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ABSTRACT

The performance of pipeline systems under seismic loading is an important consideration in regions subject to earthquakes. Experience from previous seismic events indicates that earthquake-induced permanent ground displacements are one of the key geotechnical hazards to pipelines. This paper briefly describes an evaluation of the vulnerability of a natural gas transmission system to seismic hazards, along with some of the remedial treatments that were implemented. The work was carried out for BC Gas Utility Ltd. in the Lower Mainland of British Columbia, Canada. Initially, a regional study was carried out to identify components of the gas pipeline system that are seismically most vulnerable. Following the regional study, the most vulnerable sites were identified for detailed site-specific analyses with the objective of developing remedial treatment alternatives. Two case histories are described to illustrate some of the options available for seismic upgrading of pipeline systems. The first case history describes a project where ground densification by vibro-replacement was used to reduce the risk of ground deformations at an existing gate station. The second case history describes a project where a new pipeline was installed using the method of horizontal directional drilling (HDD) to avoid potentially liquefiable zones.

INTRODUCTION

BC Gas Utility Ltd. supplies natural gas to the Greater Vancouver Region of British Columbia, on the west coast of Canada (see Fig. 1). The distribution area is situated within a region of high seismicity associated with a subduction zone off the west coast of Vancouver Island. It includes significant areas underlain by recent unconsolidated marine deltaic and alluvial sediments, some of which are considered to be susceptible to liquefaction and lateral spreading when subjected to seismic loading.

Fig. 1. Location Plan

Over 1.5 million people live in the Greater Vancouver Region, which includes the City of Vancouver. Most of the residents depend on natural gas as a source of energy for heating and other uses. In response to a general increase in awareness of seismic hazards in the region, BC Gas has undertaken an extensive seismic evaluation and upgrading program to minimize the risk of gas supply disruption to its customers as a result of an earthquake event. Given the lack of redundancy in certain areas of the supply system, combined with the resulting social, economic, and business impacts, a very low risk of disruption to the gas supply is considered acceptable to BC Gas. An annual probability less than 0.05 percent (equivalent return period 2,000 years) has been adopted as a target level for the acceptable risk of loss of gas pressure from the pipeline system. This is based on comparison with recent studies for other lifeline systems and the operational goals of BC Gas.

The main gas supply pipelines, which were the focus of this study, have a total length of about 250 km and consist of butt-welded steel pipe ranging from 200 mm to 1066 mm in diameter. These pipelines operate at pressures up to 4020 kPa (Transmission Pressure mains) and 1200 kPa (Intermediate Pressure mains). Portions of the transmission and intermediate pressure systems located within the infirm ground areas, especially those at a number of major river crossings were of particular concern.

REGIONAL STUDY

The initial phase of the study was regional in nature. The objective was to identify components of the gas system that are most vulnerable to damage which would result in disruption to supply. The pipeline system sites/components that failed to meet the seismic performance criteria were ranked based on the anticipated vulnerability and this information was used to prioritize emergency response planning and remedial measures.

The regional study included the following components:

- Prediction of seismic ground motion parameters using a regional probabilistic seismicity model;
- Mapping of seismic hazards, such as liquefaction and slope instability, using regional and site-specific data;
- Evaluation of lateral spreading deformations for a range of seismic risk levels using the Multiple Linear Regression (MLR) method developed by Bartlett & Youd (1992);
- Structural analysis of the vulnerability of the gas transmission pipelines to the identified seismic hazards using finite element analytical techniques applied to generic pipeline configurations, and a probabilistic model to account for the size and aerial distribution of zones of lateral spreading (Honegger, 1994).

Although the initial hazard assessment study was regional in nature, methods applied in previous zonation studies were extended to include limited detailed analysis. The methods adopted were developed with input from a Peer Review Panel, which included specialists from universities and industry.

SITE-SPECIFIC SEISMIC VULNERABILITY ASSESSMENT OF CRITICAL SITES & SITE REMEDIATION APPROACH

Following review of the results of the regional study, the most vulnerable sites were identified for detailed site-specific analysis with the objective of developing remedial treatment alternatives to reduce the risks. The approach adopted in the site-specific analyses essentially included the following components:

- geotechnical investigation to understand the site-specific soil and groundwater conditions;
- prediction of site-specific ground response for the identified seismic risk level including assessment of site-liquefaction potential [using the program SHAKE (Schnabel *et al.*, 1972) and liquefaction assessment using Seed *et al.* (1984)]. Analyses were carried out for seismic risk levels corresponding to 1:100, 1:475, and 1:2,000 year return periods;
- assessment of the stability of slopes (e.g. at the river banks) and computation of liquefaction-induced ground movements [slope stability analyses using programs such as SLOPE/W and XSTABL, and ground displacements computed using empirical as well as finite element mechanistic approaches such as Youd *et al.* (1999) and Byrne *et al.* (1992)]. More details on the analytical approaches are given in Wijewickreme *et al.* (1998).
- Structural analysis of the vulnerability of the gas transmission pipelines to the identified seismic hazards using the finite element computer code ANSYS in which the soil is modeled as a series of bi-linear springs. The approach is discussed in more detail in ASCE (1984) and Honegger (1994).

Based on the site-specific studies, it was concluded that some components of the pipeline system could withstand the predicted ground deformations without rupture. Where the analyses indicated that this was not the case, remedial treatment options were developed and assessed. These measures ranged from:

1. Ground treatment using methods such deep vibro-replacement and compaction grouting techniques;
2. Major re-alignment of the pipeline to avoid infirm ground areas using methods such as horizontal directional drilling (HDD);
3. Structural modification of the vertical and/or horizontal alignment of the pipeline(s) to reduce stress concentrations, and strengthening to provide increased resistance.

Two case histories where the above site-specific analysis approaches were carried out and the remedial Options 1 and 2 were applied are described in the following text.

CASE HISTORY No. 1 – GROUND IMPROVEMENT USING VIBRO-REPLACEMENT

This case history describes the use of ground improvement to seismically upgrade the BC Gas Fraser Gate Station. This gate station serves as a control point for pipelines that form one of the main arteries supplying natural gas to the City of Vancouver. The site is located on the north bank of the North Arm of the Fraser River in the south part of the City of Vancouver. During the regional study, this gate station was ranked highest in terms of seismic vulnerability.

The gate station compound is rectangular in plan (~100 m x 75 m). The plan alignments of the 508 mm and 610 mm diameter transmission pressure pipelines entering the gate station are illustrated in Fig. 2.

The site topography within the station compound and also in the east-west direction is generally flat. Prior to treatment, the riverbank within the rip-rap area, which extended to about 6 m below crest level, sloped down towards the south at slopes ranging 1H:1V to 3H:1V (horizontal:vertical). The riverbed below this level sloped southward at an average gradient of about 8% to the horizontal.

Prior to treatment, the upper soils within the station consisted of about 1.7 to 2.7 metres of loose to compact sand to sandy silt fill material. In the northern part of the gate station, the fill materials are underlain by a layer of very soft to soft silt extending to depths of about 7 m below the ground surface. In the southern part near the riverbank, the soils primarily consisted of loose to compact sand extending to depths of up to 11 metres below the

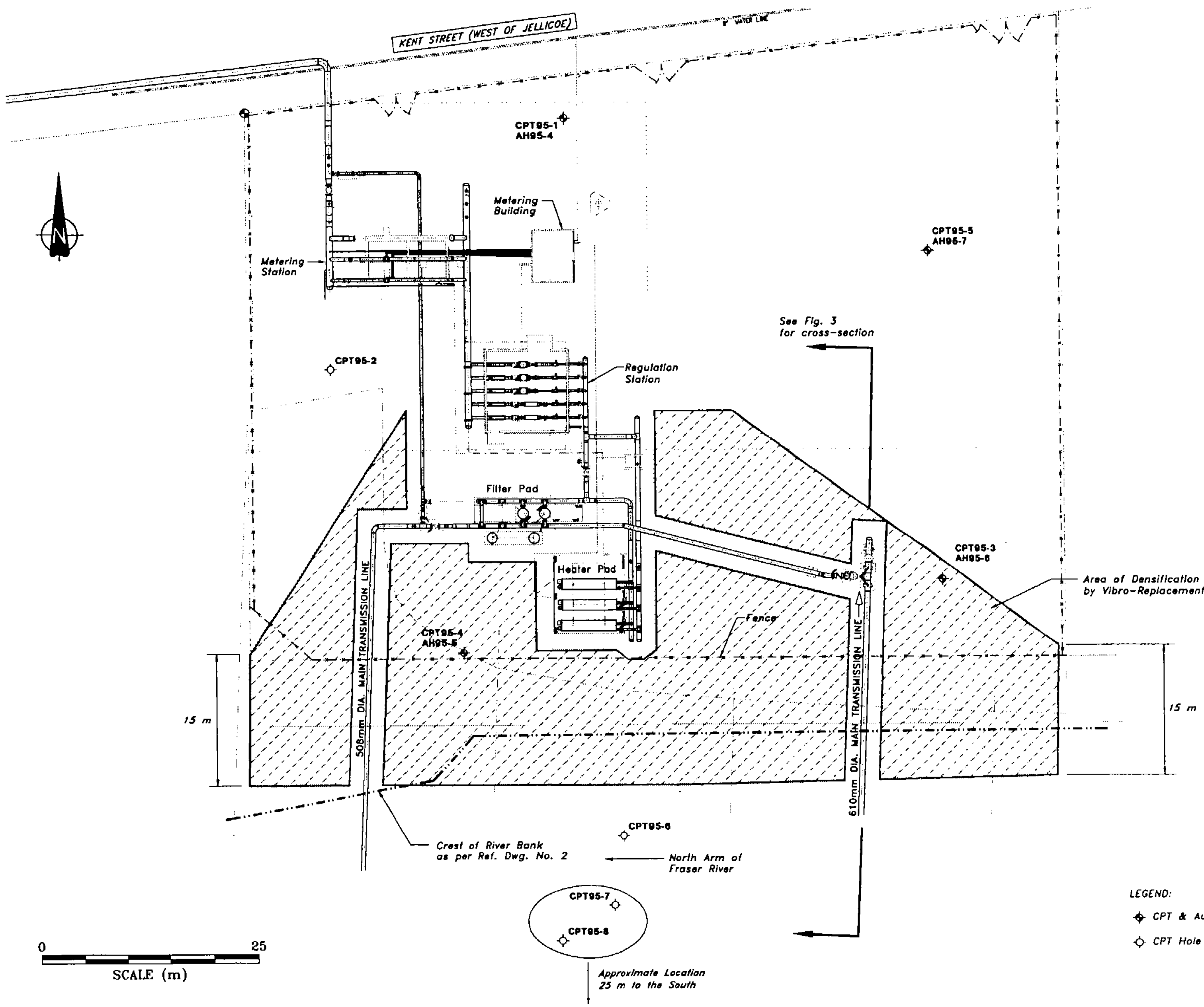

Fig. 2. BC Gas Fraser Gate Station - Site plan showing existing pipeline configurations and area of ground improvement.

ground surface. The above soil zones at the site were found to be underlain by competent compact to dense soil strata. The groundwater level within the gate station compound was at depths of about 1.0 to 3.0 metres below the ground surface.

Site-specific assessment indicated that the zones of potential liquefaction are primarily located on the south portion of the site. For all three seismic risk levels analyzed (firm ground accelerations 0.09g, 0.20g, and 0.34g, respectively and earthquake magnitude of M7), the loose sandy soils near the river bank within about the upper 12 m were determined to be liquefiable. The risk of liquefaction of the silty strata located within the northern portion of the site was classified as low. For all three seismic risk levels, the post-liquefaction stability analysis of the gate station compound indicated that there is a high risk of a flow slide towards the river (large ground displacements in excess of 3 m) for the soils in the southern part of the site. Along with lateral movements, significant vertical ground movements were also expected. Maximum computed ground deformations were compared with the computed pipe structural deformation capacities. The resulting differential earthquake-induced displacements at the station were found to exceed the estimated capacity of the pipelines by an order of magnitude indicating a high risk of damage to the station piping under earthquake loading.

Given the exceedance of the available pipeline capacity, the only remedial measures deemed practical for the gate station involved improving the ground conditions to reduce the potential earthquake-induced permanent ground deformations to less than about 150 mm. With this improvement, no modification of the existing station piping was judged to be necessary.

The effectiveness of ground improvement in reducing the liquefaction-induced ground displacements at the site was assessed using slope stability and finite element analyses. The analyses and design work indicated that the densification of the liquefiable zone combined with slope reconfiguration of the shore line to a gentler slope, would reduce the expected large earthquake-induced ground movements in the vicinity of the gate station below the structural deformation capacity of the pipelines.

The selection of the most suitable ground improvement technique was governed by several factors, such as soil conditions, equipment space restrictions, pipeline protection issues, environmental regulatory requirements, land availability etc. Based on an evaluation of these considerations, the method of vibro-replacement was considered to be the most suitable technique of ground densification for use at the gate station site. A total of 273 stone columns were installed (using the method of vibro-replacement) in a triangular pattern at 3 m centre-to-centre spacing to cover the plan area shown in Fig. 2. The vibro-replacement was performed so that the bases of all stone columns were installed to the top of the underlying hard stratum. Field verification testing was performed at selected centroids of the stone column pattern using the method of electric cone penetration testing (CPT) to confirm that the densification criteria were met.

CASE HISTORY NO. 2 – PIPELINE INSTALLATION USING THE MEHOD OF HORIZONTAL DIRECTIONAL DRILLING

This case history relates to the replacement of a key segment of an existing BC Gas 508 mm (20 in) diameter transmission pipeline river crossing with a 914 mm (36 in.) diameter, 1000 m long, pipeline installed using the method of HDD as a seismic mitigation measure. The site is located about 1 km west of the Port Mann bridge - Trans Canada Highway crossing of the Fraser River in Coquitlam/Surrey, B.C. The 508 mm BC Gas transmission pipeline in use prior to this upgrading was located at relatively shallow depths below the riverbed as a result of conventional cut-and-cover construction/installation techniques.

The Fraser River has a crest-to-crest width of approximately 500 m, and maximum water depths ranging from 20 to 25 m, at the proposed crossing location (see Fig. 3). The areas in the vicinity of both the riverbanks are generally flat and they were part of the floodplain of the Fraser River in the past. To the south of the floodplain, the pipeline corridor rises up an escarpment into the highlands of Surrey. The pipeline alignment is located in a right-of-way corridor shared with BC Hydro. BC Hydro has their existing overhead transmission lines spanning across the river and supported on high steel-frame towers. The south part of the old Fraser River floodplain is occupied by a rail yard belonging to CN Rail.

A geotechnical investigation comprising CPT testing, auger sampling, and Standard Penetration Testing (SPT) was carried out as a part of the site-specific vulnerability assessment of the existing pipeline (and also for the design of the new crossing). The inferred soil stratigraphy across the river crossing is shown in Fig. 3. The soils at the north bank of the river consist of surficial fill and overbank silts overlying an extensive deposit of Fraser River sand. The upper portion of the sand deposit, extending to depths of approximately 17 to 18 m below ground surface, was determined to be compact while the remaining lower portion of the deposit is compact to very dense. The soil conditions within the lowlands to the south of the Fraser River were noted to consist of fill materials overlying soft and compressible bog or swamp deposits consisting of interlayered peat and silt extending to about 15 m below the ground surface. These soils are in turn underlain by an extensive Fraser River sand deposit containing silt interbeds. The Fraser River sand deposit was inferred to extend across the river down to a depth of approximately 45 m below ground surface. The Fraser River sand is underlain by marine sediments consisting predominantly of silt, clayey silt and sand which in turn are underlain by competent Pre-Vashon glacial and interglacial deposits.

The groundwater level in the floodplain was at shallow depths of about 1.0 to 3.0 m below the ground surface during the period of the geotechnical investigation.

Similar to site described in the previous case history, the response of this site was analyzed for the seismic risk levels associated with firm ground accelerations of 0.10g, 0.21g, and 0.36g, respectively and an earthquake magnitude of M7. The post-liquefaction stability analyses indicated that, for the seismic

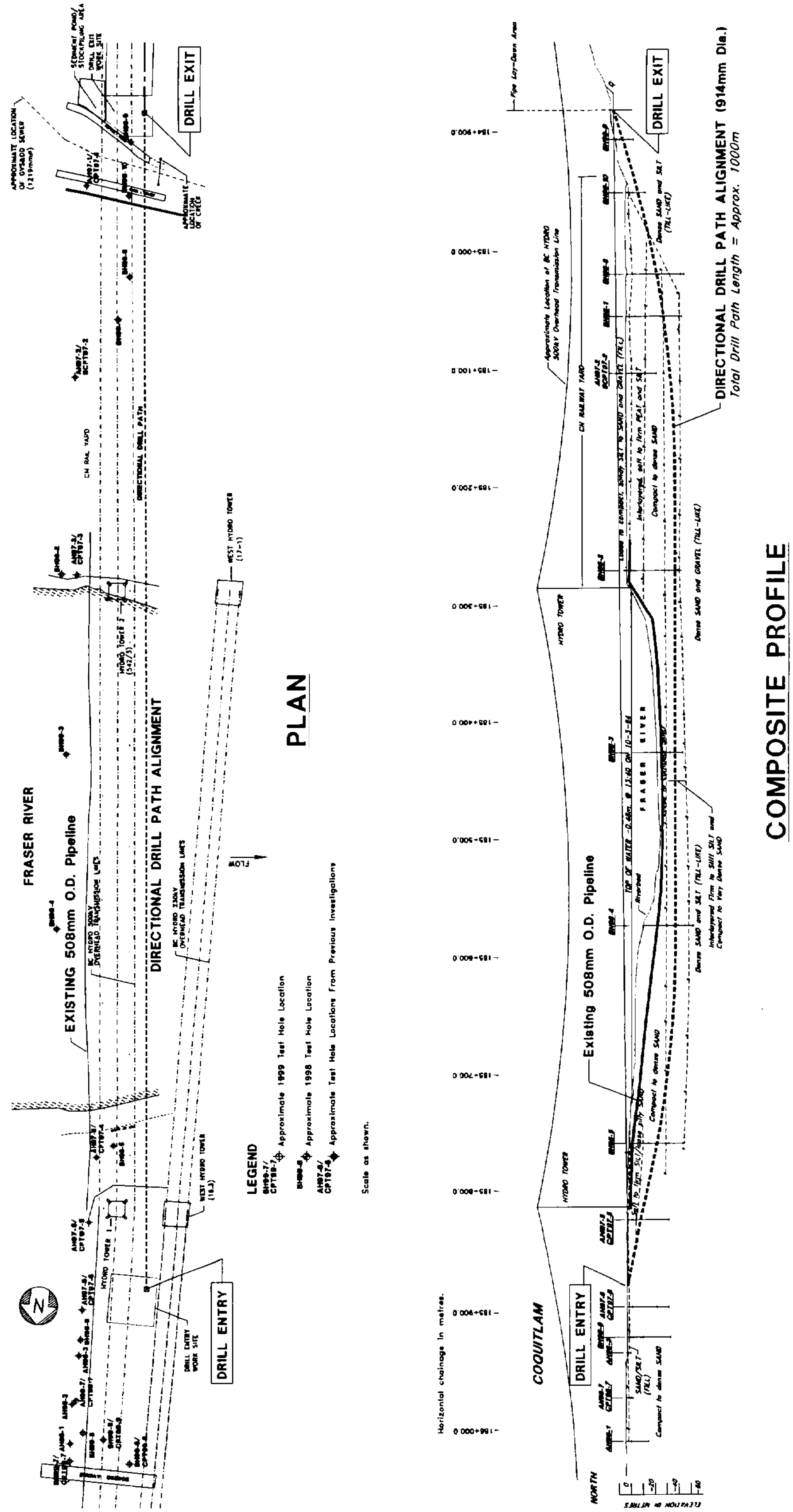

Fig. 3. BC Gas Fraser River HDD Crossing - Inferred soil stratigraphy and design drill path alignment.

loadings corresponding to all the risk levels considered, a significant part of the south bank had a high risk of developing flow slide conditions (leading to permanent lateral movements in excess of 3 m as well as significant vertical displacements). Based upon the magnitude and distribution of earthquake-induced ground movements, the existing 508 mm (20 in) pipeline was assessed to be highly vulnerable to seismic induced damage.

Practical methods available to improve the performance of the existing pipeline at the south bank of the Port Mann crossing were very limited. Ground improvement at the river bank as an option was ruled out because of several constraints related to environmental concerns with intrusion into the river, safety issues and physical constraints related to working close to existing BC Hydro electrical transmission lines and towers, and interference with the operation of the CN Rail yard. Because of these constraints, as well as the desire to mitigate identified concerns related to river bed scouring on the pipeline, major re-alignment of the pipeline was identified as the most viable solution. In addition, ongoing maintenance issues on the existing pipeline related to static settlement-induced pipe deformations across the CN Rail yard, and projected increased future transmission capacity requirements also supported the rationale for installation of a new 914 mm (36 in) gas transmission pipeline across the river.

In order to avoid the identified liquefiable and scour zones, the new pipeline had to be located at a depth in the range of 30 m to 40 m at the river banks, rising close to ground surface some 250 m to 300 m from the river's edge. This requirement precluded installation by conventional open cut techniques. A new pipeline installed well below the critical liquefiable and scour zones using Horizontal Directional Drilling (HDD) was considered the only practical method of reducing both risks to acceptable levels.

An initial study indicated that the installation of a directionally drilled pipeline crossing at this site was feasible from geotechnical, structural, and HDD design/construction points of view. Final design alignment, as shown in Fig. 3, for the HDD pipeline was designed after careful evaluation of existing site constraints such as BC Hydro electrical transmission towers, existing CN Rail yard and other utilities, as well as environmental concerns, such as the potential release of drilling fluids to the Fraser River and adjacent creeks during drilling etc. Based on this design a 915 mm (36") diameter, 1000 m long steel pipeline was installed using the method of HDD to replace the old 508 mm pipeline.

CONCLUSION

The program undertaken by BC Gas Utility Ltd. for their major gas transmission pipeline system incorporates several unique and innovative approaches to seismic hazard evaluation and mitigation of earthquake risks. A systematic approach was adopted where a regional study was initially carried out to rank the sites according to seismic vulnerability. This was followed by site-specific assessment of the most vulnerable sites, and remediation as required. Several remedial treatment measures comprising geotechnical and/or structural solutions have been developed and are being applied where it is desired to reduce the risk of earthquake damage.

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