Geotechnical design and construction aspects of the City of Vancouver Dedicated Fire Protection System

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Abstract: The Dedicated Fire Protection System (DFPS) is an integral part of the City of Vancouver's emergency preparedness plan. The main objective of the DFPS is to supply either fresh or salt water for fire fighting purposes via a network of dedicated high pressure (300 psi) steel watermains, hydrants, and two high capacity pump stations (10,000 gal/min each) and intake structures. The entire system is designed to remain functional following a major earthquake equivalent to the Maximum Credible Earthquake (MCE) for the region.

Design and construction of the system is continuing. This paper describes some of the geotechnical design and construction aspects of the pump stations, intake structures, and the watermains that have been constructed since 1993. The geotechnical and geophysical field investigation procedures that were employed to optimize the design of watermain trenches are presented, together with some of the details of the pilot testing carried out to optimize the compaction of pipe backfill materials in-situ.

Introduction

The City of Vancouver is located in an area of high seismic risk associated with a major subduction zone off the Canadian West Coast. Intra-plate earthquakes (M6-7) have been regularly recorded over the last century within the North America tectonic plate, which extends beneath Vancouver. Geological evidence also suggests that there is the potential for a much larger inter-plate earthquake (M8+) occurring within the off-shore subduction zone. A major earthquake associated with either of these sources could have devastating effects in the City of Vancouver. Prior to construction of the Dedicated Fire Protection System (DFPS), the fire-fighting system relied on the potable water supplied from the North Shore through a series of trunk mains crossing Burrard Inlet that are highly susceptible to damage during a major earthquake.

Following a review of the seismic vulnerability of the potable water system, the City of Vancouver considered it prudent to develop an alternate water supply system that could be used to fight fires in the event of a major earthquake and/or conflagration. Between 1989 and 1991, the City undertook a comprehensive study to review several alternative water supply systems for emergency fire fighting in the Central Business District and the nearby densely populated residential areas.

In 1991, the City Council approved a concept of land-based saltwater pump stations with dedicated high-pressure mains. A consultant design team was retained by the City to develop the design of the DFPS, and in 1992 the City Council approved the project for construction, in principle, over a 12-year implementation period.

The DFPS is also intended to provide day to day fire fighting capacity thereby reducing the number of existing watermains that needed upgrading and/or replacement due to maintenance and hydraulic concerns.

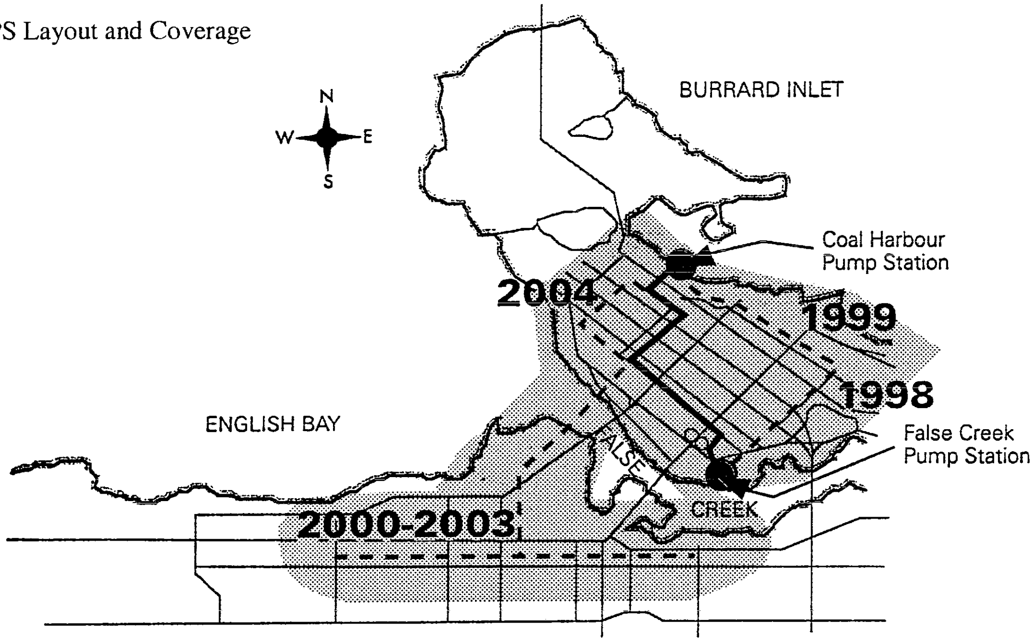
Dedicated Fire Protection System

The DFPS is being constructed in several phases; initially, it was envisaged that it would comprise four foreshore pump stations and intake structures, and approximately 22 km of 600 mm and 750 mm diameter buried dedicated watermains, as well as numerous remotely-controlled valve chambers and high capacity fire hydrants. At present, it is envisaged that two pump stations and intake structures (at Coal Harbour and False Creek) will suffice for the system that will provide coverage for the downtown core, Kitsilano and False Creek. The approved system layout and coverage is shown in Fig. 1.

The False Creek pump station includes the Main Control Centre for the system, from which all other pump stations and valves throughout the system can be operated remotely. The system is monitored and controlled by a Microwave-based Supervisory Control and Data Acquisition (SCADA) system.

The construction of the False Creek pump station and the Coal Harbour pump station, including the associated intake structures, is complete. The construction of a loop of dedicated high capacity underground watermains connecting the above pump stations, with associated valve chambers and hydrants, is also complete. The design of an underwater crossing beneath False Creek, extending the system to the Kitsilano area, along with 3 km of steel watermains, is currently being carried out.

Fig. 1: DFPS Layout and Coverage



Design Criteria for DFPS

The entire system is being designed to remain functional following a major earthquake, equivalent to the Maximum Credible Earthquake (MCE) for the region. One of the first requirements was to determine the peak horizontal ground accelerations that would be used to set the seismic design criteria for all system components. Project-specific seismic studies, which included both probabilistic and deterministic estimates, were carried out by Dr. W. Milne to establish design earthquake ground motions for the site. The studies indicated that peak firm-ground accelerations between 0.4 g and 0.6 g could be experienced under the Maximum Credible Earthquake. Following review of other similar studies conducted for the region, discussions with the members of the project team, and input from the external reviewers, a design ground acceleration of 0.5 g was selected as the design level of shaking that would provide acceptable performance within budgetary and other constraints. This stringent design requirement presented several technical challenges to the design team. A geotechnical and seismic risk assessment was carried out to assist with system layout which would avoid, to the extent practical, areas with poor ground conditions, thereby optimizing the reliability of the system. Where areas with poor ground conditions could not be avoided, designs were developed to mitigate the risk.

Intake Structures

The reliability of much of the system is achieved, in part, by incorporating redundancy, such as looping of the pipeline system, providing strategic control valves and hydrant header connections, etc. However, since it was neither practical nor economical to provide redundancy at the intakes, the design of these structures to post-seismic standards was particularly critical. The intake structures for the Coal Harbour and False Creek pump stations are both located at the foreshore slopes. The siting of these intake structures took into account many key factors including sufficient water depth at the intake site, firm-ground conditions for support of the intake structure and the associated pipeline, slope stability and deformations, navigational concerns, environmental and Department of Fisheries and Oceans (DFO) regulations, pump station siting, and economics.

The intake structures are basically reinforced concrete structures founded in competent till-like soils. They have conventional screens that can be easily raised for cleaning. These structures are designed to resist static soil and gravity loads as well as dynamic loads resulting from a 0.5 g seismic event. The lateral loads imposed by the soils behind the intake structures under the MCE seismic loading conditions governed the design as the permissible lateral displacement was limited to 50 mm. Additional restraints in the form of anchors were necessary to provide adequate sliding resistance for the intake structure. The anchors consisted of 57 mm diameter double-corrosion-protected steel bar anchors drilled and grouted into the underlying competent till-like soils and/or bedrock. In addition, ground improvement was also carried out in the areas inland from the intake sites. Dynamic compaction was utilized at both intake sites to improve/densify the loose to compact in-situ soils overlying till extending to a depth of about 8 m. Soil stratigraphy, intake location, and area of ground improvement considered for the False Creek Intake are shown in Fig. 2. This method was considered to be the most cost-effective method of ground improvement. Added reliability was provided by incorporating flexible connections between the intake structure and the intake pipe.

In order to construct intake structures at both sites, temporary cofferdams were constructed. Considering the depth of excavation and tidal fluctuation, the design of these sheet pile structures presented a challenge to designers of the temporary structures. Insufficient penetration of the sheet piles into the dense bearing stratum, as well as leakage, presented problems during construction of these structures. As a result of these difficulties at the Coal Harbour site, the contractor opted for a pre-cast intake design, which was lifted into place using a large crane. Grouting was carried out through grout holes installed in the pre-cast unit to achieve a firm subbase.

Pump Stations

Having dismissed pier and barge-mounted options, a land-based configuration was adopted by the project team for the saltwater pump stations. Pump stations located a short distance inland from the foreshore and founded in competent soils best satisfied many of the key requirements of the project team.

Based on site accessibility and several other criteria, three sites were ultimately selected for potential DFPS pump stations. They are the Coal Harbour site, the False Creek site and the Kitsilano site. The construction of the False Creek pump station was completed in 1995 followed by the completion of the Coal Harbour pump station in 1996. Several sites were evaluated for a potential third pump station in Kitsilano. However, it has since been determined that reasonable protection for areas south of False Creek can be provided without a third pump station, by constructing a secure underwater crossing which can be supplied by the two already constructed pump stations.

Both pump stations are of robust cast-in-place concrete construction in order to meet the performance and durability requirements of the project. The pumps draw from a reinforced concrete wet well, which has a base elevation of about –6.5 m (Geodetic datum) to provide sufficient water depth at lower tides.

The pump station at the Coal Harbour site is located at the southwest corner of the intersection of Hastings Street and Broughton Street. This site is underlain by sedimentary bedrock at shallow depth, making the design and construction of the pump station relatively easy and straightforward.

The pump station at the False Creek site is located south of the intersection of Homer Street and Pacific Boulevard. Poor soil conditions encountered at this site presented some technical challenges in the design and construction of the pump station and associated underground distribution pipeline. Since the base of the wet well had to be located at a pre-determined elevation of – 6.5 m, the site was excavated to competent ground and infirm soils replaced with highly compacted structural fills. The base of the pump station building was founded on the structural fills. The backfill immediately adjacent to the pump station walls primarily consists of imported fills; however, in order to minimize costs, select on-site fills were also incorporated in the design without compromising the project performance objectives. The site soil stratigraphy, design elevation of foundations, and the configuration of the pump station are shown in Fig. 3.

Distribution Pipeline

The dedicated high capacity transmission watermain system forms a skeletal grid covering an area of approximately 4,000 acres. The watermains consist of 600 mm diameter steel pipe with both internal and external coatings, and full penetration butt welds at the joints.

There are two transmission watermains connecting the False Creek and the Coal Harbour pump stations. The first extends from Pacific Boulevard along Richards Street, Drake Street, Burrard Street, Burnaby Street, Bute Street, Haro Street and Broughton Street (Fig. 4). The second follows Homer and Pender Streets.

Many factors were considered in the selection of the most appropriate routes for the distribution watermain, such as fire hose coverage, conflicts with existing utilities, traffic disturbance, subsurface conditions, etc.

One of the key geotechnical design objectives, which was identified as a means of optimizing system reliability early in the pre-design phase was to install the pipes within competent ground. This was necessary in order to maximize the post-seismic reliability of the dedicated underground mains. Where poor soil conditions were encountered below the pipe invert, excavation of the poor foundation soils and replacement with compacted soils was generally employed to ensure acceptable seismic performance. In-situ ground improvement was considered at isolated locations as an alternative.

Fig. 2: Section along False Creek Intake Site

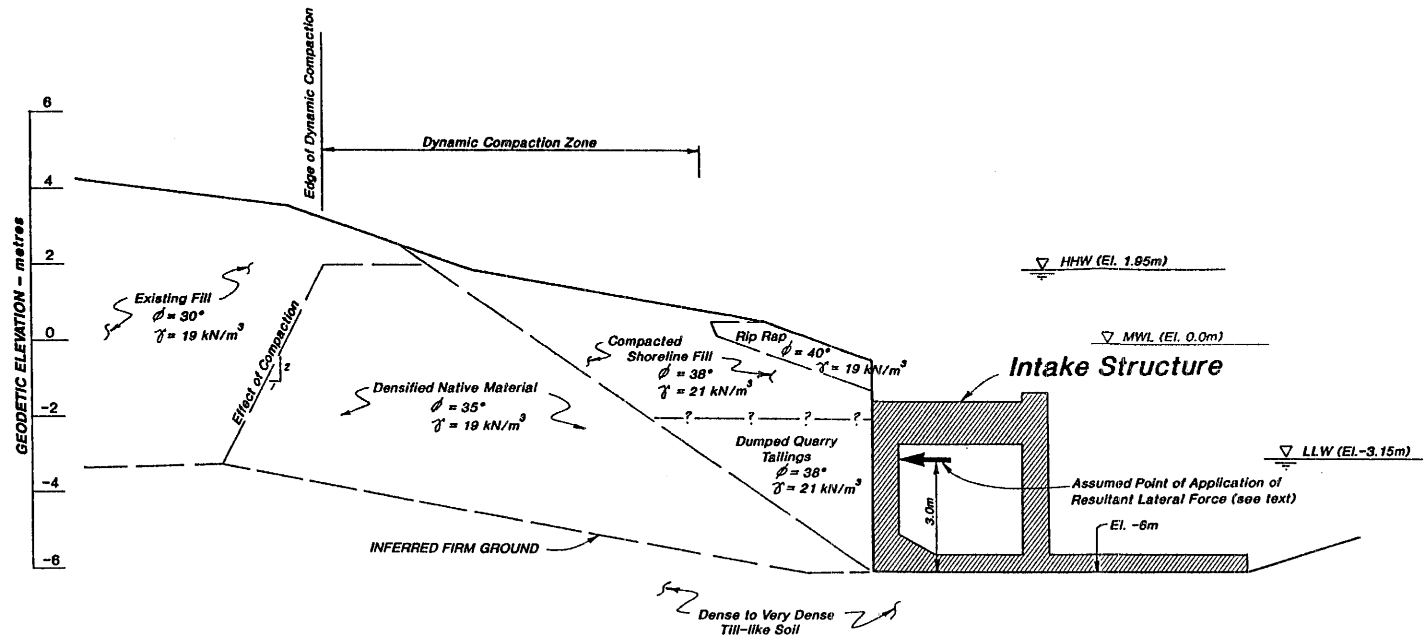


Fig. 3: Section along False Creek Pumping Station Site

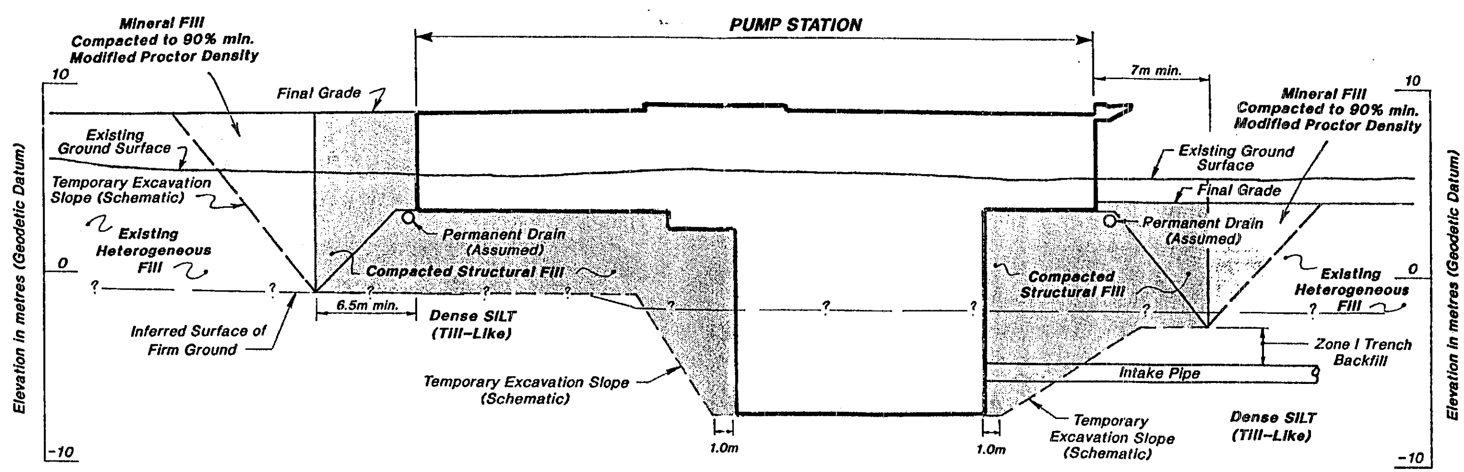
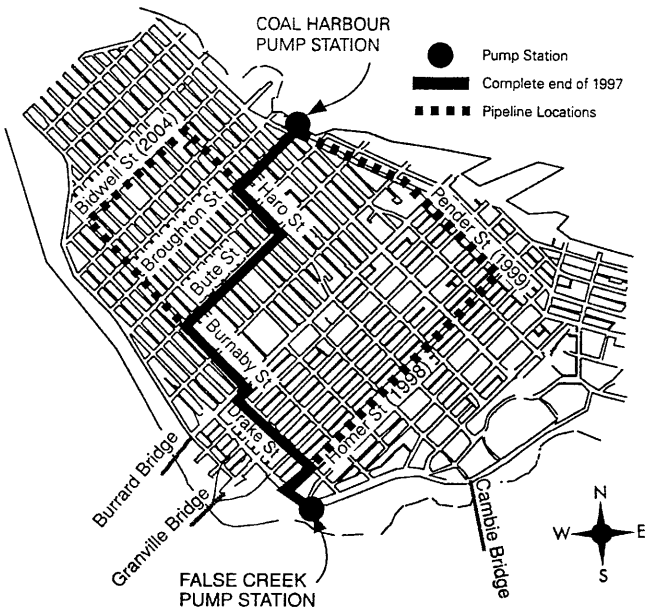


Fig. 4: DFPS Transmission Watermains



Quite often, the invert elevation of the watermains was governed by conflicts with other utilities located within the pipeline corridor.

Subsurface Investigation

In order to design the distribution system for optimum performance, it was necessary to investigate the subsurface conditions along the alignment of the watermains. Given the length of the alignment to be investigated, the anticipated depth to competent ground over most of the alignment, and road closures/traffic disruptions required in a heavily-trafficked city environment, it became apparent that careful planning of the geotechnical field investigation program should be undertaken. Generally, the field investigations were carried out in several phases. The first phase included geotechnical inspection of test pit excavations undertaken by City staff to verify/inspect underground utilities within the watermain corridor. This test pit investigation was followed by a geophysical investigation using Ground Penetrating Radar (GPR) to obtain continuos subsurface profiles; the GPR profiles were interpreted to help identify variations in subsurface conditions, major geological boundaries and any anomalies that may be present. Deeper test pits were also excavated to obtain data on the excavation characteristics of the till/bedrock. Following review of the data from these investigations, boreholes were drilled at specific locations along the alignment to obtain sufficient data on deeper subsurface strata for the geotechnical design of the watermain. This phased approach resulted in cost savings to the City. A key objective was to obtain information on the depth and extent of Vancouver's old streams and channels that crossed the watermains at a number of locations.

On average, depth to top of weathered glacial till or bedrock varied from 2 to 3 m. In some areas, bedrock was encountered at shallow depth which resulted in delays and difficult trench excavation conditions. Large boulders were encountered in glacial till that required on-site blasting and/or removal. A typical soil stratigraphy plot along the Homer Street alignment, inferred based on test pit data, borehole data, and GPR profiling, is shown in Fig. 5.

Design Issues

The design of the pipeline over most of the alignment was relatively straightforward, except for a short segment between Pacific Boulevard and the False Creek pump station. Detailed geotechnical investigations carried out for this segment indicated that the depth to competent ground (till-like soils) was deeper than the pipe invert, and that the overburden soils are loose in nature and susceptible to liquefaction and unacceptable deformations when subjected to MCE shaking. Since the deformations could potentially damage the watermain in this vital section, possible methods of increasing the reliability of the watermains were studied in detail. The methods considered included ground improvement using vibro methods (as dynamic compaction was not feasible due to proximity to high-rise structures), installation of piling to resist lateral soil movement on either side of the pipe alignment, and excavation and removal of unsuitable soils. After a cost-benefit analysis, it was decided to sub-excavate the poor soils along this section and replace them with engineered granular materials to form a stable soil wedge on which to support the watermains. Based on results of engineering analyses, the minimum width of excavation was specified as 10 m. A typical detail showing the extent of the excavation carried out is given in Fig. 6. It was also decided to incorporate flexible joints in the transition areas between competent and less-competent soils, and at selected other critical locations.

The analysis of the interaction response of the soil backfill, pipe and surrounding trench materials was considered by developing soil springs that correspond to the different directions of movement. Analyses were carried out using the computer program FLAC to derive soil springs. The results obtained for a typical trench detail are shown in Fig. 7.

Construction Issues

The watermains are being installed in phases. The Phase I watermains were constructed in 1996 and 1997. Phase II watermains were constructed in 1998 and 1999. Phase I watermains were installed by a contractor whereas the Phase II watermains were installed by the City crew.

Fig. 5: Soil Stratigraphy along Homer Street Alignment

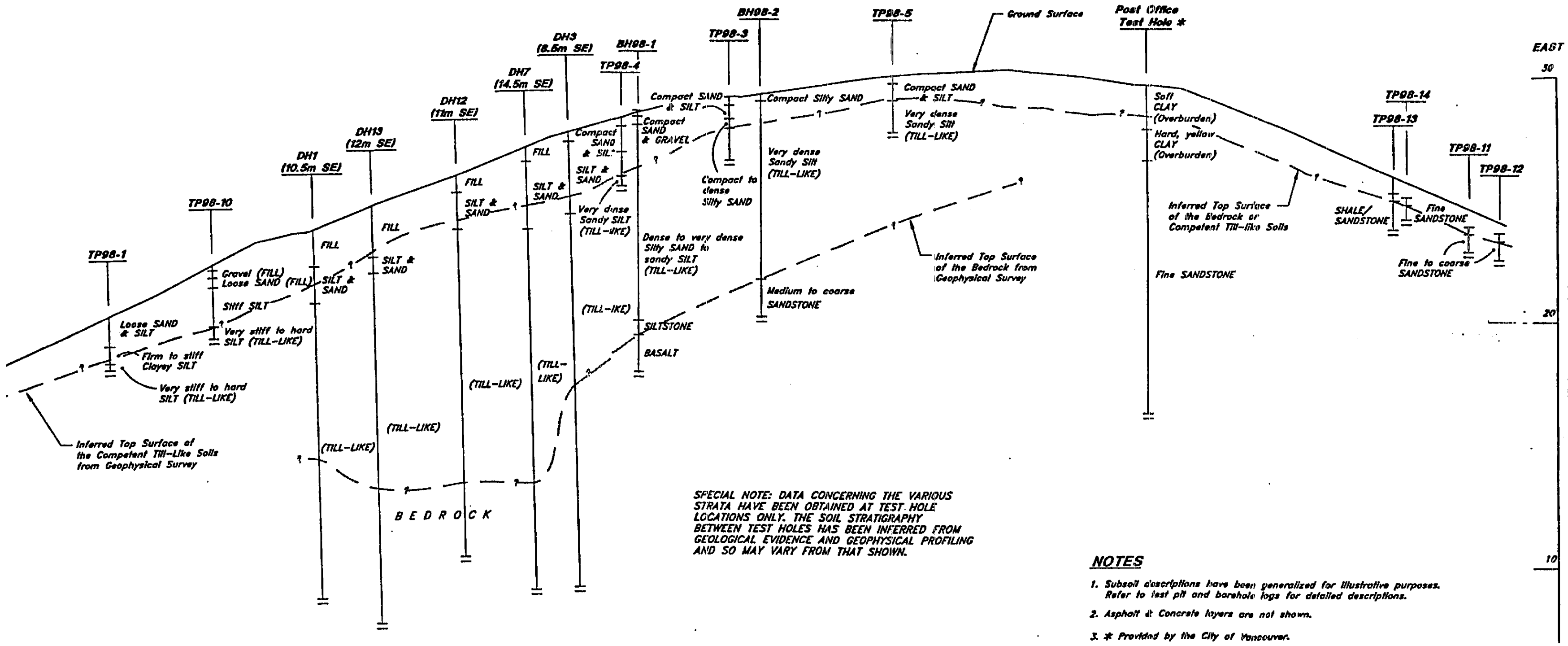


Fig. 6: Typical Section showing Trench Details

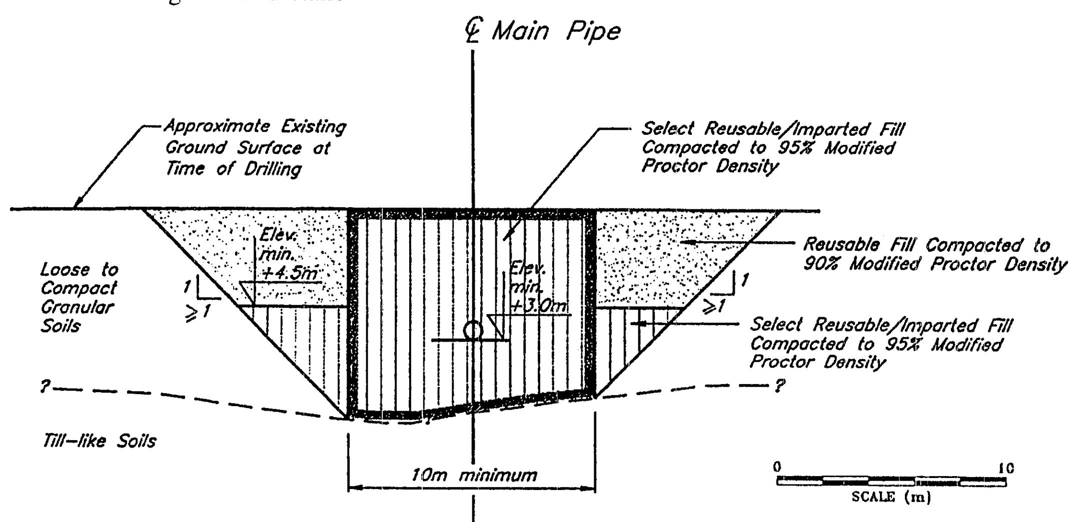
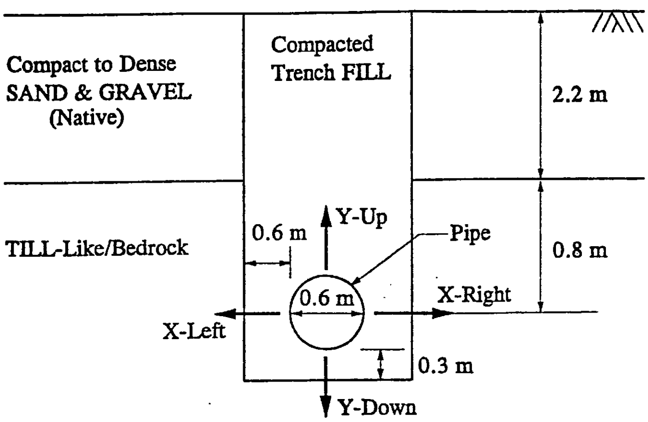
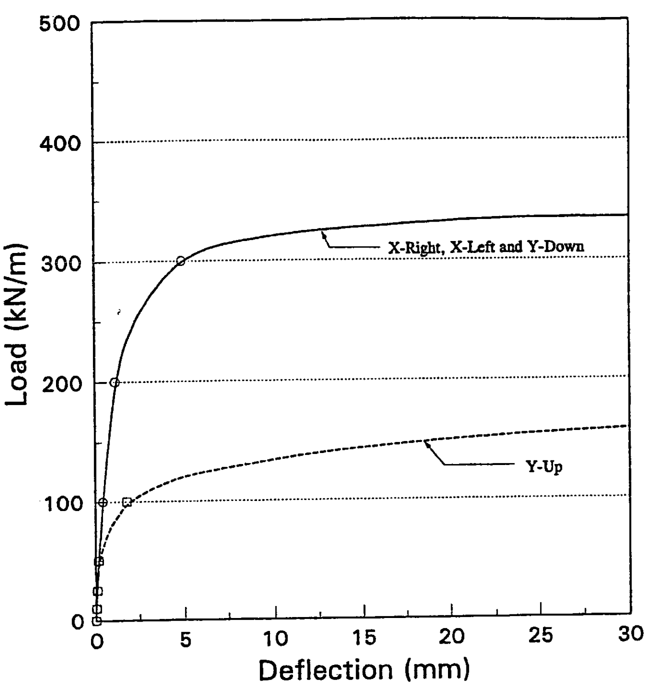


Fig. 7: Typical Trench Configuration and p-y curves





The watermains were installed in trenches that were shored using steel-caged shoring techniques. Field review services were carried out during construction to assess the stability of the trenches and to confirm that the backfill met compaction and material specifications.

In consideration of the heavy traffic volumes, potential disruption to the busy street and utility congestion, segments of the pipeline along Homer Street across Georgia Street and Smithe Street were installed using pipe-jacking methods. The watermains were constructed in till within a casing installed using pipe-jacking methods, with blasting of the boulders being required at the Georgia Street crossing. The remainder of the watermains were installed in trenches.

Following the initial phase of construction, a Value Engineering (VE) study was commissioned by the City with the goal of identifying the most cost-effective and least disruptive watermain designs and installation techniques. One of the main findings of the VE study was that increased production offered the best means of reducing costs.

As a result of this conclusion of the VE study, possible means of increasing production and reducing costs associated with the installation of the pipeline was studied in detail, as follows:

- Use a narrower and shallower trench wherever possible;
- Reduce the shoring requirements by incorporating hydraulic (or other) material placement;
- Techniques which would limit personnel-entry requirements; and
- Identify segments of trenches where the level of compaction is less critical.

As part of the review process, the strains that can be induced in the steel watermains as a result of propagation of seismic waves were reviewed in detail. Structural analysis confirmed that the strains that would be induced in the welded steel watermain, even with softened soils in the backfill, would not exceed acceptable limits, provided that there are no abrupt changes in watermain alignment and that the pipe is installed in a narrow trench excavated in competent soils. Following this assessment, it was decided that the level of pipe bedding backfill compaction could be reduced in some areas. While the backfill compaction effort was not generally relaxed, this analysis allowed Proctor compaction levels that were about 3 to 4% lower than the specified minimum (of 95% Modified Proctor) values to be accepted at certain locations.

The City undertook a pilot test program to assess the level of compaction that could be achieved in the pipe bedding materials using hydraulic placement techniques. In-situ density measurements were taken in the pilot program while varying parameters such as diameter of the spray nozzle, effective drainage requirements, material types, and procedural requirements etc. until reproducible and acceptable in-situ densities were achieved. The results of this pilot test program concluded that Modified Proctor compaction levels up to about 93% could be achieved provided that the backfill consists of free draining soils, the trench configuration/slope permits rapid drainage, water is hosed with a nozzle that is at least

50 mm in diameter, and trained personnel carry out the work.

The hydraulic placement method was utilized by the City crews in the subsequent DFPS trench work, with independent quality control testing. Only imported free-draining coarse structural backfill materials were used. This method of placement of pipe bedding materials permitted excavation of narrow trenches and construction work to be carried out without entry of personnel and compaction equipment into the trench. The process resulted in an increased rate of production and lowered costs.

Acknowledgements

Several individuals and Consulting Companies were involved in the DFPS project and their input to the formulation of the geotechnical design and construction concepts are acknowledged. In particular, we appreciate the efforts of Ted Ross of Donaldson Engineering (formerly with MTR Consultants Ltd.), Don Moore of City of Delta (formerly with City of Vancouver), Sandwell Engineering Inc., Peter Mickelson of Omni Engineering Inc., Dr. Bill McKevitt of McKevitt Engineering Ltd., and project personnel of the City of Vancouver.

The contents of this paper reflect project and site-specific requirements and procedures that have been established based on engineering analyses, discussions with experts, and using engineering judgement. They do not necessarily represent the design criteria and procedures followed by the City of Vancouver or the Consultants for other projects involving watermains, pump stations, and intake structures.

References

City of Vancouver Brochure on the Dedicated Fire Protection System.

Moore, D.E and Ross, E.C. 1996. Design Considerations for a post seismic fire protection system, AWWA Conference, San Francisco, USA.

Mickelson, P. and Moore, D.E. 1996. City of Vancouver, Dedicated Fire Protection System, Underground Piping Design Considerations, ASME Conference, San Francisco, USA.

Reid, T., Van Vliet, K. 1997, " A dedicated Water Supply System – Vital Part of Vancouver's Seismic Safety Concerns", Article in the Journal of Commerce, September 1, 1997, pp FS14.