation.

Note that such requirements can be waived, at the discretion of CN Railway, if the pipeline diameter is less than 250 mm (other restriction may also apply, e.g. medium type, pressure).

### 2.2 CPR Crossing Geotechnical Requirements

CPR (2017) document identifies the geotechnical protocol requirements for a CPR pipeline crossing. It also identifies three processes to provide and identify the required *appropriate level of engineering review*; *Minimum*, *Intermediate* and *Detailed*. The first criteria amongst other stated in the "Conditions", is associating the required level of engineering review for pipe outside diameters of less than 300 mmm (12 inches), 300 mm (912 inches) to 1500 mm (59 inches) and greater than 1500 mm (59 inches) respectively. Other factors governing the process include adjacent structures, excavation near the track, construction method, crossing angle, depth of pipe outside the "zone of potential track loading. And if one or more of the provided criteria are not met, then the process should be moved to the next class.

The protocol goal, as stated in CPR (2017) is to:

- *Provide safe track conditions during and after installation.*
- *Set out specifications and procedures to reduce problems during installation of pipe/track crossing.*
- *Specify minimum engineering standards.*
- *Assure adequate geotechnical investigation and engineering review has been completed to achieve the above goals.*
- *Allow timely processing of crossing approvals.*

Further CPR (2017) presents specific requirements for each of the 3 processes which includes geotechnical investigation, geotechnical engineer of record and settlement monitoring plans. These are, in essence, similar to CN requirements discussed in Section 3.1.1.

CPR (2008) provides track monitoring requirements including the establishment of a baseline of the track elevations prior to the start of the construction works. Such requirements are specified for 'Urgent defects' for the "Track Class" which is dependent on the freight or passenger train speed.

CPR (2014) also provides guidelines for the track movement monitoring. The document states that subsurface settlement points to be installed to "*1 m above the crown of casing profile"*. It also provides guidelines for the surface settlement monitoring points including minimum numbers and locations of such settlement monitoring points. Further, the document stipulates the following monitoring program instructions;

- *Monitoring should start before the excavation of the pits and pipe installation begins and be done at least twice per day for no less than two days. This is required to establish a reliable methodology and demonstrate the accuracy achievable.*
- *Monitoring should proceed through the construction period and should be completed at least twice daily.*
- *Monitoring should continue for at least 3 days after the completion of construction.*
- *If the is any loss of ground during pipe installation, any reason to believe settlement may be delayed or any settlement identified during installation of pipe or subsequent monitoring period, the monitoring must be continued until the proponent's geotechnical engineer deems it is safe to discontinue such monitoring.*

The document also proposes two alarm levels to be followed for the track settlement monitoring, Level 1: WARNING and Level 2: CRITICAL.

### 2.3 Geotechnical Engineer of Records

Both CN and CPR require a geotechnical engineer of record (Geo-EOR) for the pipeline crossing installation works to ensure compliance to CN or CPR requirements. The Geo-EOR role can be summarized as follows:

- Assess of the adequacy of the geotechnical investigation(s).
- Conduct a site reconnaissance to observe the surficial geology and physiography.
- Check whether the proposed construction/installation approach may or may not cause settlement of the track.
- Provide a monitoring plan if settlement of the track is a possibility.
- Review contractor's method statement and shop drawings to assess if the approach could cause track settlement.
- On-site review of the contractor's work.
- Prepare an emergency response plan.
- Inspect contractor's work to ensure adequate measures are being taken to minimize potential settlements.
- Provide threshold total and differential settlements. The Track Class and any Rail Devices/structures within the HDB vicinity shall be obtained in advance from CP or, if applicable, from CN.
- Provide contingency plan if settlement is experienced.
- Provide a final construction report addressing the geotechnical aspects of the works, completion of construction within the geotechnical specifications, and highlighting areas of concerns or on-going monitoring as per CPR or CN requirements.

It is noted that Geo-EOR is not responsible for contractor's works, but empowered to assess that actions undertaken by the contractor do not endanger the track structure.

## 3 SITE INVESTIGATIONS

### 3.1 Site Conditions

The CPR tracks are constructed on an approximately 3 m high embankment. The ground slopes 10% downwards toward the CPR track in northeast direction and 8% away from CPR track in the southwest directions. Surface water generally drains towards the southwest, and within local areas.

### 3.2 Initial Geotechnical Field Program

Two geotechnical boreholes were drilled outside of the CPR right-of-way (ROW) fence, one north and the other south of the fence, 10.3 m and 7.3 m deep respectively. Due to elevation differences between the two sides of the CPR ROW, the south borehole was approximately 16 m lower than the north borehole.

The subsurface conditions encountered in the north borehole consisted of 0.1 m thick top soil underlain by loose, fine to medium grained and uniformly graded silty sand to sand and trace clay and gravel. Clay was encountered at 1.8 m below ground surface (mbgs). The clay was 0.5 m thick and firm of medium plasticity; some silt and trace sand was noticed within the clay matrix. Silty sand underlay the clay material (at 2.3 mbgs) and extended to the maximum borehole depth of 10.3 m. The silty sand was compact, moist, fine grained and uniformly graded.

For the south borehole, a 0.1 m thick top soil was underlain by a 5.1 m thick loose to compact, uniformly graded silty sand to sand and trace clay and gravel  the subsurface condition is almost similar to that of the north one. The clay material was encountered at 5.2 mbgs, was very stiff and extended to the maximum drilled borehole depth of 7.3 m.

No groundwater was observed during the drilling and the two boreholes were dry upon completion. Both boreholes were backfilled with bentonite chips.

### 3.3 Geophysical Investigation Field Program

A geophysical investigation was completed for the site, which consisted of electrical resistivity tomography (ERT), multi-channel analysis of surface waves (MASW), and seismic refraction surveys along a 100 m section of the alignment that intersected geotechnical boreholes BH1 and BH2 (Figures 1 and 2). The ERT data were measured using an ABEM Terrameter LS multichannel resistivity meter, and using a minimum electrode interval of 1 m. An expanded gradient array acquisition sequence was used to measure changes in resistivity to depths of approximately 10 mbgs. The data were processed using RES2DINV tomographic inversion software, resulting in the colour-scaled electrical resistivity cross-section shown in Figure 1. The resistivity model helps distinguish relatively high resistivity sand/silty sand layers (yellow to pink colours; > 50 ohm-m) from low resistivity clay layers (blue colours; < 20 ohm-m). Two anomalously high resistivity zones (> 500 ohm-m) were identified beneath the railway alignment at depths between 2 mbgs and 3.5 mbgs (dotted outlines in Figure 1). Although these features were likely associated with processing artefacts caused by the change in topography across the railway berm, and the high resistivity material that comprises the rail bed ballast, they may also be associated with air-filled voids.

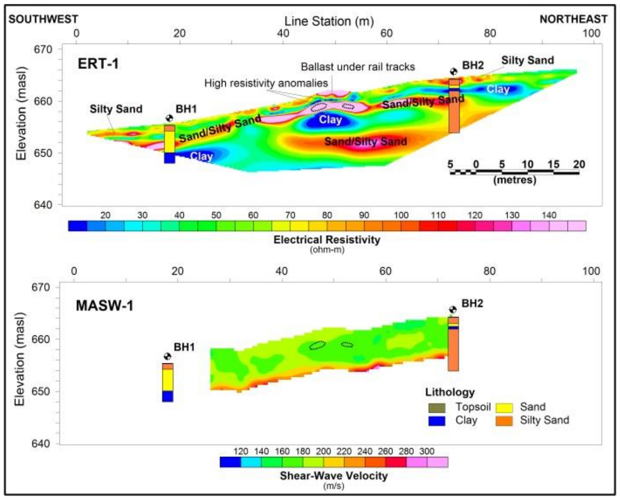


Figure 1. Geophysical ERT (top) and MASW (lower) cross-sections along a 100 m section of the proposed alignment that intersects boreholes BH1 and BH2.

The MASW and seismic refraction data were collected simultaneously along a seismic array comprising 4.5 Hz geophones at 1 m intervals. Seismic energy was generated using a sledgehammer and plate. An MASW shear-wave velocity cross-section was produced from analysis of the seismic data using SurfSeis software. The resulting shear-wave velocity cross-section revealed that the soils were relatively homogeneous with velocities predominantly varying between 140 m/s and 200 m/s (green colours in Figure 1). The seismic refraction data (not shown here) also indicated seismic velocities typical for till material (compressional-wave velocities between 500 m/s and 1500 m/s).

Even though the seismic data did not indicate the presence of distinctive voids under the railway line, it was decided that the two ERT high-resistivity anomalies should be investigated further to rule out the existence of weak zones or voids (dotted areas outlined in the top panel of Figure 1). These two anomalies were specifically targeted for the planned settlement monitoring program to confirm its nature and its possible impact on the settlement readings; refer to Section 3. Communication with CP Rail was initiated to verify whether recorded track settlement or maintenance issues were observed in the past at this location.

## 4 GEOTECHNICAL DISCUSSIONS OF THE PLANNED HORIZONTAL DIRECTIONAL BORE

The geotechnical team reviewed the HDB method statement and provided a pre-construction assessment for the planned HDB pipeline crossing method statement including bore path stability, circulation and potential loss of fluids and entry/exit locations. The followings were noted:

- The site subsurface conditions will provide favorable HDB drilling conditions.
- Fluid pressure and/or loss of drilling fluid should not be an issue since the pilot hole will be jetted through.
- The flowable material was planned to be pumped down from the Exit side (northeast side which is higher in elevation) to the Entry side (southwest side) is a good practice to ensure the fill-up of potential voids initiated during the pipeline installation.
- The planned design location of the entry and exit points are well away from the centerline of the ROW which should well minimize any potential disruptions to the CPR rail operations.
- A geotechnical site presence was recommended to supervise the construction works and provide immediate response, if and when needed.

## 5 SETTLEMENT MONITORING PLAN AND RESULTS

### 5.1 Settlement Monitoring Plan

A settlement monitoring plan for the works, which was vetted and agreed to by both the proponent and CPR, was implemented for the crossing. The plan included the installation of twenty two (22) settlement monitoring points distributed as follows, refer to Figure 2:

- A total of eight (8) surface monitoring points (50 mm square steel plates) affixed to the railway track, four (4) on each side, i.e. east and west, of the pipeline crossing. Those points were placed in pairs on the railway sleepers outside the rail track. The intent of pairing was to account of differential movement, if any, along the specific rail sleeper. The surface monitored distance was 17.45 m (approximately 57 ft) spanned equally on both sides of the pipeline crossing.
- Eight (8) shallow subsurface surface monitoring plates, four each on the north and south sides of the CPR ROW, embedded approximately 0.5 m into the existing ground. The monitoring points are 75 mm square plates welded to a 19 mm diameter steel rebar. The steel rebar is protruding 300 mm above the ground surface to be clearly visible and easily surveyed. These settlement monitoring points were placed along the centerline of the pipelines profile. Two of the monitoring plates were placed approximately 4 m away from the CPR fence, while the other two were 16 to 20 m away from the CPR fence.
- Six deep subsurface settlement monitoring points were placed at approximately 1 m above the pipeline crest. Two subsurface monitoring points were placed within the CPR ROW (one on each side of the rail) approximately 5 m from the rail centerline. The other 4 subsurface settlement monitoring points were installed approximately 5 m outside the CPR ROW (east and west of the pipelines profiles).

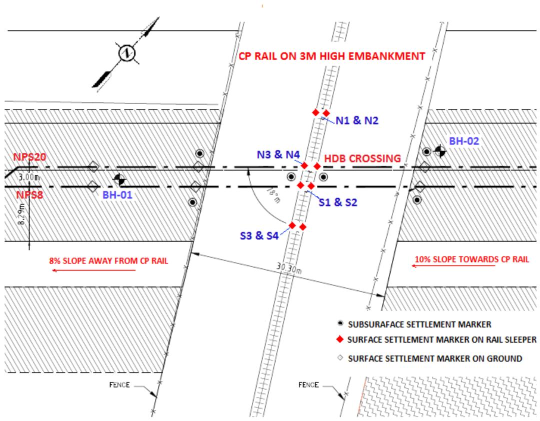


Figure 2. Location of boreholes and settlement monitoring points completed for the site.

The following are noted for the settlement monitoring points' installations:

- The subsurface settlement point planned at the location of expected anomalies was shifted by approximately 2.8 m north from the original location as the planned location was not accessible by the drilling rig due to the presence of a steep slope. This resulted in approximately 1.2 m elevation drop. As such, the installation depth was changed from 4.2 m to 3 m while the difference in elevation between the settlement plate and top of pipe was maintained as 1 m.
- One subsurface and two surface settlement monitoring points, all located outside the CPR ROW, had to be moved approximately 6 m northward as the original location was in a very soft area containing ponded water; refer to Section 2.1 and Photos 4a and 4b. The area was flat and, hence, the depth of installation was not altered.

CPR advised that the rail track at the planned crossing location is a Class 3 Track, which requires the "flag limits" provided in Table 1.

Table 1. Flag limits for the planned pipeline-rail crossing

| Criteria | Warning (mm) | Critical (mm) |
|---|---|---|
| Settlement | 25 | 50 |
| Elevation change over a 16.764 m (55 ft) fixed distance (RC/55) | 25 | 50 |

The survey monitoring was planned as follows:

- A baseline reading to be completed after installation of the settlement points. At least two sets of readings will be taken to finalize the baseline readings for accuracy.
- Twice daily during the construction period and at least three days after the completion of construction.
- Daily for one week.
- Once per week till readings completely taper off.
- Monitoring frequency will be increased if the settlement rate is steep and/or the settlement values are close to the WARNING level. As well, if there is any evidence of loss of ground, any reason to believe settlement is delayed, or any settlement is identified during installation of the pipelines or subsequent monitoring period, the monitoring will be continued until the geotechnical engineer deems it acceptable to discontinue such monitoring.

## 5.2 Settlement Monitoring Results

Two base-line surveys (for the settlement monitoring points) were completed prior to the HDB construction to confirm the results, timing of the Basel-line survey is referred to in this paper as Day 1. Construction of the HDB pipeline crossing was initiated from the south entry point where ground elevation is lower than the north side. The pilot pipe was drilled through 6 days after the conclusion of the base line survey, followed by reaming the NPS 20 pipeline in three stages which was completed on Day 9. The NPS 8 was installed without a pilot bore and was completed from Day 12 to Day 13.

Settlement monitoring was initiated on the first day of the construction, i.e. Day 6, and continued through to Day 32, temperature during the entire period ranged between $5^0$C to -$20^0$C, but mainly between -$5^0$C to -$15^0$C. The implemented frequency, adjusted from the planned frequency presented in Section 3.3 to suit the actual conditions for the crossing was as follows:

- Twice daily, one at 9:00 am and one at 1:00 pm until Day 16.
- One survey, either at 10:00 am or at 2:00 pm approximately every 3 days, i.e. 7 survey readings, thereafter.

Figure 3 presents settlements of the monitoring points along a stretch of 17.45 m of the rail (compared to 16.764 m criterial value provided in Table 1), i.e. 8.725 m both ways from the center line of the two pipelines. The maximum and minimum recorded movement (at a specific settlement monitoring point) were 6 mm and -3 mm respectively. Both the individual and average settlement values for the rail were well under the "flag limits" provided in Table 1.

It is noted that the Owner of the pipeline crossing, proactively, requested to complete another set of settlement monitoring and assessment after the freshet. Survey monitoring is yet to proceed in time for this paper mainly due to the longer freezing season experienced within the project site.

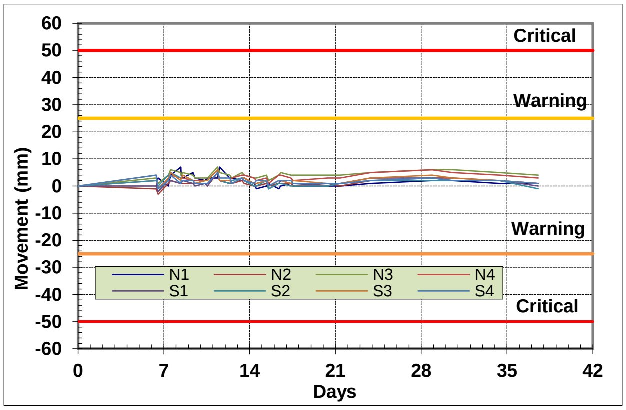


Figure 3. Average rail settlement along the 17.45 m rail track profile.

## 6 FINDINGS

The HDB method was used to construct the pipeline crossing comprising of one NPS 8 Condensate (219.1 mm outside diameter, OD) and one NPS 20 Crude Blend (508 mm OD). A settlement monitoring plan was designed and implemented for the project that satisfied the CPR crossing requirements, which yielded the following findings:

- The maximum lateral movements for the settlement points outside the CPR rail track were less than 18 mm, but generally less than 12 mm.
- Maximum vertical movements (settlements or heave) were generally less than 5 mm which is well well below the CPR Specifications of 50 mm for Class 3 Track. The readings show a stable trend throughout the monitoring period.
- On Day 37, two surface monitoring points recorded 18 mm and 13 mm vertical movement (heave) respectively. Heaving began on Day 15 and became more noticeable on Day 20. The stated points were located within a ponded area. Temperature preceding those two dates ranged from -6 to -21 degrees Celsius which froze the ponded water and likely contributed to frost heave in the vicinity of the stated two points. Heave for the two points peaked between Day 24 and Day 25 (19 mm and 15 mm respectively) and trended downward (and/or stabilizing) on Day 34 and Day 37 with magnitudes of 18 mm and 13 mm when the recorded temperatures were generally ranged zero to plus three degrees Celsius. Such movement magnitudes are, still, below CPR "flag limits" provided in Table 1. Note that the stated two points are over 25 m north of the track (and outside the CPR ROW) which, practically, will not impact the CP rail within the HDB crossing.
- CPR rail specifications require the elevation change over a fixed distance of 55 ft. (16.74 m) for a Class 3 Track to be 50 mm maximum. The total surveyed distance between points on the rail sleepers are 17.4 m apart on the south side sleepers and 17.45 m on the north side sleepers. The maximum elevation difference between the points was less than 5 mm, which is well within the CPR Specifications.
- Based on the time history, no more survey data was required beyond Day 32 as the survey points showed the settlement and/or heave rate values had substantially reduced and stabilized, and the recorded values over the entire monitoring period were well below the CPR Specifications of 50 mm for a Class 3 Track. Further, and as stated above, the higher value heave points, in addition to being below the stated CPR Specifications, are over 25 m north of the track and outside the CPR-ROW.
- The geophysical and geotechnical teams provided support to the project design team to address CPR crossing requirements.
- The geotechnical team provided and confirmed that the HDB pipeline crossing construction activities had little to minor impact on the track and adhered to the CPR pipeline crossing requirements.

The settlement monitoring results will be further assessed following the planned settlement monitoring requested by the client after the freshet season.

## 7 DISCUSSIONS AND RECOMMENDATIONS

Pipeline crossings, whether deep or shallow, have become somewhat a "routine" engineering work. . Often geotechnical discipline is not engaged early in the pipeline crossing design. Further, the geotechnical input and/or interpretations are not regularly requested early enough in the crossing design phase. The overall crossing profile may be generalized on two or three boreholes that are 50 m or more apart. The ground conditions along the profile may vary between boreholes and impact the crossing design. Geophysical investigation, when combined with the geotechnical investigation, provides more insight into the ground conditions, i.e. continuous profile (along and across the pipeline crossing profile) and helps to assess the crossing profile better.

Large claims from crossing contractors as a result of no to minor engagement of experienced geotechnical discipline from inception to the completion of the crossing works can lead to large claims against pipeline Owners.

The Authors recommend engaging an experienced geophysical and geotechnical teams in the early stages of a pipeline crossing. The geophysical and geotechnical teams can provide insight and additional information for both the permit application and design processes that will be beneficial to the project.

## 8 REFERENCES


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