Terasen Gas

Scott A. Thomson
VP, Finance & Regulatory Affairs and
Chief Financial Officer

16705 Fraser Highway
Surrey, B.C. V3S 2X7
Tel: (604) 592-7784
Fax: (604) 592-7890
Email: scott.thomson@terasengas.com
www.terasengas.com

Regulatory Affairs Correspondence
Email: regulatory.affairs@terasengas.com

May 11, 2006

British Columbia Utilities Commission
6th Floor, 900 Howe Street
Vancouver, B.C. V6Z 2N3

Attention: Mr. R.J. Pellatt, Commission Secretary

Dear Sirs:

**Re: Terasen Gas Inc. ("Terasen Gas" or the "Company")
Application for a Certificate of Public Convenience and Necessity ("CPCN")
Replacement and Upgrading of the Vancouver Low-Pressure Gas Distribution System to Distribution Pressure (the "Application")**

Pursuant to Section 45 of the *Utilities Commission Act*, Terasen Gas hereby files with the British Columbia Utilities Commission (the "Commission") twenty copies of its CPCN Application requesting approval for the replacement and upgrading of the Vancouver Low-Pressure ("LP") Gas Distribution System to Distribution Pressure ("DP").

Terasen Gas submits that prior construction methodology, practices and current system condition lead Terasen Gas to believe that the risk to the integrity of the Vancouver LP Gas Distribution System from ground disturbance, nearby excavation, and minor or significant seismic events, has exceeded acceptable levels. Utilities operating in similar seismic risk locations have also recognized the need or have been forced to undertake similar replacement programs.

Terasen Gas believes that potential consequences of a ground disturbance, excavation or a seismic event could result in gas service line and main ruptures which could leak gas in a manner difficult to quickly identify. The Company is of the view that this poses increased safety risks to Terasen Gas customers, employees, its contractors, and the general public.

With 2010 Winter Olympic activities slated to occur throughout the City of Vancouver (the "City"), Terasen Gas believes that the work to replace and upgrade the Vancouver LP Gas Distribution System to DP should be accelerated, in order to avoid loss of service at this critical time and to ensure that construction activities are not in progress during the period around the Olympic events. Ongoing coordination with City Planning Staff will ensure that the replacement of this section of the natural gas system is expedited most succinctly in conjunction with annual City paving schedules, to ensure cost effectiveness in this regard while maintaining a replacement schedule that aligns with the overall preparation for the 2010 Winter Olympics. Should a seismic event occur on the existing LP system, Terasen Gas expects that it is likely to experience a potential loss of service to a significant number of its customers. At the same time, Terasen Gas would have an extensive requirement for scarce resources, both human and material, to undertake repairs, making it extremely difficult for the Company to perform necessary emergency repairs in a responsive manner.

Terasen Gas respectfully requests that it be granted expedited approval to proceed with a scheduled replacement program. Due to the time constraints associated with the preparation for the 2010 Winter Olympics and concurrent with other infrastructure upgrade programs occurring in the affected areas in Vancouver, Terasen Gas proposes that it commence work in July, 2006 with project completion scheduled for December, 2008.

Terasen Gas will post this Application and all subsequent exhibits to its website at http://www.terasengas.com/_Publications/Regulatory/Submissions/LowerMainlandInterior/default.htm by May 13, 2006. If there are any questions regarding this Application, please contact Mr. Tom Loski, Director, Regulatory Affairs at (604) 592-7464.

Yours very truly,

TERASEN GAS INC.

Original signed by: Tom Loski

For: Scott A. Thomson

Enclosures

cc: Registered Intervenors in the TGI 2005 Annual Review

TABLE OF CONTENTS

LIST OF APPENDICES

IN THE MATTER OF THE UTILITIES COMMISSION ACT
R.S.B.C. 1996, CHAPTER 473

AND IN THE MATTER OF AN APPLICATION BY
TERASEN GAS INC. FOR
REPLACEMENT AND UPGRADING OF THE VANCOUVER LOW-PRESSURE GAS DISTRIBUTION SYSTEM TO DISTRIBUTION PRESSURE

To: The Secretary
British Columbia Utilities Commission
Sixth Floor, 900 Howe Street
Vancouver, British Columbia V6Z 2N3

1 APPLICATION

Terasen Gas Inc. ("Terasen Gas" or the "Company") hereby applies to the British Columbia Utilities Commission (the "BCUC" or the "Commission") pursuant to Section 45 of the *Utilities Commission Act*, R.S.B.C. 1996, Chapter 473, (the *"Act")* for a Certificate of Public Convenience and Necessity ("CPCN") for the replacement and upgrading of the existing Vancouver Low-Pressure ("LP") Gas Distribution System to Distribution Pressure ("DP"), Terasen Gas seeks approval of the following:

- Insertion and connection of polyethylene "PE" piping within the existing steel mains and services, (approximately 95 kilometres of main and 7100 services);
- Relocation of approximately 710 meter sets; and
- Removal and reclamation activities associated with 24 Low-Pressure Regulator Stations

(collectively, the "Project").

1.1 Applicant

1.1.1 Name, Address, and Nature of Business

Terasen Gas is a company incorporated under the laws of the Province of British Columbia and is a wholly-owned subsidiary of Terasen Inc., which in turn is a wholly-owned subsidiary of Kinder Morgan, Inc. Terasen Gas maintains an office and place of business at 16705 Fraser Highway, Surrey, British Columbia, V3S 2X7.

Terasen Gas is the largest natural gas distribution utility in British Columbia, providing sales and transportation services to residential, commercial, and industrial customers in more than 100 communities throughout British Columbia, with approximately 800,000 customers served on the mainland including the Inland, Columbia, and Lower Mainland service areas. Terasen Gas' distribution network delivers gas to more than eighty percent of the natural gas customers in British Columbia.

1.1.2 Financial Capability of Applicant

Terasen Gas is regulated by the Commission. Terasen Gas is capable of financing the Project either directly or through its parent, Terasen Inc. Terasen Gas Inc. has credit ratings for senior unsecured debentures from Dominion Bond Rating Service and Moody's Investors Service of A and A3 respectively Terasen Inc. has credit ratings for senior unsecured debentures from Dominion Bond Rating Service and Moody's Investors Service of BBB (High) and Baa2 respectively.

1.1.3 Technical Capability of Applicant

Terasen Gas has designed and constructed a system of integrated high, intermediate and low-pressure pipelines and operates more than 30,000 kilometres of natural gas transmission and natural gas distribution mains and service lines in British Columbia. This transmission and distribution infrastructure serves approximately 800,000 customers on the mainland.

1.1.4 Name, Title, and Address of Company Contact

Scott A. Thomson, C.A.
Vice President, Finance & Regulatory Affairs and Chief Financial Officer
Terasen Gas Inc.
16705 Fraser Highway
Surrey , B.C., V3S 2X7

Phone:	(604) 592-7784
Facsimile:	(604) 592-7620
E-mail:	scott.thomson@terasengas.com
Regulatory Matters:	regulatory.affairs@terasen.com

1.1.5 Name, Title, and Address of Legal Counsel

Cal Johnson, Q.C.
Fasken Martineau DuMoulin LLP
21st Floor, 1075 West Georgia Street
Vancouver, B.C. V6E 3G2
Phone: (604) 631-3130
Facsimile: (604) 632-3130
E-mail: cjohnson@van.fasken.com

1.2 Project Description

This Project consists of replacing all of Terasen Gas' remaining steel LP[1] gas system with distribution pressure[2] ("DP") polyethylene plastic ("PE") mains and services over a two and one-half year period. It is consistent with the work that has been already undertaken on the Terasen Gas system to reduce seismic risk as a result of investigations recommended by EQE International in our 1994 seismic risk assessment[3] (refer to Appendix A). Applying the philosophy and knowledge gained by working with the 1994 seismic risk assessment to identify other facilities that may warrant consideration from a seismic perspective, Terasen Gas identified the Vancouver LP Gas Distribution System as being at significant risk due to a seismic event. As the work on the facilities identified as a priority for the 1994 assessment nears completion, Terasen Gas believes that it is now appropriate to address its distribution facilities.

The existing Vancouver LP Gas Distribution System represents the last remaining sections of the original coal gas networks that served the Lower Mainland prior to the distribution of natural gas. As part of Terasen Gas's distribution network, the Vancouver LP Gas Distribution System now exclusively distributes natural gas. The remaining LP distribution system consists of approximately 95 km of mains, 7100 services, and 24 pressure regulating stations, located in five fully-developed, densely-populated neighbourhoods in the southern and western neighbourhoods within the City. Please refer to Section 3 for a more detailed description of the LP Distribution System.

[1] Low Pressure pipe in the Vancouver system generally operates at pressures of about 2 kPa.
[2] Distribution Pressure piping in the Terasen Gas system operates at pressures of 700 kPa or less, but generally no higher than 420 kPa.
[3] Seismic Risk Assessment of BC Gas Transmission and Intermediate Pressure Natural Gas Pipeline System in the Lower Mainland Region, EQE International, March, 1994

At this time, Terasen Gas is proposing to upgrade the existing LP system to Distribution Pressure (“DP”), which operates at approximately 420 kPa. Terasen Gas proposes to upgrade the system by inserting PE pipe into the remaining mains and services within the existing LP system. Terasen Gas is also proposing to remove 24 LP regulating stations and relocate approximately 710 meter sets.

Terasen Gas is proposing to upgrade the Vancouver LP Gas Distribution System in an accelerated fashion as compared to the current normal replacement strategy. An accelerated construction schedule is expected to be implemented in July of 2006. Development of design began earlier in the year, and costs incurred to date have been included in the total cost estimates of the Project. Completion is anticipated in December, 2008.

To determine which area would be addressed first, Terasen Gas considered repair history, water problems, the likelihood of redevelopment and the City’s repaving schedule. Based upon that information, Terasen Gas plans to commence with upgrading work in the Dunbar neighbourhood in 2006 and to then move to the Kerrisdale, Marpole, UBC, and Riley Park neighbourhoods in 2007 and 2008.

The total anticipated expenditure to complete the above noted works, including AFUDC, is estimated to be ***$23.7 million +/- 10%.*** A summary of these costs is provided below, with additional detail provided in Section 4.1 and Appendix B.

Table 1: Total Capital Cost Summary ($,000)

Description	**Project Total**
Project Management	$ 356
Mains	$ 13,386
Services and Meter Sets	$ 8,984
Station Removal	$ 376
Total Direct Construction and Station Removal Costs	$ 23,102
AFUDC	$ 645
Total Anticipated Expenditure (including AFUDC)	$ 23,747

This cost estimate is based on the Commission granting approval of this Application to Terasen Gas by July 1, 2006. Terasen Gas proposes that during construction, the actual costs associated with the Project be granted deferral account treatment, earning AFUDC, and that once the Project is completed, that these costs be recovered across all customer classes by the inclusion of all of these costs into the rate base of Terasen Gas.

1.3 Project Justification

The primary justification for the replacement and upgrading of the Vancouver LP Gas Distribution System is the risk to the integrity of the system from ground disturbances such as earthquakes and human derived seismic activity such as excavation.

The remaining LP system is composed of steel piping which was installed at least 50 years ago and has served its expected useful life. Due to its age, construction techniques employed at the time of installation and the fact that the system pre-dates the advent of anti-corrosion technology developments such as cathodic protection, Terasen Gas expects that the system will deteriorate at an accelerated pace and constitutes a risk to the integrity of the system as a whole. Upon review of its distribution records, Terasen Gas has identified that the LP pressure system is incurring leaks at a rate of approximately 19 times greater than the rate for relatively newer steel distribution pressure mains, which are believed to be attributable to these corrosion and outdated construction techniques. The PE pipe to be used in this Project lacks any similar deterioration mechanism.

Furthermore, Terasen Gas is concerned about the risk of a major system disruption in the event that Vancouver experiences a moderate to significant seismic event “earthquake”. The Lower Mainland is located in a zone highly prone to earthquakes and tremors. Southwestern British Columbia experiences approximately 300 small earthquakes per year and on average, experiences a significant seismic event every 10 years. Seismologists with the Geological Survey of Canada assert not only that a major destructive earthquake can occur at any time along the coast of British Columbia, but that there is a high probability that its residents will experience a moderate to strong earthquake in their lifetime.

Terasen Gas operates a LP system of a similar age and design to that operated by Pacific Gas and Electric’s (“PG&E”) in the San Francisco Bay area. In October, 1989 this region was shaken by the Loma Prieta earthquake. Many homes were deemed to be ‘uninhabitable’ and all of the LP services in these areas needed to be replaced following that event. The event significantly damaged PG&E's LP distribution system and disrupted service to 5400 customers. At that time, PG&E launched a large program to replace the bare steel and cast iron piping that was found in this area. Like Terasen Gas, at the time of the earthquake, the Company understands that PG&E operated LP distribution systems pre-dating current cathodic protection standards, which are not able to withstand a significant seismic event.

Terasen Gas believes that its proposal to upgrade the LP distribution system to DP through the use of PE pipe within mains and services will significantly reduce system integrity risk when a more significant seismic event does occur. The proposed system will have fewer joints of a more sound construction. Experience in other earthquake prone regions has shown that pipeline systems composed of PE piping have been better able to withstand ground movements and seismic events than metal piping. For example, when the 7.2 Richter scale Hyogoken-Nambu earthquake struck Kobe, Japan, in 1995 the local PE gas and water systems remained intact.

1.4 Regulatory Review of CPCN Application

Terasen Gas requests that the Commission complete its process to review this Application and reach a decision by July 1, 2006, therefore, Terasen Gas requests that review of this Application proceed by means of an expedited written review process.

2 Introduction

This Application requests that the Commission grant to Terasen Gas a CPCN for the replacement and upgrading of the Vancouver Low-Pressure (“LP”) Gas Distribution System.

As discussed in Section 3 of this Application, the Vancouver LP Gas Distribution System is composed of the last remaining sections of the original coal gas networks that served the Lower Mainland, dating back to as early as 1886. In 1956, the system was converted to exclusively distributing natural gas. The LP system consists of approximately 95 km of mains, 7100 services, and 24 pressure regulating stations located in five well established densely-populated neighbourhoods in the western portion of the City.

Terasen Gas believes that there is significant risk to the integrity of the system from ground disturbance. As a result, Terasen Gas believes that the replacement of the Vancouver LP Gas Distribution System is in the best interests of customers, employees and the public. As discussed in greater detail in Sections 4 and 5 of this Application, due to the current condition of the pipe in combination with past construction practices, even minor ground disturbances pose a risk to the integrity of the LP pipe. Terasen Gas believes that when a major seismic event does occur, there is significant risk that a large portion of the LP system will fail.

Terasen Gas believes that the approval of this Application will:

- Improve safety, reliability and integrity of the gas distribution system as a result of the installation of PE pipe and fittings;
- Reduce exposure to significant interruption of service for Vancouver LP Gas Distribution System customers due to a seismic event;
- Reduce exposure to costs associated with service reconnections to Vancouver LP Gas Distribution System customers following a seismic event;
- Reduce intrusion into customer’s premises as inside LP meter sets will be replaced with updated meter sets located outside;
- Increase system capacity to allow the addition of new customer load as a result of redevelopment or renovation thus avoiding inefficient system improvement scenarios;

- Facilitate the replacement of the Vancouver LP Gas Distribution System in a planned, cost effective manner utilizing sufficient resources;
- Reduce ongoing operating and maintenance activities related to the operation of the many pressure control stations associated with the Vancouver LP Gas Distribution System; and
- Reduce ongoing maintenance activities related to water removal and leak and break repair in the Vancouver LP Gas Distribution System.

Terasen Gas representatives have met with Mr. John Evans, Utilities Management Engineer at the City to discuss this Project. Terasen Gas will continue to work with the City as the construction schedule is finalized. The City is supportive of this Project, as it will allow for enhanced coordination with annual City paving schedules and avoid undesirable damage to the City's road infrastructure. Also, consistent with previous LP upgrade work, Terasen Gas will continue to schedule the replacement of the LP Gas Distribution System in conjunction with the City's repaving plans when feasible, as doing so will reduce the impact the combined work will have upon the public's lives and help control re-paving costs for the Project.

3 Background

3.1 History of the Vancouver LP Gas Distribution System

Manufactured coal gas, at a low pressure of approximately 2 kPa, was first distributed in the Lower Mainland to provide street lighting in Gastown prior to the incorporation of Vancouver in 1886. As the population increased, the Vancouver LP Gas Distribution System was expanded to meet demand. Available records indicate that by 1932 the length of LP gas main in the Lower Mainland was well over 800 km. The Company understands that LP gas main installation continued well into the 1950s.

In 1956 natural gas from northern British Columbia and Alberta was introduced to the Lower Mainland, eliminating the need for locally manufactured, more corrosive, environmentally hazardous, less safe and more costly coal gas. At roughly the same time, as a result of new knowledge regarding the corrosion of steel pipe, all new steel mains installed were coated and often had cathodic protection. Also, in order to efficiently support the population growth of the Lower Mainland, distribution system additions were designed to operate at higher pressures and therefore higher capacity with lower overall maintenance costs.

Over time, the aging Vancouver LP Gas Distribution System has experienced increased leakage and water ingress problems due to mechanical coupling, bell joint leakage and pipe corrosion. A recent comparison of frequency of leaks indicated that the frequency of leaks on the LP piping is 19 times that of the rest of the steel distribution system. In addition, the Vancouver LP Gas Distribution System has had insufficient capacity to cope with the demand increases within the neighbourhoods where the LP system operates.

During the 1970s and 1980s significant replacement of the Vancouver LP Gas Distribution System was undertaken, which resulted in most of the system being replaced. However, approximately 95 kilometres of LP mains still remain. It is understood that the primary criteria by which areas were replaced were leak history and the time required for emergency response. Also, in some instances, localized development and redevelopment contributed to the earlier replacement of specific sections of the LP gas distribution system. As a result of these criteria for replacement, many of the central locations of LP gas distribution system in Vancouver were not replaced.

With respect to the distribution system, Terasen Gas has and continues to make prudent expenditures while managing the risk profile of this asset, as part of its overall system integrity program. Of significant importance are the risks associated with third party damage, post earthquake emergency response, and indications of pipe deterioration. With respect to all three of these concerns, Terasen Gas is of the view that the operation of the Vancouver LP Gas Distribution System poses an unacceptable risk and thus the timely replacement of this system is necessary.

3.2 Seismic Integrity Upgrading Projects

The proposed replacement of the Vancouver LP Gas Distribution System is consistent with other seismic integrity work undertaken on Terasen Gas' facilities.

With respect to its facilities in the Lower Mainland, Terasen Gas has been concerned that some may be at an unacceptable level of risk due to the likelihood of a seismic event occurring.

In 1994, Terasen Gas commissioned a seismic risk assessment of its Lower Mainland facilities by EQE International of Oakland, California. The assessment focused on the Lower Mainland Transmission System, the key Lower Mainland stations, and intermediate pressure ("IP") pipelines greater than 219 mm diameter. Please refer to Appendix A to view a copy of the study. The assessment identified a number of sites that required further investigation due to risk from a seismic perspective. These investigations were undertaken and recommendations were prepared to mitigate high levels of seismic risk.

Since 1994, Terasen Gas has acted upon the recommendations developed for these sites and has completed the majority of the required stabilization and replacement projects, including:

- Stabilization of the Fraser Gate Station site in Vancouver;
- Stabilization of the Cape Horn Valve Station site in Coquitlam;
- Replacement of the IP pipeline crossings of the Nicomekl and Serpentine Rivers in Surrey;
- Replacement of a 610 mm transmission pressure pipeline crossing of the Fraser River with a 914 mm horizontally, directionally drilled crossing between Surrey and Coquitlam; and

- Replacement of the 508 mm and 609 mm IP crossings of Highway 1 at First Avenue in Vancouver.

As the work on the facilities identified as a priority by the 1994 assessment nears completion, Terasen Gas believes that it is now appropriate to address distribution facility seismic risk.

Terasen Gas has applied the philosophy and knowledge gained from the 1994 assessment to identify distribution system facilities that may warrant consideration from a seismic risk perspective. As a result, Terasen Gas identified the Vancouver LP Gas Distribution System and the Mission Intermediate Pressure (“IP”) System as being at significant risk due to a seismic event. The upgrade of the Mission IP system is not included in this Application, but will be the subject of a separate CPCN Application.

4 Project Description

4.1 Scope

The scope and methodology for the replacement of the Vancouver LP Gas Distribution System consists of replacing all of the remaining steel LP gas system with distribution pressure[4] ("DP") polyethylene plastic ("PE") mains and services using an "insertion" method over a two and one-half year period. The construction methodology involves inserting into an existing, larger-diameter steel LP pipe a new smaller diameter PE DP pipe. The insertion method significantly reduces the cost of underground installation by minimizing total excavation required. Furthermore, a new system of PE pipe will withstand ground disturbances much more effectively.

The Vancouver LP Gas Distribution System is located in an established, densely-populated area. Due to the work carried out in the 1970s and 1980s, the majority of the Vancouver LP Gas System has been replaced. However, still in service are approximately 95 km of LP main and 7,100 LP services to commercial establishments, residences, schools, and hospitals.

The remainder of the LP gas distribution system is generally located in five neighbourhoods that will be addressed in the order indicated in Table 2, with some exceptions due to municipal paving plans, redevelopment, and efficiency. A map showing the locations of the remaining LP gas system is included in Appendix C.

Table 2: Neighbourhoods with LP Gas System

	Neighbourhood	LP Main Remaining (km)	Services Remaining (#)
1	Dunbar	28	2861
2	Kerrisdale	29	1614
3	Marpole	22	1455
4	UBC	6	330
5	Riley Park	10	840

[4] Distribution Pressure piping on the Terasen Gas system operate at pressures of 700 kPa or less, but generally no higher than 420 kPa.

4.2 Capital Cost of Project

4.2.1 Project Cost Estimate

The total anticipated expenditure to implement the above noted works is estimated to be approximately ***$23.7 million +/- 10%.*** The estimated expenditure by year is indicated in the following table, with further detail provided in Appendix B.

Table 3 - Estimate of Projected Costs by Year ($'000's)

Line Item	2006	2007	2008	Total
Project Management				
Project Management	140	90	45	275
Training & Evaluation	40	20	21	81
Mains				
Labour - Company	752	958	994	2,704
Labour - Contract	2,032	3,274	3,540	8,846
Materials	446	679	712	1,836
Services & Meter Sets				
Labour - Company (including permits)	554	725	689	1,967
Labour - Contract	1,284	2,223	2,053	5,560
Materials				
Service	278	455	410	1,143
Meters & Regulators	44	72	65	181
Electrofusion PTT	31	54	48	132
Stations				
Company field labour - station removal	30	61	56	147
Surface Rehabilitation - station removal	45	95	89	229
Total Direct Costs	**5,674**	**8,706**	**8,723**	**23,102**
AFUDC	158	243	244	645
Total Planned Project Costs	**5,832**	**8,949**	**8,967**	**23,747**

Please refer to Appendix B, which contains a more detailed breakdown of costs.

4.2.2 Cost Estimate

The primary risks to cost, and schedule, for this Project consist of the availability of contract resources and the effect on local construction and labour rates due to an anticipated reduction of available labour during the years leading up to the 2010 Olympics.

Terasen Gas is of the view that the planned use of Project-dedicated contractor personnel, as opposed to assigning work to Company personnel on a piece meal basis, will help ensure that overall costs for this Project will not exceed estimated values. As well, to secure contractor resources, Terasen Gas has tendered a four-year construction services contract for this Project, which would include the work contemplated for the Mission IP Project, the subject of a separate CPCN application, and is in the contract-awarding phase at present. Terasen Gas is very confident that the contractor portion of the estimates provided herein will be consistent with the estimates that it has evaluated during the bid process. Section 9 provides further detail on the bid process.

4.2.3 Project Schedule

It is proposed that the replacement and upgrading of the Vancouver LP Gas Distribution System will be undertaken over a two and one-half year period with completion anticipated in December, 2008. As stated in Section 4.2.2, Terasen Gas believes that the primary risk to meeting the proposed schedule is the availability of contract resources. This will be mitigated by the terms of the contract (refer to Section 9.2 regarding the contractor resource).

The annual components of the replacement program will be planned during the winter months of the previous year to allow the start of construction early the following year. The replacement plan for 2006 has been prepared and is ready to be implemented. The plan will be presented to the City Planning Staff for review in late May, 2006.

To determine which area would be addressed first, Terasen Gas considered repair history, water problems, the likelihood of redevelopment and the City's repaving schedule. By scheduling replacement work based upon these criteria, a reduction in maintenance expenditures of approximately $49,400 is anticipated during 2007. In addition, the first year's work will address some key capacity concerns.

Only one critical date exists and that is with regard to the approval of this Application. It is requested that this approval be granted by July 1, 2006 to facilitate Terasen Gas taking advantage of work volume discounts in order to manage the total cost of this Project (refer to Section 9.2 regarding the contractor resource).

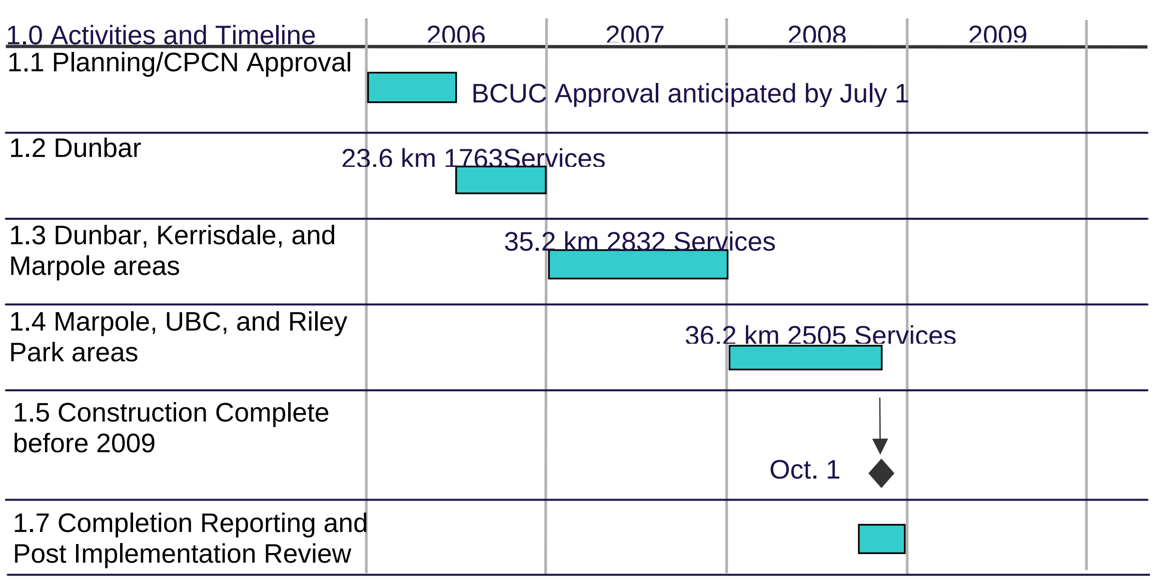
Phase 1: Dunbar (2006)

- A large number of leaks have been identified and repaired. Due to the frequency and severity of leaks this is the area of greatest concern;
- The system pressures are lowest with respect to serving existing and new customers;
- Growth in the middle of this area will necessitate significant unplanned system reinforcement; and
- There are 5 stations in this area that, in addition to not meeting current company design standards, have concerns with respect to Workers Compensation Board ("WCB") regulations.

Phase 2 – 5: Kerrisdale, Marpole, UBC, and Riley Park (2007 and 2008)

- A significant number of leaks have been identified; and
- There are 3 stations in these areas that, in addition to not meeting current company design standards, have concerns with respect to WCB regulations. The remaining 16 stations will be removed as the system is upgraded.

Table 4 - Vancouver Low-Pressure Replacement Project Schedule



4.3 Physical, Social and Environmental Impacts

4.3.1 Impact of Construction

The undertaking of a Project such as this could have a significant effect upon the daily lives of the public. Construction will result in an increase in vehicle traffic and noise in the neighbourhoods and could pose a safety hazard. Gas service will have to be disrupted in order to perform the work required. Safety and minimizing the impact of construction to the public is of highest priority to Terasen Gas. While Terasen Gas does not believe it is possible to eliminate these concerns, the Company works very closely with contractors to achieve those goals. The impact that the construction will have upon the customers and the general public will be mitigated through the following means:

- employing an effective communication plan;
- ensuring job site safety;
- ensuring environmental protection; and
- optimal external coordination.

4.3.1.1 Mitigative Measures

The impact the construction will have upon the customers and the general public will be mitigated by employing an effective communication plan; ensuring job site safety and environmental protection; and striving for external coordination.

4.3.1.2 Communication

Extensive communication will occur with affected residents as Terasen Gas prepares to replace each section of the Vancouver LP Gas Distribution System. It is anticipated that public communication will initially take the form of a written advisement, followed by direct contact with each resident to discuss his or her concerns. The general public and the customers of Terasen Gas will also be provided with key contacts to call if they have specific concerns that are unaddressed by the general communication.

Construction work will be undertaken in consideration of the public's and customer's routine whenever practical. Gas service will be restored in a planned manner so as not to significantly disrupt affected residents' regular lifestyle schedules.

4.3.1.3 Jobsite Safety

Worker and public Safety, as with all Terasen Gas projects, is of key importance as this Project proceeds. Terasen Gas will require that the work site will be left in a manner that does not pose serious risk to the general public or its customers.

During construction, the methodology for the replacement of the Vancouver LP Gas Distribution System will consist of inserting a new smaller diameter PE DP pipe into the existing larger-diameter steel LP pipe. The intention of the proposed methodology is to minimize excavation and hence the risk and significant costs associated with open excavations. As insertion requires much less excavation, it poses a minimal hindrance to pedestrian and vehicle flows and allowing greater ease of access to property.

Generally, any work carried out will meet the requirements of the B.C. Occupational Health and Safety Regulations which focus on worker safety. As well, the safety requirements contained in the provincial Gas Safety Regulations and Gas Safety Code will be met in order to ensure public and customer safety.

4.3.1.4 Environmental Protection

Following a seismic event, the insertion method would not be as viable an alternative due to the extensive soil shifting and filling in of the existing pipes. As a result, widespread system replacements that would be required would likely have to be carried out using open excavation, since the existing, affected pipe would not yield the clearance required for the insertion methodology to be employed. When compared with excavation, the planned used of the insertion method will allow Terasen Gas to carry out the replacement work by using permitted utility running lines without having to conduct significant excavations within existing thoroughfares and property. As a result of less excavation, silt run-off prevention measures are simplified and reduced, and excavation work near waterways can be avoided.

4.3.1.5 External Coordination

Terasen Gas will also be attempting to schedule the replacement of the LP Gas Distribution System in conjunction with the City's repaving plans. This will reduce the impact the combined work will have upon the public's lives and help control re-paving costs for the Project.

4.3.2 Benefits

This Project is in the interests of customers, employees and the general public. This Project will bring the following benefits both initially and over the long term.

4.3.2.1 Safety

The installation of polyethylene plastic pipe and fittings will result in improved safety, reliability and integrity of the gas distribution system. It will almost eliminate the risk to approximately 7,100 customers of a significant gas distribution service interruption if a seismic event were to occur while the LP system was still in operation.

4.3.2.2 Reduced Risk of Event Driven Costs

Conducting this work now will reduce the potential risk to all customers for the significantly increased costs of service reconnections to Vancouver LP Gas Distribution System customers after a seismic event.

4.3.2.3 Reduced Operational Costs

This replacement will reduce ongoing operating and maintenance activities, and thus costs, related to the operation of the many pressure control stations associated with the Vancouver LP Gas Distribution System and the necessity for water removal and leak and break repair in the Vancouver LP Gas Distribution System. This is discussed in more detail in Section 5.4.

4.3.2.4 Capacity Improvements

The upgrading of the system to distribution pressure will facilitate the addition of new customer load that currently cannot be handled by the LP system, thus avoiding dissatisfied customers and, as well, preventing inefficient system improvement scenarios.

4.4 Project Impact on Service Area

As stated in Section 2, Terasen Gas is of the view that this Project will deliver significant safety and service benefits to the five neighbourhoods served by the existing LP system. (refer to the drawing included in Appendix C). As well, this Project, although not expanding the service area, will increase system capacity to allow the addition of new customers and new customer load as a result of increased density through redevelopment or renovation occurring in these areas, thus avoiding inefficient system improvement scenarios.

5 Project Justification

5.1 System Integrity

The primary justification for the replacement and upgrading of the Vancouver LP Gas Distribution System is the significant risk to the integrity of the system from ground disturbance. Due to past construction practices and techniques, and the current condition of the piping, even minor ground disturbances nearby pose a risk to the integrity of the pipe, with the result often being gas leakage.

Terasen Gas has a number of concerns regarding the integrity of the existing Vancouver LP Gas Distribution System, but believes that the replacement of the existing steel system with a DP PE system will address these concerns. Specifically these concerns are as follows:

5.1.1 Cathodic Protection

The Vancouver LP Gas Distribution System has been operated since its installation with no coating or poor coating and no cathodic protection. When originally constructed, cathodic protection was not mandated by industry standards; however, later, it was realized that cathodic protection is a key component of the overall integrity of any steel pipeline system. Cathodic protection cannot be cost effectively applied to the Vancouver LP Gas Distribution System due to the amount of bare steel pipe and, as a result, based on excavations of the Vancouver LP Gas Distribution System, the Company is aware that there are instances where the pipe has corroded completely through (refer to photographs contained in Appendix D). Recent calculations indicate that the frequency of leaks on the LP piping is 19 times the frequency of the rest of the steel distribution system. As such, in many locations, it is likely that the LP gas is only contained by the compacted soil surrounding the pipe and when this soil is disturbed leakage will occur. As well, if this soil is disturbed when the ground is saturated with water, the result is the intrusion of water into the system that often interrupts service to our customers by filling the service line or house piping with water or ice.

5.1.2 Pipe Joining Methods

Over time three methods were primarily used on the LP system to join sections of pipe together. While each of these methods was considered efficient at the time, over time each of them has gradually become problematic. These methods, described in greater detail below, include single pass gas pipe welds, bell and spigot joints and mechanical couplings.

5.1.2.1 Single Pass Oxyacetylene Gas Welds

Steel pipe installed in the LP system before the mid-1950s was often joined by a single-pass oxyacetylene gas weld. This type of joint has a large heat-affected zone and potentially higher carbon content than if the joint had been arc welded or a multi-pass oxyacetylene weld. Consequently, the older LP joints are more brittle than newer multi-pass oxyacetylene or arc welded joints.

LP pipe welds were removed from separate locations in the LP system for chemical and metallurgical analysis in 1994 following two instances of partial circumferential weld failures on a 323 mm steel LP main caused by ground disturbance from adjacent municipal construction work. The resulting analysis indicated that the method of oxyacetylene gas welding, coupled with poor workmanship when aligning the pipe ends, produced welds that were likely to fail prematurely.

5.1.2.2 Bell and Spigot Joints

Many LP steel mains were joined by bell and spigot joints, or sleeves and crosses, which were sealed with lead and hemp. The integrity of this type of seal depended upon the moisture content of the manufactured gas swelling the hemp between the bell and spigot. With natural gas replacing manufactured gas in 1957, the moisture content of the gas became significantly lower and consequently leakage from these joints has increased over time. It is not known today how many of these joints remain in the system, but it is believed that the number is significant.

5.1.2.3 Mechanical Couplings

LP steel mains were also often joined by mechanical couplings. These couplings were used to make connections to new main extensions and for repair purposes. It is believed that there are a number of unrecorded, unanchored mechanical couplings installed in the LP system. The couplings are highly susceptible to failure, i.e. pull out, during ground disturbance.

5.1.3 Isolation Valves

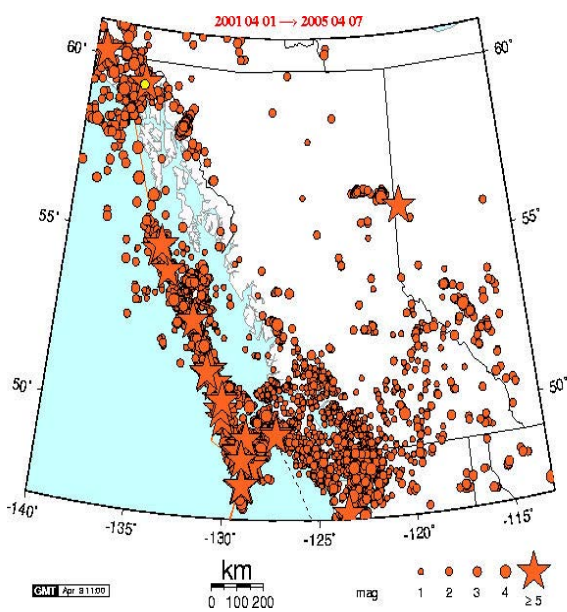
The Vancouver LP Gas Distribution System does not have any isolation valves because they were not required by industry standards at the time of construction. Complicating the implementation of any plan to install isolation valves is the fact that LP systems typically have multiple stations and feeds serving the same area. This would necessitate many valves to isolate any particular section of main to the point of being very impractical. This makes emergency and routine maintenance more difficult, as multiple bag-off operations are needed to stop the flow of gas. In the event of an earthquake, system isolation would become next to impossible. The replacement DP system will have isolation valves installed and as well PE pipe can be squeezed off quite easily to control the flow of gas.

5.2 Seismic Risk

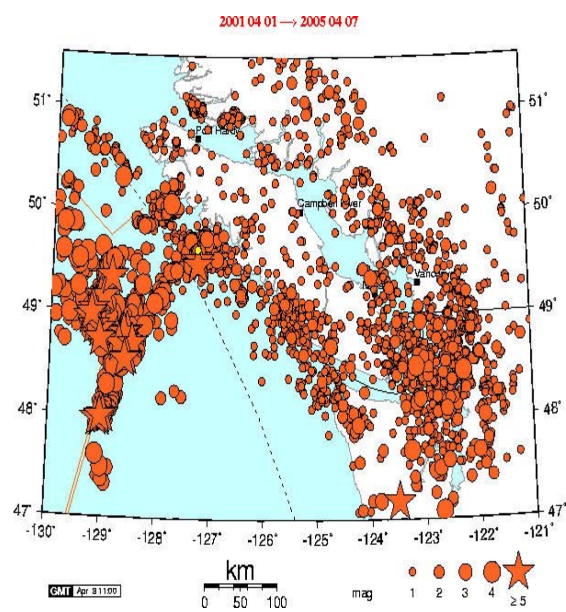
An area of significant concern is the possibility of a significant seismic event. As a result of past world wide events Terasen Gas is of the view that continued operation of the Vancouver LP Gas Distribution System poses a significant risk of damage or rupture during a major, or minor seismic event.

The following information, from the Earthquakes Canada website and database of Natural Resources Canada, indicates the seismic events that occurred in B.C. and the Lower Mainland / Vancouver Island area over a four year period up to April, 2005. These figures show that large numbers of earthquakes are occurring on a regular basis and demonstrate the high concentration of earthquakes in the Lower Mainland and Vancouver Island.

B.C.



Lower Mainland / Vancouver Island



Fortunately, the seismic events that have been felt in Vancouver have been no more than minor tremors and little damage, to date, to the Vancouver LP Gas Distribution System can be attributed to them; however, seismologists, according to the Geological Survey of Canada, now know that a major destructive earthquake can occur at any time along the coast of British Columbia. Exactly when the earthquake will happen cannot be predicted, but there is a high probability that inhabitants of the Canadian West Coast will be shaken by a moderate-to-strong earthquake during their lifetime[5].

The Juan de Fuca and North America plates are currently locked together, causing strain to build up in the earth's crust. It is this squeezing of the crust that causes the 300 or so small earthquakes that are located in southwestern British Columbia each year, and the less frequent (once per decade, on average), damaging crustal earthquakes, one example being the magnitude 7.3 earthquake on central Vancouver Island in 1946. At some time in the future, these plates will snap loose, generating a huge offshore "subduction" earthquake - one similar to the 1964 M 9.2 Alaska earthquake, or the 1960 M 9.5 Chile earthquake. Current crustal deformation movements in this area provide evidence for this. There is also geological evidence indicating that huge subduction earthquakes have struck this coast every 300-800 years[6].

5.2.1 Extent of System Damage

Based on the experience of U.S. gas distribution companies that have experienced a significant seismic event on their LP systems, the ground motions of a significant earthquake would likely result in a large number of joint failures and gas leaks on the fragile Vancouver LP Gas Distribution System.

The Loma Prieta earthquake, Richter Magnitude 7.1 and lasting 10 – 15 seconds, caused significant damage to the Pacific Gas and Electric LP system. In three cases, as described in Table 5, the complete loss of the systems resulted. This demonstrates that considerable damage to a LP system comparable to the Vancouver LP Gas Distribution System has happened as a result of a significant seismic event. Terasen Gas serves approximately 7,100 customers via its Vancouver LP Gas Distribution System and believes it would experience similar destruction or even greater considering the potential for a much more significant earthquake as described above.

[5] As stated in “Prepare to Survive a Major Earthquake”, Government of Canada

Table 5: Impact of Loma Prieta Earthquake

Name of System	Method of Shutdown	Number of Services Affected	Number of Customers Affected
Watsonville	3 LP regulator stations	144	160
Los Gatos	2 sectionalizing valves	130	140
Marina District	1 LP regulator station and 12 sectionalizing valves	1,590	5,100

As a result of the effect the Loma Prieta earthquake had upon the LP systems belonging to Pacific Gas and Electric, the natural gas industry has learned that in order to withstand the effects of permanent ground displacement, buried piping must either have the ability to move with the ground, or sufficient strength to force the ground to move around the pipe. Older piping is much more susceptible to damage from permanent ground displacement because of weaknesses from corrosion, outdated construction methods or less sturdy materials. The response of buried piping depends on a number of factors, including joint strength, wall thickness, diameter, material properties, soil strength, and the amount and variation of ground displacement associated with the earthquake hazard (California Seismic Safety Commission, 2002).

By replacing the existing LP steel system with a DP PE system service, reliability of the system will be significantly increased. A PE system will have fewer and very much sounder joints and will lack any significant deterioration mechanism. As a result of investigations of past events, it has been found that PE systems can normally resist ground movement and subsidence without problem. An extreme example of this was the 1995, Richter 7.2, earthquake in Kobe, Japan. The PE gas and water systems survived and remained intact while multiple failures occurred in pipelines made from other materials.

5.2.2 Extent of Emergency Response

Terasen Gas is well prepared to respond to a routine emergency on the Vancouver LP Gas Distribution System. Emergency plans, procedures, and infrastructures are in place and

[6] Taken from British Columbia Institute of Technology Civil and Structural Engineering Technology Program Unit 1: Earthquakes

company personnel are trained to respond to any scale of emergency; however, given the vulnerability of the Vancouver LP Gas Distribution System to ground movement and the lack of isolation valves on the system, Terasen Gas might not be able to deploy a quality and timely emergency response due to circumstances following a seismic event.

The circumstances after a major earthquake might include the following:

- The earthquake will likely rupture many LP mains and cause the soil to shift around other mains that have holes in them;
- Broken mains and holes will silently release LP gas;
    - LP gas escaping from a broken main does not have enough energy to displace the soil above it and draw attention. (In contrast, a broken DP main will displace some soil above and be more visible and easily detectable.)
- Escaping LP gas will spread out under and through typical street infrastructure such as roads, sidewalks, driveways, and storm lines;
- Ground saturated with water will cause water to enter the system through the breaks and holes; and
- Transportation corridors will be congested and impassable.

Due to the complex interconnected network of mains, Terasen Gas does not have any continuously monitored telemetry on the Vancouver LP Gas Distribution System. Telemetry, even at several locations, would not provide useful information due to the multiple flow paths of the gas. Based on prior emergencies, it is anticipated that the exceptionally high and immediate demand on the public telecommunications networks, combined with system damage that will occur, will result in a shut down of the public telephone system immediately following a significant seismic event. Transportation corridors will likely be blocked. As Terasen Gas' emergency response depends on field intelligence, based partially on public feedback and clear transportation corridors, Terasen Gas may not be able to manage emergency response on the Vancouver LP Gas Distribution System in an effective, efficient and timely manner. This will mean that Terasen Gas will not be able or available to pro-actively search for leaking LP mains and services.

When the emergency response on the Vancouver LP Gas System is completed after a major earthquake, Terasen Gas will be faced with the enormous task of identifying the customers who have lost gas service, shutting their gas meter off, replacing the LP system, and relighting affected customers. Mains and services may be severed, not line up any more or be plugged with soil, preventing the quicker and more economic insertion method of repair, thus further delaying the return of service to customers.

After experiencing the devastating impact of the Loma Prieta[7] earthquake, Pacific Gas and Electric required the following resources.

Table 6: Pacific Gas and Electric Resource Requirements (Loma Prieta)

LP System	Length of LP Main Replaced (km)	Main Replacement (days)	Resources Required	Hours Worked per Day
Watsonville	2.0	18	7 crews of 3 people	10
Los Gatos	2.2	7	2 crews of 25 people	24
Marina District	16.2	24	• 400 construction people • 100 service people • 20 estimators	12 hour shifts
Total	**20.4**	**49**		

5.3 Improved Emergency Response Flexibility

Terasen Gas will continue to be able to provide safe and reliable service to its customers as a result of completing the work described in this Application. Because the proposed PE DP mains and services will maintain their integrity when either seismic events or adjacent excavation occurs, fewer gas leaks and incidents of emergency response are expected, which should allow Terasen Gas personnel to focus on other emergency matters and, therefore, should translate into faster emergency response times and service restoration.

[7] The Loma Prieta Earthquake occurred on October 17, 1989, at a magnitude of 6.9 (moment magnitude; surface-wave magnitude, 7.1). The earthquake severely shook the San Francisco and Monterey Bay regions.

The training provided to the contractor to carry out the replacement of the Vancouver LP Gas Distribution System will translate into additional resources to undertake other repairs when the need arises. This will support Terasen Gas' objective to undertake repairs in an effective, timely manner.

5.4 Reduced Maintenance and Repairs

There are four categories of failures which have historically been experienced on the Vancouver LP Gas Distribution System:

- Fitting and joint degradation leaks;
- Corrosion leaks;
- Ground movement breaks; and
- Third party damage incidents.

Terasen Gas has implemented monitoring programs to identify LP mains that are experiencing leak and break events. Despite numerous efforts to remediate and manage the Vancouver LP Gas Distribution System, leak and break frequencies for the LP system are significantly higher than the frequencies associated with gas mains constructed from protected steel and polyethylene materials.

The replacement of the Vancouver LP Gas Distribution System will result in a significant reduction in the number of service delivery problems and resource requirements due to water getting into the system. Over the last 3 years, Terasen Gas has spent approximately $135,000 annually to ensure that the Vancouver LP Gas Distribution System provides reliable service to its customers. This involves pumping water out of sections of the system and relighting customers who lose service due to low system pressure or water that makes its way into the system. These types of expenditures should not be required on the newer steel or on the proposed PE DP system installations.

There have been several incidents where water main breaks have resulted in damage to the LP system. Each such occurrence invariably affects a number of customers whose gas service is interrupted. As a result, inconvenient re-lights must be coordinated between Terasen Gas and the customers affected.

5.5 Reduced Operating Requirements and Costs

Replacement and upgrading of the Vancouver LP Gas Distribution System will allow Terasen Gas to eliminate approximately $62,600 in recurring operational costs associated with LP regulating stations. Removal of the remaining 24 LP regulating stations will reduce operating requirements by eliminating training needs for station mechanics who maintain and operate the stations, chart changing expenditure, and the costs associated with maintaining LP parts inventory.

5.6 Reduced Capital Upgrades

Replacement of the Vancouver LP Gas Distribution System will allow Terasen Gas to avoid a number of capital upgrades to this system. Contained in Appendix E are photos of a typical LP station of concern and a typical IP station that meets WCB requirements.

Replacing and upgrading of the Vancouver LP Gas Distribution System and tying it into the existing DP system will allow removal of all of the existing LP regulating stations. The avoided capital expenditure will be between $720,000 and $1,680,000 depending upon the actual deficiencies existing at each station and site restrictions due to the following considerations:

- Over time the WCB Occupational Health and Safety Regulation has been updated to ensure worker safety. Significant changes have occurred with regard to ergonomic and de-energization requirements. With respect to the requirements of both of these issues, the existing stations are deficient in varying degrees. The obvious ergonomic difficulty is that the maintenance technician must lie on his front while attempting to perform equipment checks and testing and also contend with poor lighting. With regard to de-energization the stations lack isolation valves and thus when the technician performs work “bagging off” or “double bagging off” is necessary to ensure worker safety; however, in performing these operations, the worker may be exposed to leaking gas.

- Many of the remaining 24 LP regulating stations do not meet the current Terasen Gas pressure control station design standards. If this work were to not take place, capital upgrades would likely be required on all LP regulating stations to bring them up to the current applicable standard.

6 Cost of Service Impact

Terasen Gas is requesting that it be granted permission to add total Project expenditures to rate base, in the year immediately following completion. This proposed treatment of costs is consistent with that which has been approved in past proceedings for other system integrity initiatives which have been deemed to be in the interests of both customers and of the utility. Furthermore, as work will be completed and put into service on a main-by main or “block-by-block” basis, Terasen Gas seeks as part of the approval to add work completed in each calendar year to rate base with amortization commencing in the following year. AFUDC will be earned on the asset before it goes into rate base.

Based upon the total construction cost estimate of $23.747 Million (including AFUDC), Terasen Gas has estimated that over a 5 year period (2007 to 2011), on a levelized basis, the average cost of service is $1.457 Million. When compared to the approved 2006 delivery margin of $494.672 Million, this equates to an effective increase of approximately 0.29%.

7 Other Applications and Approvals

7.1 Design, Construction and Operations

Design and construction approvals for the replacement of the Vancouver LP Gas Distribution System will be obtained from the City in accordance with established agreements. Terasen Gas representatives have met with City officials and described the Company's plans and received a favourable response to this work with no unusual concerns identified.

Terasen Gas has also discussed this Project with the British Columbia Safety Authority and has received its support for this work. A Provincial Gas Inspector will work with Terasen Gas as this Project proceeds.

7.2 Site Rezoning and Land Purchase

Site rezoning and land purchases are not required for the work associated with the Replacement and Upgrading of the Vancouver LP Gas Distribution System.

7.3 Private Land Rights and Access Road Use

Private land rights and access road use will be in accordance with established agreements and repairs will be completed to the standard existing prior to the work being undertaken.

8 Public Consultation

Extensive communication will occur with residents as Terasen Gas prepares to replace each section of the Vancouver LP Gas Distribution System. It is anticipated that public communication will initially take the form of a written advisement followed by direct contact with each resident to discuss his or her concerns. The general public and the customers of Terasen Gas will also be provided with key contacts to address any of their specific concerns which are unaddressed by the general communication.

9 Resource Requirements

9.1 Organization

An experienced project manager, who will be assisted by a project specialist, will direct project management and design.

Mechanical and system design will be provided by in house engineering resources; however, any geotechnical design will be outsourced. Mechanical design is expected to be minimal as the new PE system will rely on standard materials and components.

Due to the significant volume of work, actual replacement of the Vancouver LP Gas Distribution System with standard DP system components will be carried out by contractor personnel, trained and monitored by experienced Terasen Gas installation personnel. Contractor resources are discussed further in Section 9.2. The contractor is expected to ensure that public and worker safety, quality work, and customer satisfaction are of highest importance.

In summary, the following table indicates the resources required.

Table 7: Service Resource Requirements

Contract	**Requirement Duration**
Project Manager	Initially requiring full time commitment, will decrease to 33% during last year
Prime Contractor	Throughout project for all mains and services
Paving	Throughout project (City of Vancouver)
Flagging	Throughout project
Terasen Gas	
Project specialist	Will decrease as project proceeds
Instructor	Training period at beginning of project and worker evaluation throughout
Installation crew	5 km of main and 310 services in each year and removal of stations as required
Distribution Mechanic 1	System pressure and flow control throughout project during contractor work
Install Coordinator 1	Planning of services and customer relations throughout project
Customer Service 1	Alter meter sets and house-piping as required throughout project

9.2 Contractor Resource

To accomplish the replacement of the Vancouver LP Gas Distribution System over the estimated Project term of two and one-half years, it was necessary to secure, through Terasen Gas' established RFP process, a qualified contract construction workforce for the entire period. This was done by adding the LP work to the scope of the four-year standard construction services contract, so as to secure the resources required, and to achieve a better pricing scenario for the related types of construction work including that required for the Mission IP project which is the subject of a separate CPCN application by Terasen Gas.

The intent is to award the construction services contract to a single contractor in order to provide the contractor with a base line level of work for the term of the Project. Terasen Gas has received bids from several companies interested in carrying out the work described in the construction services contract. Upon review of the tenders received it is evident that this has resulted in favourable construction rates. However, based on the terms of the tender and form of contract it is important that this Project be initiated as quickly as possible so that the contractor can obtain equipment and mobilize personnel in a timely manner and thus at reasonable cost. However, based on the terms of the tender and form of contract, it is important that this Project be initiated as quickly as possible so that the contractor can obtain equipment, mobilize personnel in a timely manner, and take advantage of the summer construction period, resulting in cost savings for the Project. A delay in awarding and initiating the work will result in higher unit costs and thus will increase the total cost of the Project.

It is intended that the construction services contract will include the following terms:

- Tiered pricing based on volumes of LP replacement work;
- Contract award date of June 1st, 2006 and an expiry date May 31st, 2010;
- Option to renew every 24 months;
- CPI increases every second year;
- Pay items for sand and gravel, traffic control, saw cutting, and trucking;
- Requirement for quality framework and reporting; and

- Factory focus performance breakdown measures and controls.

Any contractors hired to carry out work are required to conform with all existing Occupational Health and Safety Regulations and will be expected to take all reasonable measures to ensure there is no additional risk to the safety of the public as a result of the work. As such, their performance will be measured to ensure high standards of public and worker safety; quality work; and customer satisfaction are maintained throughout the term of the contract.

9.3 Materials

The majority of the materials used for this Project are standard materials used in Terasen Gas' gas distribution system, namely PE pipe and fittings; however, as a result of the significant size of the Project, Terasen Gas feels that it is the opportune time to expand the use of two new technologies for the benefit of its customers.

9.3.1 OPCO Regulators

Terasen Gas has recently worked with the BC Safety Authority to be granted approval to use a new type of regulator throughout its system. The OPCO regulator is similar to existing technologies; however, it has an additional safety feature that prevents the venting of gas when the regulator senses a downstream pressure that is too high. The primary benefit of this feature is that the BC Safety Authority was able to approve its use with reduced clearance requirements (i.e. less than those specified by the B.C. Gas Safety Code), allowing for greater flexibility with respect to meter set location and a lower probability that costly regulator vent piping will be required[8]. The incremental cost of implementing this new technology is approximately $150.00 per regulator installed; however often this cost will be the lower cost option compared to either extending the service to a regulation compliant location or installing regulator vent piping from a traditional regulator. Terasen Gas expects to install approximately 2100 of these regulators throughout the areas associated with this Project.

9.3.2 Electrofusion Joints and Service Tees

Terasen Gas has been introducing electrofusion fittings into its system on a gradual basis; however, with the increasing sophistication of the associated control devices Terasen Gas believes that this Project is an opportunity to expand the use of electrofusion joints and service fittings due to lesser training requirements and greater control over fusion quality and records. The expected incremental cost of implementing this technology is approximately $21.00 per main connection; however, this is offset by fewer training requirements and higher fusion quality.

[8] Clearance and venting requirements are specified in the B.C. Gas Safety Code.

Appendix A

Seismic Risk Assessment of BC Gas Transmission and Intermediate Pressure Natural Gas Pipeline System in the Lower Mainland Region, EQE International, March, 1994

Appendix B

Cost Estimate Calculations

Appendix C

Map

Appendix D

Photographs of corroded pipe

Appendix E

Typical LP Station – Ergonomic and De-energization Concerns

Typical IP Station – Easy Access and Isolation Valves

Appendix A

R.A. DANGLEY

EQE INTERNATIONAL

SEISMIC RISK ASSESSMENT OF BC GAS TRANSMISSION AND INTERMEDIATE PRESSURE NATURAL GAS PIPELINE SYSTEM IN THE LOWER MAINLAND REGION

March, 1994

Prepared for:

BC GAS INC.
1111 West Georgia Street
Vancouver, British Columbia
CANADA

EQE INTERNATIONAL

INTERNATIONAL

SEISMIC RISK ASSESSMENT OF BC GAS TRANSMISSION AND INTERMEDIATE PRESSURE NATURAL GAS PIPELINE SYSTEM IN THE LOWER MAINLAND REGION

March, 1994

Prepared by:

EQE INTERNATIONAL, INC.
18101 Von Karman Ave, Suite 400
Irvine, California
UNITED STATES

TABLE OF CONTENTS

ATTACHMENTS

TABLES

FIGURES

EXECUTIVE SUMMARY

A systematic review of seismic risks has been completed for the BC GAS Lower Mainland natural gas distribution system. The scope of this review included transmission and large diameter (greater than NPS 8) intermediate pressure pipelines and the associated aboveground facilities. In addition, a review was performed of the aboveground facilities between Hope and Huntingdon where gas is obtained directly from the West Coast Energy transmission pipeline. Pipelines located on bridges were not included as part of the scope for this risk assessment. Lateral spread movement associated with liquefaction is the principal hazard to the pipelines. Wave propagation and local subsidence was evaluated as being generally unable to produce sufficient levels of strain in the pipe to lead to rupture under the conditions assumed for the risk assessment. The impact of pipeline ruptures on the gas distribution were not investigated as part of this study. An evaluation of the response of the gas distribution system to possible pipeline ruptures at high risk locations is expected to be performed by BC GAS. The systems evaluation is essential to determining the priority for implementation of future mitigative measures.

Liquefaction occurs when severe, prolonged ground shaking in saturated undrained sand deposits produces soil strains sufficient to raise pore water pressure levels to the point that intergranular contact stresses disappear. At this point, the sand deposit takes on the characteristics of a fluid and can be ejected to the surface, flow along boundaries of deeper, non-liquefied deposits or lose shear strength. A lateral spread occurs when liquefaction leads to permanent lateral ground deformation. Estimates of potential lateral spread deformations were obtained using a method based upon the correlation of data from past earthquakes. Input required for estimating potential lateral spread displacements on a regional basis included earthquake magnitude, epicentral distance and general soil properties.

The objective of the risk assessment was to identify features of the BC GAS pipeline system that had a potential for long term disruption of gas supply. Given the lack of redundancy in the gas supply pipelines, a very low level of risk was determined to be acceptable. Based on a comparison with other seismic assessments conducted for electric and water utilities and highway bridges, an equivalent return period for disruption in the natural gas supply of 2000 years was felt to be an acceptable level of risk. The risk assessment scope did not include a systems analysis of the natural gas system. Recommendations provided in this report were based upon assumptions that rupture of key pipelines would disrupt gas supply to a large portion of the BC GAS service area.

A probabilistic approach was taken in defining potential earthquake hazards. This approach provides a means to account for the contribution of earthquakes that might occur over a wide area. The alternative approach, often used in regions like California where the seismic hazard is better defined, is to assume that seismic hazards are generated by one or more earthquakes occurring along known faults. The magnitudes of the earthquakes are selected based upon the level of conservatism desired and the knowledge regarding the tectonic regime (e.g., slip rate, magnitude recurrence relationship, maximum rupture length, time since last event). Considering the great deal of uncertainty associated with the seismicity of the Vancouver region, the probabilistic approach to estimating seismic hazards was felt to be most appropriate for this regional study. The potential impact of a large earthquake within the Cascadia Subduction Zone was assessed separately using deterministic methods.

Approach to the Assessment of Seismic Risk

The review was regional in nature. That is, no attempt was made to search out and verify local site conditions applicable to the in-scope pipeline right-of-ways. Much of the lateral spread hazard estimation was made based on surficial geology characteristics contained in large scale maps (1:25,000 or greater). Where possible, use was made of more detailed information from past project experience in the study area, more detailed maps, and direct observations in the field.

The risk assessment procedure involved several key steps:

1. Regional estimates of probabilistic ground shaking hazard were obtained using the most recent available seismicity model for the Vancouver region.

2. Potentially liquefiable deposits were identified and mapped into a Geographical Information System (GIS). It is important to recognize that surficial geology information only identifies areas where there is a high likelihood of liquefaction and subsequent lateral spread deformation. Site specific data is generally necessary to quantify risk. The approach taken is believed to be conservative with respect to hazard identification at many locations. Therefore, site-specific studies are primarily a means to determine if the seismic hazard is less than what has been assumed.

3. Characteristic earthquake magnitudes and epicentral distances were estimated to provide an equivalent earthquake scenario for evaluation of potential lateral spread displacements.

4. Estimates of lateral spread displacement were made for all potentially liquefiable deposits. These displacement estimates were made on a regional basis using limited topographical data. A more rigorous study, using site-specific topographic and subsurface data, would likely result in modified estimates, and may identify other areas where lateral spreading may occur.

5. Pipeline route information was translated from existing BC GAS drawing files into a GIS format.

6. Segments of pipelines in potentially liquefiable deposits, referred to as "slope groups", were identified based on an evaluation of their susceptibility to lateral spread displacement. Slope group information was entered into the GIS database. This information included the pipe diameter, orientation of the pipe segment with respect to the assumed direction of lateral spread displacement, and the pipeline configuration (e.g., ell or tee).

7. Non-linear finite element analyses were performed to provide estimates of the vulnerability of pipelines to lateral spread ground displacements. The results were used to determine likelihood of pipeline rupture.

8. The cumulative probability of pipeline rupture from seismic hazards with return periods of 475, 1000 and 2000 years was estimated for each slope group. The results were used to rank the slope groups according to risk.

In addition to the above efforts to assess the risk of pipeline rupture, aboveground facilities were reviewed to identify potential structural and equipment vulnerabilities to ground shaking and lateral spread displacement.

Limitations of Conclusions Drawn from the Regional Risk Assessment

Any regional risk assessment is limited by the quantity of data that can be incorporated into a generic evaluation methodology and the quality of the data that is available. In this risk assessment, we have necessarily incorporated several assumptions pertaining to quantification of seismic risk. These assumptions were necessary to account for unavailable information or to maintain a manageable scope for the risk assessment. Assumptions are discussed in detail in the body of the report. Results presented in this report need to be used with some caution when extended to particular pipeline locations. Local fill materials or pipeline strength characteristics (e.g., depth of burial, steel yield, wall thickness) may differ from those assumed in the risk assessment. The assumptions employed in the risk assessment are generally conservative for the most vulnerable portions of the pipeline system at river crossings. To address possible differences between actual field conditions and the assumptions of the risk assessment, we recommend that the most critical portions of the BC GAS pipeline system from the standpoint of maintaining gas supply undergo a site specific seismic evaluation regardless of the relative risk ranking derived in the regional risk assessment.

We also encourage efforts on the part of BC GAS to collect information on specific conditions known to differ substantially from those assumed in the risk assessment. Examples of site specific information include locations of construction over peat, sites experiencing on-going settlement, locations of miter joints, and more specific delineation of pipeline material and thickness for the metropolitan Vancouver district. This information could be reviewed at a later date to determine if there is a significant change in the findings presented in this report.

Implementation of the Risk Assessment Approach

Ground shaking hazard was expressed in terms of peak firm-ground acceleration. The level of ground shaking was modified to give an effective acceleration value that accounted for the effect of softer site conditions. Soft soil results in amplification of low levels of ground shaking and reduction of high levels of ground shaking. The effective acceleration values were used for assessing the likely performance of aboveground structures, systems and components.

The probabilistic seismicity model used for the BC GAS review was developed by BC Hydro International, Ltd. and has been extensively reviewed by experts familiar with the seismology of the Vancouver region. This model was used to generate ground acceleration hazard curves at 14 selected locations within the study area. These hazard curves plot the peak ground acceleration versus the annual exceedance probability. The annual exceedance probability represents the chance of a value being exceeded at least once over the period of one year. The annual exceedance probability can also be considered as the inverse of the return period, in years.

The probabilistic hazard approach does not directly provide the information necessary to implement the empirical model used to estimate potential lateral spread displacement. Specific estimates of magnitude and epicentral distance are needed. In the BC GAS study, the 80th percentile earthquake magnitude contributing to a particular point estimate of probabilistic ground shaking hazard was used to compute potential lateral spread displacement. Equivalent epicentral distance was back-calculated using the 80th percentile earthquake magnitude and attenuation relationships in the seismicity model.

A very large earthquake along the Cascadia Subduction Zone is a potential hazard for the Lower Mainland service area. This event was not included in the probabilistic seismicity model. The main reason for this is the lack of information regarding the level of activity. Instead, the relative effect of a large subduction earthquake was evaluated by examining ground shaking and lateral spread hazards for earthquake magnitudes between 7.75 and 9.0. Considering the current estimate of the maximum earthquake magnitude for the subduction zone is between 8 and 8.25, it was concluded that the ground shaking hazard is not significantly greater than what was considered in the probabilistic hazard approach.

Lateral spread displacement estimates were also examined for subduction earthquakes of magnitude 8 and 8.25. The results indicated that the lateral spread hazard for a subduction zone earthquake of magnitude 8 was no more severe than the displacements estimated for a hazard with a return period of 2000 years. For a magnitude 8.25 subduction earthquake, the estimated displacements were considerably greater than displacement estimates used in the risk assessment. However, it should be understood that the level of confidence in the predictions decreases with increasing earthquake magnitude, because of limitations of the present database. It is the opinion of the EQE Team that the approach used in estimating lateral spread risk to the BC GAS system envelopes the subduction zone earthquake as it is presently understood, except perhaps in the extreme western portion of the study area.

Results from the Seismic Risk Assessment

As a result of the risk assessment, approximately 49 pipeline slope groups were identified as having a risk of rupture greater than that corresponding to a 2,000-year return period. Of these 49 slope groups, the top 30 are associated with a risk corresponding to a return period less than 475 years. Unless a systems evaluation identifies other locations as more critical, it is recommended that priority be given to the top 10 ranked slope groups with a return period for pipeline rupture estimated to be less than about 200 years.

Generally, the most vulnerable areas of the pipeline system are in the vicinity of major river crossings and eight of the ten slope groups identified as having the greatest risk are at river crossings. A common feature related to pipeline vulnerability is the presence of pipeline bends that tend to anchor the pipeline and present the opportunity for very high local bending stresses. Recommendations for the riskiest pipeline locations include site specific investigations to confirm the potential for lateral spread deformations, detailed assessment of the impact of these deformations on the pipeline, and development of alternative pipeline alignments to reduce the likelihood of pipeline damage in the event of lateral spread deformations.

Serious concerns were expressed for the Fraser, River, and Pattullo gate station facilities. Fraser and River gate stations are believed to be at relatively high risk to severe damage from lateral spread displacements. The Pattullo gate station site is founded on a peat deposit and has experienced considerable settlement in the past. This settlement is expected to continue and poses a threat to facility operation under normal conditions. Severe damage to structures and aboveground systems at the Pattullo site is judged to be highly likely in the event of moderate earthquake ground shaking.

Other potential concerns identified during the aboveground facility review include unanchored or poorly anchored equipment components that could slide or overturn under moderate amounts of ground shaking. Of particular importance are small, unanchored gas heaters and other gas-fueled equipment within structures. Under ground shaking, movement of these equipment items could damage attached small-diameter piping and result in a potential fire or explosive hazard.

Sliding or movement of other unanchored equipment items is not expected to result in significant interruption of the gas supply. However, the findings from the aboveground facility review need to be examined by BC GAS operations personnel to determine if they could disrupt recovery operations.

The large fills adjacent to the pipeline in Burns Bog, Delta represent a hazard to the pipeline under seismic loading conditions. The risk associated with these fills will change with time, as the fills are developed and the foundations soils consolidate. Although the pipeline in this area is considered to be capable of withstanding large deformations without rupture, pipeline damage could occur as a result of very large deformations or anomalous subsurface conditions.

Recommendations

Recommendations based on the risk assessment fall into three categories. Certain activities involving minor capital expenditure are recommended for implementation at the earliest convenience to eliminate potential seismic hazards. Additional investigations are a second category. Recommended activities focus on quantifying the impact of identified seismic hazards or providing a site-specific assessment of risk. The third category is related to long term system planning. These recommendations involve significant modifications or additions to pipelines and aboveground facilities

Recommendations to Eliminate Identified Hazards

Upgrading anchorage of aboveground facility equipment and components should be started as soon as possible. Anchorage can be carried out as a maintenance activity. Priority should be given to small gas-fed equipment inside structures. This may require simple anchorage guidelines be supplied to field personnel performing the modifications. Anchorage upgrades should also be considered for key equipment items necessary for continued monitoring of gas system operation. This category of equipment includes radio transmission equipment, backup power systems and remote valve control equipment.

Recommendations for Additional Hazard Investigation

The relatively high risk assigned to certain pipeline configurations was significantly influenced by what are believed to be conservative assumptions in the risk assessment. For these locations, additional investigation to determine the site specific hazard is considered worthwhile. Key questions to be answered by the additional investigation are the likelihood of liquefaction and the potential ground deformations relative to the pipeline alignment. These investigations might require site specific soil borings, testing to characterize the strength of site soil deposits, and analytical evaluation of ground deformation and pipeline response.

Five locations (ranked 6 through 10) are recommended for additional site-specific evaluation:

1. North Vancouver near the Second Narrows bridge
2. Near the Fort Langley gate station
3. Near the Hammond gate station

4. Near the Metro Gas Center

5. In West Vancouver near the Capilano River

Recommendations for further evaluation are based on a qualitative assessment of potential conservatism in assessing of risk and the potential for identifying alternatives to lower the estimated risk. Two outcomes are anticipated from the site specific evaluations. A lower risk of rupture may be determined resulting in a change in priority of the site in question. A site-specific evaluation may also provide the basis for recommended alteration of the pipeline alignment to lower seismic hazards to an acceptable level.

The scope of the risk assessment did not include a detailed review of bridge crossings. The Mission, Pattullo, and Second Narrows bridges are used for river crossings by three major pipelines. An assessment of these bridges, including an investigation into upgrade activities by the BC Ministry of Transportation is recommended.

Recommendations for Future Planning of Pipeline System Modifications

The regional risk assessment of the BC GAS pipeline system has provided identification of portions of the pipeline route considered to have the greatest potential risk for seismic damage. Equally important is the consideration of locations and pipeline alignments critical for maintaining gas supply. The results of a systems evaluation should be combined with the findings of this risk assessment to arrive at a final priority of locations. We recommend that site-specific evaluation of seismic hazards and expected pipeline performance be performed at locations identified as critical from the recommended system evaluation.

Many of the high risk locations identified in the seismic risk assessment are at river crossings which was not unexpected. Portions of the pipeline system determined to be at greatest risk include the 20-inch and 24-inch transmission pipelines in the vicinity of the crossings of the north and south arms of the Fraser River and the Pattullo site. From our understanding of the BC GAS system, these pipelines are also expected to be critical to maintaining gas service.

Further investigation and analysis to quantify the seismic hazard at these locations could be carried out to better define the relative risks and to assist in planning and scheduling remedial action. Alternatively, the existence of a significant seismic hazard could be accepted and steps put into motion to avoid the hazard, or minimize the potential impact. The following actions could be considered to minimize the effect of the seismic hazard at these locations:

1. Consider mitigation measures, such as ground improvement, to reduce or eliminate the risk at the most critical sites. The Fraser and River gate stations are two such critical sites. Alternatively, relocate Fraser and River gate stations to avoid potentially large lateral spread displacements near the river bank

2. Accept possible pipeline rupture at Fraser and River gate stations and provide alternate pipeline supply to the Metropolitan Vancouver. This could be accomplished by crossing the Fraser River north of Ferguson gate station. The length of pipeline crossing infirm ground is minimized by following this route. The alternate route will require a combination of new transmission pipelines and additional intermediate pressure pipelines to provide system redundancy. Detailed investigation of the river crossing and the expected response of the pipeline is recommended prior to proceeding with this high-cost activity.

3. Relocate or provide site stabilization of the Pattullo gate station. The structure at Pattullo is believed to be founded on piles while the buried piping is not. This piping is likely to be stressed due to ongoing ground settlement. If site stabilization or relocation is not possible in the near term, it is recommended that the station piping be modified by routing as much piping as possible on the surface with provisions for accommodating future ground settlement.

These activities are major projects and require considerable planning, supported by necessary site-specific information. The recommendation for providing alternate supply lines to Metropolitan Vancouver entails great expense and needs to be studied with consideration of future gas demand, right-of-way access and capital budget availability.

Emergency planning is a key element in the response to seismic hazards that has not been addressed in this risk assessment. Consideration should be given to operational actions that might be taken in the event of disruption in the main gas supply to minimize the impact on area inhabitants. Some actions that may be considered include the following:

1. Shutdown of major industrial customers and largely non-residential areas to preserve some heating capacity

2. Coordination with other governmental and utility agencies to develop an emergency energy response plan for the public in the event of a major earthquake

3. Examine temporary operations measures that could increase gas supply in emergency situations (e.g., boosting pressure in certain intermediate pressure lines that still have gas supply)

Finally, the main gas supply to the Vancouver region is provided by the West Coast Energy pipeline. Efforts should be taken to contact West Coast Energy and determine what provisions they have taken to identify hazards to their pipeline (both seismic and non-seismic) and their plans for responding to the presence of those hazards.

1. BACKGROUND

Natural gas is supplied to the Vancouver region via a limited network of high-pressure transmission and intermediate-pressure trunk pipelines. Given the recent identification of a potentially large earthquake hazard for the gas service area, BC GAS was interested to identify vulnerable portions of these pipelines. Of particular concern is the potential for loss of gas supply to the greater Vancouver area as a result of catastrophic damage to the gas supply pipelines. The existing pipeline system is not highly redundant and the potential for extended gas outages given severe damage to a large supply pipeline is quite high.

This report presents the findings of a team of consultants headed by EQE INTERNATIONAL INC. (EQE). Key organizations participating on the EQE Team included GOLDER ASSOCIATES LTD., KENNEDY/JENKS CONSULTANTS and BC HYDRO INTERNATIONAL LTD. In addition, selected individuals served as advisory experts to the EQE Team. These included Professor T. Leslie Youd of Brigham Young University, Professor Thomas D. O'Rourke of Cornell University, Mr. Peter W. McDonough, and Dr. C.B. Crouse of DAMES AND MOORE.

The seismic risk assessment focused on transmission and intermediate pressure pipelines with nominal diameters of at least 8 inches. Also included in the scope of the assessment were 43 aboveground stations on the in-scope pipelines and 7 aboveground stations on the Pacific Gas Transmission pipeline between Hope and Huntingdon. All pipelines in the study scope are fabricated of steel with full penetration welded joints. The pipelines are of relatively recent construction and were considered to be consistent with the quality of pipelines constructed to current criteria.

Aside from ground shaking, the study included consideration of potential earthquake hazards related to liquefaction, lateral spread movement, and earthquake-triggered slope failures. Of the hazards considered, the potential for lateral spread ground movement was by far the most serious.

The goal of the pipeline system risk assessment was to make BC GAS aware of what portions of their system are most vulnerable to catastrophic damage and identify potential options for risk reduction. In accordance with these goals, the study set priorities for potential catastrophic damage locations according to risk and provided recommendations for prevention or mitigation of damage. It is felt that the information assembled in this study will also be very useful in planning future gas system projects.

The criteria used to assess pipeline and structural performance were developed to be consistent with catastrophic failure as opposed to minor leakage. In setting evaluation criteria, catastrophic repairs were considered to be associated with a major drop in downstream pressure or an extended outage of pipeline operation. This level of pipeline performance requires consideration of pipeline response well beyond what is allowed in normal design practice. Unfortunately, the behavior of pipelines subjected to these extreme loading conditions is not well defined. To investigate the impact of failure criteria on the risk assessment, estimated pipeline performance was examined for various levels of failure criteria.

Evaluating the risks of postulated earthquake hazards to the pipeline system required the EQE Team to develop a thorough understanding of several issues:

1. Earthquake source mechanisms and characterization
2. Regional characterization of soil strength properties
3. Implementation of semi-empirical methods for estimating the magnitude of lateral spread displacements
4. Extrapolation of distribution and dimensions of lateral spreading from patterns identified in past earthquakes
5. Response of pipelines to large imposed ground deformations
6. Behavior of aboveground structures and equipment in past earthquakes
7. Implementation of Geographical Information System (GIS) methodologies to assist in regional lifeline assessments

The companies and individuals brought together to perform this study have recognized expertise in the above technical areas. This is particularly true with respect to estimating lateral spreading displacements.

Preparations for the study began in mid-June. However, significant project activity began following a kick-off meeting with key EQE Team members and BC GAS personnel at the BC GAS office in downtown Vancouver on July 21, 1993. In this meeting, goals of the study and an approach for performing the risk assessment were agreed upon. Efforts immediately after the July meeting concentrated on preparation of digital base maps of the region and estimation of lateral spreading displacements. A preliminary report was provided to BC GAS on

September 17, 1993. This report summarized the progress to that time and provided BC GAS with a preliminary list of pipeline locations determined to be the most critical. Considerable effort after September 17 was expended in finalizing details of the methodology for quantitative estimates of lateral spread displacements. Lateral spread displacement estimates were completed by late October, 1993. Implementation of the risk assessment methodology proceeded into mid-November. Results were presented to BC GAS on January 26, 1994 at their office in downtown Vancouver. This final report includes additions and modifications resulting from discussions during this presentation.

2. OVERVIEW OF APPROACH

In any earthquake risk assessment study for a regional lifeline network, it is important to keep in mind the objectives of the project and the limitations of the methodology being employed. A summary of the methodology and supporting investigations for the BC GAS risk assessment is useful for framing the detailed discussions that follow.

2.1 Defining the Earthquake Hazard

The developing recognition of the potential for large, infrequent earthquakes associated with the Cascadia Subduction Zone is the driving factor for assessing risks to the BC GAS pipeline system. Knowing their existing system was installed without consideration for earthquake effects, BC GAS has an interest in upgrading the performance of their system to resist earthquake damage. A key question in planning system upgrades is how to efficiently allocate limited resources. With this in mind, the study undertaken by the EQE Team should not be viewed solely as an estimate of the quantitative risk of pipeline failure. Instead, we have systematically carried out estimates of risk to be used to identify the relative risk for different parts of the pipeline system.

The extreme uncertainty of fundamental aspects of hazard and response definition is the primary reason for limiting on absolute numerical risk estimates. With respect to hazard definition, it is necessary to have a reliable estimate of ground shaking intensity, the occurrence of liquefaction, the related occurrence of lateral spread movement, the size of the lateral spread and the direction and magnitude of lateral spread displacements with respect to the pipeline or aboveground facility.

Reliable potential ground shaking estimates are limited to areas of high seismic activity or fault zones that have well defined evidence of earthquake-related fault offset from surface trenching. In other situations, seismologists rely on regional estimates of tectonic movement, micro-earthquake studies and hypothetical earthquake source mechanisms. As a result, there can be a wide variation in estimates of earthquake hazard among different researchers as new hypotheses of tectonic deformation are developed. This is especially true in regions like southwestern Canada where the earthquake activity is not well defined.

Nonetheless, estimating earthquake ground shaking is perhaps the best understood of the potential earthquake hazards. Translating estimates of ground shaking to estimates of hazards related to liquefaction and the associated occurrence of lateral spread movement is currently an area of basic research. Engineering approaches are based on semi-empirical correlations with past earthquake observations or detailed theoretical analyses. There are efforts to develop analytical methods based on detailed modeling of saturated soils subjected to ground shaking. These detailed methods are best applied to well-defined, site-specific studies that can be related to past earthquake or experimental response.

2.2 Pipeline Response

The situation with respect to high inherent uncertainty in definition of the ground motion hazard improves slightly when examining the performance of buried pipelines subjected to large ground deformations. There is a fair amount of research data on the response of pipelines loaded to or slightly beyond the point of initiation of pipe wall buckling. Conversely, there is little information on the response of modern welded-steel buried pipelines under large compressive and bending strains caused by severe ground deformations. In particular, no information exists to corroborate extrapolation of small-scale tests on the distributions of forces imposed on the pipeline from the surrounding soil. Qualitative data from observations of pipeline response to ground settlement, landslides and underground structures experiments indicates that modern, welded-steel pipelines can readily withstand moderate amounts of ground deformation without risk of rupture.

Past studies of buried gas pipeline systems in the United States and Japan have relied upon earthquake data as a means to predict future performance. In these studies, pipeline damage is expressed in terms of the number of breaks occurring per unit length of pipeline, typically per mile or per kilometer. These vulnerability relationships are limited to the types of pipelines that have been damaged in past earthquakes and the types of earthquake hazard causing the damage. Pipeline types for which sufficient data exist include cast-iron, threaded steel, pre-cast and prestressed concrete. Examples of vulnerability relationships are shown in Figures 2-1 and 2-2. Note that existing vulnerability relationships cannot distinguish variation in pipeline performance with diameter, wall thickness or material yield strength. Also, a newly installed pipeline system designed to criteria based on earthquake hazards is evaluated as having the same risk as a similar pipeline installed with no consideration for earthquake hazards. Most importantly, existing vulnerability relationships are not capable of identifying specific locations of pipeline damage.

Because of these limitations, past evaluations of earthquake performance of buried pipelines focus on system-wide performance. They have merit when one is interested in knowing general information such as the total number of repairs and estimated time to restore full service for very large regions with many redundant system components.

It was decided that existing methodologies were incapable of providing the information desired by BC GAS. Instead, pipeline vulnerability for the BC GAS study was based on numerous detailed analyses of generic pipeline configurations. Detailed analysis of pipeline response to large ground deformation has been in use for over 20 years. The analyses are typically carried out using finite element modeling techniques that account for post-yield pipe strains, large deformation and non-linear soil strength characteristics.

Another decision in assessing earthquake risk to pipelines was to limit consideration to those hazards related to large permanent ground deformation. Past experience indicates that ground shaking has negligible impact on modern, well-maintained, butt-welded, steel pipelines. Similarly, the tendency for the pipeline to float in liquefied soil typically results in only moderate displacement which is distributed over considerable pipeline length. Experience with modern steel pipelines indicates that this loading condition has minimal chance of causing pipeline rupture.

Rupture of buried, welded steel pipelines is most often a result of severe compressive buckling of the pipe wall. Compressive buckling can result from axial loads or locally high bending moments. Because of the poor understanding of pipe wall response following the onset of compressive wrinkling, considerable conservatism is used in specifying compressive strain values for new design or for evaluation of pipelines for continued long-term service.

A consequence of the decision to use quantitative pipeline vulnerabilities tied to detailed analyses was the need to provide quantitative descriptions of the ground deformation hazard. This is in sharp contrast to currently available lateral spread vulnerability relationships which only differentiate regional hazard based on the potential for liquefaction.

Estimates of risk for the BC GAS study were conducted using two approaches. One approach used mean estimates of hazards and vulnerabilities to identify suspected locations of potential failure for specific levels of earthquake risk. Another approach estimated cumulative risk based upon combining the effects of three levels of earthquake hazard.

The following discussions focus on the approaches used in the BC GAS study to provide definition of earthquake hazard. A more detailed description of the process for assessing pipeline risk is also provided.

2.3 Prioritizing Locations at Risk From Pipeline Rupture

Assessment of the likelihood of catastrophic pipeline damage was performed by comparing the capacity of the pipeline to withstand imposed ground deformations with the estimated occurrence of ground motions in excess of this capacity. Inputs to the loading portion of the assessment included the probability that lateral spreads would occur at a particular point of the pipeline alignment, the orientation of the direction of lateral spreading with respect to the pipeline alignment, computed magnitude of lateral spreading displacements, and lateral spread size. On the capacity side, required information included the pipeline diameter and configuration. Based on a review of the pipeline system, configurations investigated for vulnerability were limited to straight sections, ells and tees.

The primary challenge of this approach was the definition of inputs to the loading description. In particular, there has not been systematic review of the physical size attributes of lateral spreads in past earthquakes. Since these attributes were essential to the BC GAS risk assessment, a limited amount of new research was necessary to characterize the lateral spread phenomena. The results of this research are discussed in Section 3.4.

Another challenge to the risk assessment was determining the number of analyses to be performed to define pipeline vulnerability. Because of the scheduling constraints for the project, it was not possible to wait until all locations of potential lateral spread movement were identified and determine the feasibility of analyzing specific locations. Therefore, a broad range of analyses were performed in which pipe diameter, material, configuration and soil properties were varied. Judicious selection of analysis cases resulted in less than 60 analyses being performed out of the more than 350 possible combinations. Analytical derivation of pipeline vulnerabilities is summarized in Section 4.

Identification of locations with a potential for catastrophic failure was performed using two basic approaches. The two approaches differed primarily in the manner in which priorities for damage were assigned to specific locations. The two approaches are identified as "Mean Performance" and "Cumulative Probability" assessments.

2.3.1 Mean Performance Assessment

The Mean Performance approach to risk assessment was worked out in the July 21 working group meeting at BC GAS. The approach consists of the following steps:

1. Identify portions of the pipeline alignment for which the slopes of the terrain are sufficient to result in a lateral spread given liquefaction occurs.

2. Determine a subset of the pipeline alignments identified in Step 1 for which lateral spread displacements are estimated.

3. Assign the portions of pipeline alignments from Step 2 to one of the basic configurations used in quantifying pipeline vulnerability (straight, ell, or tee). This assignment will also identify whether pipeline vulnerability is governed by lateral spread displacement or the length of pipeline within the lateral spread.

4. For each pipeline alignment selected, compare the mean lateral spread length or displacement associated with an annual exceedance probability of 0.0005 (at least one event in 2000 years) with the vulnerability criteria established for catastrophic failure.

5. Categorize the pipeline alignment in question as either having sufficient capacity or being likely to fail based upon the comparison in Step 4.

6. Repeat Steps 4 and 5 for earthquake hazards corresponding to higher annual probabilities of exceedance (0.001 and 0.002).

7. Prioritize the pipeline locations from high to low vulnerability according to the lowest earthquake hazard for which the failure criteria are exceeded (i.e., exceeding failure criteria for hazards with an annual exceedance probability of 0.001 is more critical than exceeding failure criteria for hazards with an annual exceedance probability of 0.0005).

In devising the above approach, it was assumed that a few high-priority locations would be identified at the low level of hazard definition. In reality, locations identified as having exceeded the pipeline capacity were similar at the three levels of earthquake hazard considered.

2.3.2 Cumulative Probability Assessment

In studying past earthquake data to identify lateral spread characteristics (dimensions and portion of area affected), a sufficient quantity of observations was collected to allow some probabilistic definition. An alternate procedure was developed to allow prioritization of pipeline locations based on a cumulative estimate of risk that made use of these observations.

The Cumulative Probability approach used to assess the BC GAS pipeline system included probabilistic estimates of the occurrence of lateral spread movement along a specific portion of the pipeline alignment, the amount of spread displacement, the length of pipeline subjected to lateral spread movement, and the cumulative effect of contributions to risk from various levels of earthquake hazard. The basic approach for identifying portions of the pipeline at risk was generally similar to the Mean Performance approach:

1. Identify portions of the pipeline alignment for which the slopes of the terrain are sufficient to result in a lateral spread given liquefaction occurs.

2. Determine a subset of the pipeline alignments identified in Step 1 for which lateral spread displacements are estimated.

3. Assign the portions of pipeline alignments from Step 2 to one of the basic configurations used in quantifying pipeline vulnerability (straight, ell, or tee). This assignment will also identify whether pipeline vulnerability is governed by lateral spread displacement or the length of pipeline within the lateral spread.

4. For a particular level of earthquake hazard (0.002, 0.001, or 0.0005), determine the mean lateral spreading displacement.

5. Compute the probability that spread displacement or spread length will exceed the failure criteria determined in Step 4.

6. Adjust the probability computed in Step 6 to account for the overall probability of lateral spread occurrence. This is the probability of failure associated with the specific level of seismic hazard.

7. Repeat Steps 5 through 7 for the remaining levels of seismic hazard.

8. Compute the cumulative probability of failure from the failure probabilities at various levels of earthquake hazard.

9. Prioritize the locations identified in Step 2 according to the failure probability computed in Step 9.

The above approach accounts for the contribution to overall risk at varying levels of earthquake hazard in a very approximate fashion. Given the considerable level of uncertainty associated with the entire risk assessment process, further refinement was considered unnecessary. The principal reason for using the cumulative probability approach was to provide an alternate mechanism for ranking the risk to specific portions of the pipeline alignment.

2.4 Assessment of Aboveground Gas Facilities

Aboveground facilities were also evaluated for potential impact on interruption of gas service. The aboveground facility assessment was performed using information gathered from visits to each in-scope facility and a review of BC GAS files. Two rounds of facility visits were conducted. One round focused on the geotechnical conditions at the facilities and assessed the likelihood of damage from severe ground deformations. The second round reviewed facility equipment and structures to ascertain seismically vulnerable conditions.

Aboveground facilities identified as having a high likelihood for being exposed to severe ground failure were considered to sustain heavy damage to both structures and key equipment items such as scrubbers, filters and large heaters. Although the ground failure condition was considered a governing mode of damage, the facility review did ascertain ground shaking vulnerability. The ground shaking review served to identify potential weakness at the facility that would not be remedied if actions were taken to limit the impact of ground failure.

Assessment of aboveground facilities for ground shaking occurred in two phases. In the first phase, a documented review was performed of each facility to identify structural details and equipment configurations that have shown to respond poorly in past earthquakes. The second phase examined the data collected in the first phase and made assessments as to the likelihood of facility damage being sufficient to cause system interruption.

Estimates of ground shaking for the aboveground facilities were estimated using the hazard curves available at the time of review and generic soil amplification relationships to account for different ground motion at "soft" sites. For the purposes of the facility reviews, a site in an area with a moderate to very high liquefaction susceptibility rating was considered "soft".

The results of the aboveground facility evaluations was a qualitative estimate of the likelihood that the facility could maintain gas supply to the system. Aboveground facilities were rated as having a "Low", "Moderate", or "High" likelihood of maintaining operation. These ratings addressed structural integrity issues and impact of failures on loss of gas supply. In some cases, although the likelihood of gas supply interruption was considered low, some concern existed for the possibility of fire related to small gas leaks. Situations felt to be especially susceptible to post earthquake fire were noted. Fire considerations did not lead to changes in the overall serviceability ratings given to the aboveground stations.

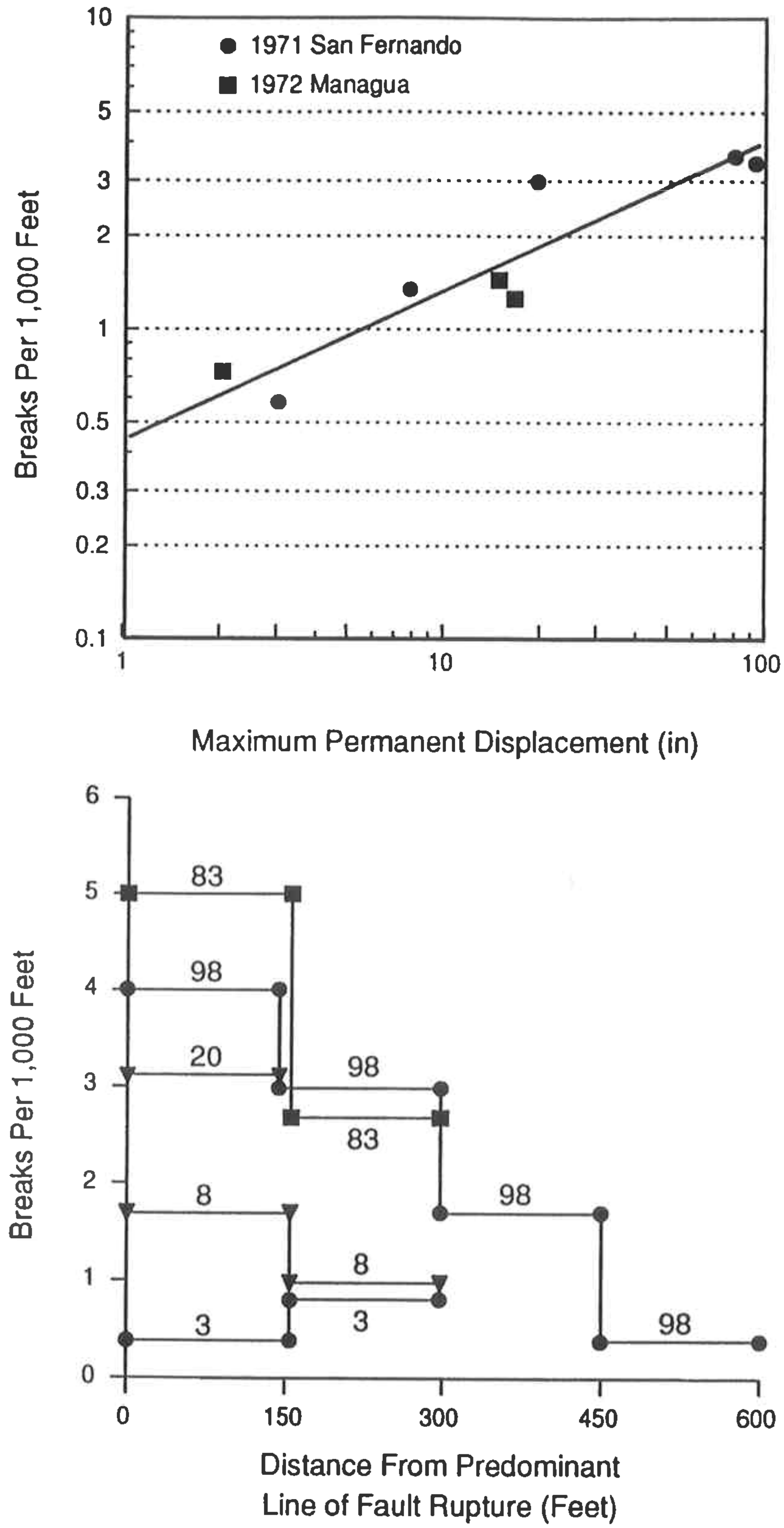


Figure 2-1: Examples of Empirical Pipeline Damage Relationships Used for Cases of Ground Deformation

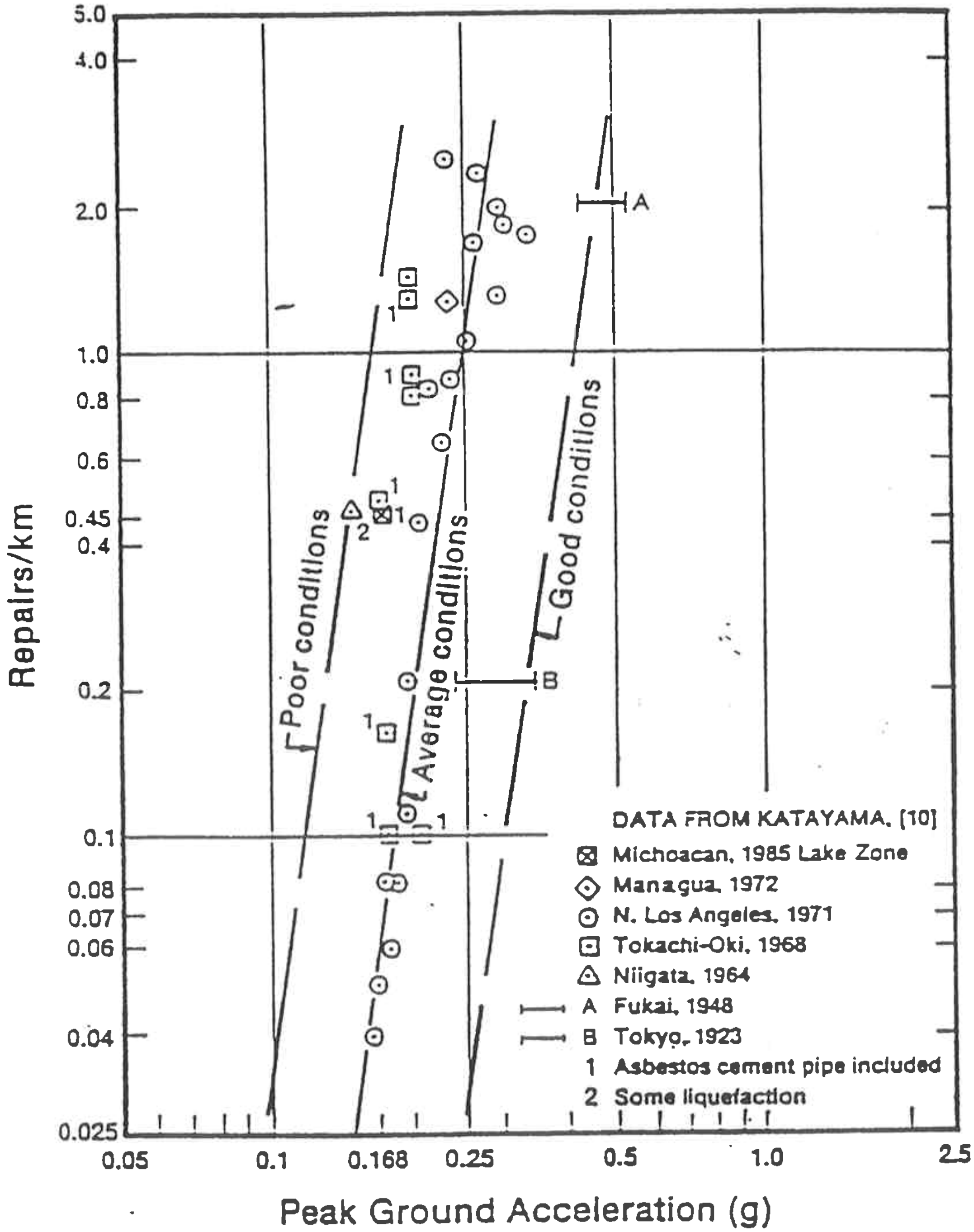


Figure 2-2: Example of Empirical Pipeline Damage Relationship Based on Level of Peak Horizontal Ground Acceleration

3. DEFINITION OF EARTHQUAKE HAZARDS

The Lower Mainland Region of British Columbia is located in Seismic Zone 4, which is one of the zones of highest seismic risk as defined in the National Building Code of Canada (NBCC, 1990). The seismicity results from the thrusting of the offshore Juan de Fuca Plate beneath the continental North America Plate. There are three basic sources of earthquakes affecting the study area:

1. Relatively shallow crustal earthquakes (depths in the order of 20 km);

2. Deeper earthquakes (about 60 km depth) within the subducted plate; and

3. Very large inter-plate earthquakes, often referred to as "mega-thrust" or "subduction" earthquakes.

Earthquakes within the first two categories (intra-plate) have been recorded at regular intervals during the last several decades. The largest are those near Campbell River in 1946 (M = 7.3), near Olympia in 1949 (M = 7.1) and near Seattle/Tacoma in 1965 (M = 6.5). A very large earthquake is also reported to have occurred in central Washington state in 1872. Earthquakes from these sources are commonly included in probabilistic and deterministic seismicity models, such as the NBCC model.

Large subduction earthquakes have not occurred in the region in historic time. However, there is geological evidence that they have occurred in the past (possibly at 300 to 400 year intervals), and the measured accumulation of strain between the tectonic plates suggests that they should be expected in the future. The general consensus is that the upper-board magnitude of a large subduction earthquake would be in the order of 8.0 to 8.5. However, because of the greater epicentral distance from the Lower Mainland, the intensity of ground shaking is not expected to be greater than for the smaller intra-plate earthquakes. The primary concern with respect to the subduction earthquake is the duration of shaking, expected to be in the order of 2 to 3 minutes, or more than five times that of the intra-plate earthquakes.

Earthquake hazard definitions for the BC GAS risk assessment were based upon regional seismic zonation procedures comparable to those used in recent seismic hazard studies for other utilities in the Vancouver region. Probabilistic estimates of earthquake ground shaking hazard were made for selected locations within the BC GAS study area. This information formed the input to semi-empirical approaches for estimating lateral spread potential and resulting lateral spread displacement. A separate, deterministic assessment of the potential contribution of a very large event associated with the Cascadia Subduction Zone was also included as part of the earthquake hazard definition process.

The BC GAS Coastal Pipeline System is located in the Lower Mainland Region of British Columbia. The Lower Mainland covers a triangular shaped area of about 3000 km^2 bounded by the Coast Mountains to the North, the Cascade mountains to the south and southeast, and by the Strait of Georgia to the west. The Fraser River extends through the area and has developed a delta some 31 km long by 24 km wide. Water tables in the study area are typically very close to the surface. The geotechnical/geological data used in the study was primarily obtained from the GOLDER ASSOCIATES in-house data base and available surficial geology maps of the Vancouver, New Westminster, Mission and Chilliwack areas prepared by the Geological Survey of Canada (GSC). In addition, the following geological/geotechnical and topographic information was made available for use in the study:

1. Geotechnical information pertaining to some electrical transmission tower sites (provided by BC HYDRO INTERNATIONAL)

2. Topographic information at BC GAS transmission pipeline river crossings, (provided by BC GAS)

3. Report titled "Liquefaction Hazard Assessment for the Lower Mainland Region", dated November 1992, prepared jointly by the Geotechnical Department of BC HYDRO INTERNATIONAL Hydroelectric Engineering Division, and Klohn Leonoff (provided by BC GAS)

4. Volumes I and II of the report titled "Seismic Design Investigation, Tilbury Island LNG Plant, Delta, B.C.", dated September 24, 1981, submitted to BC HYDRO INTERNATIONAL and Power Authority - Gas Division by Klohn Leonoff Ltd. (provided by BC GAS)

5. Some information on surface topography (about 20 years old) for Lulu Island (provided by the City of Richmond)

3.1 Estimates of Ground Shaking Hazard

Recently BC HYDRO INTERNATIONAL carried out a detailed review of the seismicity in British Columbia. Based on the results of this study, they have developed a new probabilistic seismicity model, and this model was used for the seismic risk analysis of the BC GAS pipeline system.

Seismic risk assessments were performed by BC HYDRO INTERNATIONAL to obtain ground motions at selected points within the pipeline system. Based on their analyses, the following information was provided to GOLDER ASSOCIATES.

3.1.1 Probabilistic Approach

1. Peak horizontal ground accelerations at 14 selected points within the BC GAS pipeline system. (Locations No. 1 through 14 as shown in Figure 3-1a and Figure 3-1b). Peak horizontal ground accelerations were computed for both median and mean + one standard deviation attenuation relations.

2. Distributions of magnitude and distance contributions to seismic risk at 3 selected points on the BC GAS system. (Locations No. 3, 8, and 13 of Figure 3-1a and 3-1b) using both mean and mean + one standard deviation attenuation relations.

3. Back-calculated source distances corresponding to the 80th percentile magnitude contributions for the Locations No. 3, 8, and 13 using both mean and mean + one standard deviation attenuation relations.

3.1.2 Deterministic Approach

Deterministic estimates of firm ground motions, due to subduction events, at the Locations No. 3, 8, and 13 for magnitude scenarios ranging from 7.75 to 9.0.

The details of the above seismic risk analyses can be found in Appendix A in Attachment 1 which contains the report No. H2790 dated November, 1993, produced by BC HYDRO INTERNATIONAL.

3.2 Identification of Liquefaction Potential

Identification of areas susceptible to liquefaction hazard is a major component in assessing the performance of the pipeline system under earthquake loading conditions. The approach proposed by Youd and Perkins (1978) provides a general method for mapping the liquefaction susceptibility based on the geological characteristics of a given area. Youd and Perkins (1978) have defined "liquefaction susceptibility" as the capacity of the soil to resist liquefaction.

The primary factors influencing the liquefaction susceptibility of a given soil have been found to be:

1. Age of the deposit (e.g. Late Holocene deposits have a higher susceptibility to liquefaction under intense seismic shaking when compared to older Pleistocene deposits)

2. Relative density of soil (e.g. loose saturated cohesionless soils have a higher susceptibility to liquefaction when compared to dense saturated cohesionless soils)

3. Particle size of the soil (e.g. saturated sands and silts of low plasticity are more susceptible to liquefaction than clayey silts and clays of high plasticity)

4. Depth to water table (e.g. if the water table is lower than about 10 m, or if the water table is below the sediment that is of concern, the likelihood of liquefaction is low. The exception to this may be a case where perched water is encountered although the normal ground water level is well below the deposits of concern)

The Youd and Perkins (1978) approach provides a convenient and effective method of assessing the liquefaction susceptibility of a large area for a regional zonation study, such as that of the present study, where general surficial geological data is available but site-specific data is limited. In the present work, the liquefaction susceptibility of the Lower Mainland within the area of BC GAS transmission pipelines was assessed based on the Youd and Perkins approach. Information on the general soil conditions within a given area was obtained primarily using the surficial geology maps prepared by the GSC, supplemented with data available in the GOLDER ASSOCIATES borehole database and geotechnical information received from BC HYDRO INTERNATIONAL. In the areas where no specific subsurface information was available, the area was classified entirely based on the data from the GSC surficial geology maps.

The liquefaction susceptibility of the BC GAS transmission pipeline area has been classified using the above methodology, and the results are presented in Figure 3-2. The map has been developed to identify the liquefaction susceptibility of a given area of the BC GAS pipeline system using a relative scale varying from the designations of "Very Low" to "Very High" as shown in the legend. According to this relative scale of liquefaction susceptibility, the zones classified as "Very High", "High", or "Moderate" are likely to liquefy under seismic loading whereas those designated as "Low" and "Very Low" are unlikely to liquefy. "Moderate" classifications would require higher intensity shaking, or greater duration, for liquefaction to occur than those classified "Very High" or "High".

Since the map has been constructed primarily using regional data, as opposed to site-specific information, the designation of any given location in Figure 3-2 should be considered more as a general indicator of the potential for liquefiable segments lying beneath a particular site. Conversely, there is some probability that a particular site will not liquefy. Therefore, the information in Figure 3-2 was used only for the general assessment of the system vulnerability. Detailed assessment of liquefaction potential should be carried out for site-specific assessment of risk.

Most of the boundaries of the different zones identified in Figure 3-2 have been based on the boundaries given in the GSC surficial geology maps. Therefore, these boundaries should be considered as approximate only. Also, since this map has been prepared specifically for this BC GAS study, the level of care and effort applied in the vicinity of BC GAS transmission pipelines was greater than in other areas.

Although the areas susceptible to liquefaction are generally prone to liquefaction-induced ground movement, susceptibility to liquefaction does not necessarily imply that damaging permanent ground movements will occur. This is primarily because other additional factors, such as surface topography, intensity and duration of earthquake shaking, also play a key role in influencing the magnitude of permanent ground movements.

3.2.1 High to Very High Susceptibility to Liquefaction

Generally all the areas covered with Holocene sediments and having very shallow water table conditions have been classified as having high to very high liquefaction susceptibility. The most recent sediments identified by the designation Fa in the surface geology maps (in the Delta and Richmond areas) can be classified as areas very highly susceptible to liquefaction (see Figure 3-2).

3.2.2 Moderate Susceptibility to Liquefaction

The areas that could be considered as moderate in terms of liquefaction susceptibility are identified in Figure 3-2. These include sand and gravel (Holocene) deposits, mountain stream deposits, and marine shore and fluvial sands. Areas having significant thickness of peat underlain by organic silt have also been given the liquefaction susceptibility designation as moderate (covered with peat), because the vulnerability of the shallow BC GAS pipelines in this area will likely be controlled more by the peat and organic silt than the underlying granular soils.

3.2.3 Low to Very Low Susceptibility to Liquefaction

The areas of Pre-tertiary and Tertiary bedrock and almost all the areas having surficial Pleistocene deposits, are generally expected to perform well under seismic loading, and these have been classified as having low to very low susceptibility to liquefaction.

3.2.4 Variable from Low to High Susceptibility to Liquefaction

Several zones within the study area have been developed by placing fill over the native soils. Areas in the vicinity of False Creek and the south shore terminal areas of Burrard Inlet are some areas of land that have been reclaimed by filling. The fill materials vary from gravels, sands, and silts to construction debris and other refuse. Because of the variations in the fill type and the level of compaction at the time of placement, these materials have highly variable in-situ relative densities and composition. For this reason, they have been classified as variable form Low to High in terms of liquefaction susceptibility.

3.3 Estimating Lateral Spread Displacements

A primary concern with respect to pipeline performance involves the temporary and permanent ground displacements which are expected to occur under seismic loading conditions. These are of particular concern in "soft ground" areas, where amplification and liquefaction may result in large deformations or slope failure.

Areas underlain by competent soil (essentially those classified as low to very low in terms of liquefaction susceptibility) are not generally expected to experience permanent ground deformations under earthquake loading. Moreover, variations in the transient movements within these areas are expected to occur over significantly larger distances, not leading to abrupt differential movements. Seismic loading could still impose differential movements in competent ground areas, such as in the vicinity of anomalies, such as ditches, steep/unstable slopes, and service trenches.

Loose or soft ground areas will be subjected to transient ground oscillations during seismic loading. Furthermore, the areas susceptible to liquefaction could undergo significant permanent vertical and lateral deformations, even in gently sloping terrain. The magnitude of permanent deformations is generally expected to increase with increasing magnitude of earthquake accelerations and the duration of seismic shaking.

Larger permanent lateral deformations are expected to occur where steep channel side slopes, road embankments and ditches exist in the areas of soft soil. In terms of pipeline vulnerability, vertical deformations have been found to be less critical than those in the lateral direction.

3.3.1 Methodology for Estimation of Ground Displacements

As a result of recent research work, several analytical and empirical methods have been developed for estimating the magnitude of lateral spread displacements. Of the methods to estimate liquefaction-induced ground displacements, those proposed by Byrne (1991), Hamada et al. (1987) and Bartlett and Youd (1992) are less rigorous in terms of usage and are more appropriate for regional studies. On the other hand, methods such as Byrne et al. (1992), Finn et al. (1986), and Prevost (1991) involve time consuming finite element analyses, which are more appropriate for detailed site-specific analyses requiring a greater level of confidence.

A method for computing lateral displacements that is relatively simple and which has the capability to account for differences in the soil conditions, topographic features such as ground slope, and the earthquake risk, was considered to be the most appropriate tool for the present study. The Bartlett and Youd (1992) MLR model was adopted for predicting median lateral permanent ground surface displacements in the present study. The method proposed by Bartlett and Youd (1992) has been developed based on Multiple Linear Regression (MLR) analyses of earthquake, topographical, soils, and geological data associated with lateral spreads resulting from eight major earthquakes (1906 San Francisco, 1964 Alaska, 1964 Niigata, 1971 San Fernando, 1979 Imperial valley, 1983 Borah Peak Idaho, 1983 Nihonkai-Chubu, 1987 Superstition Hills). In the MLR model, two equations have been developed to predict median values of permanent lateral ground surface displacements in the vicinity of river banks or free faces (Free-face equation) as well as generally sloping conditions (Ground Slope Equation) at sites susceptible to liquefaction. The model has the capability to account for the effects of seismicity parameters (magnitude and distance) as well as soil conditions.

The Bartlett-Youd database includes measured displacements from both subduction and non-subduction earthquake events. Therefore, it can be argued that the MLR model derived from this database is applicable in the prediction of displacements resulting from both subduction as well as non-subduction events. The increased duration of shaking is taken into account by the magnitude term in the equations.

3.3.2 Selection of Parameters for MLR Model

The following parameters are required in the computation of permanent lateral displacements using the Bartlett and Youd MLR equations (see Appendix B of Attachment 1 for detailed description of the methodology).

Soil Parameters:	Thickness (T_{15}) of the soil layers having Standard Penetration Resistance $(N_1)_{60} < 15$; Average particle size (D_{50}) and the percentage of particles finer than 0.075 mm in those layers having $(N_1)_{60} < 15$.
Topographic Parameters:	Ground slope (S) in percent, if the topography is gently sloping; Free face ratio (W) in percent in the vicinity of channels or river banks.
Seismic Parameters:	The value for the magnitude (M) of the earthquakes; and the earthquake source distance (R)

Soil parameters, considered to be representative of each geographic area having similar soil conditions, were derived from the available borehole data information. For each area, an "average" soil profile and parameters were constructed based on these data.

Topographic parameters at the river crossings were mainly derived from the topographic survey drawings provided by BC GAS. However, information received from BC GAS for some of the river crossings did not contain adequate information to construct the ground surface topography. In such situations, the topography was estimated based on our previous knowledge of the area and/or observations made during our site inspections.

Although the earthquake magnitude that is to be used in the MLR model should have a single value, the probabilistic seismic risk for a given site is associated with contributions from many earthquake events having a range of magnitudes. (see the results of seismic risk analyses carried out by BC HYDRO INTERNATIONAL in Appendix A in Attachment 1). In selection of a single representative magnitude value for application in the MLR equations, using both the median value of the magnitude distribution for a given risk level, or that corresponding to the 80th percentile contribution was considered as discussed below and in Appendix B of Attachment 1.

According to Bartlett and Youd (1992), the MLR model has been developed primarily based on data from relatively stiff sites where ground motion amplification from firm ground to ground surface was moderate compared to that expected at sites having relatively soft soil conditions. In order to apply their equations to compute lateral spread in soft soil sites, Bartlett and Youd (1992) have proposed some modifications to account for higher ground motion amplifications. In this approach a reduced equivalent source distance (R_{eq}) value is proposed for use in the MLR equations instead of using the actual source distance for a given earthquake scenario. The determination of R_{eq} essentially involves the determination of ground surface acceleration, and the use of a chart developed by Bartlett and Youd (1992) where the R_{eq} value is presented as a function of ground surface acceleration and the magnitude of the earthquake.

Considering the nature of this study, the number of locations where ground displacements are to be computed, and the simplicity of the MLR method for displacement estimates, the computation of ground surface accelerations using detailed earthquake ground motion response analyses was not warranted. Therefore the relation proposed by Idriss et al. (1990) was used to obtain the ground surface accelerations in soft soil sites. Previous detailed seismic response analyses carried out by others for the Fraser delta area (Earthquake Task Force Report for the Fraser Delta, 1991) indicate that, in the absence of site-specific analyses, the use of the above Idriss et al. (1990) relation to obtain the ground surface accelerations in soft soil sites from the firm ground acceleration is reasonable.

Since almost all the sites of moderate to high liquefaction susceptibility within the BC GAS transmission system have relatively deep soft soil conditions, a decision had to be made whether or not to use the MLR model with correction for ground motion amplification. Following initial discussions with the panel of experts, test calculations of ground displacements were carried out considering a selected soft soil site having a high liquefaction susceptibility and available soils information. These values were then compared with other independent simplified methods of Hamada (1987) and Byrne (1991), as well as field observations, to carry out sensitivity analyses to investigate the impact of ground motion amplification corrections, ground motion attenuation relations, and selection of earthquake magnitude.

Use of the MLR model with mean attenuation relations, M values corresponding to 80th percentile of the magnitude contributions, and a correction for ground motion amplification, results in reasonable agreement with estimates using the Hamada and Byrne simplified models. Moreover, the computed displacement values are found to be in reasonable agreement with field observations such as those made during the 1964 Niigata earthquake. Therefore, it was concluded that the above approach (i.e., mean attenuation 80th percentile M, and Idriss et al. correction for ground motion amplification) was a reasonable approach to compute ground displacements for the present study.

3.3.3 Intra-plate Earthquakes

As discussed in Section 2, the system vulnerability of the BC GAS transmission pipeline system is being assessed for three levels of earthquake risk, corresponding to 475 year, 1,000 year, and 2,000 year earthquake return periods. In the probabilistic seismic risk analyses carried out by BC HYDRO INTERNATIONAL for the above risk levels, subduction (or megathrust) events have not been considered.

3.3.4 Lateral Spread Displacement Estimates

The median estimates of permanent lateral ground displacements corresponding to the above risk levels were evaluated using the MLR equations for those areas of the system designated as having moderate, high and very high liquefaction susceptibility.

River Crossings

Median estimates of permanent lateral ground displacements were computed at the following critical river crossings within the system (the locations are identified in Figure 3-3).

(A) North Arm of Fraser River (between Fraser and River Gate Stations)

(B) South Arm of Fraser River (between Nelson and Tilbury Gate Stations)

(C) Fraser River (west of Port Mann Bridge)

(D) Pitt River (southeast of Trenton Gate Station)

(E) Fraser River - Russell Reach (south of Albion Gate Station)

(F) Fraser River - Bedford Channel (north of Fort Langley Gate Station)

Other small river crossings have not been assessed specifically.

The results of the computed median permanent lateral ground surface displacements for the above river crossings are presented in the Tables D1 through D12 in Appendix D of Attachment A. For each risk level, the results have been presented to give the variation of computed displacements with respect to the distance away from the crest of the river bank.

It can be noted that displacements of 2 m or more are predicted to occur at each river crossing considered above, even for a 475 year return period event. Larger displacements are estimated for the lower risk levels (1,000 year and 2,000 year) considered in the analysis.

Bartlett and Youd (1992) have indicated that a computed value of median lateral displacements greater than 5 m could be considered as an indication of a potential flow slide situation. If this criteria is adopted, flow slide conditions should be expected under a 2,000 year level earthquake at all of the river banks, with the exception of Russell Reach south bank where ground movements in the order of 3 m at the slope crest are predicted to occur.

Under levels of shaking corresponding to a 1,000 year return period, application of this criterion suggests that there is potential for flow slides to develop at the following locations.

1. South Arm of Fraser River - North Bank (South of Nelson Gate Station)
2. Fraser River - South Bank (West of Port Mann Bridge)
3. Pitt River - West Bank (South of Lougheed Highway)

4. Russell Reach - North Bank (South of Albion Gate Station)

5. Bedford Channel - North and South Banks (North of Fort Langley Gate Station)

Relatively large lateral ground movements (in the order of 3 m or more) are estimated at the crests of the remaining river banks considered above for an earthquake hazard with a 1,000 year return period, except at the Russell Reach south bank, which is estimated to experience somewhat lesser lateral crest movements in the order of 2 m.

Generally Flat Areas

The limited available topographic data, and our visual observations during field visits indicate that, except at those locations where anomalies such as ditches, dykes, river banks, road embankments etc. are encountered, the ground slopes are likely to range from about 0.05% or lower to about 0.5% within the generally flat low-lying areas where the susceptibility to liquefaction is greatest. Therefore, displacements were computed for assumed 0.5%, 0.25%, 0.1%, and 0.05% ground slope conditions using the MLR Ground Slope equation.

The results are presented in Figures D1 through D17 of Attachment 1, where the computed median permanent lateral ground surface displacement is plotted against the ground slope for the three risk levels corresponding to hazards associated with 475 year, and 1,000 year, and 2,000 year return periods. Each of the above figures corresponds to the computed displacements for the areas identified in Figure 3-4.

As expected, the results of the analyses indicate that the lateral ground displacements for a given area and for a given ground slope increase with decreasing seismic risk level. For a ground slope of 0.0% the MLR model would predict zero displacements regardless of the values used for the other parameters.

3.3.5 Lateral Spread Displacements for Intra-plate Earthquakes

On a deterministic basis, the firm ground accelerations at selected locations have been estimated by BC HYDRO INTERNATIONAL, for scenarios corresponding to several earthquake magnitudes as discussed in Section 2.3 and Appendix A of Attachment 1.

Permanent lateral ground displacements corresponding to earthquake magnitudes of M = 8.0 and M = 8.25 were computed for two selected generally flat areas within the BC GAS pipeline system (i.e. Richmond and Albion). The results for the two areas are presented in Figures 3-5 and 3-6, respectively.

From the results of BC HYDRO INTERNATIONAL seismic risk analysis, it may be noted that the predicted horizontal firm ground accelerations for the Richmond area for the deterministic M = 8.0 and M = 8.25 subduction events are about 25% higher than those for the Albion (Fort Langley) area.

The estimated median displacements for the Albion area for the M = 8 and M = 8.25 deterministic events are comparable to those computed for probabilistic hazards with a 475 and 1,000 year return period respectively, as shown in Figure 3-6. On the other hand, the estimated median displacement for the M = 8.0 event for the Richmond area (Figure 3-5) is comparable to that computed for a much lower (2,000 year return period) seismic risk level, reflecting the effect of the higher estimated ground motions at sites closer to the assumed source. Much larger displacements are computed within the Richmond area for the M = 8.25 event. However, we understand that the accuracy of the MLR model may be questionable for earthquakes having magnitudes, M > 8, due to the limited data.

Based on the above comparisons, it appears that if the vulnerability analyses are performed for an event corresponding to a 2,000 year return period, it would likely encompass the system performance under a subduction scenario of magnitude M = 8, but that larger displacements should be expected for M > 8.0. Further analyses would be required if the system vulnerability is to be assessed for a subduction earthquake having M > 8.

3.3.6 Variation in Estimates of Lateral Displacement

Predictions from the MLR model should not be considered as single value predictions for a given set of seismic, topographic, and soil parameters, but rather as an average estimate of the likely displacements corresponding to those conditions.

Considering the "spread" of the database used in the development of the MLR model, Bartlett and Youd (1992) have shown that almost all the measured displacements fall within upper and lower bounds of twice and half the median displacements estimated from the MLR model equations, respectively. They have also suggested a probabilistic approach to estimate the displacements, which will provide an upper limit of predicted displacement for a given confidence level.

3.3.7 Limitations

The MLR model has been developed based on Multiple Linear Regression analyses of data associated with lateral spreads from eight major earthquakes. It is important to recognize that it is not a complete worldwide data base, and that it may change with time as more data are incorporated. Moreover, the "soft soil" correction has been developed from limited data, and therefore may not be generally applicable to other sites.

Bartlett and Youd (1992) have suggested that the MLR variables used for a given situation should fall within the following bounds.

(a) 6.0 < earthquake magnitude < 8.0

(b) Source distance, R, within the bounds given in Table 3.1.

(c) 0.1g < maximum horizontal acceleration < 0.5g

(d) 1% < free face slope < 20%

(e) 0.1% < ground slope < 6%

(f) 1 m < thickness of deposit with normalized standard penetration resistance at 60% hammer energy, SPT $(N_1)_{60}$, less than 15 <15 m

(g) 0 m < depth to base of liquefied layer < 20 m

(h) Average particle size $(D_{50})_{15}$ and average fines content F_{15} within T_{15} to fall within the limits given in Figure 3-7.

The seismic parameters, M and Req, used in the computations carried out for the present study were within the specified limits in (a), (b), and (c) above, except the higher M = 8.25 value that was used for assessment of the subduction event.

The topographic parameters, S and W used in the computations were in compliance with the ranges given above, except at the crests of some river banks where the W value was found to be higher than 20%. At these locations computations were carried out assuming a W = 20% (see Appendix D of Attachment 1 for details) and the risk of a flow slide has been noted.

Considering the available data on the soil parameters, the average particle sizes $(D_{50})_{15}$ and average fines contents F_{15} of the sands and silty sands which were mainly contributing to the displacements were essentially falling within the limits defined by Figure 3-7. Although the $(D_{50})_{15}$ and F_{15} of most of the silt layers encountered in the study did not classify within these limits, any error in the computed value of the displacements as a result of this deficiency is considered minimal because of the relatively small values of displacements computed by the model for the layers with high fines content.

In addition to the uncertainties inherent in the model, the computed displacements will also be affected by the uncertainties in the estimation of representative input parameters.

The input soil parameters, $(D_{50})_{15}$, T_{15}, F_{15}, were computed based on an "average" soil profile constructed based on the available borehole data for a given area. The boundaries of these areas were identified so that the soil layering and density conditions within each area could be considered as reasonably uniform for the purpose of the study. The anticipated "spread" in the actual $(D_{50})_{15}$, T_{15}, F_{15} within an identified area is not expected to be wide in comparison to the values assumed for the average profile. Therefore, variations in the computed displacements arising due to the variability of the input soil parameters to the MLR model are not expected to be excessive.

Although we have used the magnitude value corresponding to the 80th percentile contribution as the input M value for the MLR model, the calculated probabilistic ground motions include contributions from a range of earthquake magnitudes (see Appendix A in Attachment 1). Therefore in a probabilistic context, the median displacement computed using the MLR model, for a given site and a given risk level, should be represented by a contribution of a range median displacements rather than a single value.

3.3.8 Permanent Vertical Ground Displacements

Saturated loose sands, such as those found in some areas of the BC GAS system, are expected to generate excess pore pressures under seismic loading, and settle as the pore pressures dissipate. Tokimatsu and Seed (1987) proposed a method for estimating such settlements and have compared the predicted displacements with field measurements.

Based on this method, in generally flat terrain, a vertical settlement corresponding to about 2% to 3% of the thickness of the liquefied soil layer could be expected for loose sands found within the areas which are susceptible to liquefaction in the present study. Although we have not estimated the expected settlements in detail for each area of concern, we estimate that the settlements in most of the generally flat areas which are susceptible to liquefaction would be in the order of 0.3 m or less, and unlikely to exceed 0.5 m.

Much larger vertical movements should be expected at river crossings, in the vicinity of such features as dykes, ditches, and road embankments. Estimation of the vertical deformations at such locations would involve rigorous analyses, which are beyond the scope of the current study.

3.3.9 Other Hazards Related to Pipeline Vulnerability Analysis

In addition to the lateral spreading expected at the river crossings and the generally flat areas which are susceptible liquefaction, other potential hazards, in terms of lateral spreading, local slope failures, or flotation due to uplift have been identified at the following pipeline locations. (Note: These hazards, however, do not include those expected at BC GAS Gate Stations, which are discussed separately in Section 7).

1. Failures associated with landfills placed over very weak soils in Burns Bog (adjacent to the pipeline) combined with adjacent BC HYDRO INTERNATIONAL transmission tower foundations.

2. Local failure deformations at the Serpentine and Nicomekl River crossings.

3. Local failure deformation at crossings of all ditches, and road embankments within the areas identified as susceptible to liquefaction(e.g., Highway No. 99 crossing in Delta, ditches in Richmond, Serpentine/Nicomekl flats, and the Huntington lacustrine deposits).

4. Possible pipeline flotation at locations where soil cover or anchoring is not adequate.

No effort has been made to quantify the risks associated with the above as part of this current study. Further analysis would be required if they are considered critical to assessment of pipeline vulnerability.

3.4 Characterization of Lateral Spread Deformations

The decision to maximize the use of quantitative measures of pipeline vulnerability necessitated defining key lateral spread geometric constraints. In particular, it was desired to have some point estimate of the likelihood of lateral spread occurrence and dimension of lateral spreads deformation relative to the orientation of the in-scope pipelines.

A review of the technical literature on lateral spreading revealed that this level of detail had not previously been investigated. For the BC GAS study, an investigation was made to determine if the necessary information could be extracted from reported permanent ground deformations caused by past earthquakes. Two of the most detailed and voluminous studies on lateral spread displacements include papers on observations following the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes in Japan (NCEER, 1992). A previous study by Hamada et al. (1986) examined these data to identify variations in displacement patterns within lateral spreads. However, no attempt was made to quantify other dimensional characteristics of the lateral spreads.

For the BC GAS study, data from the Niigata and Nihonkai-Chubu earthquakes were reexamined to determine the distribution of lateral spread dimensions and the occurrence of lateral spreading. These data were considered appropriate for extrapolation to the BC GAS study for two reasons. First, the earthquakes had durations of strong shaking that bound those considered applicable for the source mechanisms used to generate ground shaking hazard estimates. The Niigata earthquake had a duration of well over 2 minutes with peak ground acceleration on the order of 0.16g. The Nihonkai-Chubu earthquake had duration of approximately 20 seconds with peak ground acceleration on the order of 0.22g. Second, the source mechanisms for the Japanese earthquakes were roughly similar to those used in the BC GAS study. Both earthquakes were related to offshore subduction mechanisms, had relatively large magnitudes (7.5 for Niigata and 7.7 for Nihonkai-Chubu), and epicentral distances to the areas where displacements were studied of 50 km to 150 km.

From the reported observations of permanent ground deformation in NCEER-92-0001 (1992), boundaries were drawn around regions judged to be limits of lateral spread deformation. This approach to identification and interpretation of lateral spread boundaries was based on several assumptions:

1. Areas where permanent ground deformations were not measured had no lateral spread movements

2. The total area mapped in the figures in NCEER-92-0001 was susceptible to lateral spread movement

3. Large changes in displacement vector direction were indications of lateral spread boundaries

Past earthquake investigations have identified a dependence of lateral spread boundaries and direction of movement on surface topography and the subsurface profile of the liquefiable stratum. Where additional surface information could be obtained from the maps in NCEER-92-0001, it was used to temper judgements on the location of lateral spread boundaries.

The pattern of movement within the lateral spread is believed to be of minor importance. This is based on past analytical experience with site specific evaluations of pipeline response to imposed ground deformations. No attempt was made to characterize patterns in the NCEER-92-0001 maps. Reproductions of specific lateral spread maps and the estimated lateral spread boundaries are provided in Appendix B of Attachment 2.

Information collected for the lateral spread data included longitudinal length, transverse length and circumference. The longitudinal length of the lateral spread was measured as the greatest spread dimension parallel to the predominant direction of spread displacement. Transverse length was measured as the greatest spread dimension perpendicular to the predominant direction of spread movement.

3.4.1 Measurement of Lateral Spread Dimensions

Measurements were first collected from mapped displacements along the Shinano River between the Bandai Bridge and Sekiya-Cho (Section 3, Figure 5 in NCEER-92-0001). An example of the determination of lateral spread dimensions from the NCEER-92-0001 report is provided in Figure 3-8. The results were plotted in histogram format as shown in Figure 3-9. It was immediately apparent that there was a strong trend in measurements. This initial investigation into estimating extent of lateral spreads included a population of only 50.

These results were encouraging and the process was repeated for other displacement maps for the two Japanese earthquakes. This resulted in the identification of 156 spreads. When the measurements from these additional data sources were examined, their distribution (Figure 3-10) was found to be nearly identical to those collected in the first set of data.

The consistency in the results of the interpretation of lateral spread boundaries from the mapping of displacements appears to indicate a large degree of insensitivity to the precision in boundary determination. Examination of the spread patterns determined from the displacement measurements in NCEER-92-0001 did not reveal a particular pattern of spread designation (see Appendix B of Attachment 2). A detailed investigation to explain the results obtained from the lateral spread measurements was felt to be outside the scope of the BC GAS study.

The histograms of measurement data were the basis of empirical probability density functions. A cumulative probability curve was constructed for longitudinal spread length as shown in Figure 3-11. This curve was used to estimate the probability of spread lengths greater than that associated with the pipeline failure criteria. A similar relationship was not needed for the transverse direction as vulnerability was established as a function of ground displacement magnitude for ground movements perpendicular to the pipeline axis.

3.4.2 Estimates of Lateral Spread Coverage

Even in areas experiencing severe lateral spread damage, there is a considerable area in which lateral spread movements were absent. This is an important characteristic when assessing the risk to specific portions of the pipeline alignment. The preferred approach to evaluating lateral spreads occurrence in a region would be to measure the areas within estimated lateral spread boundaries for regions with similar potential for forming lateral spreads. In such a study, similarity would be established by the propensity for liquefaction and the physical geology of the setting (e.g., topography, liquefied layer thickness, slope of the underlying non-liquefied soil deposit). This in-depth evaluation was beyond the scope of this project.

For the assessment of BC GAS pipelines, a uniform risk factor was estimated based on simplifying assumptions regarding the ratio of lateral spread area to total area. It was assumed that all of the areas ground displacements were mapped had the same potential for lateral spread formation. Lateral spread area was related to measured longitudinal and transverse spread dimensions using a simple formula based on measured lateral and transverse spread dimensions.

where A_{LS} = area assigned to lateral spread
L_T = transverse dimension of lateral spread
L_L = longitudinal dimension of lateral spread

The formula is based upon lateral spread boundaries being rectangular in shape. Given the limited amount of data and the assumptions and approximations used, it was decided to use an upperbound value of 34%. The 34% estimate was felt to be applicable to those areas within a kilometer of major river channels or the coast. At other locations, this percentage should be much less. In this study, a 50% reduction to 17% was assumed.

Table 3.1

Minimum Epicentral Distance (R) Values for Various Earthquake Magnitudes
(Bartlett and Youd, 1992)

M	R(km)
6.5	0.25
7.0	1
7.5	5
8.0	10
8.5	25
9.0	50

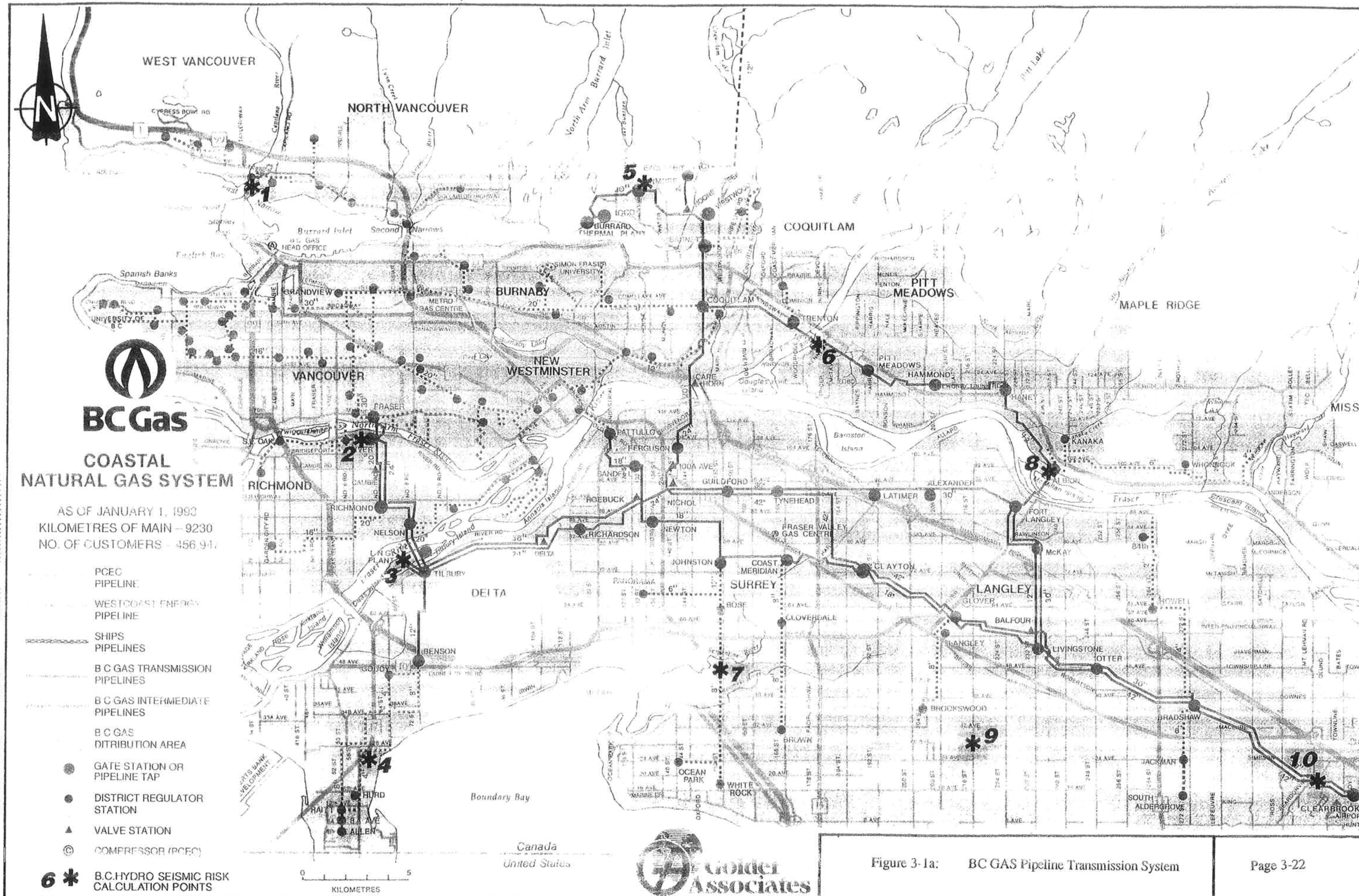


Figure 3-1a: BC GAS Pipeline Transmission System

PROJECT NO. 932-1102 DRAWN d. REVIEWED ... DATE Nov. '93

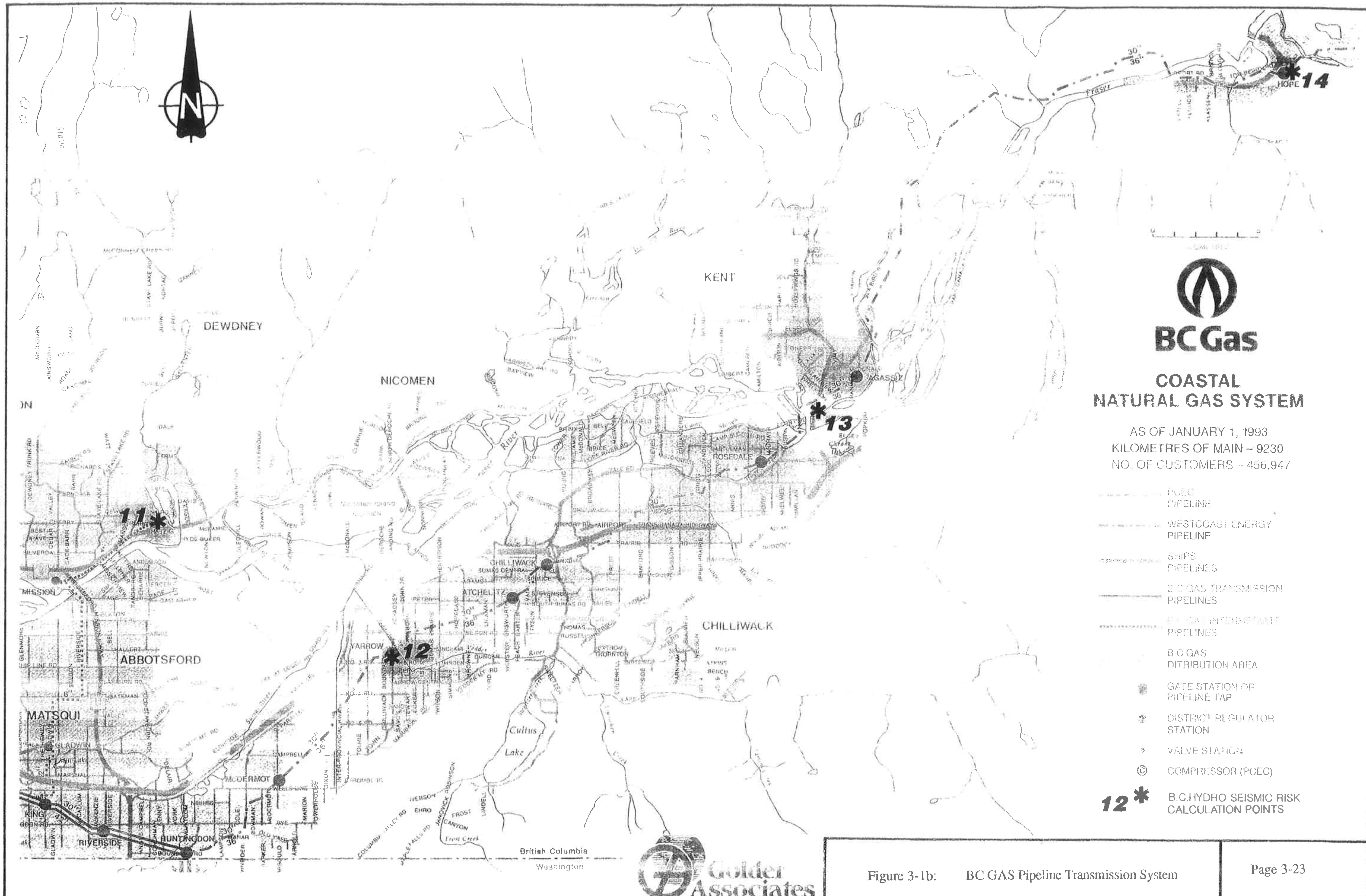
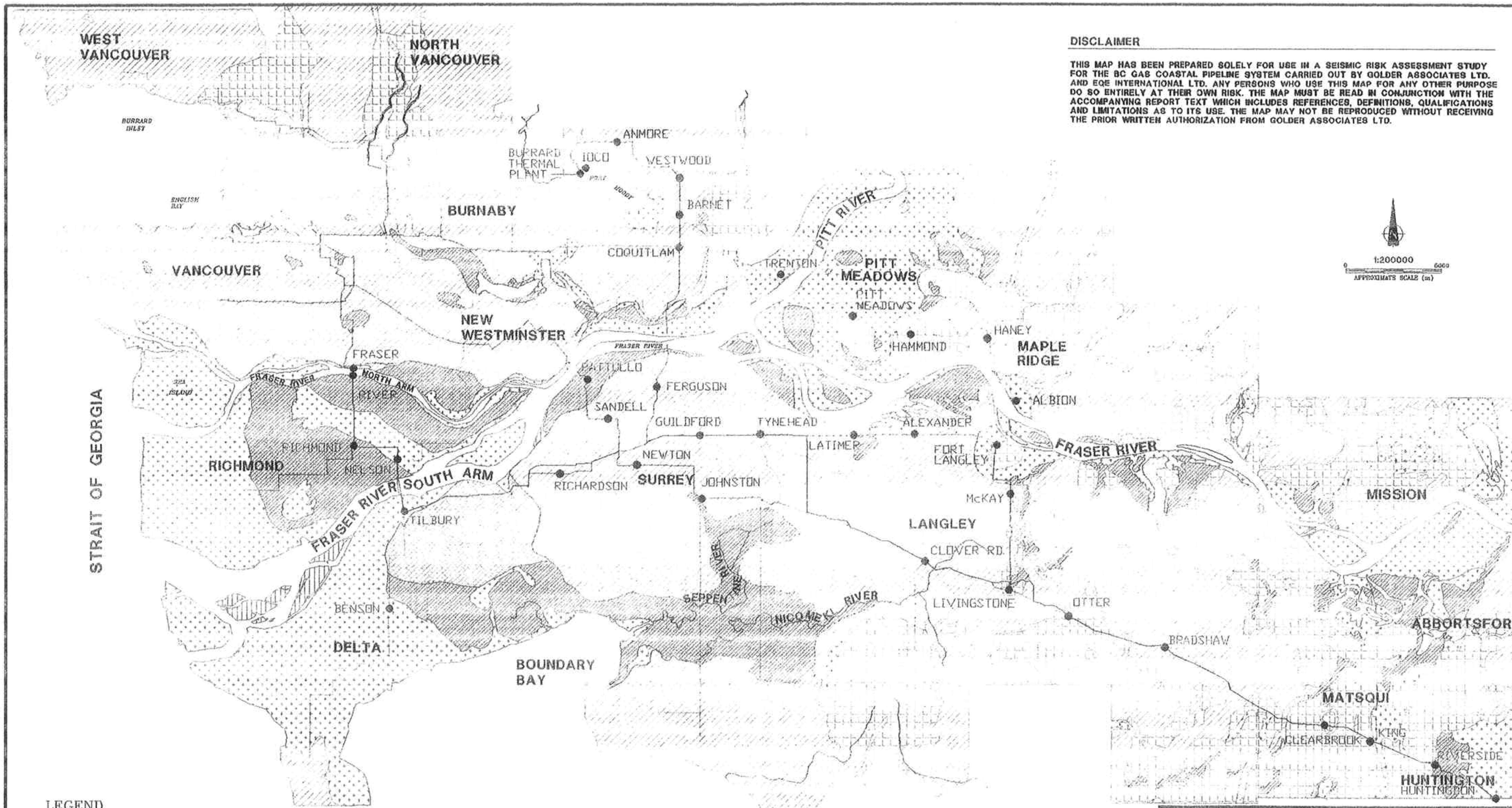


Figure 3-1b: BC GAS Pipeline Transmission System

PROJECT NO. 932-1102 DRAWN J. REVIEWED DW DATE Nov. '93



DISCLAIMER

THIS MAP HAS BEEN PREPARED SOLELY FOR USE IN A SEISMIC RISK ASSESSMENT STUDY FOR THE BC GAS COASTAL PIPELINE SYSTEM CARRIED OUT BY GOLDER ASSOCIATES LTD. AND EQE INTERNATIONAL LTD. ANY PERSONS WHO USE THIS MAP FOR ANY OTHER PURPOSE DO SO ENTIRELY AT THEIR OWN RISK. THE MAP MUST BE READ IN CONJUNCTION WITH THE ACCOMPANYING REPORT TEXT WHICH INCLUDES REFERENCES, DEFINITIONS, QUALIFICATIONS AND LIMITATIONS AS TO ITS USE. THE MAP MAY NOT BE REPRODUCED WITHOUT RECEIVING THE PRIOR WRITTEN AUTHORIZATION FROM GOLDER ASSOCIATES LTD.

LEGEND

- B.C. Gas Gate Stations
- Very High
- High
- High (Covered with Peat)
- Moderate
- Moderate (Covered with Peat)
- Variable (From Low to High)
- Very Low
- Low
- Low (Covered with Peat)

Golder Associates

SEISMIC RISK ANALYSIS OF
B.C. GAS COASTAL PIPELINE SYSTEM

Figure 3-2: Liquefaction Susceptibility for BC GAS Study Area

Drawn: NTO	Date: 11-01-93	Page 3-24
Chk'd: D.W.	Project: 932-1102	

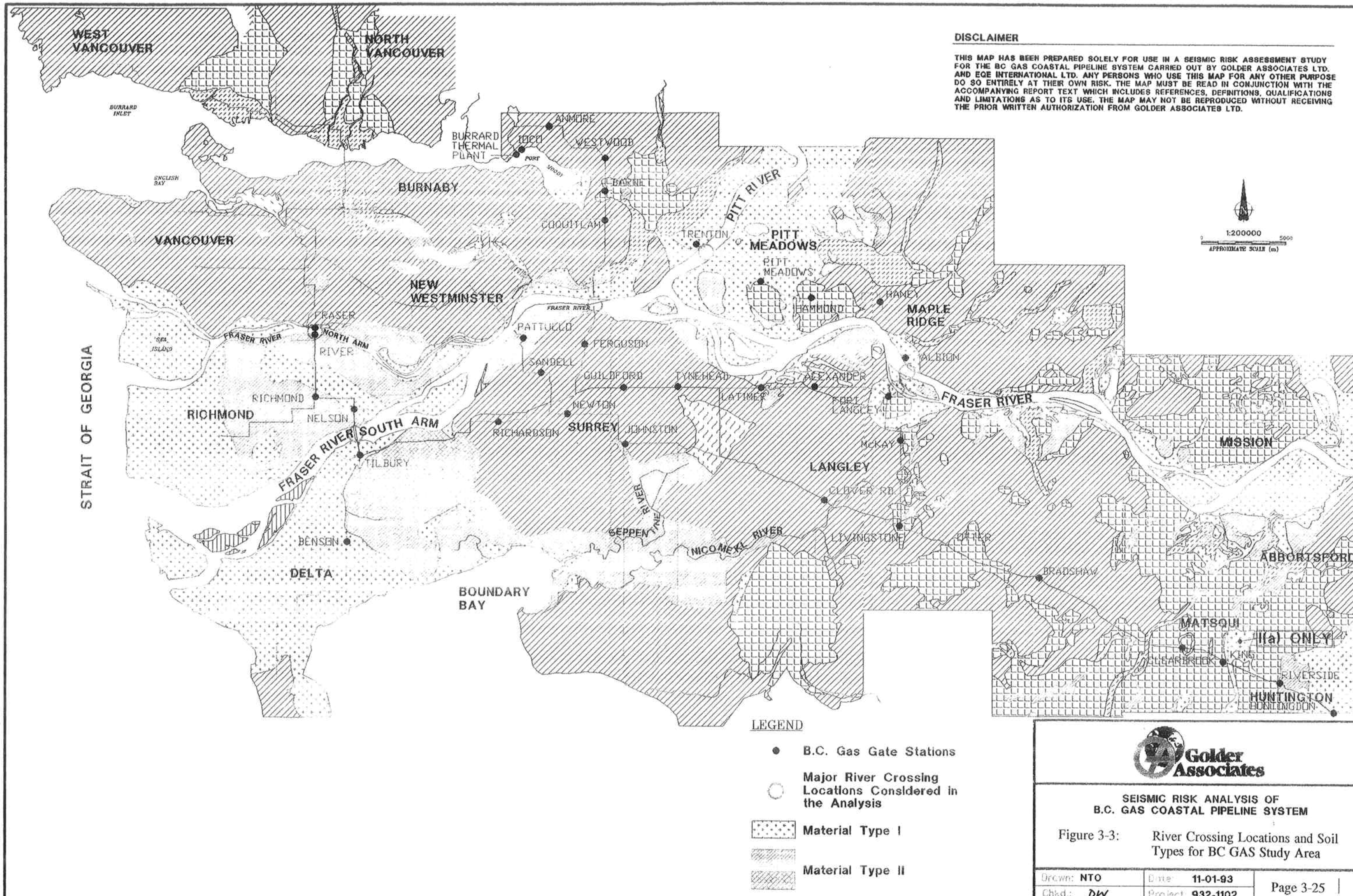
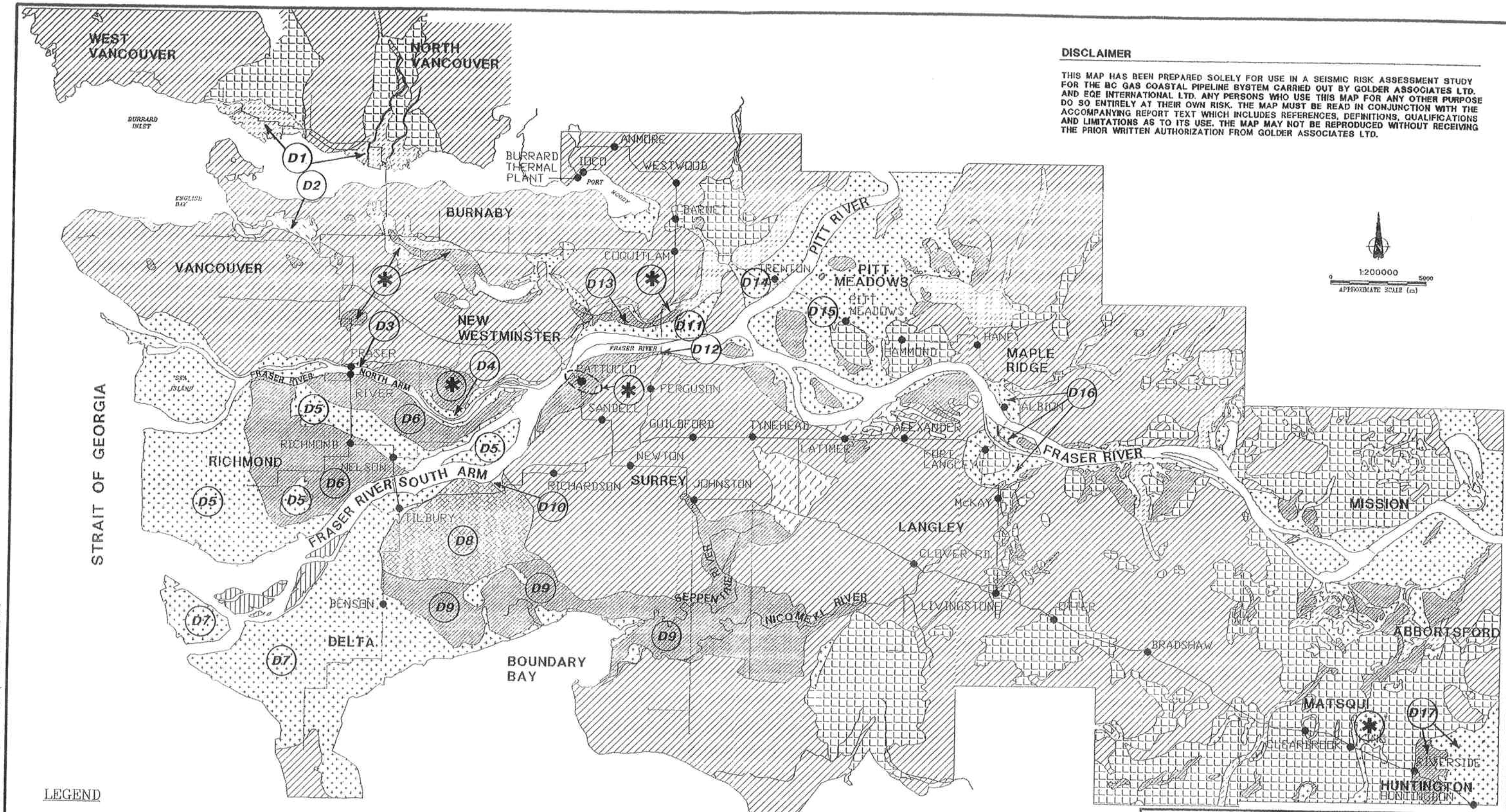


Figure 3-3: River Crossing Locations and Soil Types for BC GAS Study Area



DISCLAIMER

THIS MAP HAS BEEN PREPARED SOLELY FOR USE IN A SEISMIC RISK ASSESSMENT STUDY FOR THE BC GAS COASTAL PIPELINE SYSTEM CARRIED OUT BY GOLDER ASSOCIATES LTD. AND EQE INTERNATIONAL LTD. ANY PERSONS WHO USE THIS MAP FOR ANY OTHER PURPOSE DO SO ENTIRELY AT THEIR OWN RISK. THE MAP MUST BE READ IN CONJUNCTION WITH THE ACCOMPANYING REPORT TEXT WHICH INCLUDES REFERENCES, DEFINITIONS, QUALIFICATIONS AND LIMITATIONS AS TO ITS USE. THE MAP MAY NOT BE REPRODUCED WITHOUT RECEIVING THE PRIOR WRITTEN AUTHORIZATION FROM GOLDER ASSOCIATES LTD.

LEGEND

LIQUEFACTION SUSCEPTIBILITY

- Very High
- High
- High (Covered with Peat)
- Moderate
- Moderate (Covered with Peat)
- Variable (From Low to High)
- Very Low
- Low
- Low (Covered with Peat)
- D17 Refer to Figure D17
- ✱ Refer to Table D13
- • B.C. Gas Gate Stations

Golder Associates

SEISMIC RISK ANALYSIS OF B.C. GAS COASTAL PIPELINE SYSTEM

Figure 3-4: Locations of Lateral Spread Displacement Calculations

Drawn: NTO	Date: 11-01-93	Page 3-26
Chkd.: DW	Project. 932-1102	

CADD FILE: [NETSERVER: GOLDNET]DIR: H: \ 932-1102\1102-BOT.DWG

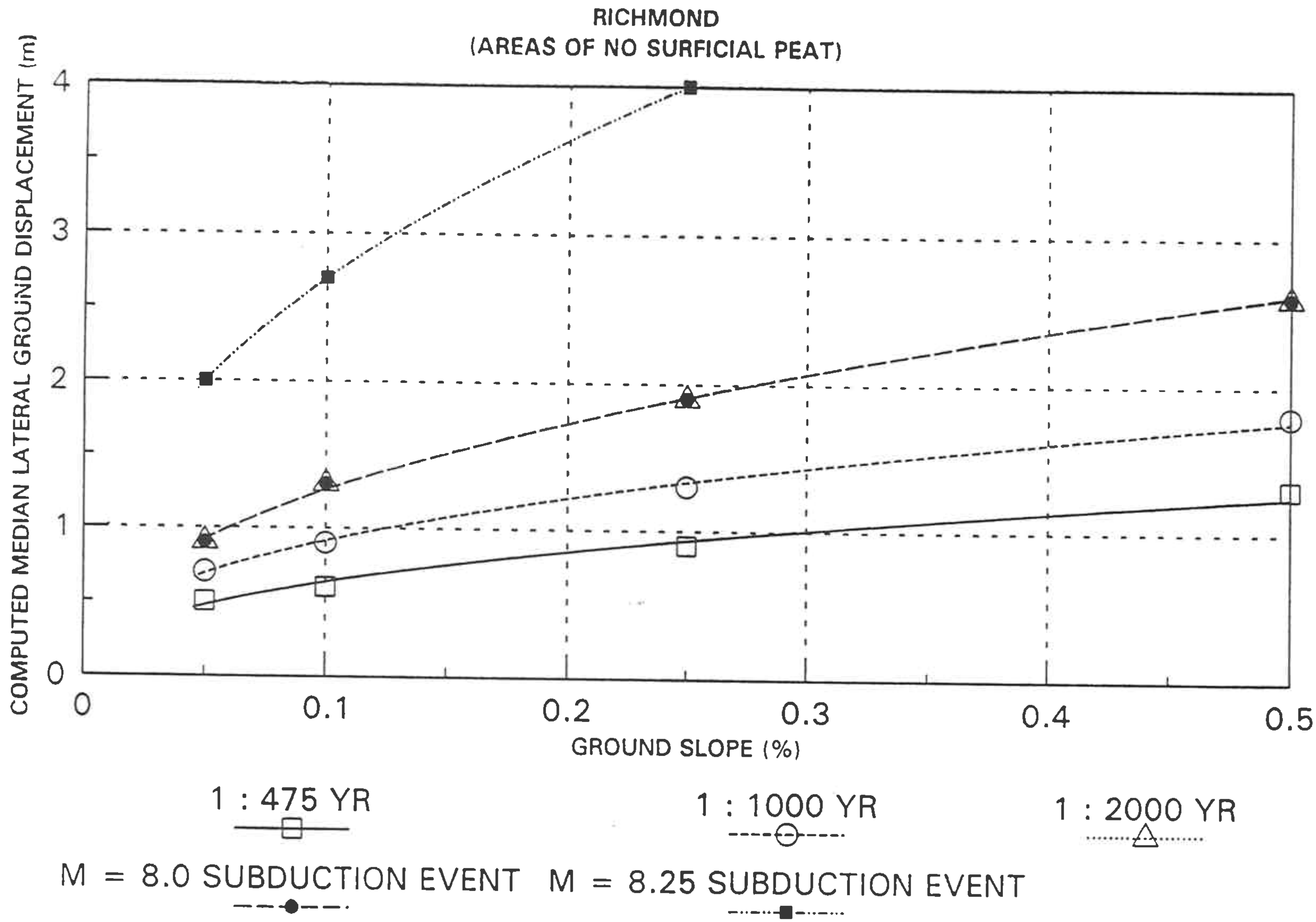


Figure 3-5: Computed Median Lateral Spread Displacement Using Bartlett and Youd (1992) MLR Method for Richmond Area

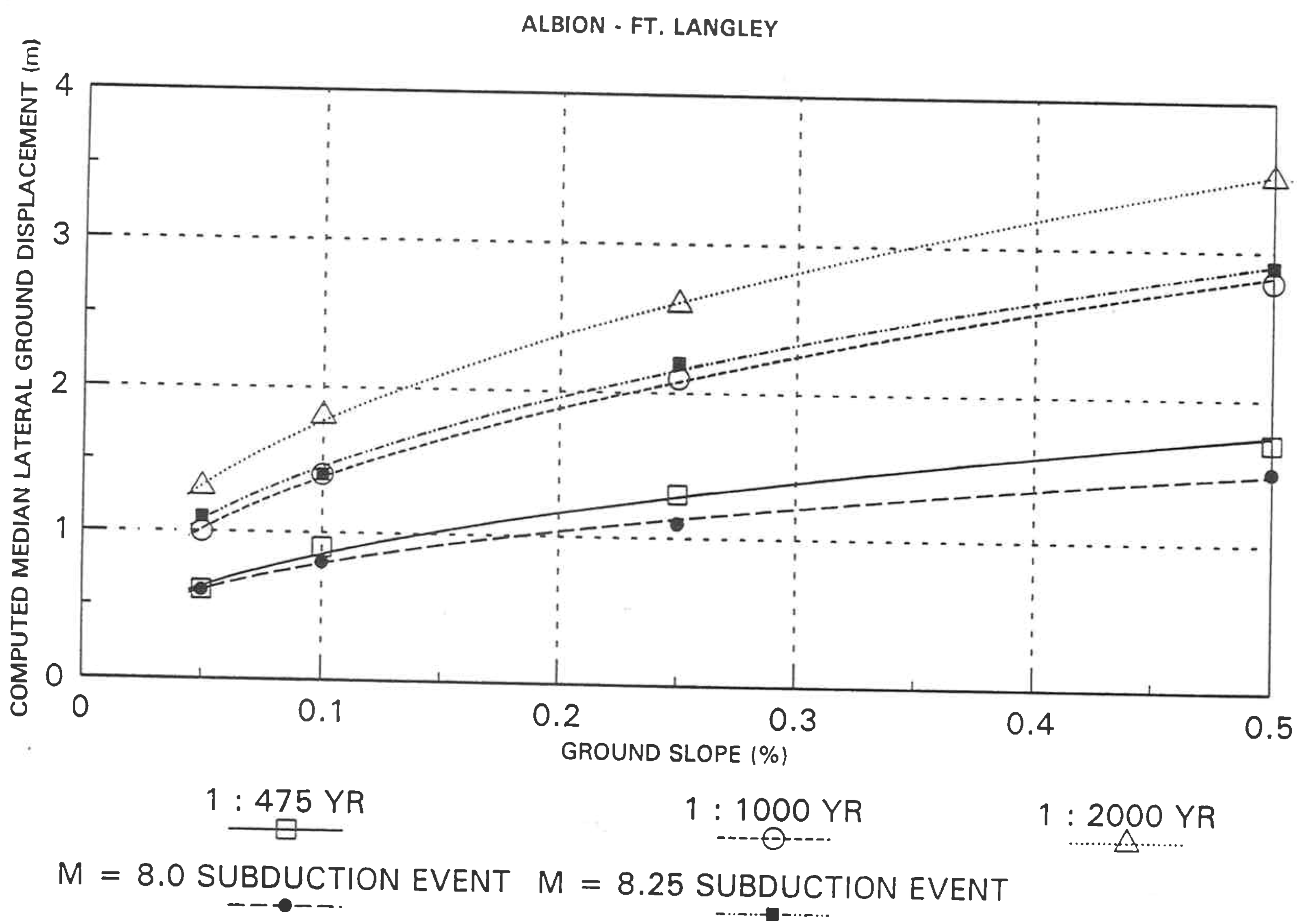


Figure 3-6: Computed Median Lateral Spread Displacement Using Bartlett and Youd (1992) MLR Method for Albion-Ft. Langley Area

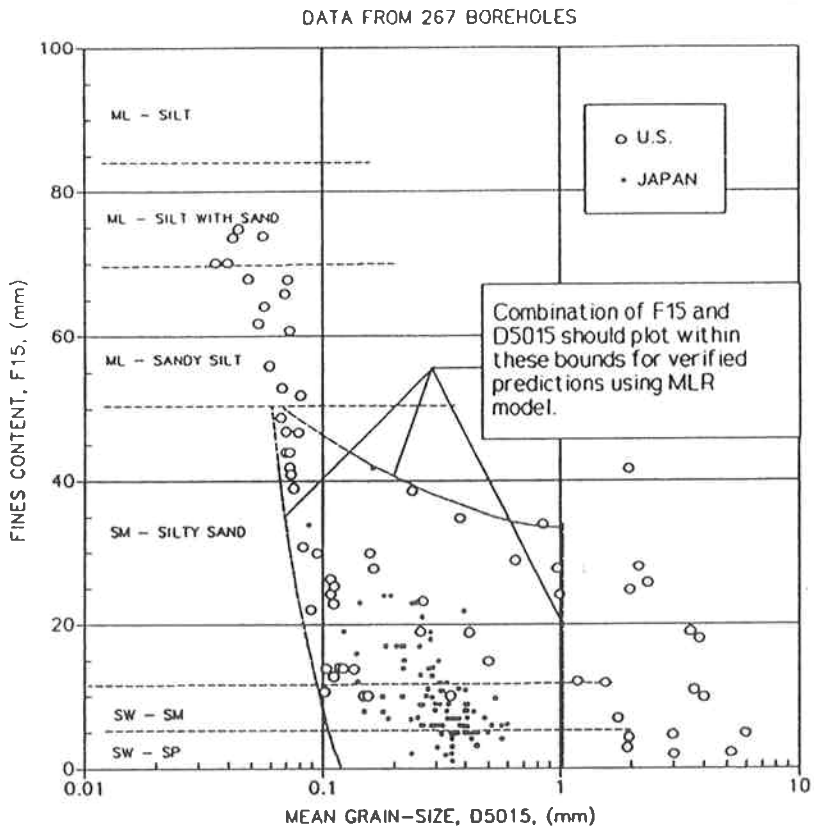


Figure 3-7: Recommended Range of F15 and (D(50)15 for MLR Equations

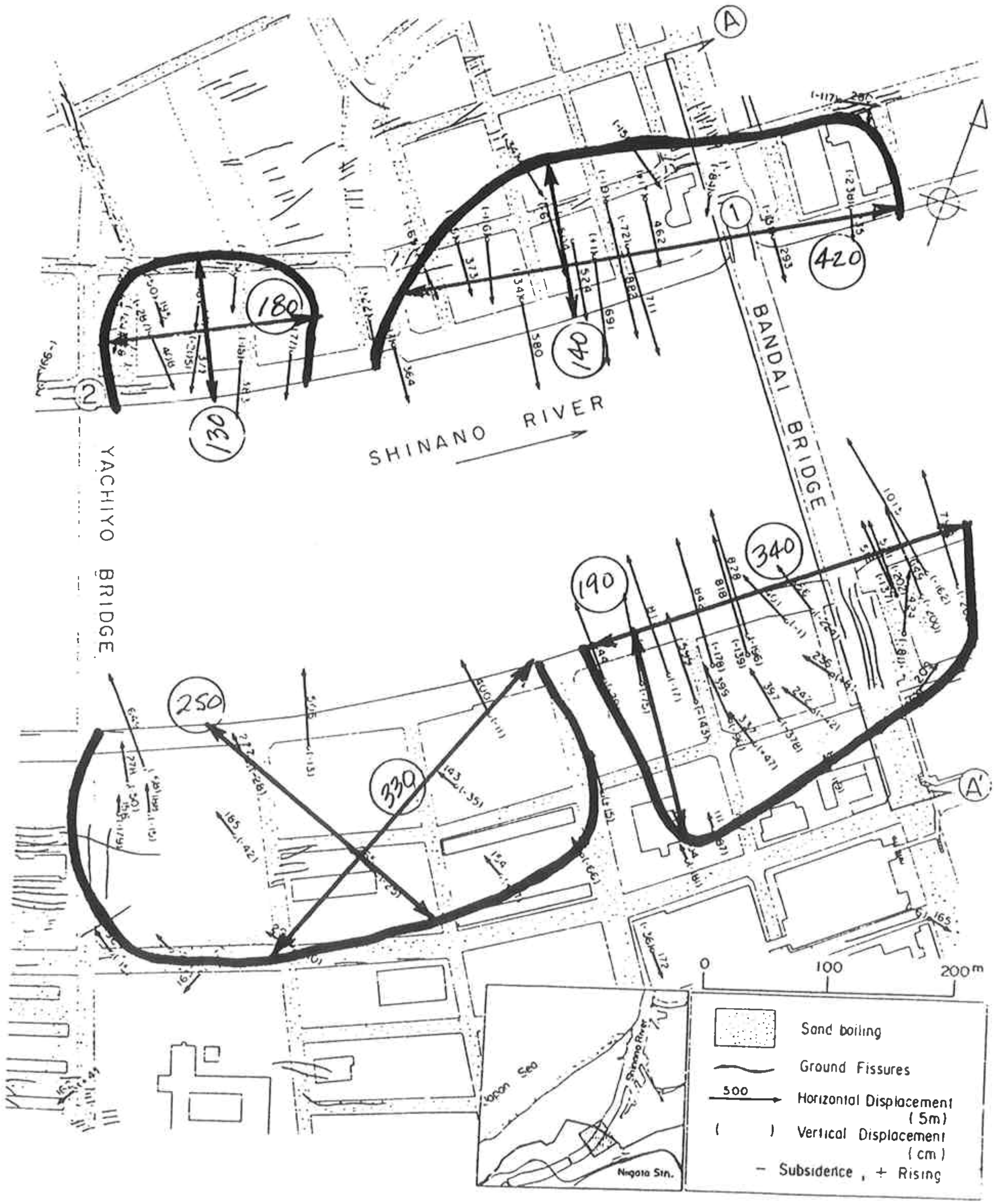


Figure 3-8: Example of Extraction of Lateral Spread Information

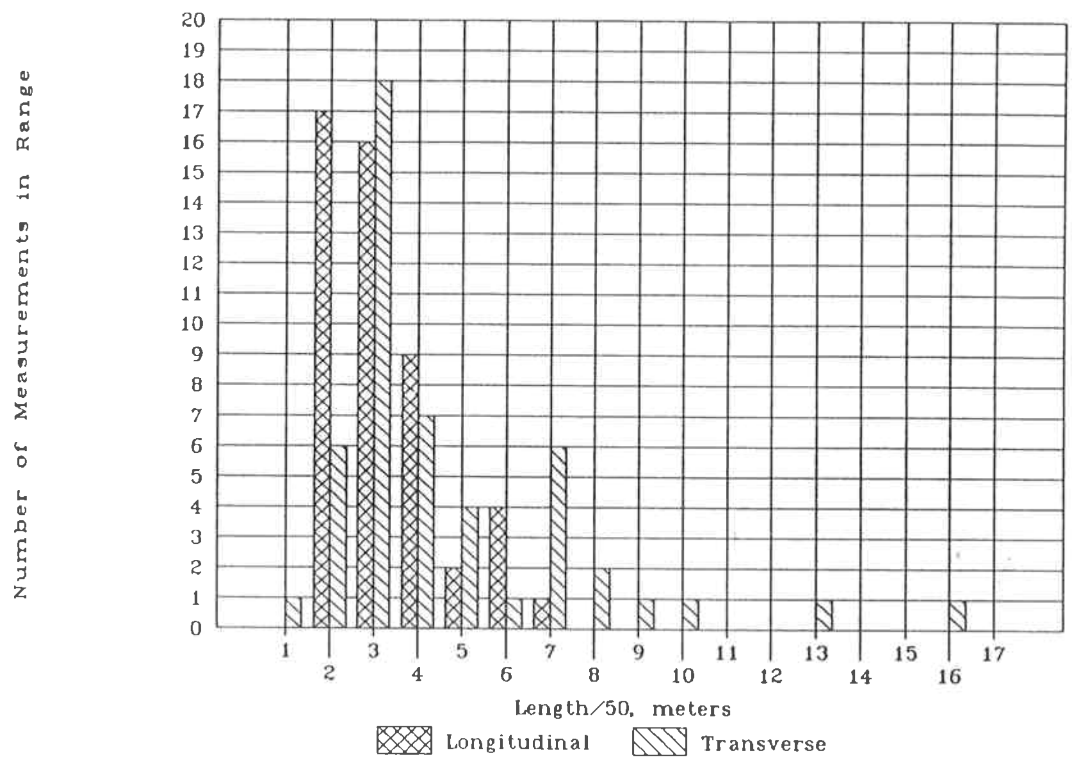


Figure 3-9: Distribution of Measured Lateral Spread Longitudinal and Transverse Dimensions for 50 Lateral Spread Zones Identified in NCEER-92-0001

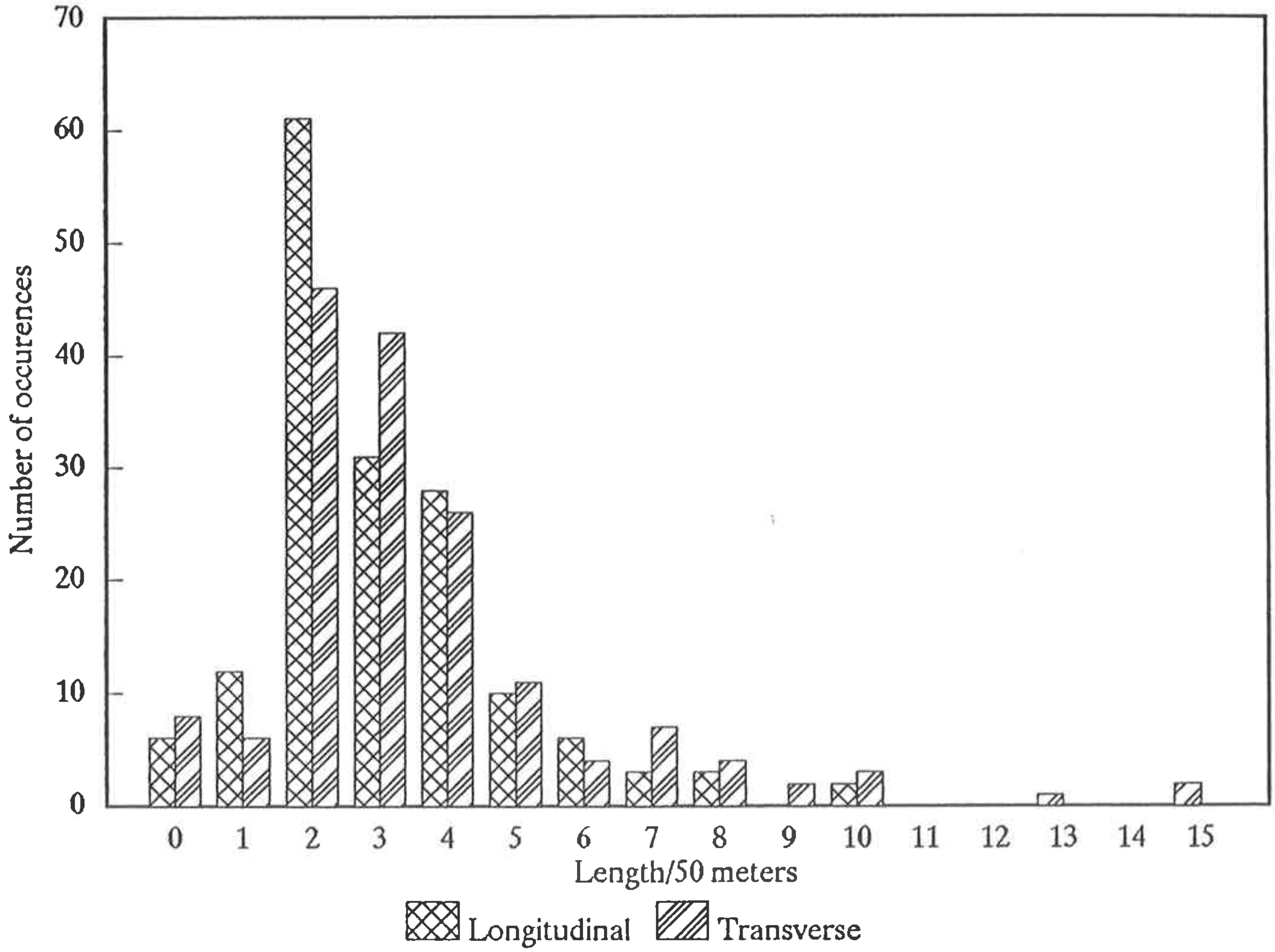


Figure 3-10: Distribution of Measured Lateral Spread Longitudinal and Transverse Dimensions for 150 Lateral Spread Zones Identified in Appendix A of Attachment 2

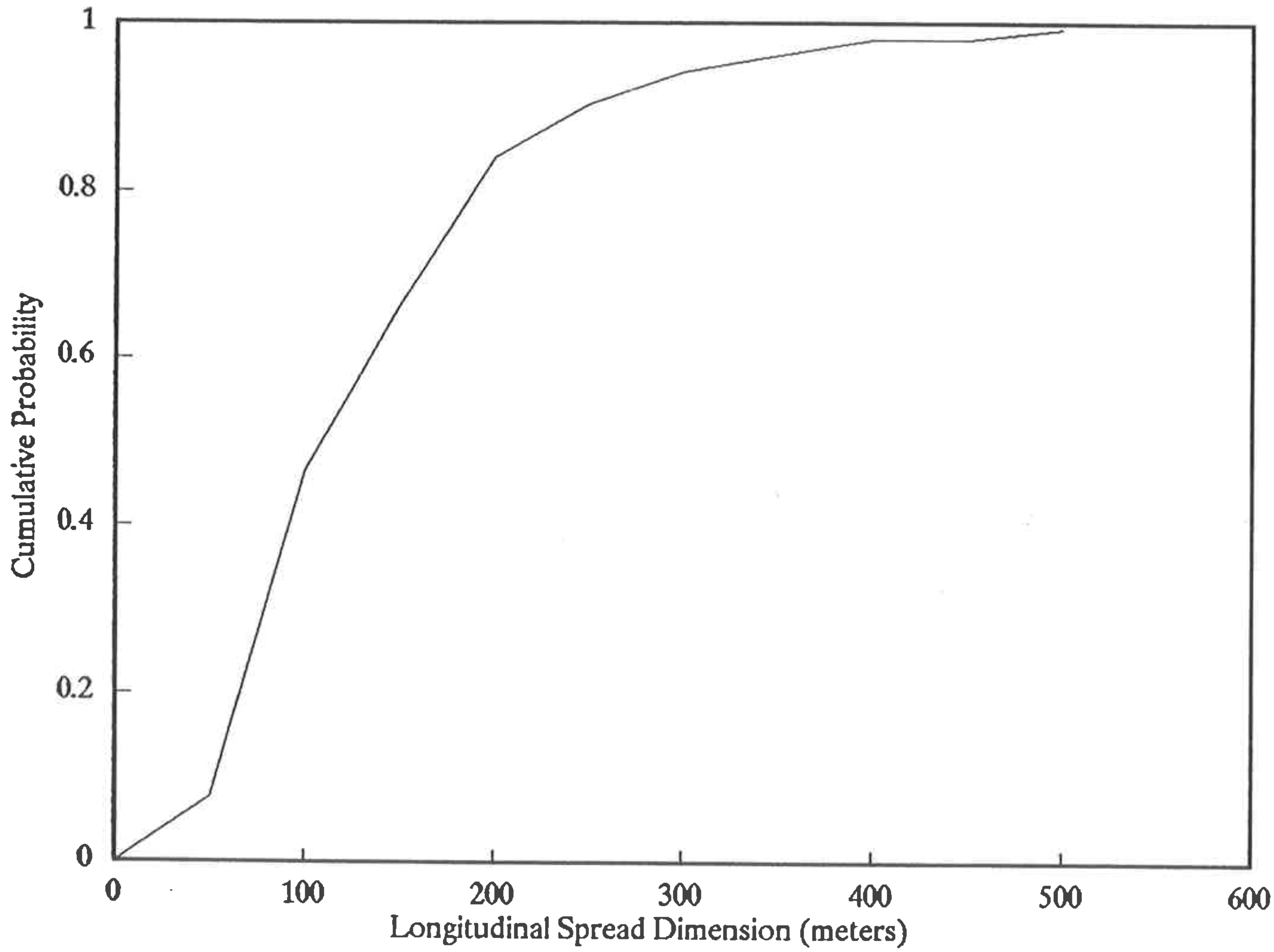


Figure 3-11: Inferred Probabilistic Density Function for Lateral Spread Longitudinal Length

4. DETERMINATION OF PIPELINE VULNERABILITY

Pipeline vulnerabilities have traditionally been determined from examination of damage in past earthquakes. The greatest strengths of these vulnerability relationships are their tie to past earthquake experience. A significant weakness is the lack of details on pipeline condition and earthquake hazard in the past data. They have no ability to distinguish between for soil type, pipeline configuration, pipe diameter, material grade or wall thickness. From an engineering mechanics perspective, these parameters are very important to assessing pipeline performance. For the BC GAS pipelines considered in this study, available vulnerability relationships would have assigned every pipeline in the BC GAS study the same vulnerability.

Analytical techniques allow the assessment of a wide variety of parameters. The use of analytical methods for determining pipeline vulnerability is not suitable for every situation. This is especially true for municipal water, natural gas and sewage systems that use pipelines with non-structural or weak joints (e.g., mortar, lead, gasket, bolted).

Developing pipeline vulnerabilities for the BC GAS study from analysis results was determined to be the only viable option for providing the desired details on pipeline performance. Vulnerabilities were developed in three steps. First, the potential population of pipeline parameters were defined. Second, a set of pipeline analysis cases was selected that was most representative of the majority of pipeline. Finally, results of the analyses were translated into expressions of pipeline vulnerability that could be implemented in the risk assessment. Details of the analyses to develop pipeline vulnerability relationships are provided in Attachment 2.

4.1 Background on Analysis of Buried Pipeline Response to Imposed Ground Deformations

Experience in the oil and gas industry with respect to the analytical evaluation of buried pipeline response to large permanent ground deformation dates back to the mid-1970's. This experience includes simple evaluation methodologies as well as more sophisticated finite element approaches. A brief summary of this history and the experience of pipelines undergoing large ground deformations is presented as a means to introduce discussion of analytical results.

4.1.1 Buried Pipeline Behavior Under Ground Deformation Loading

Relative movement of the surrounding soil with respect to a buried structural element imparts loads on that element. The magnitude of these loads was initially investigated to understand the performance of footings, piles and soil anchors. In the early to late 1970's, several research programs developed soil loading relationships specifically for buried pipelines. A key characteristic of soil loading is that it increases only to the point at which gross failure of the soil occurs. For example, the maximum lateral load that can be imparted to a buried pipe is related to the load necessary to develop a failure plane in the soil. Once this load has been reached, further relative displacement serves primarily to move soil along the failure plane. This is illustrated in Figure 4-1. Note that under large lateral loading, Figure 4-1 shows the pipe undergoing some vertical uplift as it follows the failure plane of the soil. This behavior has been confirmed in small-scale laboratory tests (e.g., Trautmann and O'Rourke, 1983). This upward movement tends to relieve strains in the pipeline and was not accounted for in this evaluation.

The limited nature of soil loading on the pipeline is commonly represented in analytical approaches by modeling the soil with bilinear springs. This approach is generally conservative because forces necessary to carry soil along the established failure planes are typically less than those needed to initially generate failure. An approximate analogy in mechanics is the relationship between static and sliding friction.

Finite element approaches provide a means to rapidly investigate the effects of changes in backfill characteristics, pipeline material, wall thickness, and route selection. The guidelines for implementing a finite element analysis have changed little in the last 15 to 20 years. General guidance for the analytical treatment of pipelines subjected to large ground deformations is provided in the American Society of Civil Engineers (ASCE) publication, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984). The primary advancement in the past 10 years has been in the availability of powerful desktop personal computers and compatible non-linear analysis software that accounts for material yielding and large deformations.

4.1.2 Implementation of Ground Deformations in the Analysis

The finite element computer code ANSYS (a product of Swanson Analysis Systems, Inc.) was used to perform analyses for selected generic pipeline configurations. The approach involved modeling the soil surrounding the pipeline with discrete non-linear springs representing the soil stiffness and maximum loads that can be transferred to the pipe by the soil. The development of the computer model for this analysis approach is illustrated in Figure 4-2.

In analyzing the response of pipelines to permanent ground deformation, the focus is on the interface zones between regions undergoing different types or rates of movement. In the case of a lateral spread, two such zones defining the lateral extent of the slide can be considered. If the spread is sufficiently wide, only one interface zone need be examined at a time. In this case, the ground deformations are nearly identical to those occurring as a result of surface faulting. The pipeline is modeled with pipe elements that allow computation of maximum strains in the pipe under the combined loading of internal pressure and external soil loading. More detailed modeling is used near the boundary zone to capture local nonlinear pipe behavior.

Of primary interest in the analysis of the pipeline response is the magnitude of longitudinal strain created by the imposed ground deformations. The computer program calculates strain at eight points around the circumference of the pipe. These points are illustrated in Figure 4-3. When maximum strains are presented, they are from one of these two points.

The soil is modeled with bilinear springs attached at each node. One end of the spring is attached to the pipe element while the base is fixed. Ground deformations are simulated by imposing displacements to the base of the spring elements that are identical to the free-field ground deformation. This situation is illustrated schematically in Figure 4-4.

4.2 Identification of Pipeline Parameters

Pipeline parameters include specific pipe properties as well as the characteristics of the soils in which the pipe is buried. Pipe property data were obtained from BC GAS records and from pipeline system maps. For the Fraser Valley District, information was provided in the form of an inventory table. Fraser Valley data included pipe diameter, wall thickness, material yield strength, pipeline beginning and end points, total length of pipeline, date of construction, and applicable construction specification. For the Vancouver district, pipe information was obtained from a system map and was limited to pipe diameter.

The pipeline vulnerability analysis carried out by EQE requires typical strength parameters for the soils within those areas susceptible to significant earthquake-induced ground displacements. Due to the variability of the thickness of surficial layers, and without site-specific geotechnical information, it was not practical to designate one soil type for a given area. Therefore, the

B.C.G. pipeline system area was divided into zones, within which the two predominant soil types most likely to be encountered within 3 to 4 m of ground surface have been identified. It should be understood that the boundaries between the material zones are approximate only. These zones are identified in Figure 3-3. The two soil types corresponding to each material zone are presented in Table 4.2.

Based upon a review of the general soil conditions along the pipeline, two generic classes of in-situ soils were identified. In addition, it was assumed that the backfill material around all pipe was a relatively compact, well-graded sand. Formulations for maximum axial and lateral soil forces considered to be acting on buried pipe were computed assuming a 3-foot depth of soil cover and using the relationships in Table 4.3 (ASCE, 1984). Maximum soil forces on the pipe are plotted as a function of diameter and shown in Figures 4-5 (axial) and 4-6 (lateral). In selecting parameters for the computer analyses, axial and lateral soil force relations were conservatively chosen as shown in Figures 4-5 and 4-6.

This information was used to construct a matrix of possible pipeline characteristics to be analyzed. The matrix is provided in Table 4.3. To account for the lack of data regarding pipes in the Metropolitan Vancouver district, wall thickness and material strength was assumed to identical to those of the most prevalent pipe with the same diameter in the Fraser Valley district.

4.3 Analysis of Pipeline Configurations

Analysis of pipeline response was initiated concurrently with the development of the earthquake hazard definition. This decision was made to accommodate the project schedule since it allowed initiation of system risk assessment to roughly coincide with completion of the earthquake hazard assessment. To carry out the analyses, it was necessary to select pipeline configurations representative of the alignments of the BC GAS system. After review of the detailed system maps, it was decided to limit the analyses to straight, 90° ell and 90° tee configurations. For each of these general configurations, ground deformations were considered to act parallel and perpendicular to the orientation of the pipe. A total of seven analytical models were considered. These are illustrated in Figure 4-7.

The models in Figure 4-7 for ground deformation parallel to the pipe do not describe the manner in which this phenomena was modeled in the analysis. Instead, analyzing the effect of ground deformations parallel to the pipe used an applied force to represent the cumulative force on the pipe from relative axial soil displacement. This force was later related to an equivalent required length at lateral spread.

As seen in Table 4.1, six grades of steel exist in the BC GAS pipeline system; Grade A, Grade B, X42, X52, X60 and X65. Stress strain curves used in the analyses to represent these different grades of steel are shown in Figure 4-9.

Considering the total number of pipeline parameters, soil types and analysis configurations led to a possible 950 different analyses were possible. This number of analyses was far beyond the project scope. Selection of analysis cases was prioritized considering the following:

1. Not all pipelines were found in both types of soil
2. Not all pipelines were in areas that were potentially liquefiable
3. Ignoring certain pipeline parameters affects a very small percentage of the total system
4. Some scaling of results could be used to estimate vulnerabilities for cases not selected for analysis

A total of 59 analyses were performed for the BC GAS study. These are identified in the matrix of possible analysis cases shown in Table 4.4. Table 4.4 also indicates those cases that were later found to be not necessary because of lack of representation in the BC GAS system.

An additional 8 cases were analyzed to assess the sensitivity of parameter variation on the calculation of maximum longitudinal strain. These cases examined the impact of material strength variation and changes in assumed lateral spread width.

4.4 Evaluation Criteria

The focus of this evaluation is the ability of the proposed pipeline to accommodate abrupt ground displacements or differential deformations that may arise from lateral spreads. Strains in the pipeline are limited to the level necessary to conform to the differential ground deformation. For this reason, it is common to impose strain limit criteria as opposed to limiting stresses in the pipeline. Use of strain-based criteria is a unique aspect of buried pipeline evaluations.

There are no universal guidelines on establishing an appropriate strain criteria. One reason for this is the dependency of the criteria on the intended level of performance for the pipeline. The assessment of risk to BC GAS pipelines was focused on prediction of pipeline rupture. Selection of appropriate strain criteria took this into account. Judgements regarding strain criteria also considered the approximate nature of using generalized vulnerabilities to account for pipeline behavior.

In the absence of bends, intersections or other configurations that tend to anchor the pipeline, evaluations of pipeline typically permit tensile strains to reach 3% to 5% (ASCE, 1984). Since these strain levels still contain a significant level of conservatism, tensile rupture of the pipeline was not considered a credible failure mode unless computed tensile strains exceeded 7%. The 7% tensile strain is believed to correspond to a mean probability of rupture.

In all cases, pipeline vulnerability was based upon limiting compressive strains. The theoretical wrinkling limit was selected as a best estimate of compressive strain at pipeline rupture. Preference for selection of the theoretical wrinkling limit was driven primarily by the lack of test data relating rupture to strain. More detailed discussion of the basis for selecting strain criteria is presented in Attachment 2.

To assess the impact of different assumptions for pipeline rupture criteria, risk assessments were also performed using 1/4 of the theoretical wrinkling strain and the lesser of 3 times the wrinkling strain or 5% failure criteria. The lower strain value was considered to be representative of a 10% probability of failure while the upper strain value was considered to be representative of a 90% probability of failure.

4.5 Translating Analysis Results to Vulnerability Criteria

Summary results of the analyses are presented in Appendix A of Attachment 2. Analyses were not performed for the case of a straight pipeline configuration subjected to lateral spread movement parallel to the pipeline. These cases were computed with simple hand calculations that used the maximum longitudinal force that could be transferred to the pipe to compute the length of lateral spread necessary to achieve a specified compressive force in the pipe. The pipe force used in the calculation was obtained by assuming a uniform longitudinal stress in the pipe at the strain level of interest. Key characteristics of the analytical results are discussed below.

Using the results from the pipeline analyses, a table of pipeline rupture criteria was developed. This table, presented as Table 4.4, consisted of specified lateral spread displacements or lengths corresponding to a specific strain limit. For the vulnerability table, linear interpolation was used to determine the necessary displacement or force corresponding to a specific strain criteria.

Scaling was also necessary to obtain vulnerabilities for pipeline conditions not covered by specific analyses. In all cases, scaling was performed to obtain vulnerabilities for pipelines bracketed by cases for which analysis results were available.

Several approaches were investigated to scale analysis results to cases for which analyses were not conducted. None of these proved to be especially satisfactory owing to the nonlinear nature of pipeline response at post-yield strain levels (especially for ells and tees) and the large effect of soil strength for the two soil types used in the analyses.

Vulnerabilities for which scaling was relied upon are indicated by the shaded numbers in Table 4.4. Of the 37 vulnerabilities needed to investigate the BC GAS pipeline system, 23 were obtained directly from analysis results. This means that approximately 50% of the analyses performed were not used in the risk assessment. It is also worthwhile to note that delaying the pipeline analyses until the completion of the GIS mapping would have allowed most conditions to be represented by an analysis case.

Forces used in the analyses were conservatively translated into equivalent lengths of pipeline in a lateral spread. This was done using the maximum axial force that the soil could transfer to the pipe in the following relationship:

$$L_{sr} = F_c / F_a$$

where L_{sr} = required lateral spread length
F_c = computed force in pipeline
F_a = maximum axial force per unit length transferable to the pipeline

This relationship assumed that there are no bends or other conditions in the pipeline configuration that could resist some of the soil load transferred to the pipe.

No analyses were performed for straight sections of pipe subjected to lateral spread movements parallel to the pipeline axis. Instead, the length of lateral spread was determined by computing an equivalent value of F_c using the relationship below.

$$F_c = A_p \times \sigma_c$$

where A_p = pipe cross sectional area

σ_c = stress at a specified failure criteria

The value of σ_c was taken to be 1.0, 1.5 and 2 times the pipe material yield stress for the 10%, mean, and 90% failure probability criteria, respectively.

Table 4.1

Matrix of Potential Finite Element Analysis Cases

PIPE DIAMETER (in)	WALL THICKNESS (in)	STEEL GRADE	SOIL TYPE		STRAIGHT LONG.	STRAIGHT TRANS.	ELL LONG.	ELL TRANS.	TEE LONG. I	TEE LONG. II	TEE TRANS.
8	0.188	30	SOIL TYPE I	X		X	X	X	X	X	X
			SOIL TYPE II	X		X	X	X			
8	0.188	42	SOIL TYPE I	X		X		X			
			SOIL TYPE II								
8	0.250	30	SOIL TYPE I								
			SOIL TYPE II								
8	0.322	42	SOIL TYPE I								
			SOIL TYPE II								
8	0.500	42	SOIL TYPE I								
			SOIL TYPE II								
12	0.250	30	SOIL TYPE I								
			SOIL TYPE II								
12	0.250	42	SOIL TYPE I	X		X	X	X	X	X	X
			SOIL TYPE II	X		X	X	X			
12	0.322	52	SOIL TYPE I								
			SOIL TYPE II								
12	0.375	30	SOIL TYPE I								
			SOIL TYPE II								
12	0.375	42	SOIL TYPE I								
			SOIL TYPE II								
16	0.250	42	SOIL TYPE I								
			SOIL TYPE II	X				X			
18	0.250	42	SOIL TYPE I								
			SOIL TYPE II	X		X	X	X			
20	0.281	42	SOIL TYPE I	X			X	X			
			SOIL TYPE II								
20	0.500	42	SOIL TYPE I								
			SOIL TYPE II								
24	0.270	42	SOIL TYPE I								
			SOIL TYPE II								
24	0.281	52	SOIL TYPE I								
			SOIL TYPE II								
24	0.344	42	SOIL TYPE I	X		X	X	X	X	X	X
			SOIL TYPE II	X		X	X	X			
24	0.344	52	SOIL TYPE I	X		X		X			
			SOIL TYPE II								
24	0.500	52	SOIL TYPE I								
			SOIL TYPE II								
30	0.418	42	SOIL TYPE I	X			X	X			
			SOIL TYPE II								
36	0.344	60	SOIL TYPE I	X		X	X	X	X	X	X
			SOIL TYPE II	X		X	X	X			
36	0.351	60	SOIL TYPE I								
			SOIL TYPE II								
42	0.375	65	SOIL TYPE I								
			SOIL TYPE II	X		X	X	X			
42	0.390	65	SOIL TYPE I								
			SOIL TYPE II								
42	0.500	60	SOIL TYPE I								

"X" REPRESENTS CASES ANALYZED

SHADED BLOCKS INDICATES CASES USED IN RISK ANALYSIS

Table 4.2

Soil Properties Used to Represent Those in the BC GAS Study Area

Soil Group	Cohesion (kPa)	Internal Friction Angle (deg)	Dry Density (kN/m^3)
Compact Sand Backfill	0	34	19
Loose Sand Backfill	0	32	16
Loose Sand and/or Silty Sand (Material Group I)	0	30-32	18
Soft Peat (Material Group II)	7-15	0	12
Soft Silts and/or Clayey Silts (Material Group I and II)	15-30	0	18

Table 4.3

Soil Strength Relationships Used to Define Equivalent Soil Springs for the Pipeline Analyses (ASCE, 1984)

COMPONENT	RELATIONSHIP FOR FULLY BURIED PIPELINES	SOURCE OF RELATIONSHIP
AXIAL (t-x curves)	$t_u = \begin{cases} \pi D \alpha S_u & \text{for clay} \\ \frac{\pi D}{2} \bar{\gamma} H (1 + K_o) \tan\delta & \text{for sand} \end{cases}$ $x_u = \begin{cases} \text{0.1 to 0.2 inches for dense to loose sand} \\ \text{0.2 to 0.4 inches for stiff to soft clay} \end{cases}$	Inferred from pile shaft load transfer theory NOTE: K_o applies for at-rest conditions. However, the coefficient of soil pressure may be substantially higher in zones of large relative displacement between the pipeline and the soil.
TRANSVERSE HORIZONTAL (p-y curves)	$p_u = \begin{cases} S_u N_{ch} D & \text{for clay} \\ \bar{\gamma} H N_{qh} D & \text{for sand} \end{cases}$ $y_u = \begin{cases} \text{0.07 to 0.10}(H + D/2) & \text{for loose sand} \\ \text{0.03 to 0.05}(H + D/2) & \text{for medium sand} \\ \text{0.02 to 0.03}(H + D/2) & \text{for dense sand} \\ \text{0.03 to 0.05}(H + D/2) & \text{for stiff to soft clay} \end{cases}$ $p = \frac{y}{A' + B'y}$ (for sands) $A' = 0.15\, y_u/p_u$ $B' = 0.85/p_u$	Inferred from footing and vertical anchor plate pull-out capacity theory and laboratory tests on model pipelines simulating horizontal pipe movements (Audibert et al., 1977, 1978; Trautmann and O'Rourke, 1983a)

Table 4.4

Criteria Used to Identify Conditions Associated with Pipeline Rupture

PIPE DIAMETER (NOMINAL, in)		FAILURE PROBABILIT	STRAIGHT TRANS. (m)	STRAIGHT LONG. (m)	ELL TRANS. (m)	ELL LONG. (m)	TEE LONG. I (m)	TEE TRANS. (m)
8	SOIL I	10%	4	97	0.8	17	N/A	0.1
		MEAN	4	145	1.9	20	N/A	1
		90%	4	340	4	72	N/A	4
	SOIL II	10%	2.4	97	0.3	10	N/A	0.2
		MEAN	4	145	2.2	13	N/A	1.2
		90%	4	193	4	13	N/A	4
12	SOIL I	10%	4	170	0.2	19	180	0.1
		MEAN	4	255	0.9	26	260	4
		90%	4	340	4	38	980	4
	SOIL II	10%	4	170	0.4	13	N/A	0.2
		MEAN	4	255	1.5	19	N/A	4
		90%	4	340	4	32	N/A	4
16	SOIL I	10%	4	153	0.3	20	N/A	0.1
		MEAN	4	230	1	27	N/A	1
		90%	4	307	4	37	N/A	4
	SOIL II	10%	4	153	0.3	14	N/A	0.2
		MEAN	4	230	1.2	18	N/A	1.2
		90%	4	307	4	25	N/A	4
18	SOIL I	10%	4	150	0.1	20	N/A	0.1
		MEAN	4	225	0.8	27	N/A	0.8
		90%	4	300	4	37	N/A	4
	SOIL II	10%	4	150	0.2	14	N/A	0.2
		MEAN	4	225	0.8	17	N/A	0.8
		90%	4	300	4	20	N/A	4
20	SOIL I	10%	4	200	0.1	22	N/A	0.1
		MEAN	4	300	0.5	29	N/A	0.5
		90%	4	400	4	36	N/A	4
	SOIL II	10%	4	200	0.2	14	N/A	0.2
		MEAN	4	300	1	18	N/A	1
		90%	4	400	4	25	N/A	4
24	SOIL I	10%	0.7	193	0.2	31	N/A	0.1
		MEAN	4	290	0.5	35	N/A	0.5
		90%	4	387	4	45	N/A	4
	SOIL II	10%	4	193	0.3	18	N/A	0.2
		MEAN	4	290	1	22	N/A	1
		90%	4	387	4	31	N/A	4
30	SOIL I	10%	0.7	180	0.1	31	N/A	0.1
		MEAN	4	270	0.5	41	N/A	0.5
		90%	4	360	4	50	N/A	2
	SOIL II	10%	1.5	180	0.2	21	N/A	0.2
		MEAN	4	270	1	26	N/A	1
		90%	4	360	4	35	N/A	4
36	SOIL I	10%	0.6	247	0.1	32	N/A	0.1
		MEAN	4	370	0.3	43	N/A	0.3
		90%	4	493	1.4	52	N/A	1
	SOIL II	10%	1.5	247	0.2	21	N/A	0.2
		MEAN	4	370	0.7	27	N/A	0.7
		90%	4	493	4	43	N/A	2
42	SOIL I	10%	0.6	273	0.1	31	N/A	0.1
		MEAN	4	410	0.3	41	N/A	0.3
		90%	4	547	4	50	N/A	1
	SOIL II	10%	1.5	273	0.2	21	N/A	0.2
		MEAN	4	410	0.7	26	N/A	0.7
		90%	4	547	4	26	N/A	2

NOTES:

1) No analyses were performed for ground movements greater than 4m

2) N/A indicates that this condition was not needed in risk assessment

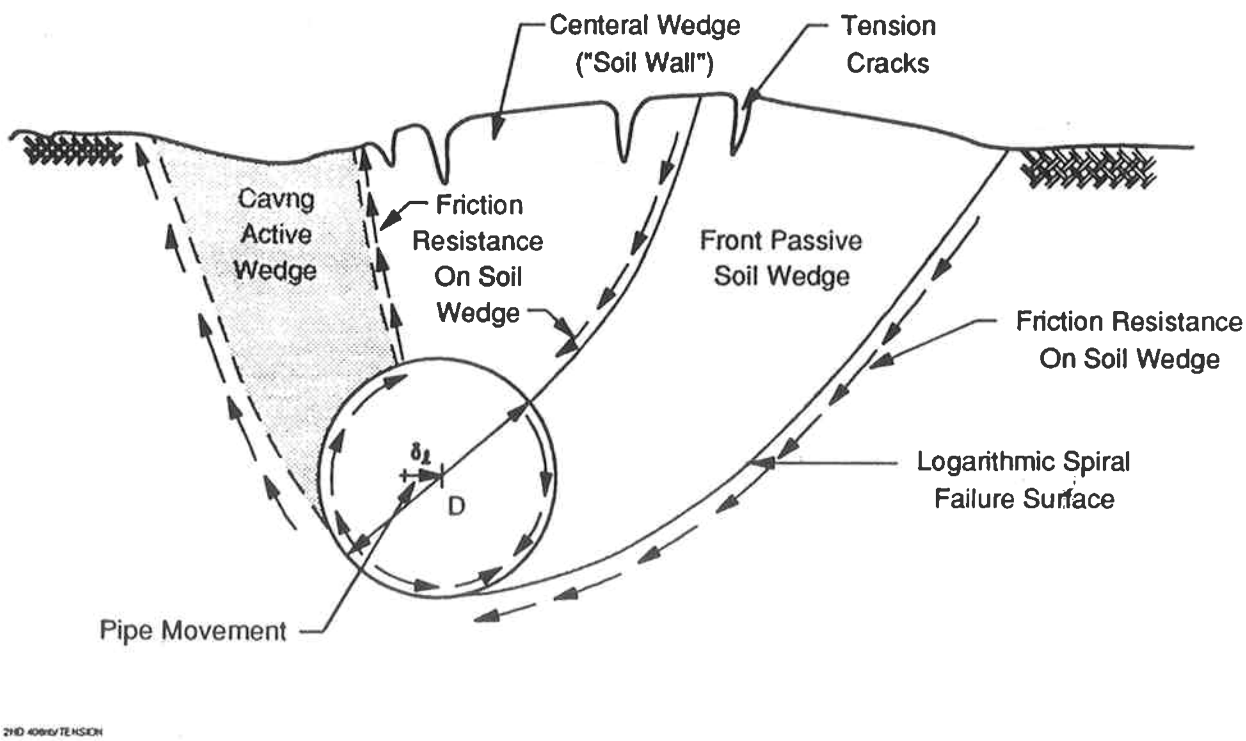


Figure 4-1: Generalized Pattern of Ground Failure for Pipeline Subjected to Relative Lateral Ground Deformation

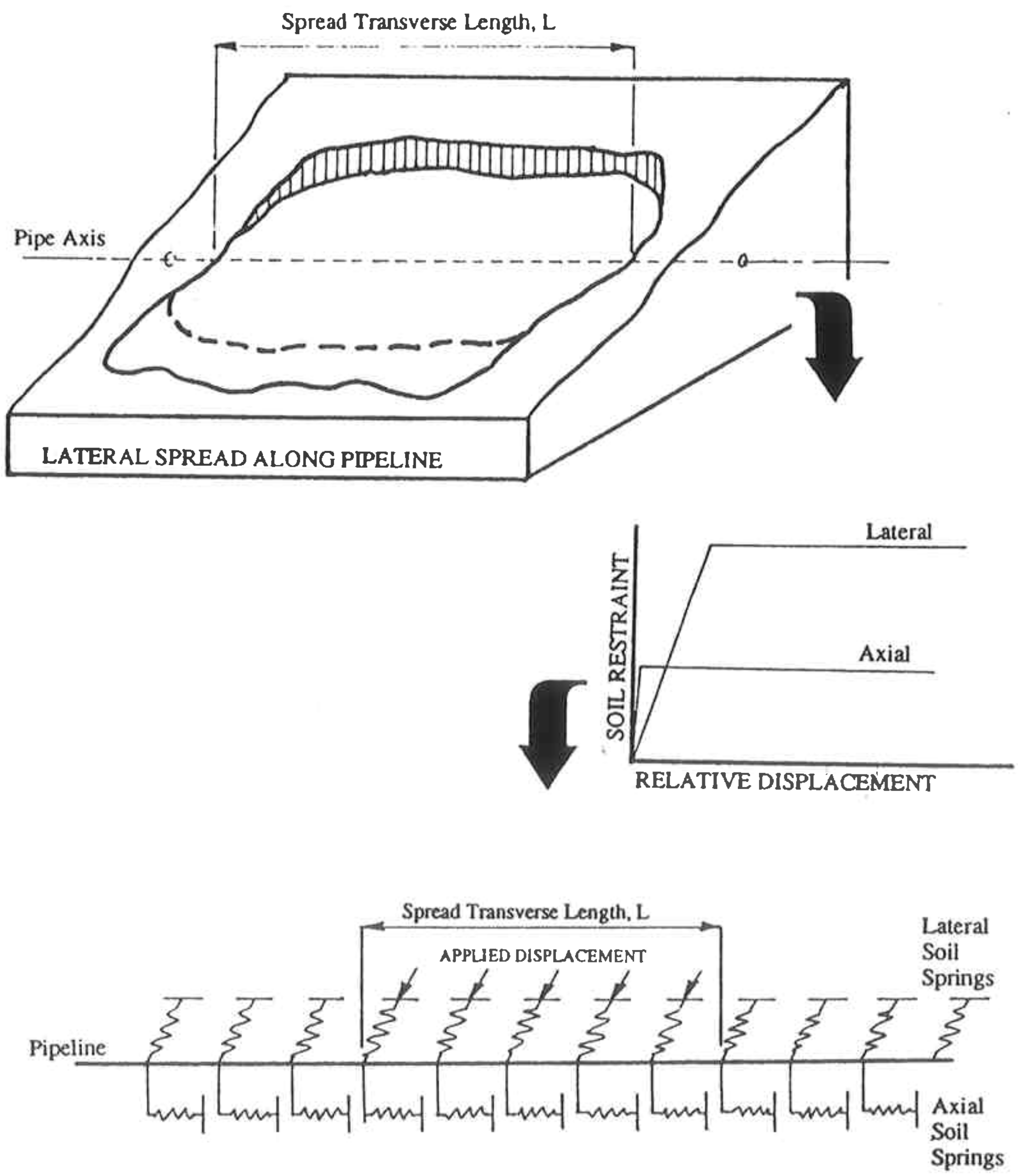


Figure 4-2: Modeling Pipeline Response in a Finite Element Analysis

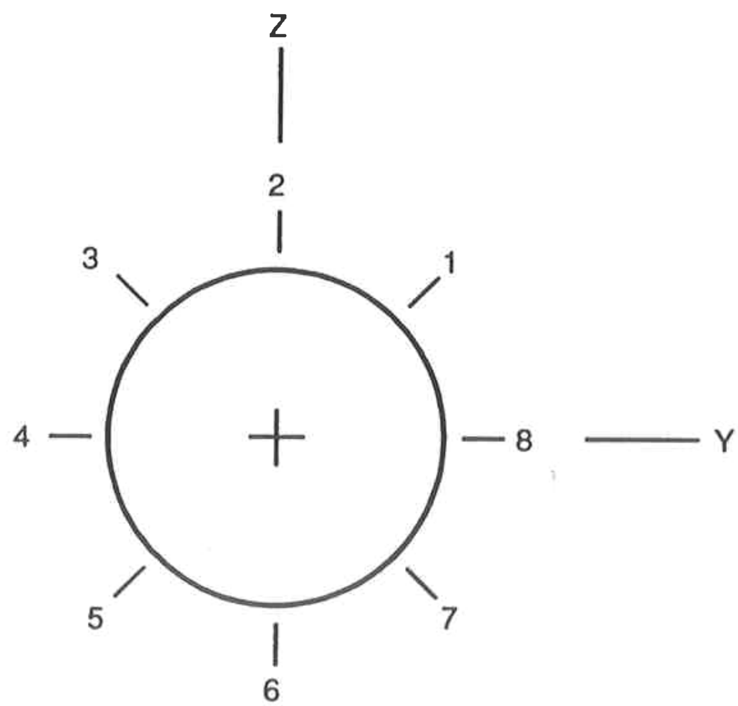


Figure 4-3: Locations of Strain Computed in ANSYS Pipe Element

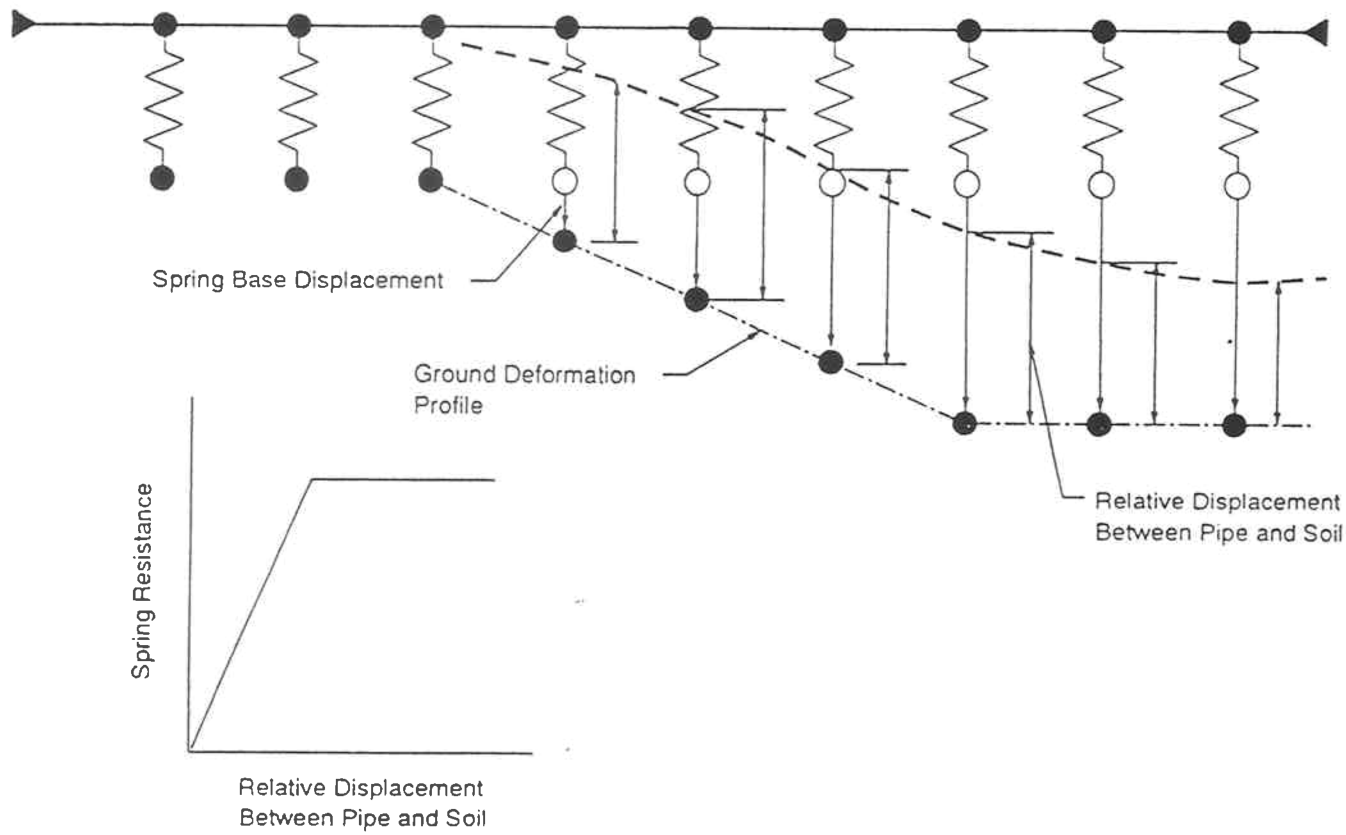


Figure 4-4: Application of Relative Ground Deformations in Finite Element Analysis

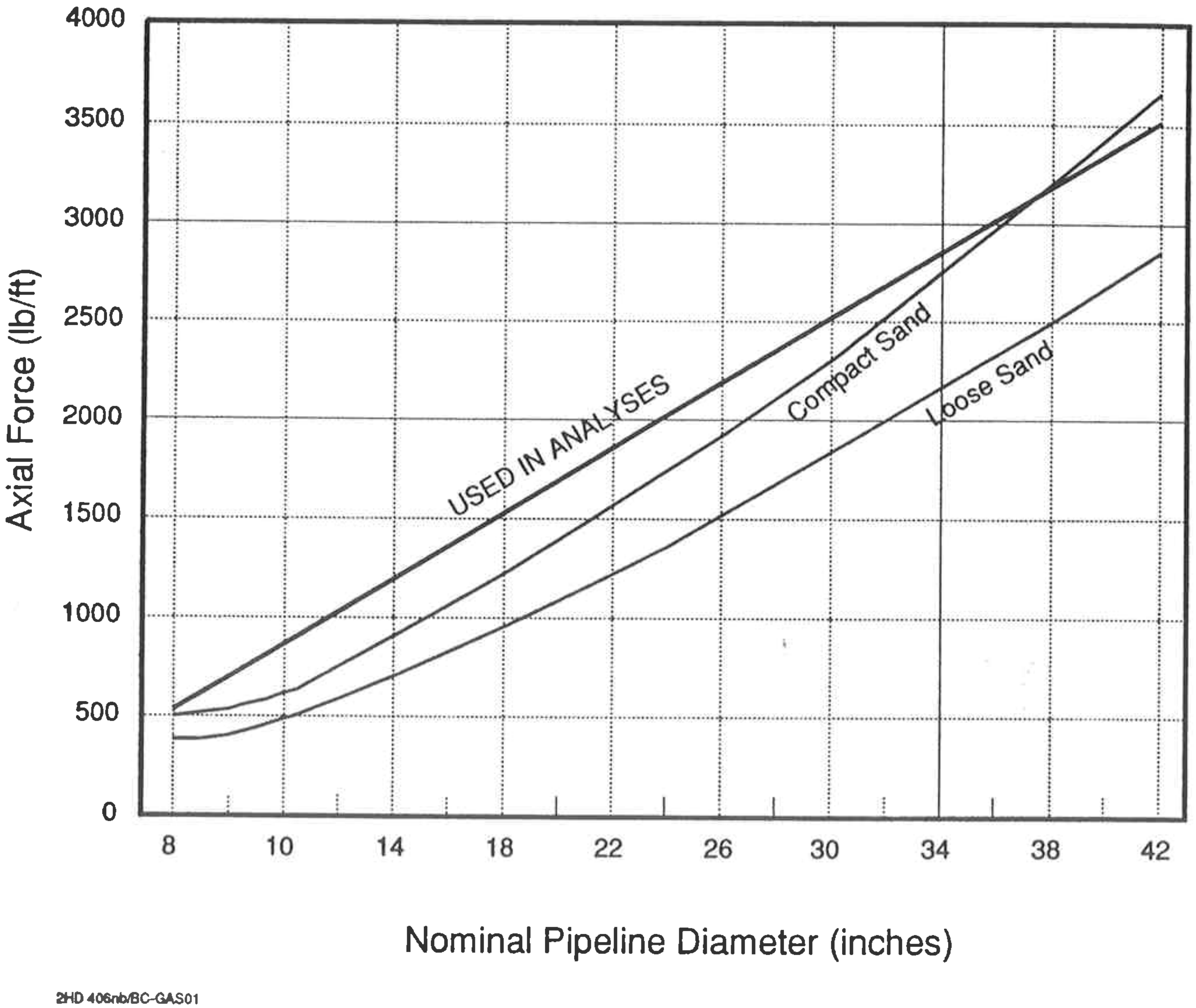


Figure 4-5: Axial Soil Loading Computed for BC GAS Pipeline Analyses

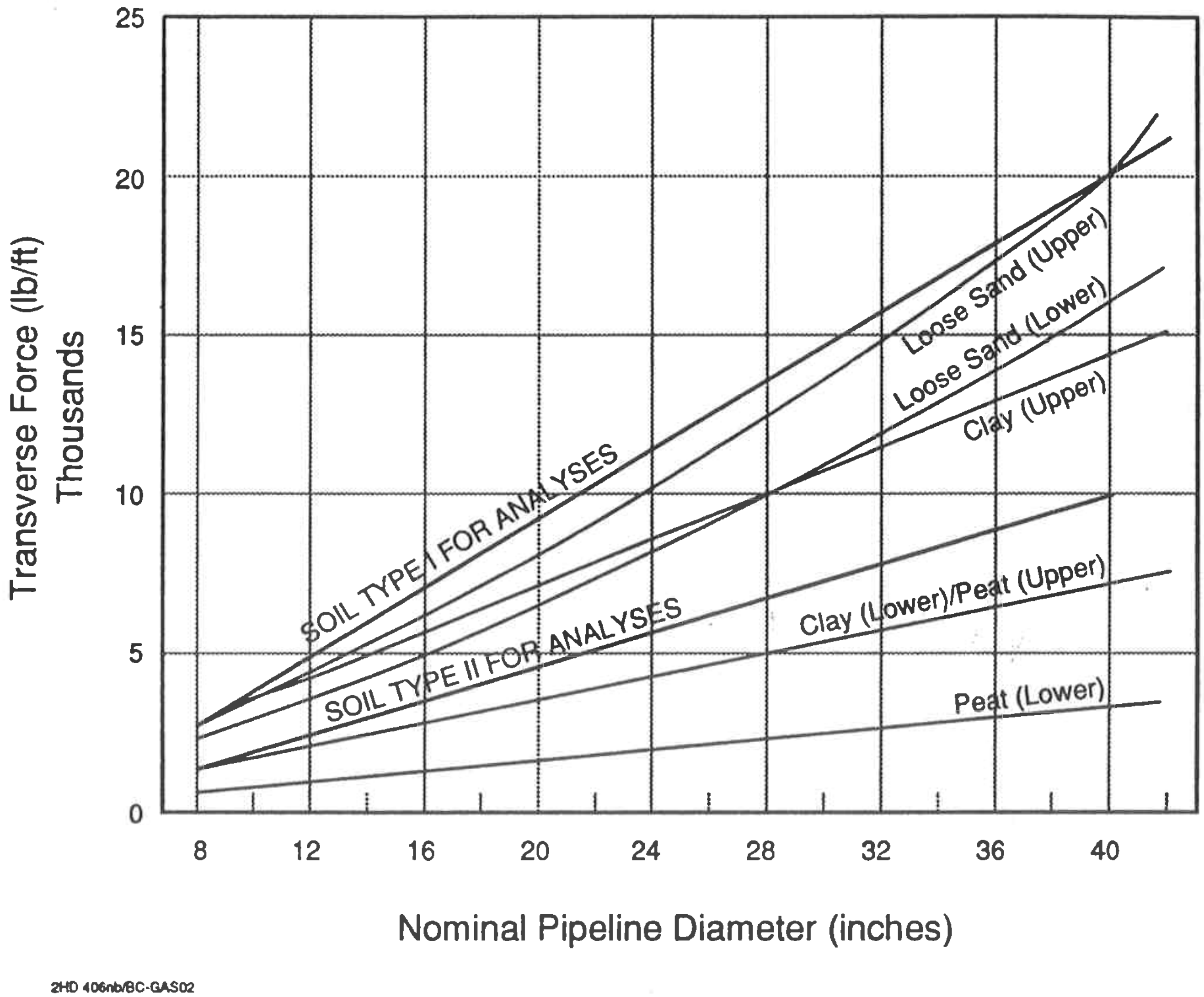


Figure 4-6: Lateral Soil Loading Computed for BC GAS Pipeline Analyses

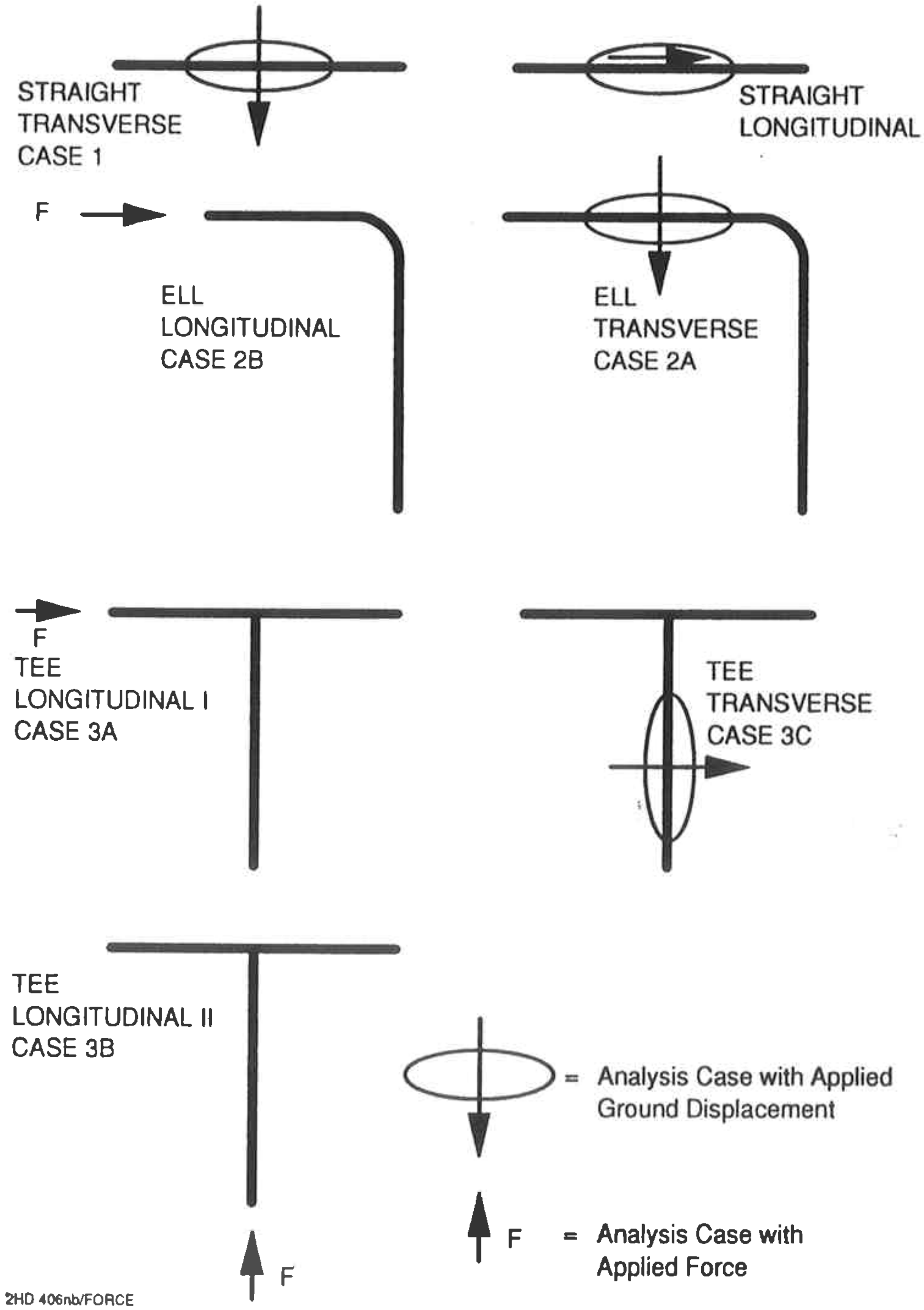
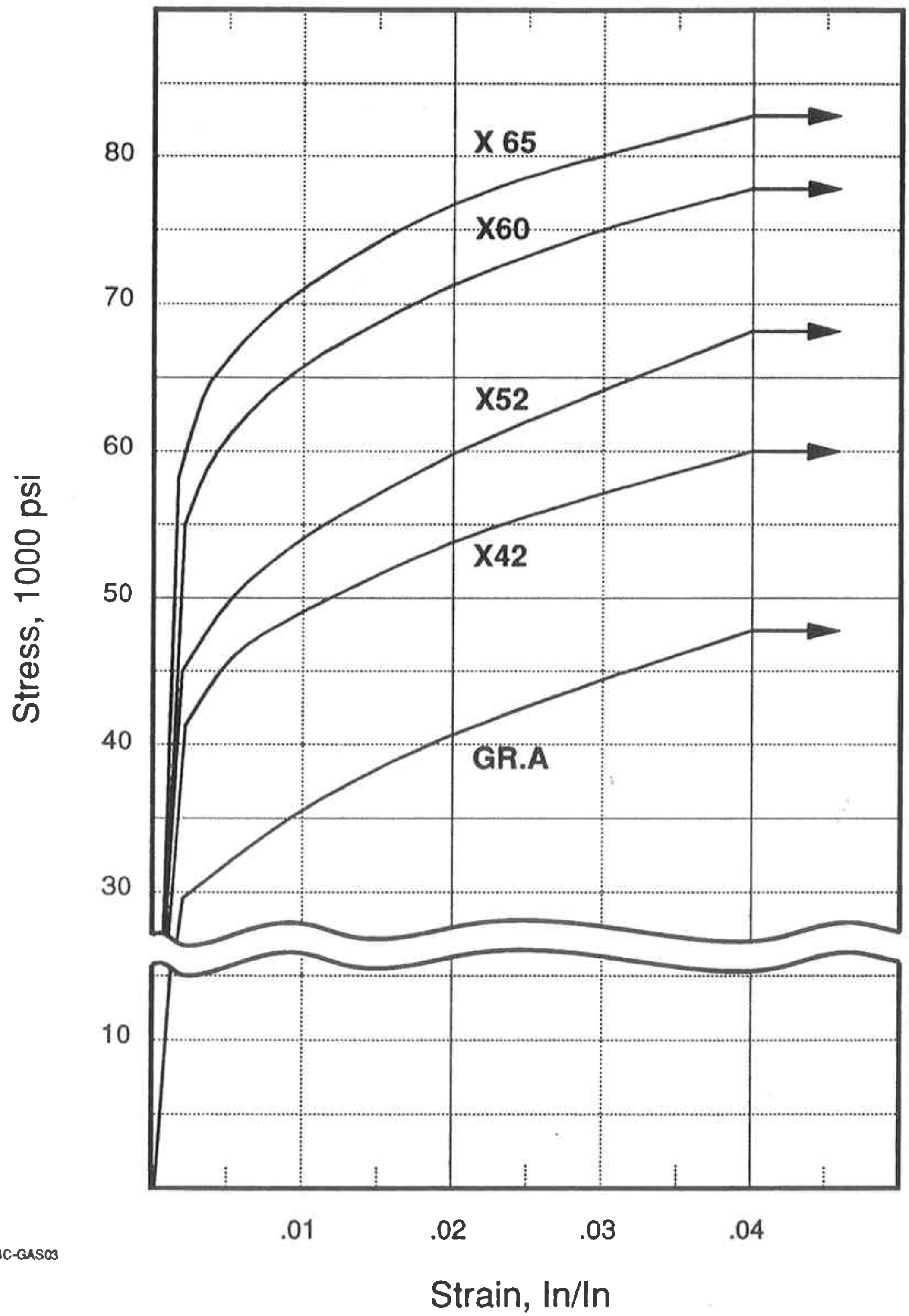


Figure 4-7: Pipeline Configurations Analyzed for BC GAS Study



2HD 406nb/BC-GAS03

Figure 4-8: Stress vs. Strain Curves Used to Represent Pipeline Steels in BC GAS Analyses

5. MAPPING OF HAZARDS AND PIPELINE SYSTEM

To implement the regional seismic risk assessment, it was decided to utilize digital data from within a Geographic Information System (GIS). ArcCAD (ARC-INFO GIS software operating within the AutoCAD environment) was the GIS system used to develop the project databases. The general approach entails combining digitized hazard information and available BC GAS facility information. Vulnerability models may then be applied to the resulting pipeline-hazard database to assess system risk.

5.1 Base Map Development

5.1.1 Digital Data Received from BC GAS

Digital data files received from BC GAS served as the starting point for the digital databases utilized in the analysis. Mapping for the various regions of the BC GAS system is handled in different regional offices. Consequently, the data files received were developed by two different sources; one for the Fraser Valley area and one for the Greater Vancouver area. Because the data are maintained by different offices, the data format is not identical. Specifically, while both map sets were developed at the same scale (1 map unit = 1 meter), only one (Greater Vancouver) is maintained in the local Universal Transverse Mercator (UTM) projection (Zone 10). This was important for developing overlays to be used with published 1:54,000 maps from G.S.C.

For ease of data transfer, multiple data files were developed in DXF format for each study sub-area. Six files were needed to transfer the data for the Greater Vancouver area, while the Fraser Valley data is comprised of 5 data files. These DXF files were imported into AutoCAD, which served as the map production platform. Each data file contained the following information:

1. Transmission and intermediate pressure pipelines, with line designation information

2. Limited street and roadway information in the areas adjacent to the pipelines

3. Coastal and river boundaries

Preliminary file editing was performed to verify the presence of all pipe included in the analysis, and eliminate any pipelines smaller that 8 inches in diameter. Pipelines were aggregated into layers according to pipeline diameter. These revised data files were provided to GOLDER ASSOCIATES for use in the digitization of areas of liquefaction, and ground deformation hazard.

5.1.2 Hazard Mapping Performed by GOLDER ASSOCIATES

Using the digitized coastline, pipelines and street information, GOLDER ASSOCIATES digitized the boundaries of the areas of liquefaction susceptibility for each of the eleven BC GAS data files. These data files became the basis for the hazards database.

5.1.3 Limitations Associated with Mapped Data

The process by which the regional databases were developed results in various limitations. First, liquefaction boundaries were digitized in an approximate way from the detailed coastal boundaries in the original BC GAS data file, and therefore are not exact boundaries. Second, data for the two major sub-areas (Fraser Valley and Greater Vancouver) had to be assembled from individual data files, requiring file editing and boundary matching. Finally, the data files for the two sub-areas had to be merged, requiring the translation of the Fraser Valley map into UTM 10. For these reasons, the databases will not overlay exactly on a precise base map, and all boundaries should be considered approximately located. Such overlays should not be used for site-specific assessment, and are intended for use in this regional assessment only.

5.2 Creation of GIS Databases

The development of the final GIS database was accomplished through a series of data overlays. Each map file was converted into a true GIS database, and relevant attributes were associated with each polygonal area of specific ground deformation hazard or pipeline segment. The GIS overlays were manipulated to associate the hazard data with the appropriate pipeline segment. Details of the database development and overlay are discussed below.

5.2.1 Liquefaction and Lateral Spread Displacement Database

The liquefaction susceptibility boundary map was converted into a GIS database with the following attributes for each area:

1. Liquefaction susceptibility category (Very High, High, High Covered with Peat, Moderate, Moderate Covered with Peat, Low, Low Covered with Peat or Very Low)

2. Estimated displacement, in meters, for the 2,000-year return period hazard as developed by GOLDER ASSOCIATES

3. Estimated displacement for the 1,000 year return period hazard

4. Estimated displacement for the 1 in 475 year return period hazard

5.2.2 Pipeline Properties

The pipeline data extracted from the original BC GAS data were converted into a GIS database, and for each pipeline segment, the following attributes were stored:

1. Pipeline diameter (inches)

2. Pipeline wall thickness, as determined from available information (Data were not available for the Greater Vancouver area, so predominant characteristics from the Fraser Valley area were assumed)

3. Pipeline material (yield strength and material designation)

4. Length of pipeline segment in a particular hazard area as determined by the GIS.

5.2.3 Areas of Ground Slope

To determine the areas within the larger liquefaction susceptibility zones that might be subject to lateral spreading, regional topographic information was examined. For the bulk of the study area, locations along the pipelines where ground slope exceeded 0.5% were identified using topographic maps at a scale of 1:50,000 . On Lulu Island, more detailed information was available. Maps received from the City of Richmond were used to identify areas where ground slope exceeded 0.1%. The locations of these areas were incorporated into the digital database by identifying impacted pipeline segments. For each impacted segment, the following information was incorporated into the existing pipeline database:

1. A "Slope Group Number" assigned to each segment of pipeline transversing a region with slopes large enough to be considered potential lateral spread area.

2. Direction of ground slope relative to the pipeline (longitudinal or transverse)

3. Percent slope (for Lulu Island only)

4. Applicable analysis case for vulnerability modeling (ell, tee, etc.)

5.2.4 Final GIS Database

The final database compilation was accomplished by a GIS overlay of the pipeline database as described above, onto the liquefaction/displacement database. As a consequence, each pipeline segment was ascribed the attributes of the hazard area through which it traversed. This database was completed with the addition of soil type information for those pipeline segments falling within the sloped areas. For each such pipeline segment, the original surficial geology/liquefaction susceptibility maps supplied by GOLDER ASSOCIATES were consulted to determine the applicable soil strength characteristics as defined by GOLDER ASSOCIATES.

The resulting GIS database may be used to plot pipelines and hazards according to various parameters (i.e., highlight all pipelines greater than 20 inches in diameter, within sloped areas, subject to possible transverse displacements), and generates a database file in standard DBF format containing all attributes for each pipeline segment. This database file, imported into a spreadsheet program, allowed for manipulation of the data and implementation of vulnerability modeling algorithms.

6. RESULTS OF THE PIPELINE RISK ASSESSMENT

Implementation of the pipeline risk assessment was performed in a computer spreadsheet. As discussed in Section 2, two approaches for assessing the pipeline system were carried out. Details of the implementation of these approaches are provided below followed by a discussion of the findings.

Some general results from the overall philosophy in assessing the BC GAS pipeline system apply regardless of the risk assessment approach used. The GIS database for the BC GAS pipeline system contains 152 km of pipeline located in areas susceptible to liquefaction (i.e., not classified as either Low or Very Low). In our experience, risk assessment approaches employed in similar studies that have relied upon vulnerability relationships based on poor quality data from past earthquakes would have identified a majority of the 152 km of pipeline in liquefaction susceptible areas as highly vulnerable to rupture.

Identification of portions of the system in areas susceptible to lateral spreading based upon surface topography reduced the length of pipeline subjected to risk to 43.4 km, a 72% reduction in scope. A total of 68 slope groups have been defined giving an average of 640 meters of pipe within a slope group. Pipeline length within a slope group varied from 39 meters to 2,450 meters with only about 20% having pipeline lengths greater than 1 km.

6.1 Mean Performance Assessment

The implementation of the Mean Performance assessment is outlined in the flowchart in Figure 6-1. A failure condition exists for a particular pipeline segment being evaluated whenever the specified hazard exceeds the pipeline capacity as defined by the pipeline vulnerability tables. Determining pipeline capacity requires identifying key parameters for a segment of pipeline being considered.

6.1.1 Implementation Procedure

The first step is to determine which vulnerability criteria, lateral spread length or lateral spread displacement, are to be used. If the ground slope is longitudinal along the pipeline, the length criteria is applied, while for transverse loading, the displacement criteria is applied. Once the appropriate ground deformation direction is determined, the hazard can be defined as either the mean lateral spread displacement or the mean longitudinal length of the lateral spread. The second step is to identify the pipeline configuration as either straight, an ell or a tee. The final step in identifying parameters for selecting the vulnerability criteria is to obtain the pipeline diameter and the type of soil. With this information, the appropriate pipeline capacity can be selected. The capacity values are all considered to be mean estimates for pipeline rupture.

If the pipe capacity is not greater than the hazard, failure is assumed to occur in the pipe segment under consideration. Note that no correction in the assessment is possible to account for the probability that the pipeline may not be in the spread. However, the fact that there is a fairly high likelihood that a particular pipeline segment will not be in a lateral spread zone effectively reduces the overall risk of failure. This reduction is the same for both displacement and length comparison.

If it is assumed that there is a 34% chance of lateral spread occurrence for all pipe segments, the impact of the probability of lateral spread occurrence can be translated into an increase in the return period for the seismic hazard. In this case, the effective return periods examined using this approach for hazards defined at return periods of 475, 1,000 and 2,000 years are, respectively, 1,400, 2,940 and 5,880 years. The effective return periods for some pipeline segments are actually higher than those listed above since they are not near major rivers or shorelines and thus have a chance of lateral spread occurrence less than the 34% assumed. Another way of looking at the impact of the estimate of lateral spread probability of occurrence for a particular pipe segment is to back calculate the hazard return period that would identify failure locations with a 2,000 year return period. Using the 34% chance for occurrence, net failure return period of 2,000 years requires a hazard return period of 680 years.

The difference in liquefaction susceptibility is also accounted for in the procedure. For estimating lateral spread displacement, soil characteristics are accounted for explicitly in the Bartlett and Youd procedure. An alternate method was necessary for modifying estimates of lateral spread length. Soil deposits classified as having a moderate susceptibility to liquefaction were assumed to be 33% less likely to experience lateral spreading than deposits classified as having high or very high susceptibility. This assumption is based upon judgement and prior knowledge of the general characteristics of soil deposit characteristics.

6.1.2 Results of the Mean Performance Assessment

Overall results from the mean performance assessment are illustrated by the pie charts in Figure 6-2. The pie charts illustrate the ratio of pipeline segments with insufficient capacity for various earthquake hazard levels. Also indicated in the pie charts is the ratio between pipeline segments failing under length and displacement considerations.

There is no change in the percentage of failure for pipeline segments evaluated or the basis of lateral spread length. The lack of change is the result of an assumed independence of lateral spread size with earthquake hazard level. There is no basis for assuming such a relationship. Furthermore, it may not be reasonable to expect a strong relationship between the physical size of lateral spread zones and change in hazard level.

The only change in the number of pipeline segments identified as failing occurs in the population of segments governed by lateral spread displacement criteria. There is a small increase between the number of failures at the 475-year hazard and the 1,000-year hazard. The percentage of pipeline segments identified as not failing drops 4.3% (50.7% to 55.0%) between the 475-year hazard and the 1000-year hazard. The change is slightly greater between the 1,000-year and the 2,000-year hazard. The portion of pipeline segments not failing at the 2,000-year hazard drops 7.1% from 50.7% to 43.6%.

The number of slope groups is the failure bin changes by 9 in going from the 475-year return period to the 2,000-year return period. Using the hazard return period as a means to prioritize slope groups, three categories can be defined:

1) Slope groups failing at the 475-year seismic hazard

2) Slope groups failing at the 1,000-year seismic hazard but not at the 475-year seismic hazard

3) Slope groups failing at the 2,000-year seismic hazard but not the 1,000-year hazard

6.2 Cumulative Probability of Risk Assessment

The results from the mean performance assessment identified 36 high-priority slope groups. This was not the level of differentiation originally envisioned for the BC GAS pipeline system. No attempt was made to further delineate specific pipeline segments failing at the lowest hazard level.

Instead, an alternate approach was used based on the lateral spread measurement investigation and the resulting detailed description of lateral spread areal characteristics. The primary differences in this approach were the incorporation of probabilistic estimates of lateral spread occurrence, magnitude of ground deformation and length of spread along the pipeline. In addition, the cumulative contribution to pipeline risk from hazards with varying recurrence rates was estimated.

6.2.1 Implementation Procedure

The cumulative probability approach examined the relative seismic vulnerability of piping segments within each slope group. Failure probabilities of each pipeline segment were determined using the pipeline capacity estimates established in Section 4 and the hazard definitions presented in Section 3.

The procedure for determining the probability of failure for an individual pipeline segment is diagrammed in Figure 6-3. As with the mean performance assessment, this approach began with an examination of a particular segment's location relative to the ground slope to determine which failure criteria to apply. If the ground slope was longitudinal along the pipeline, the length criteria were applied, while for transverse loading, the displacement criteria were applied. Once the appropriate criteria were determined, the pipeline capacity was selected from a table of values. Table selection was based on the pipeline diameter, the local soil type, and configuration (straight, ell or tee).

When the criterion for comparison was length, the pipeline segment length was first compared to the lateral spread length. Failure of a pipeline segment was only considered possible if the pipe segment length was greater than the length corresponding to the tabulated criteria for failure. If the pipe segment length was sufficient to pose a concern for failure, the probability of lateral spread occurrence on the pipeline segment in question given liquefaction occurs.

1. For pipeline segments within 1 km of a major river or shoreline, the probability of failure was taken equal to the probability that the spread length will exceed the failure criterion multiplied by the likelihood that a lateral spread occurs on the pipeline segment (see Section 3.4). This latter probability was estimated to be 0.34.

2. For pipeline segments located away from major rivers, probability of failure was estimated as previously described with the exception that the probability associated with lateral spread occurrence on the pipeline segment was significantly less. For the purposes of this

assessment, it was assumed that the probability was 0.17, about half of the probability for pipelines located near a major river or shoreline.

The probability of failure for a particular pipeline segment and a particular level of earthquake hazard was computed as the product of the probability of pipeline failure and the probability of liquefaction.

When the criteria under consideration is the magnitude of ground displacement, the probability of pipeline segment failure is determined from the probability that the ground displacements will exceed the capacity criteria as determined from the vulnerability values tabulated according to pipeline diameter, soil type, and pipeline configuration. Bartlett & Youd (1992) provides a method for performing a site specific evaluation of the probability distribution for various lateral spread deformation. Rather than trying to employ this cumbersome process into the risk assessment, a simplification was made based on the observed scatter of data presented in Bartlett & Youd (1992). It was assumed that the ground displacements, as determined by Bartlett and Youd (1992), are normally distributed. The probability that lateral spread displacements were greater than twice the mean displacement was assumed to be 2%. With these assumptions, the probability that the displacements exceed the failure criteria was determined as shown below:

$$P_{fi} = P(D_{LS} >= D_C) = 1.0 - \Phi,R\ [\ ((2.05 \text{ x } D_C)/D_{mean}) - 2.05\ ]$$

where P_{fi} = probability of failure for segment i

$\Phi(x)$ = the standard normal variable as tabulated in common statistical textbooks (e.g., Devore, 1982)

D_{LS} = lateral spread displacement

D_C = pipeline segment lateral spread displacement capacity

D_{mean} = the lateral spread displacement determined for the 2,000, 1,000, or 475 year events

When the criterion being considered is length of lateral spread along the pipeline, the distribution of lateral spread measurements was used in lieu of $\Phi(x)$. The cumulative density function derived from the measurement data is provided in Figure 3-11. In addition, if the soil is classified as having a moderate susceptibility to liquefaction, the probability of failure is factored by 0.67.

For a particular slope group, the overall probability of failure in a given event was computed from the individual failure probabilities of the pipeline segments within the slope group as follows:

$$P_{FSH} = 1.0 - \pi\,(1 - P_{fi} \times P_H)$$

where P_{FSH} = failure probability of a particular slope group for a particular level of earthquake hazard

π = product over all segments, i, in the slope group

P_H = probability associated with the earthquake hazard = $(\text{return period})^{-1}$

To estimate the relative risk of a particular slope group in all of the events, the probabilities for various earthquake hazard levels was combined to determine one overall annual probability of failure:

$$P_F = 1.0 - \pi\,P_{FSH}$$

6.2.2 Results from the Cumulative Probability Approach

Slope groups for the cumulative probability approach are identified in Figure 6-4. Implementation of the cumulative probability assessment allowed each of the slope groups to be given a relative ranking according to risk.

For an assessment performed with mean failure criteria, 19 (28%) of the 68 slope groups were ranked as having an annual failure probability less than 0.0005 (2,000-year return period). Of the remaining 49 slope groups, 31 had annual failure probabilities estimated as greater than 0.0021 (475-year return period). The portion of the BC GAS pipeline system considered to be at greatest risk are the slope groups with estimated annual risks of failure greater than about 0.005. This is approximately equivalent to a 10% chance (atleast once) of failure in the next 20 years. Ten slope groups fall into this category of greatest risk. A map indicating the ranking and estimated failure probability for the 68 slope groups identified in the risk assessment is shown in Figure 6-5. A larger scale map with the same information contained in Figure 6-5 but overlaid onto a regional topographic map is also provided in Attachment 3.

As stated, the results reported above utilized what was judged to be mean estimates of pipeline strain capacity prior to rupture. To examine the sensitivity of our results to this assumption, the assessment methodology was repeated for strain capacity estimates judged to be representative of 10% and 90% failure probability. The slope group identification for the 10% and 90% failure criteria correspond to the ranking from the mean criteria.

Rankings of the computed risk for the two alternate failure criteria are shown in Figure 6-6. The mean ranking of slope groups in Figure 6-5 correspond to the ranking identifies in Figure 6-4. Only slope groups with mean estimated annual failure probabilities greater than 0.0005 are shown in Figure 6-6. Note that the number of slope groups with estimated annual failure probabilities greater than 0.0005 varies from 38 at the 90% chance of failure criteria to 53 at the 10% chance of failure criteria. However, since the amount of risk considered acceptable is quite low, the impact of increasing the number of cases falling into a relatively high risk ranking is less important. On the other hand, the number of slope groups with estimated annual failure probability greater than 0.0021 (1/475), varies from 7 to 40 for the 90% and 10% chance of failure criteria, respectively. Clearly, the more liberal failure criteria decreases the magnitude of the annual failure probability estimate.

The number of discrepancies between slope groups ranked in the top 10 and 20 according to risk can be easily compared. Using the mean criteria as a basis, the number of different slope groups in the top 10 is 4 and 3 for the 90% and 10% failure criteria, respectively. In looking at the top 20 slope groups, the discrepancies are also similar with 9 for the 90% and 10% failure criterion. The conclusion from the comparison of risk based on a wide range of failure criterion is that the methodology is moderately sensitive to the selection of a particular criterion. Less than half of the highest ranked slope groups are subject to change by altering the pipeline failure criterion.

It is interesting to compare the results of the cumulative probability assessment with the specific mean assessment. A direct comparison is not possible because of the manner in which different earthquake hazards are integrated into the cumulative probability assessment. Also, the specific mean approach examines individual pipe segments while the cumulative probability approach examines segments in the context of slope groups Using the approach discussed in the working group meeting with BC GAS on July 21, 1993, approximately 56% of the slope group segments included in the risk assessment would be candidates for modification because they were identified as failing under the 2,000-year hazard. The cumulative probability assessment identifies 72% of the slope groups as candidates for modification. Assuming that the percentage number of segments, represents a length of pipeline, similar to the percentage of slope groups, results from the two approaches is fairly comparable (within 20% to 30%). However, only the cumulative probability assessment provides a picture of the relative ranking of candidate slope groups.

As pointed out in Section 2, estimates of earthquake risk have a high degree of inherent uncertainty. To help put the above numbers in perspective, it is useful to compare these findings with a recent assessment of the potential for rupture of a key natural gas pipeline to a major metropolitan region in southern California. The California assessment found that the chances of losing the pipeline due to rupture at a fault crossing over the next 50 years was on the order of 30%. For comparison, only the top five slope groups examined in the BC GAS risk assessment have a similar level of risk. A majority of the BC GAS pipeline system is at a much lower seismic risk than similar systems in seismically active areas like California.

Detailed pipeline alignment maps for the top 10 slope groups ranked by risk are provided in Figure 6-7 through 6-16. These maps indicate that a large majority of the highest risk location are characterized by a large number of elbows in the pipeline alignment. Since elbows are much more vulnerable to ground deformation, the cumulative risk of rupture for a large number of elbows can be quite high. The other common characteristic for many of the alignments in Figure 6-7 through 6-10 is the proximity to a major river.

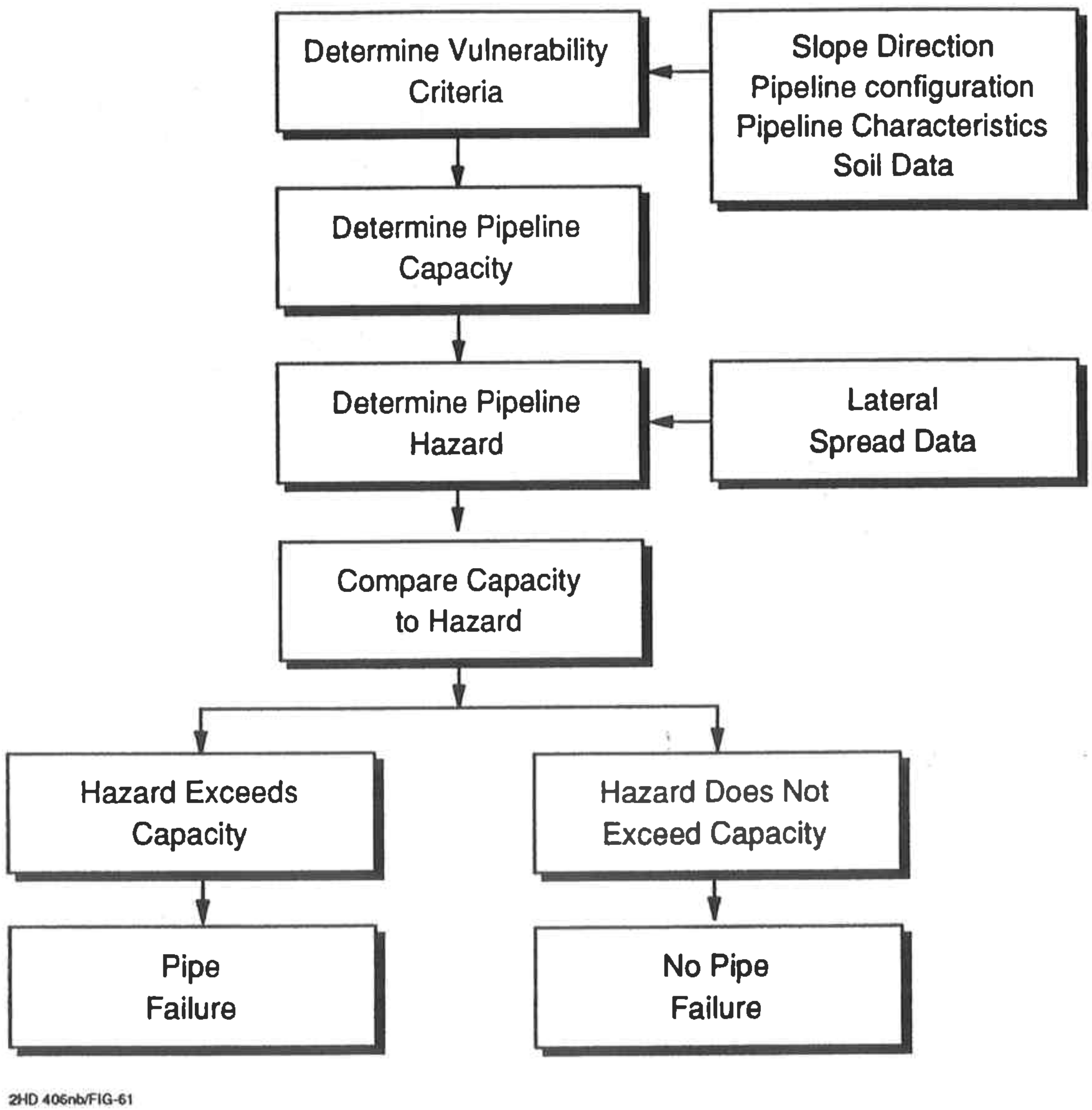


Figure 6-1: Process for Implementation of Specific Mean Assessment

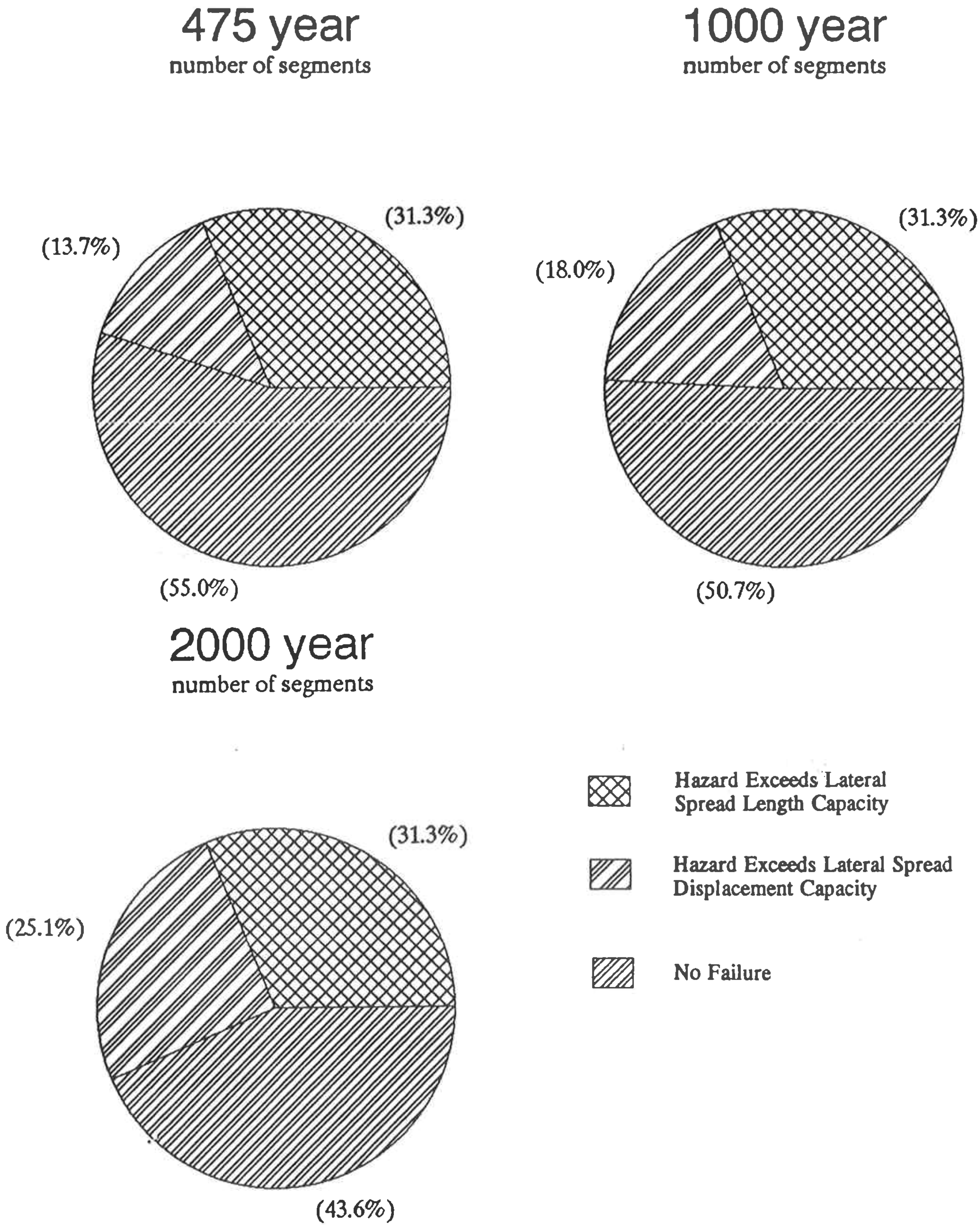


Figure 6-2: Variation in Evaluation of Pipeline Slope Groups Using the Specific Mean Approach for Varying Levels of Earthquake Hazard Occurrence

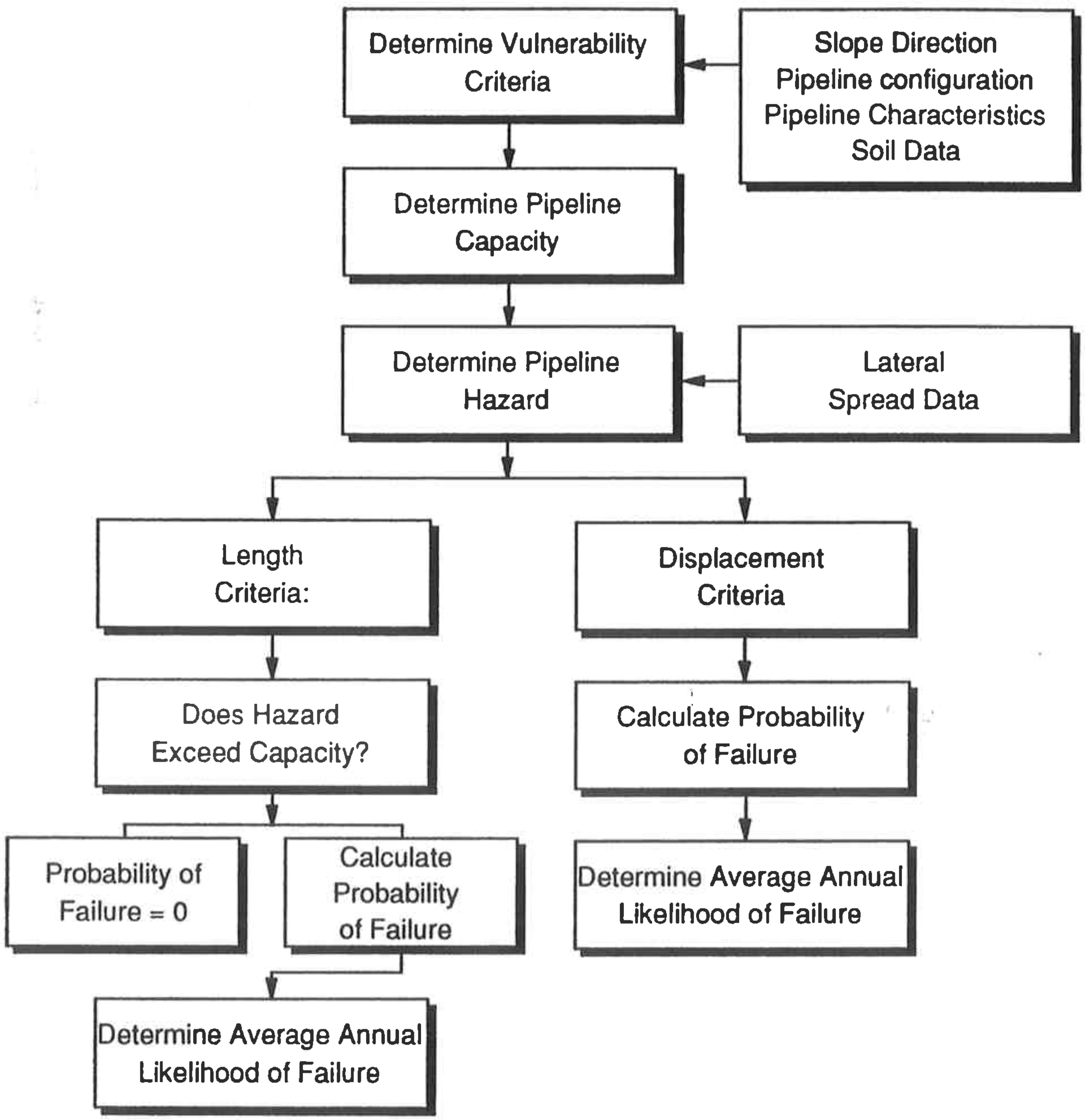
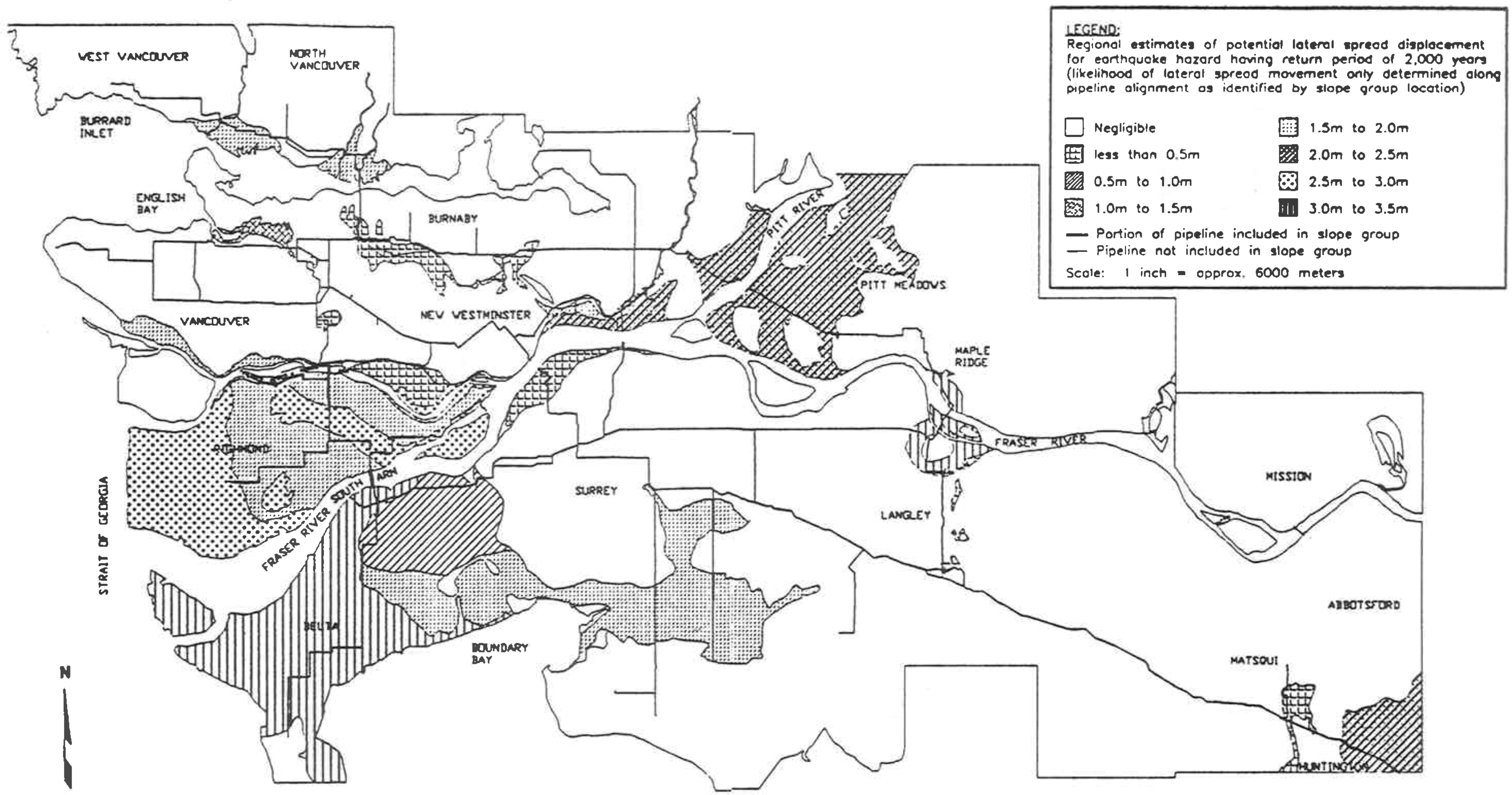


Figure 6-3: Process for Implementation of Cumulative Risk Assessment

2HD 406nb/FIG-63



DISCLAIMER
THIS MAP HAS BEEN PREPARED SOLELY FOR USE IN A SEISMIC RISK ASSESSMENT STUDY FOR THE BC GAS COASTAL PIPELINE SYSTEM CARRIED OUT BY GOLDER ASSOCIATES LTD. AND EQE INTERNATIONAL INC. ANY PERSONS WHO USE THIS MAP FOR ANY OTHER PURPOSE DO SO ENTIRELY AT THEIR OWN RISK. THE MAP MUST BE READ IN CONJUNCTION WITH THE ACCOMPANYING REPORT TEXT WHICH INCLUDES REFERENCES, DEFINITIONS, QUALIFICATIONS AND LIMITATIONS AS TO ITS USE. THE MAP MAY NOT BE REPRODUCED WITHOUT RECEIVING THE PRIOR WRITTEN AUTHORIZATION FROM BC GAS.

SEISMIC RISK ASSESSMENT FOR BC GAS COASTAL PIPELINE SYSTEM	EQE INTERNATIONAL
LOCATION OF PIPELINE ALIGNMENT AND LATERAL SPREAD DISPLACEMENTS	JOB NO. 36241.01

Figure 6-4: Slope Groups Identified for Inclusion in the Cumulative Risk Assessment

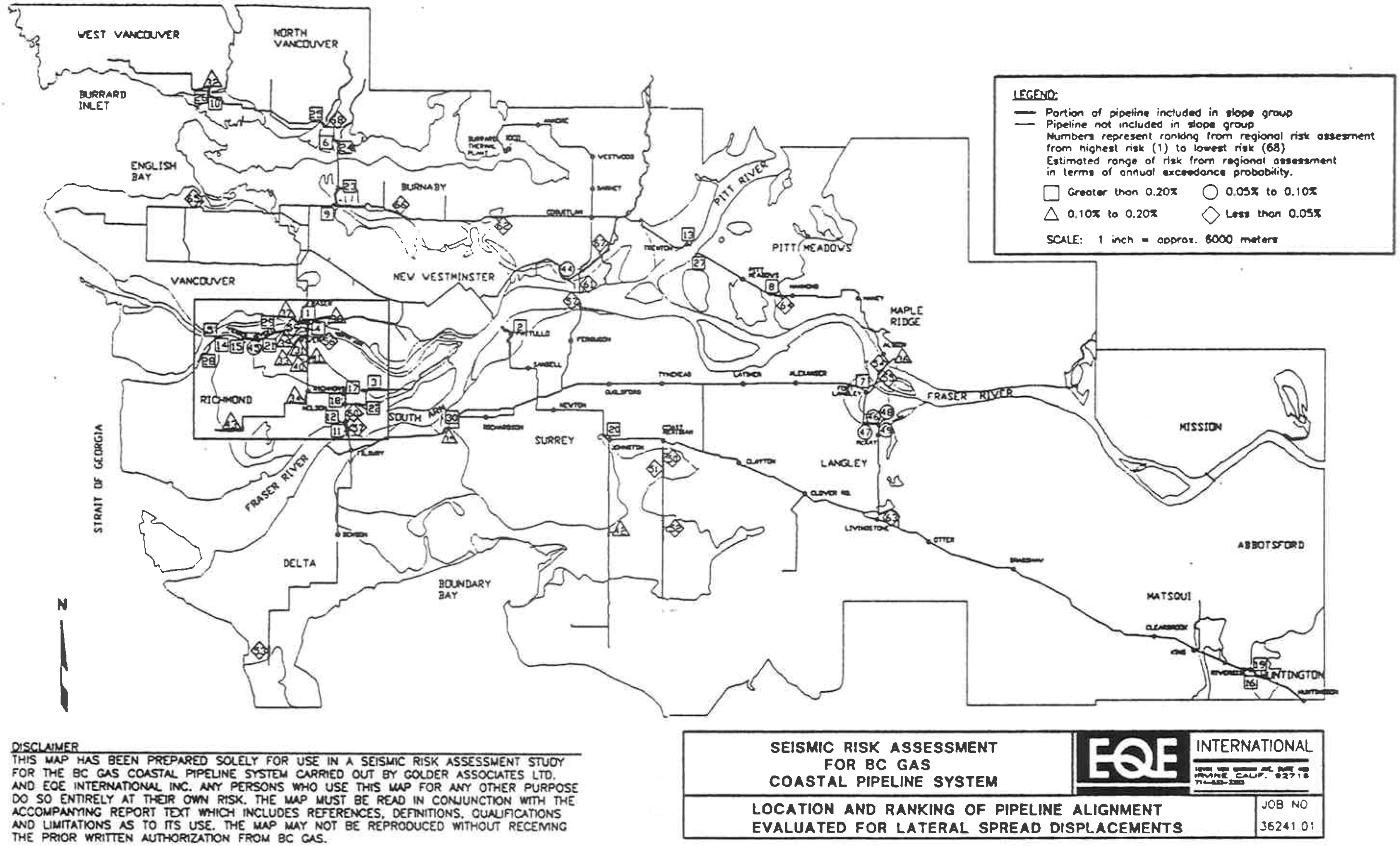


Figure 6-5a: Map of Identified Pipeline Rupture Locations and Relative Ranking by Risk

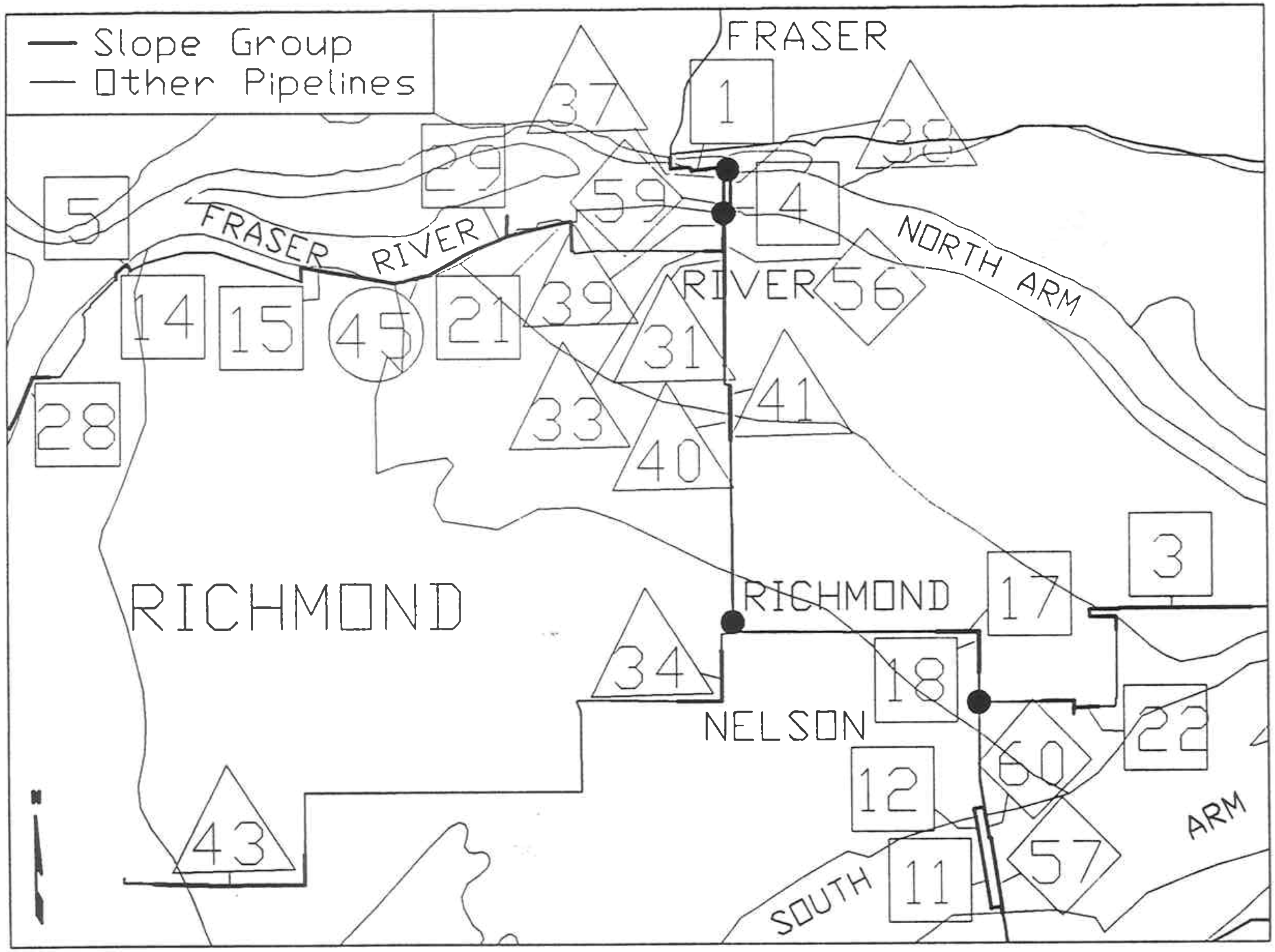


Figure 6-5b: Enlarged View of Region from Figure 6.5a

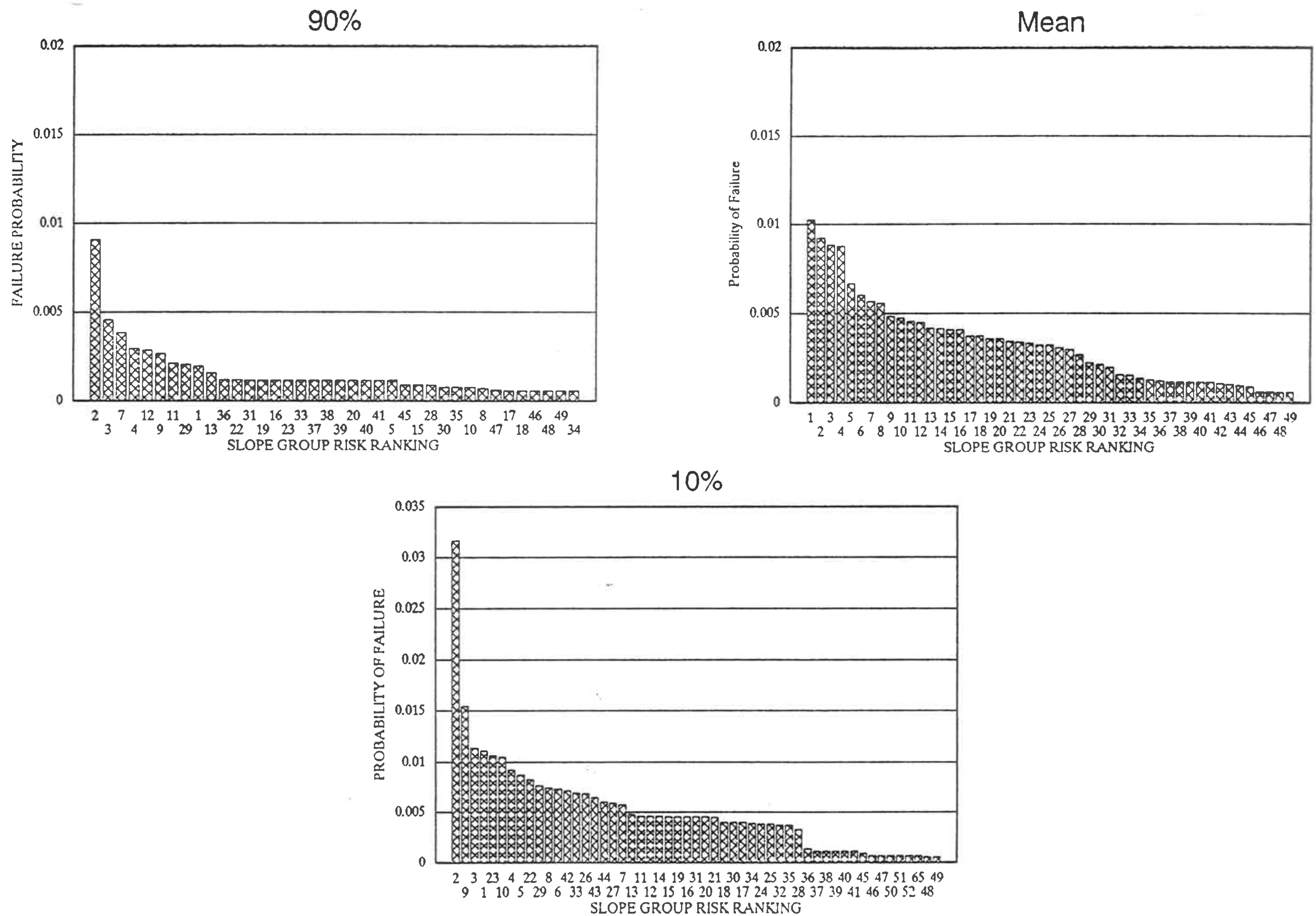


Figure 6-6: Variation in Annual Probability of Failure from Cumulative Risk Assessment with Different Assumptions of Failure Criteria

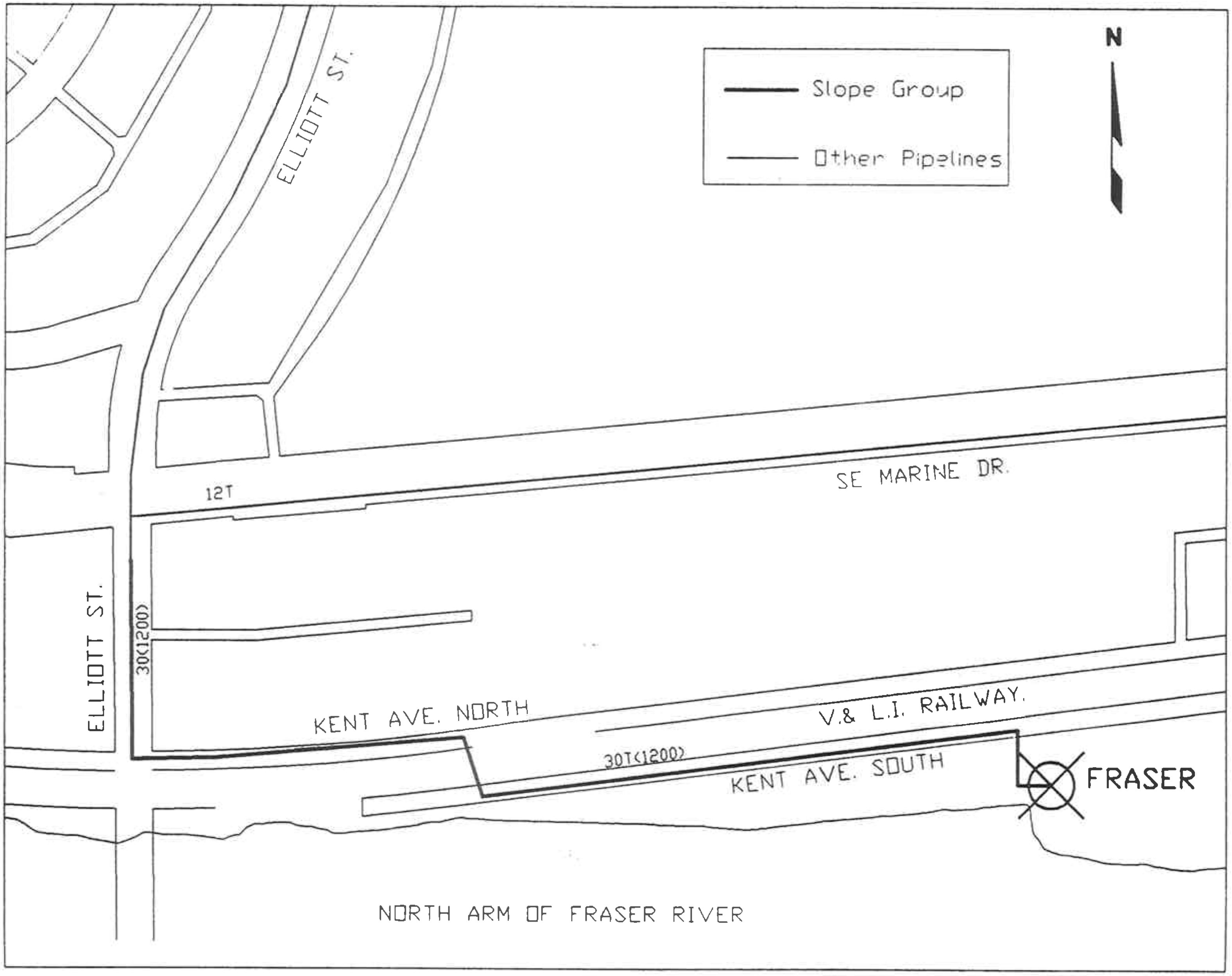


Figure 6-7: Enlarged View of Slope Group Ranked 1st By Risk

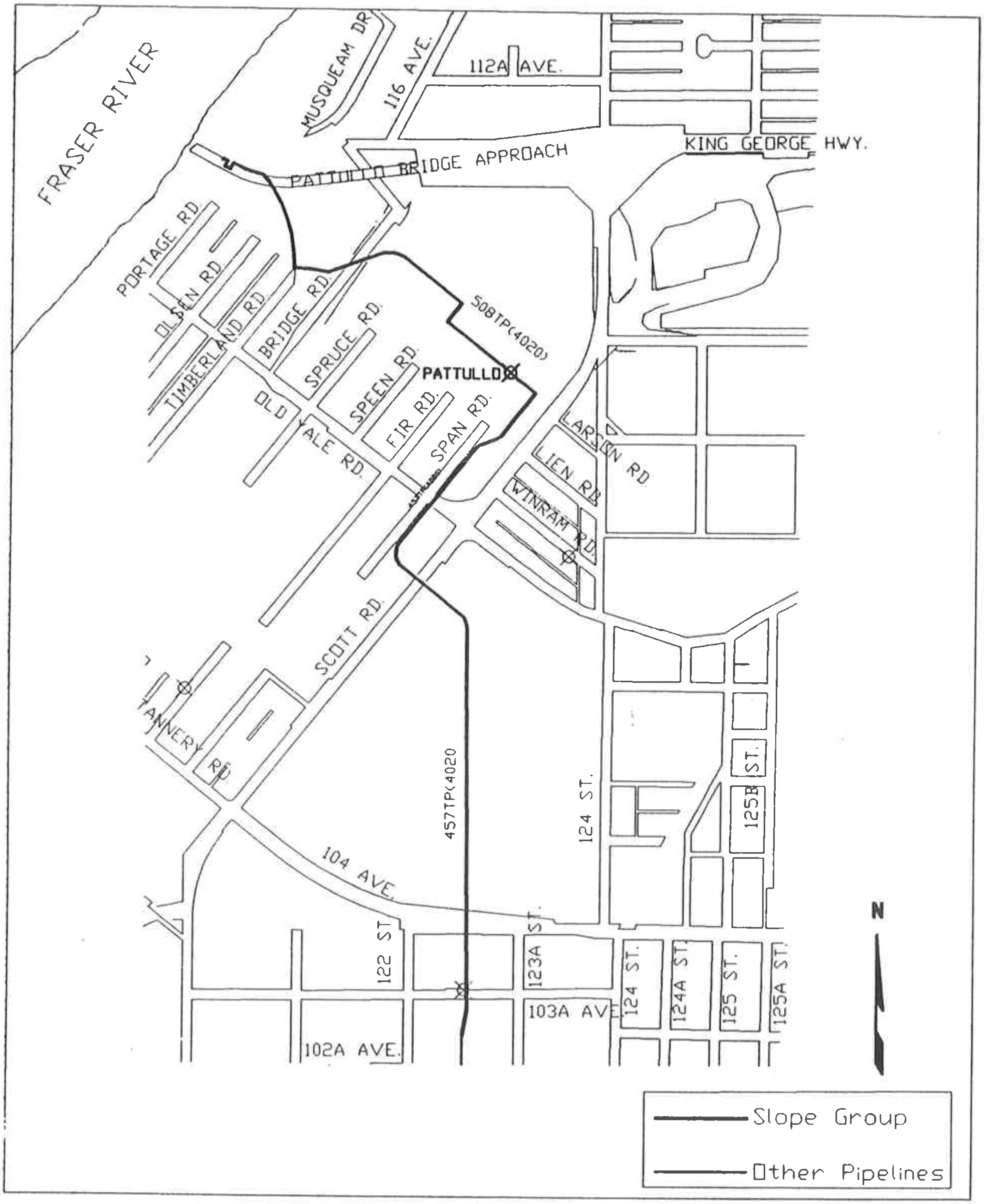


Figure 6-8: Enlarged View of Slope Group Ranked 2nd By Risk

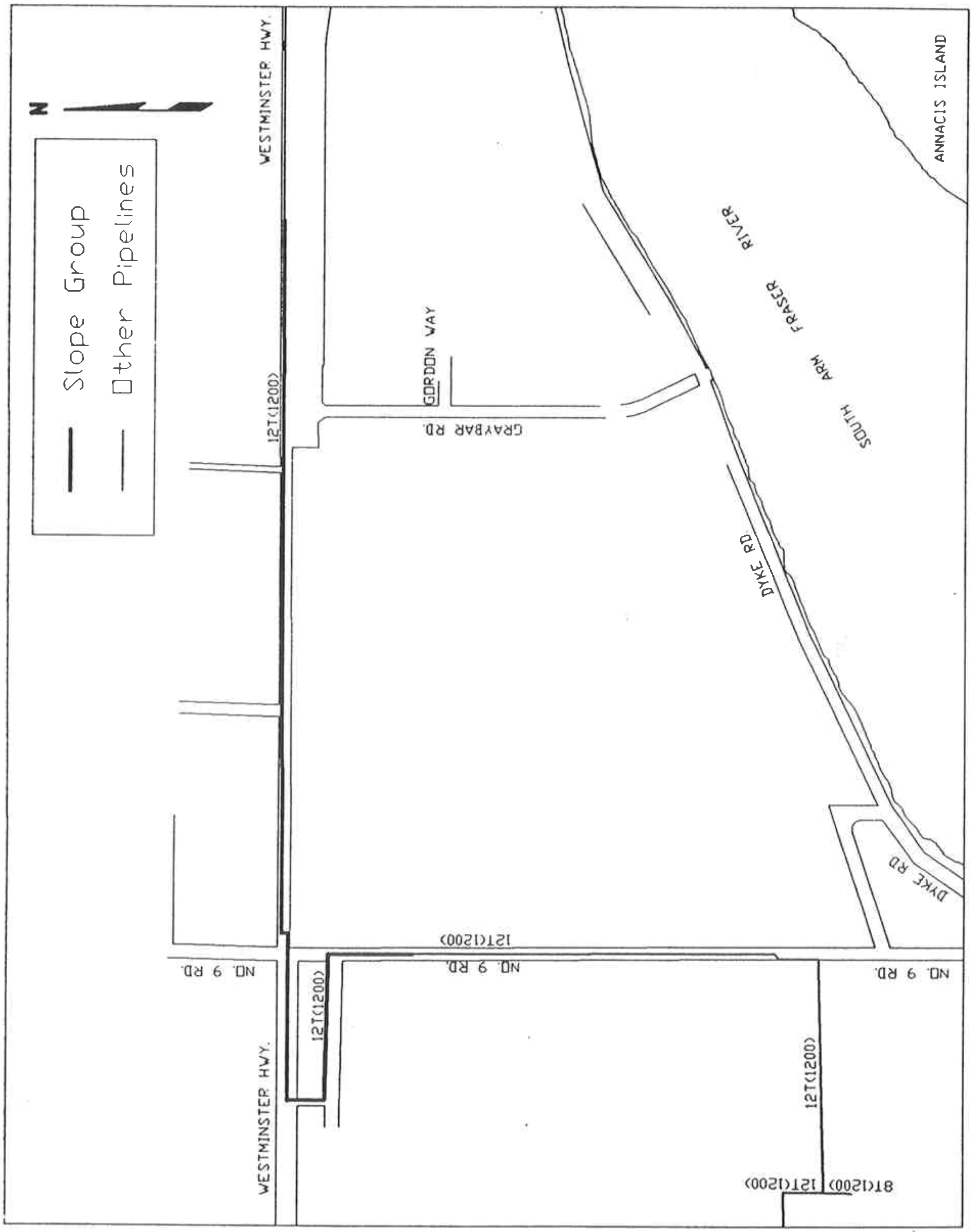


Figure 6-9: Enlarged View of Slope Group Ranked 3rd By Risk

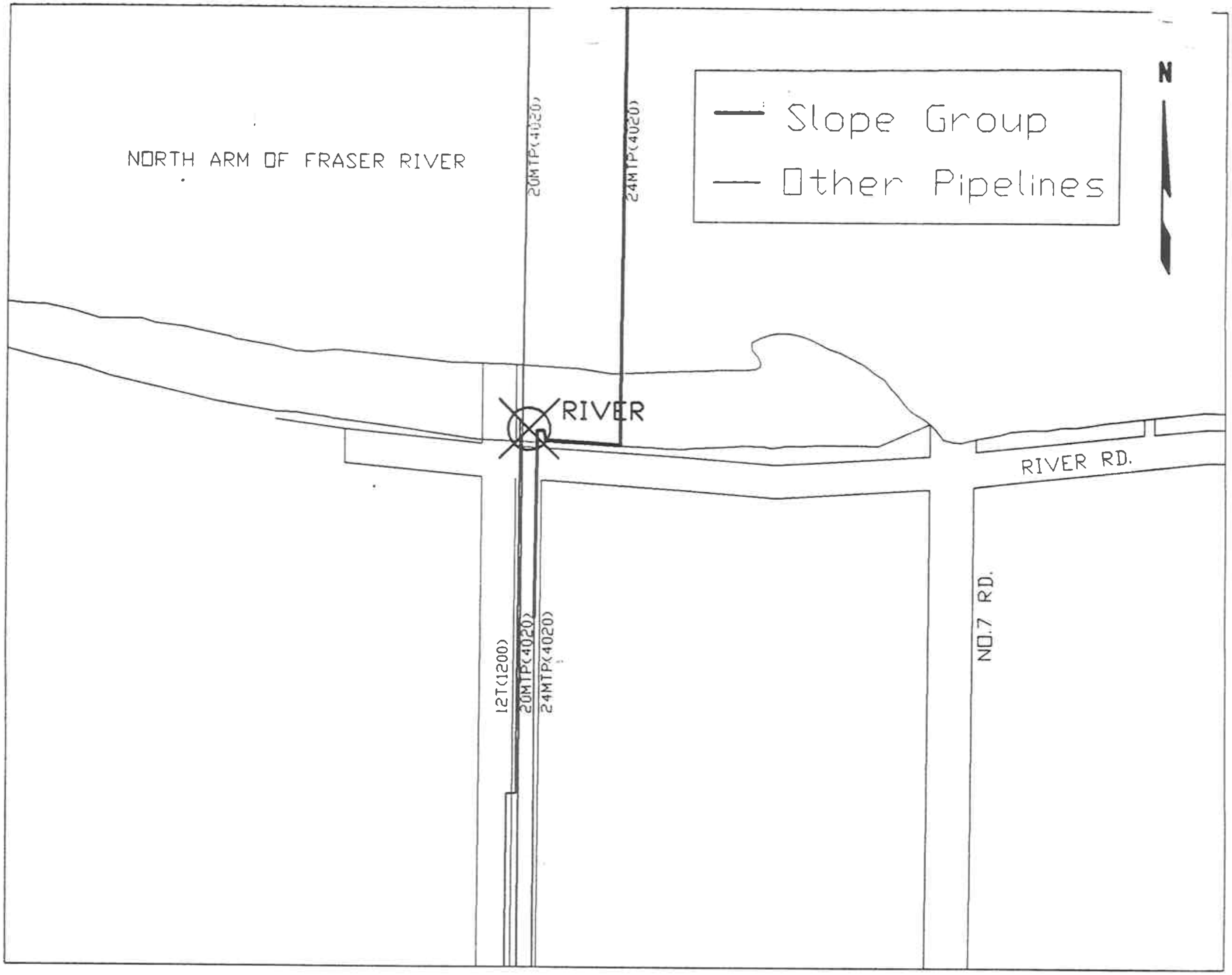


Figure 6-10: Enlarged View of Slope Group Ranked 4th By Risk

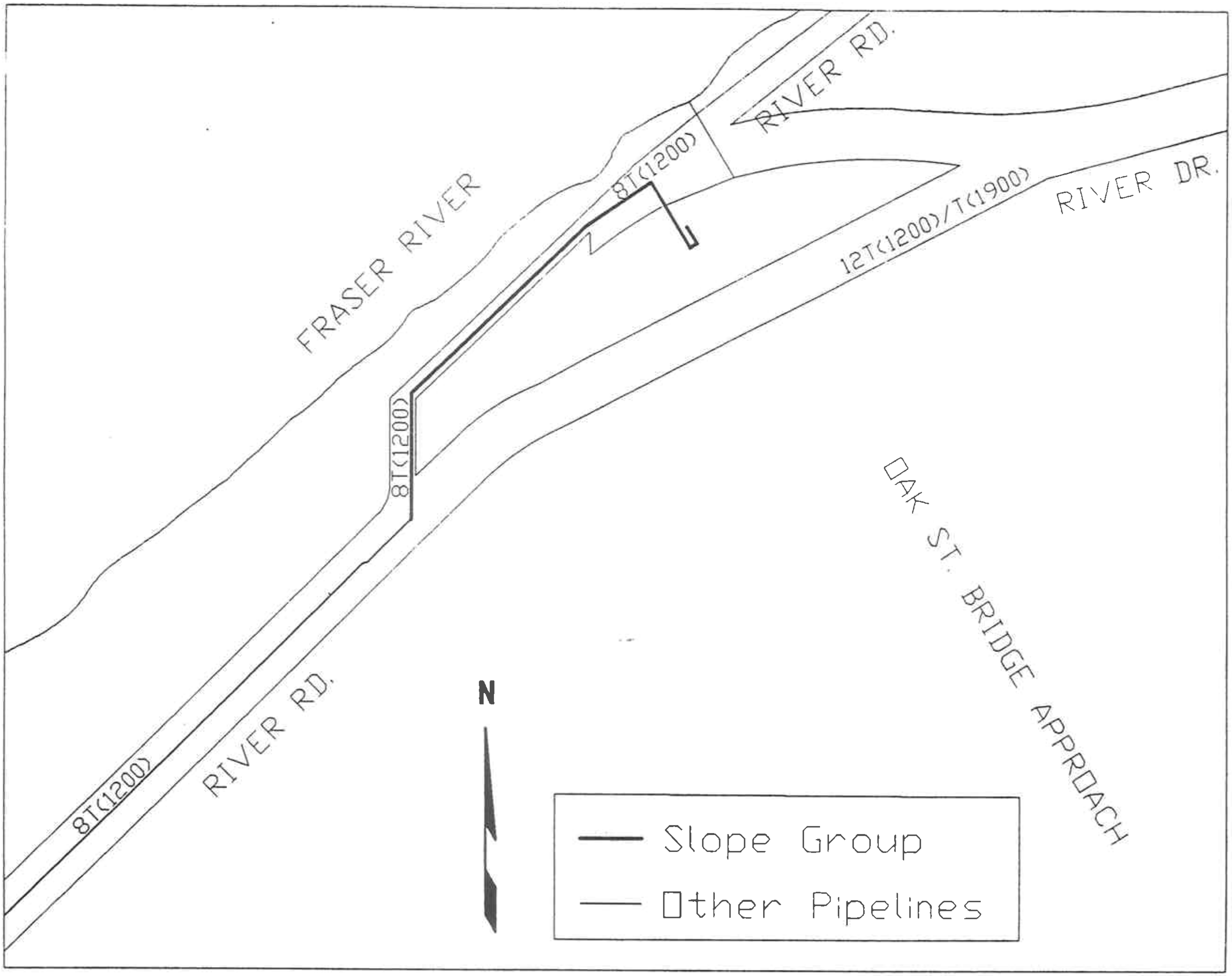


Figure 6-11: Enlarged View of Slope Group Ranked 5th By Risk

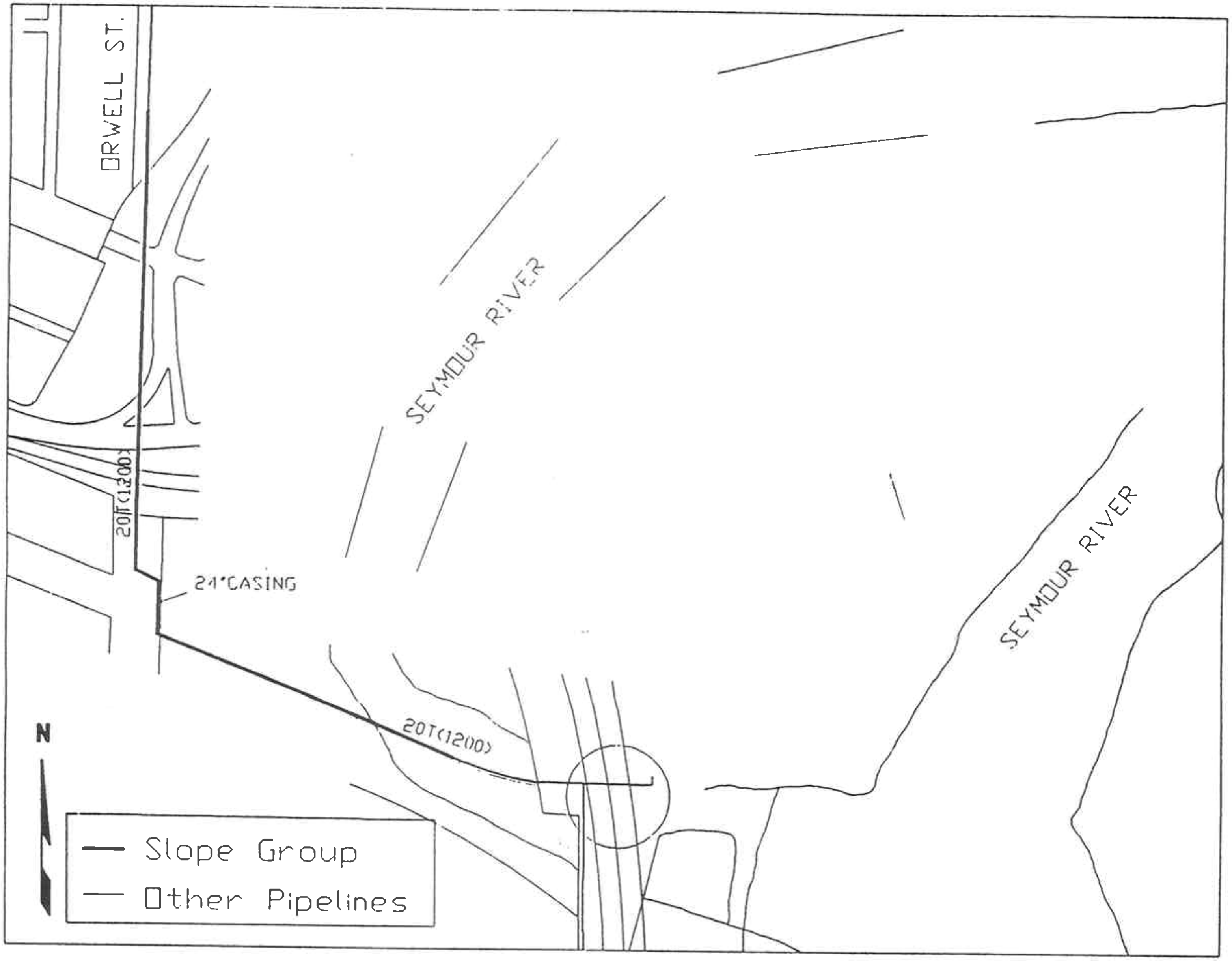


Figure 6-12: Enlarged View of Slope Group Ranked 6th By Risk

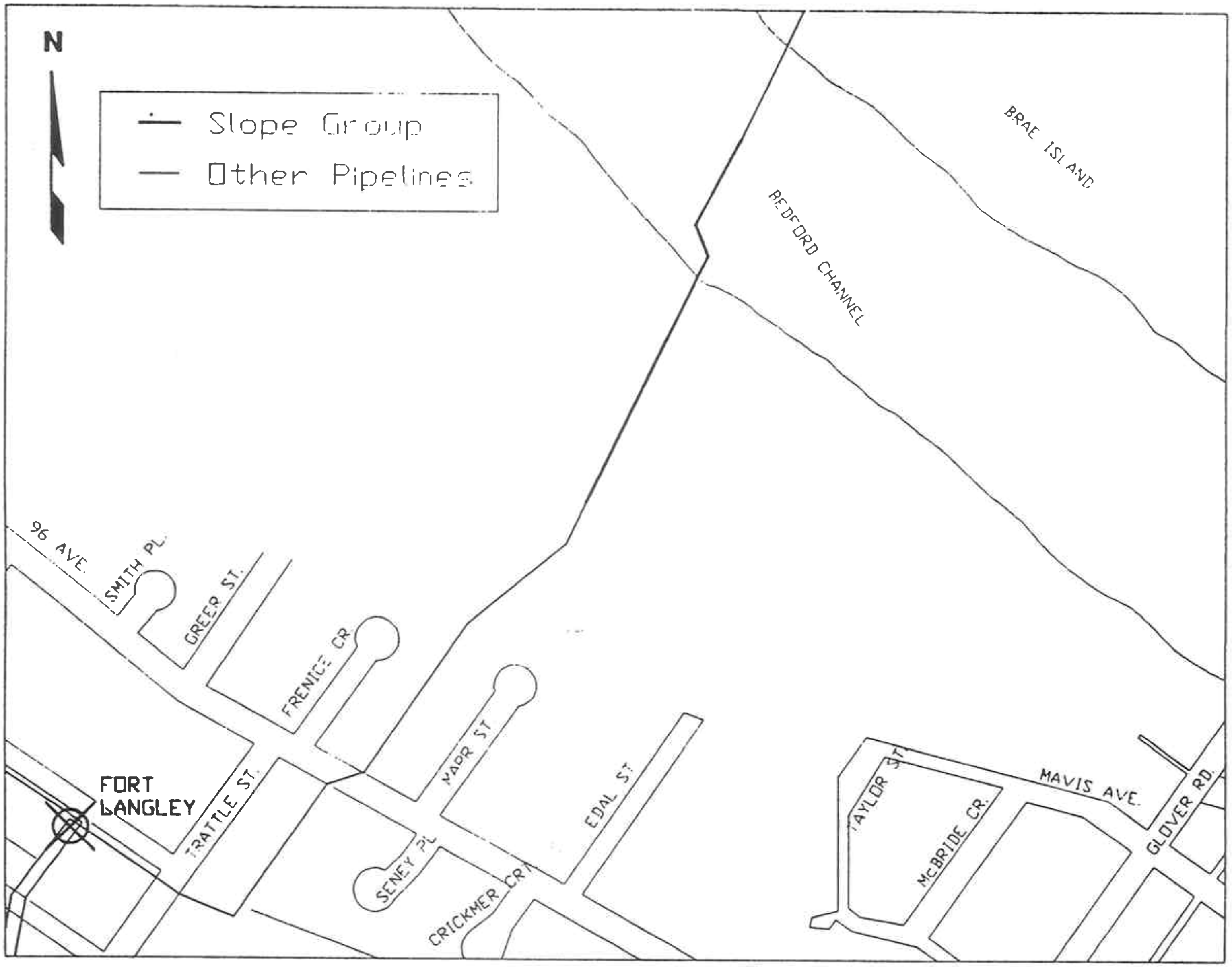


Figure 6-13: Enlarged View of Slope Group Ranked 7th By Risk

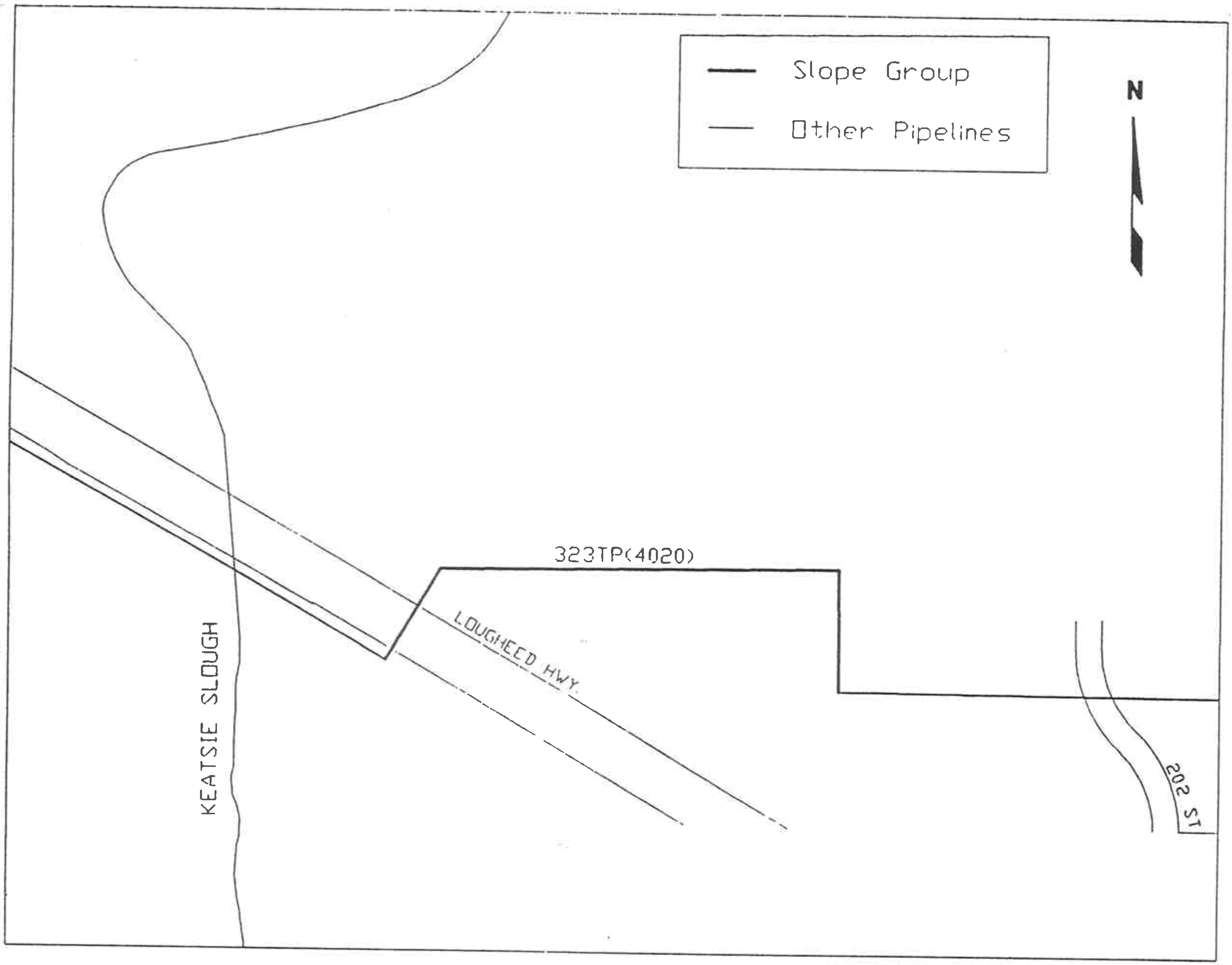


Figure 6-14: Enlarged View of Slope Group Ranked 8th By Risk

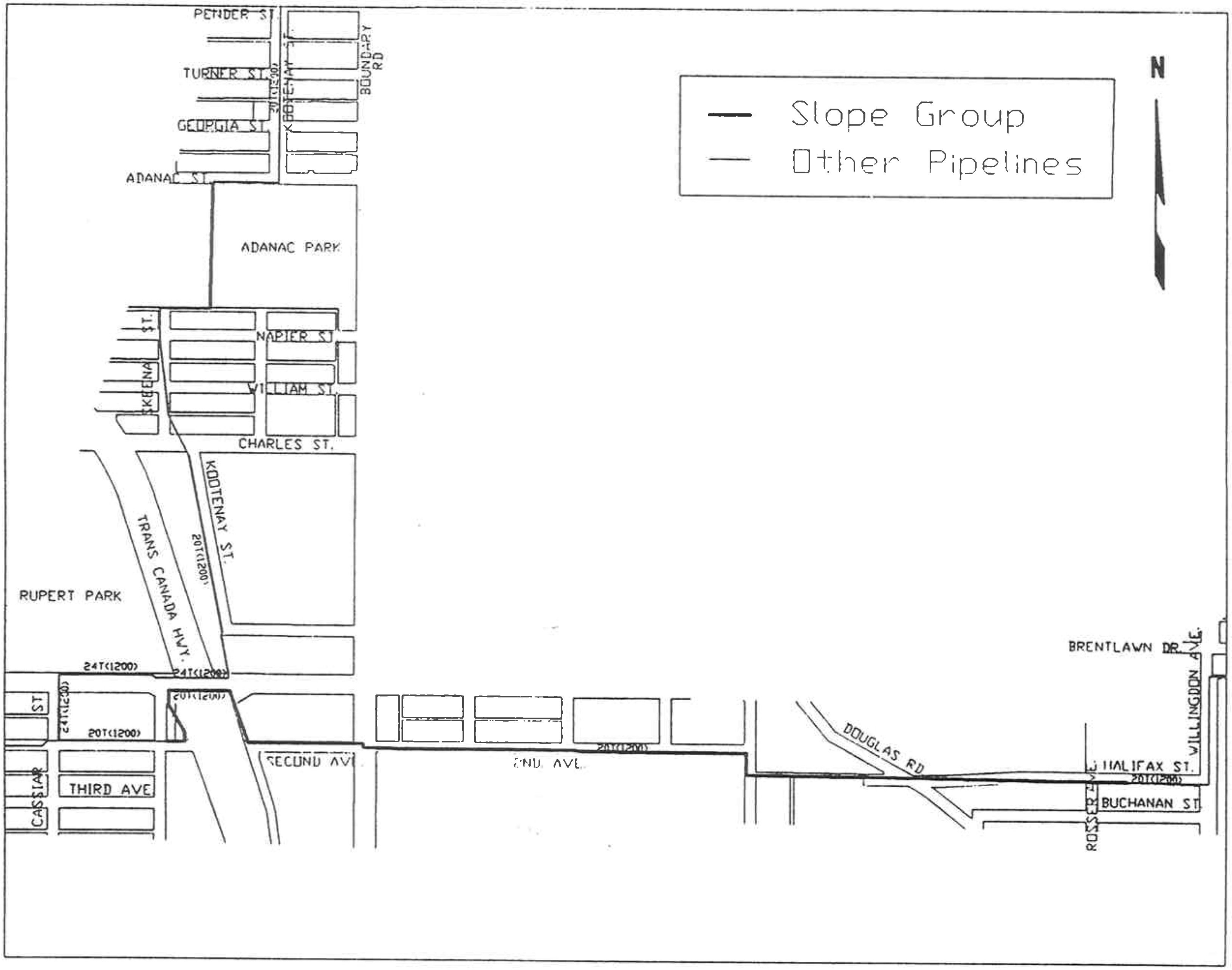


Figure 6-15: Enlarged View of Slope Group Ranked 9th By Risk

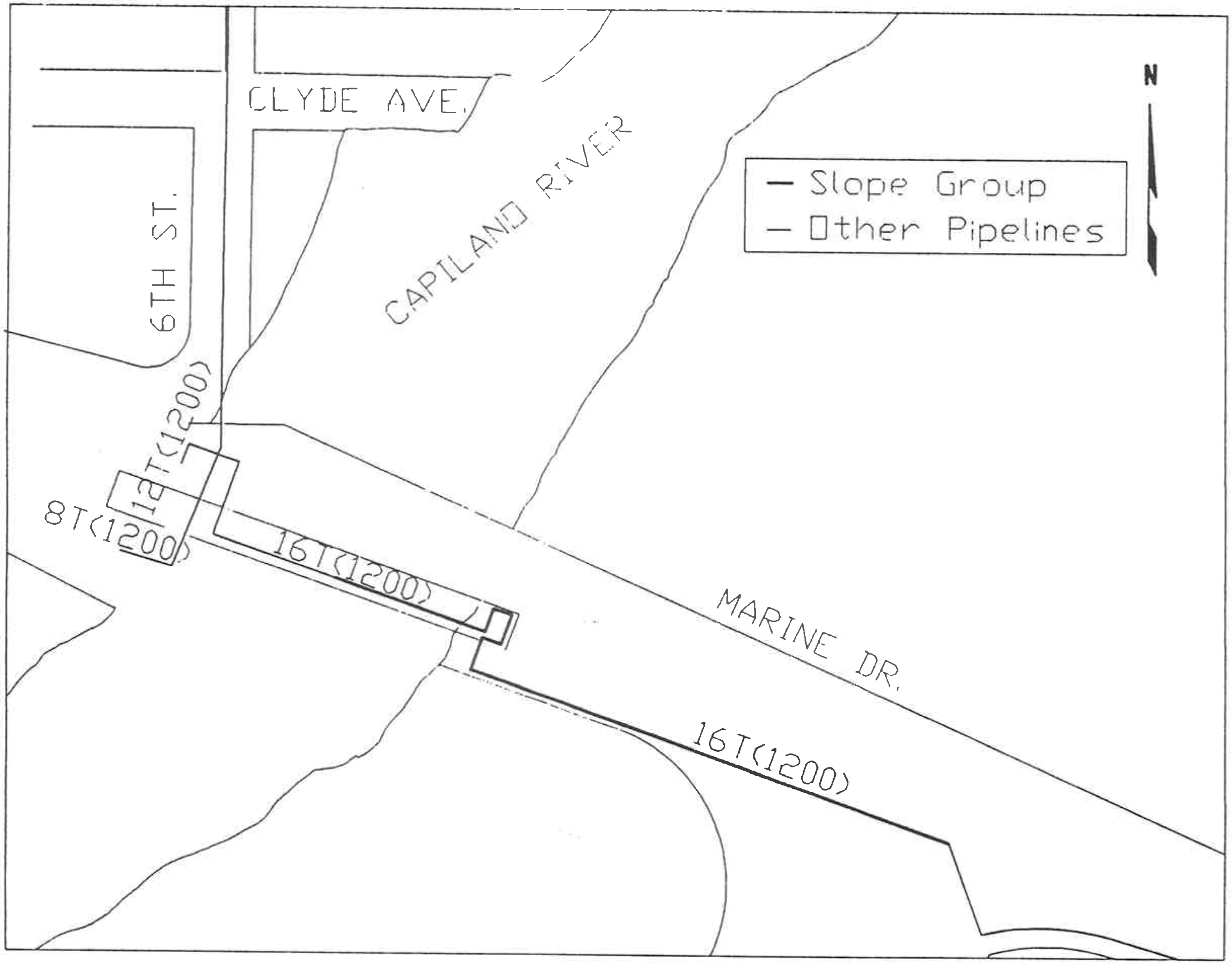


Figure 6-16: Enlarged View of Slope Group Ranked 10th By Risk

7. ABOVEGROUND FACILITY REVIEW FINDINGS

Findings from the review of equipment and structural configurations at the aboveground facilities included in the scope of the BC GAS study are contained in Attachment 4. The review was conducted at an early stage of the project and made use of conservative estimates of firm ground acceleration available at the time. Facility reviews were performed based on firm ground accelerations estimated at one standard deviation above the mean. These estimates are consistent with established acceleration values contained in Canadian building code requirements. Since we were trying to provide an estimate of failure and not to establish retrofits to bring facilities up to current design, it is our opinion that assessing facility performance should incorporate mean estimates of acceleration. This philosophy resulted in reduced accelerations associated with the "Upper Level Earthquake" in Attachment 4. The more appropriate level of acceleration for evaluating aboveground facilities was a value close to that assigned to the "Lower Level Earthquake." This means that the "Lower Level Earthquake" in Attachment 4 actually corresponds to the level of ground shaking associated with a earthquake hazard consistent with a 2,000-year return period. Results from a review for the "Upper Level Earthquake" in Attachment 4 should be ignored in reviewing facility performance in this study is concerned.

7.1 Description of Aboveground Gas Facility Assessment

A list of the aboveground facilities reviewed for the BC GAS study is provided in Table 7.1. This table also summarizes the peak ground acceleration values used in assessing the expected performance of facility components. The accelerations in Table 7.1 include site amplification from firm ground acceleration estimates based on the relationship of Seed (1984). Two sets of facility reviews were performed; one to examine potential ground shaking effects and one to assess the potential consequences for permanent ground deformations.

7.1.1 Ground Shaking Review

Examination of the in-scope aboveground facilities resulted in identification of 174 conditions selected because of their importance or because of obviously poor seismic detailing practice. These are summarized in Table 7.2 by facility. Each condition was ranked as Low, Moderate or High depending on the judgement made regarding it's seismic vulnerability. More details, including photographs, of the observed conditions is provided in Attachment 4.

The initial review of aboveground facilities focused on information gathering and did not ascertain potential facility impact during this phase of the facility reviews. A subsequent, review of the field data was conducted to further group the field findings into three categories:

Critical	A vulnerable condition that could lead to significant disruption of gas service
Important	A vulnerable condition that could produce minimal disruption of gas service but could interfere with normal operation at the facility. Correction of the vulnerability may require engineered modifications.
Maintenance	A vulnerable condition that is judged to have little impact on maintaining gas supply in the pipeline system. Possible consequences for conditions in this category include minor gas leaks from small low-pressure lines, toppling of equipment, and blockage of personnel access or egress form a facility. Mitigating the vulnerable conditions can normally be performed as part of facility maintenance.

Minor gas leakage associated with slight flange separation or severing of small, low-pressure gas lines was not considered significant to maintaining operation of the gas transmission pipeline. It should be recognized that such conditions present a possibility for fire and possibly explosion. Consideration should be given to proper support or restraint of small equipment items identified in the facility visit that have a potential for some gas leakage. This normally requires very little engineering effort and can be handled as part of a regular maintenance activity.

7.1.2 Structural Evaluation for Ground Shaking

All of the structures located at the above ground facilities reviewed in this study are small, one-story structures with regular plan configurations and few openings in their walls. Construction types for aboveground facility structures include metal, reinforced concrete, reinforced concrete with CMU (Concrete Masonry Unit) infill and load bearing CMU or masonry.

As a class of structures, reinforced concrete with CMU infill and load bearing CMU or masonry structures have performed poorly in past earthquakes. However, the earthquake performance of single-story structures of the size and configuration found at the BC GAS facilities has been very good. Therefore, structural review during site visits sought to identify irregularities in structure conditions that could be of concern with respect to seismic performance. Examples include visible cracking of walls, floors, or near piping penetrations; signs of structural repair; and evidence of ongoing ground deformation.

7.1.3 Ground Failure Review

The review of ground failure concerns examined the same facilities covered by the ground shaking review. In addition, assessments were made of bridge crossings and portions of the West Coast Energy pipeline at the Vedder Canal crossing and the aerial crossing the Fraser river near Floods.

With respect to gate and regulator stations, the Fraser Gate Station and River Gate Station are believed to be exposed to the greatest risk from earthquake-induced ground deformation. These two stations are located at the north and south banks of the North Arm of the Fraser River and could be subjected to large lateral spread movements. The River Gate Station is also at risk of lateral spread movements towards the deep ditch to the south of the station.

Pattullo Gate Station is believed to be at risk from possible amplified ground shaking associated with the fill placed over the very weak soils. The structures at the station are founded on piles which could be susceptible to damage under severe ground shaking.

Although not within the scope of the BC GAS risk assessment, the West Coast Energy Vedder Canal crossing and aerial crossing of the Fraser River were also visited. In our opinion, these sites (and others) may warrant further assessment to ascertain their earthquake risk relative to the BC GAS pipeline system.

7.2 Summary of Findings From the Aboveground Gas Facility Assessment

An overall assessment of the chances that aboveground facilities would remain functional if subjected to the review level seismic hazard was made based upon the above categorization and findings from the geotechnical assessment for the occurrence of a lateral spread at the facility. The overall assessment rated each aboveground facilities chances for continued function as High, Moderate or Low.

Of the 50 in-scope facilities, 26 are believed to be at minimal risk to interruption of service. Of the remaining 24, only 4 are believed to have a low chance of continued service. The remaining 20 facilities have been judged to have a moderate chance of providing continued service for the 1 in 2000 year earthquake hazard. A summary of the 24 stations that are not believed to have a high likelihood for continued service is presented in Table 7.3. Also provided in Table 7.3 is the primary reason for rating the facility as potentially vulnerable.

7.3 Pipelines Located on Highway Bridges

Three of the pipeline crossings in the scope of this study are on highway bridges, namely the Pattullo Bridge, the Second Narrows Bridge, and the Mission Bridge (small 200 mm diameter line). The vulnerability of the pipelines at these locations will depend on the performance of the bridge foundations and structures, as well as the interaction with the pipeline. Analysis of the vulnerability of the pipeline at bridge crossings could therefore only be made in conjunction with analysis of the seismic performance of the bridges themselves.

The bridges are owned by the B.C. Ministry of Transportation & Highways who have been reviewing and developing their design standards in recent years. Our understanding of their present requirements for seismic assessment of existing major bridges (such as those listed above) is that the structures should behave elastically with minimal damage under a 100 year return period event (Seismic Design and Rehabilitation Criteria for Transportation Facilities, February 14, 1992). Some damage is acceptable under a 475 year event, providing that the structure does not collapse. We understand that new major bridges will be designed to more stringent seismic standards.

We are aware that the Ministry has carried out a recent seismic assessment for the Second Narrows Bridge. GOLDER ASSOCIATES provided geotechnical input to a study of the Pattullo Bridge some ten years ago, when widening was being considered. We are not aware of the design standards used for the Mission Bridge, although this is a newer structure.

Initiation of a thorough assessment of the bridge crossings would require discussions with the Ministry concerning the present condition and future upgrading plans for their structures. These should be initiated by BC GAS in relation to their agreements for utilization of the bridge crossings. The following general comments can be made, however:

1. The bridges are located in areas where the liquefaction susceptibility is moderate to high.

2. Because the seismic design criteria have increased since the bridges were built, it is reasonable to assume that some damage may occur under current seismic design levels.

3. Pipelines attached to the bridges may be more vulnerable than underwater crossings because pier and abutment displacements or rotations can lead to collapse of support spans. Moreover, pipelines attached to structural members or penetrating abutments may be locally constrained and are thus subject to concentrated deformation from soil movements adjacent to the bridges.

Table 7.1

Aboveground BC GAS Facilities Included in the Scope for Ground Shaking Vulnerabilities

No.	Gate Station	PGA
1	Benson	.33
2	Tilbury	.32
3	Chatterton Chemical	
4	Nelson	.32
5	Richmond	.32
6	River Road	.31
7	Fraser	.31
8	Richardson	.24
9	Newton	.24
10	Sandell	.24
11	Pattullo	.32
12	Johnston	.25
13	Coast Meridian	.25
14	Guildford	.23
15	Tynehead	.23
16	Clayton	.25
17	Glover	.26
18	Livingstone	.26
19	Otter	.26
20	Bradshaw	.26
21	Clearbrook	.25
22	King	.25
23	Riverside	.25
24	Huntingdon	.33
25	McDermot	.33

No.	Gate Station	PGA
26	Yarrow	.33
27	Atchelitz	.33
28	Chilliwack	.33
29	Rosedale	.27
30	Agassiz	.27
31	Hope	.24
32	Latimer	.24
33	Alexander	.24
34	Fort Langley	.24
35	McKay	.24
36	Ferguson	.23
37	Coquitiam	.20
38	Barnet	.20
39	Westwood	.18
40	Eagle Mountain	.18
41	Anmore	.18
42	IOCO	.18
43	Burrard Thermal Plant	.18
44	Trenton	.32
45	Pitt Meadows	.21
46	Hammond	.23
47	Haney	.24
48	Albion	.33
49	Mission	.34
50	Goudy	.33

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Benson Gate Station			
Meter Stand	Flexibility and rust of stand.	Low to Moderate	Maintenance
Heater Meter	Supported by unanchored wood and CMU blocks.	Low to Moderate	Maintenance
Heater Filter	Unanchored.	Low to Moderate	Important
Notes: None			
Tilbury Gate Station			
Regulator Building		Low	N/A
Heater	Supported by unanchored rails.	Moderate to High	Important
Helium Cylinders	Only restrained with a single chain at the top.	Moderate to High	Maintenance
Monitoring Equipment	Apparently unanchored and unrestrained.	High	Important
Meter	Rests on an unanchored stand.	Low to Moderate	Maintenance
Outside Valves and Piping	Anchor bolts not fully grouted.	Moderate	Maintenance
Notes: None			
Chatterton Chemical Gate Station			
Notes: Chatterton Gate Station is not accessible and is not currently operating.			
Nelson Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Test Building	None (metal building).	Low	N/A
Outside Piping and Valves	Anchor bolts not fully grouted, cracking of one concrete pedestal.	Low to Moderate	Maintenance
Meter test piping/set-up	Unanchored.	High	Maintenance
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Richmond Gate Station			
Regulator Building		Low	N/A
Heater Building	None (metal building).	Low	N/A
Heater	Supported by unanchored rails.	Moderate	Important
Heater Expansion Tank Stand	Unanchored.	Moderate	Important
Notes: None			
River Road Gate Station			
Regulator Building	None (metal building).	Low	N/A
Lockers	Unanchored.	High	Maintenance
Outside Piping and Valves	Anchor bolts are not fully grouted.	Low to Moderate	
Notes: River Road Gate Station is immediately adjacent to the Fraser River bank			
Fraser Gate Station			
Regulator Building	Reinforced concrete building.	Low	N/A
Regulator Piping and Valves	Pipe support stands are not anchored.	Low to Moderate	Maintenance
Heaters	Unanchored.	High	Important
Station Pipe Inlet	Anchor bolts not fully grouted.	Low to Moderate	N/A
Telemetry Building	See CMU building discussion.	Unknown	N/A
Telemetry Cabinets	Unanchored and unrestrained.	High	Important
Notes: Fraser Gate Station is immediately adjacent to the Fraser River bank			
Richardson Gate Station			
Regulator Building	CMU building.	Low	N/A
Heater	Support frame is unanchored.	Moderate	Important
Regulator Pipe Flange Support Frame	Frame is unanchored. Frame strength is also questionable.	Moderate to High	Important
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Newton Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate to High	Important
Outside valves and piping	Pipe support stands are unanchored.	Low	
Notes: None			
Sandell Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand	Fairly flexible.	Low to Moderate	Maintenance
Heater	Some heater anchor bolts are missing nuts. Heater meter rests on wood blocks. Battery is unanchored (there is slack in attached cables).	Moderate	Important
Notes: None			
Pattullo Gate Station			
Regulator Building	Ground settlement, on the order of 3 to 4 feet, has occurred throughout the gate stations site. Differential displacement has stressed the outlet piping on the north end of the Pattullo Gate Station.	High	Critical
Heater Meter and Filter	Filter is unanchored and meter rests on wood blocks.	Low to Moderate	Important (Filter)
Control Equipment Building	See reinforced concrete building discussion.	Low	Important
Control, Alarm and Other Miscellaneous Cabinets	Unanchored. Some cabinets are on rollers.	High	Important
Piping and Valve Support Foundations	Settlement around foundations will result in increased forces on foundations.	Moderate to High	Important
Notes: None.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Johnston Gate Station			
Heater	Unanchored.	Moderate	Important
Valves and Piping	Pipe support stands are not double nutted and the anchor bolts are not fully grouted.	Low to Moderate	Maintenance
Notes: None			
Coast Meridian Gate Station			
Regulator Building	None (metal building).	Low	
Heater and Filter	Anchorage of heater is unknown. Filter is unanchored.	Moderate	Important
Notes: None			
Guildford Gate Station			
Regulator Building	Reinforced concrete building.	Low	N/A
Heater	Unanchored heater sits on rails.	Moderate to High	Important
Outside Meter	Rests on unanchored wood blocks.	Low to Moderate	Maintenance
Filter	Anchor bolts are not fully grouted.	Low	Maintenance
Notes: None			
Tynehead Gate Station			
Regulator Building	None (metal building).	Low	N/A
Filter	Unanchored.	Low to Moderate	
Regulator Building Meter	Flexibility could result in damage to attached tubing.	Low	Maintenance
Heater and Meter	Heater is anchored into a rail system that is unanchored. Meter rests on wood blocks that sit on an unanchored table.	Low to Moderate	Important (Heater)
Outside Pipe Supports	Anchor bolts are not fully grouted.	Low	Maintenance
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Clayton Gate Station			
Regulator Building	None (metal building).	Low	N/A
Filter	Anchor bolts are not fully grouted.	Low	Maintenance
Heater	Apparently unanchored.	Moderate to High	Important
Notes: None			
Glover Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate to High	Important
Notes: None			
Livingstone Gate Station			
Regulator Building	None (metal building).	Low	N/A
Notes: Floor slab appears to have settled differently with respect to foundation.			
Otter Gate Station			
Regulator Building	Metal building on skid. Skid is probably anchored. Building movement and damage to building contents may be possible.	Low	Important
Heater	Could not determine anchorage (assume unanchored).	Moderate to High	Important
Notes: Sloped creek bank is immediately beyond Otter Gate Station boundary			
Bradshaw Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Could not verify complete anchorage.	Moderate	Important
Notes: None			
Clearbrook Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Apparently unanchored.	Moderate to High	Important
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
King Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heaters	Some bolts are missing or of questionable strength.	Low to Moderate	Important
Notes: None			
Riverside Gate Station			
Regulator Building	None (metal building).	Low	N/A
Control Box Stand	Movement of control box stand could break attached tubing or result in failure of the stand.	Moderate	Maintenance
Heater	Bolt nuts are loose.	Low	Maintenance
Notes: Riverside Gate Station is located on a cut in a hillside.			
Huntindon Gate Station			
Electrical Cabinet (Odorant Injection Building)	Unanchored.	High	Maintenance
Odorant Injection Building	None (metal building).	Low	N/A
Odorant Injection Tanks	Anchored but tank movement may break attached piping.	Low to Moderate	Maintenance
Junction Box Near Inlet to Northwest Pipeline	Ability of conduit to accommodate movement of junction box is unknown.	Low to Moderate	Maintenance
Valve System on Outlet to Northwest Pipeline	Strength of support is questionable. New braces to be added by B.C. Gas would be adequate.	Moderate to High	Maintenance
Regulator Station #2 Pipe Stands	Stands could kick-out.	Low to Moderate	Maintenance
Regulator Station #2 Building	None (metal building).	Low	N/A
Regulator Station #1 Building	None (metal building).	Low	N/A
"Old" Control Building	None (metal building).	Low	N/A

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
McDermot Gate Station			
Regulator Building	None (metal building).	Low	N/A
Regulator Building Meter Stand	Breakage of attached tubing possible from movement of meter.	Low to Moderate	Maintenance
Barrels	Unrestrained.	Moderate to High	Maintenance
Notes: None			
Yarrow Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Some bolt nuts are missing, and some bolt shafts do not extend up enough to be nutted.	Moderate	Maintenance
Notes: None			
Atchelitz Gate Station			
Regulator Building	Brick masonry building.	Low	N/A
Heater and Heater Meter	Unanchored.	Moderate to High	
Notes: None			
Chilliwack Gate Station			
Regulator Building	CMU building.	Low	N/A
Piping Outside of Regulator Building	Pipe supports are unstable with respect to lateral loads.	High	Maintenance
Control System Panels (Odorant Housing Cover)	Resistance of stand to lateral loads is questionable.	Moderate	Maintenance
Heater	Unanchored.	High	Important
Electrical Cabinet Building	CMU building.	Low	N/A
Electrical Cabinets	Unanchored. One cabinet is on rollers.	High	Important
Air Cooler	Rests unanchored on a cabinet.	High	Maintenance
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Alexander Gate Station			
Regulator Building	Metal building on skids. Skid is probably unanchored. Building movement and damage to building contents may be possible.	Low	Critical
Heater	Anchored, but bolt nuts are missing.	Moderate	Maintenance
Notes: None			
Fort Langley Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate	Important
Notes: None			
McKay Gate Station			
Notes: No buildings or apparent deficiencies.			
Ferguson Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Heater is unanchored. Heater meter is supported by wood blocks.	Moderate	Important
Notes: None			
Coquitlam Gate Station			
Regulator Building	CMU building.	Low	N/A
Control Building	CMU building.	Low	N/A
Power Supply and Other Cabinets	Unanchored. Some cabinets are on rollers.	Moderate to High	Important
Gas Cylinder Storage	Some cylinders are completely unrestrained. Other cylinders are restrained with only one chain.	High	Maintenance
Methanol Barrel	Sits on unanchored saddle frame.	Moderate to High	Maintenance

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Anmore Gate Station			
Note: The Anmore Gate Station is a simple station without any buildings or apparent deficiencies.			
IOCO Gate Station			
Heater	Unanchored. The front legs extend about 2 inches beyond the edge of the concrete pad.	Moderate	Important
Note: The IOCO Gate Station is located on a cut in a hillside.			
Burrard Thermal Gate Station			
Gas Metering Station	CMU building.	Low	N/A
Electrical/Power Cabinets	Cabinets are unanchored. Some cabinets are on rollers.	Moderate to High	Important
Regulator Building	Reinforced concrete building.	Low	N/A
Filter	Unanchored.	Low	Important
Pipe Stands in Regulator Building	Some pipe stands are on wood blocks. Some pipe stands are threaded into unanchored channel sections.	Low to Moderate	Maintenance
Generator Building	CMU building.	Low	N/A
Fuel Tank	Angle leg supports are probably inadequate.	Moderate	
Barrels	Unrestrained.	Moderate	Maintenance
Heaters, Heater Filters, and Motors	Bolts or bolt nuts are missing on heater anchors. Unanchored filters and motors rest on wood blocks that sit on unanchored tables.	Low to Moderate	Maintenance
Heater Area Pipe Supports	Wood blocks are used for pipe supports.	Low	Maintenance
Notes: The Burrard Thermal Gate Station is located on a cut in a hillside on the bank of Burrard Inlet.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Albion Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand	Flexibility of stand may result in displacements that sever attached tubing.	Low to Moderate	Maintenance
Notes: None			
Mission Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Bolt nuts are loose or missing.	Low to Moderate	Maintenance
Notes: Filter is unanchored and is supported by only one leg. Because filter center of gravity is near the same height as the attached piping, it is probably OK.			
Goudy Gate Station			
Pipe Support Stands	Pipe support stands are unanchored and movable.	Low to Moderate	Maintenance
Notes: None			

Equipment upgrades can be carried out as part of a maintenance activity with very little engineering support required. This is especially true for the BC GAS facilities for which there are a great number of similar components. To implement such a maintenance activity, it is necessary to provide facility maintenance personnel with sufficient information to allow them to identify potential deficiencies and alternatives for correcting suspected deficiencies. In our experience, this information is best transmitted in the form of standard equipment anchorage requirements. These requirements typically associate minimal anchorage (e.g., bolt, weld, expansion anchor) with various equipment parameters such as plan dimension, height, and weight. An effective aid in carrying out these minor upgrades is to provide field personnel with simple screening charts and diagrams that graphically relate anchorage requirements to equipment configurations. The absence of detailed engineering input is offset by conservatism in the anchorage requirements.

If such a facility upgrade program is carried out, we believe that all of the aboveground facilities identified as having a "Moderate" chance for maintaining continued service can be placed in the "High" category.

8.2.2 Investigations of BC GAS System Operation

The findings from our assessment of the BC GAS pipeline system have been prioritized in terms of risk for failure. For planning future modifications, it is most important to further prioritize the likely points of failure in terms of the importance for maintaining a minimum level of system function. This requires a systems analysis to assess gas supply to key service areas. From discussions in the working group meeting of July 21, 1993, it is our understanding that BC GAS intends to incorporate the information presented in this report into such an analysis.

8.2.3 Modify Walls at Latimer Station

The block wall barriers at the Latimer Station should be modified such that they are no longer a falling hazard. The modification may consist of strengthening the wall, providing protective covering for fragile components, or removing the block walls.

8.2.4 Detailed Review of the Huntingdon Gate Station

Proper function of the control equipment at the Huntingdon Gate Station is essential for supplying gas to the BC GAS system. A thorough review of the structures, electrical

Recommendations for further evaluation are based on a qualitative assessment of potential conservatism in assessing of risk and the potential for identifying alternatives to lower the estimated risk. Two outcomes are anticipated from the site specific evaluations. A lower risk of rupture may be determined resulting in a change in priority of the site in question. A site specific evaluation may also provide the basis for recommended alteration of the pipeline alignment to lower seismic hazards to an acceptable level.

8.3.2 Review Bridge Crossings

The Mission, Pattullo and Second Narrows bridges are used by BC GAS to cross rivers. The performance of these bridges should be assessed to better define the risks to the BC GAS pipelines. This may include independent analyses or simply monitoring the activities of the BC Ministry of Transportation.

8.4 Recommendations for Future Planning of Pipeline System Modifications

8.4.1 High Risk River Crossings

Many of the high risk locations identified in the seismic risk assessment are at river crossings which was not unexpected. Portions of the pipeline system determined to be at greatest risk include the 20-inch and 24-inch transmission pipelines in the vicinity of the crossings f the north and south arms of the Fraser River and the Pattullo site. From our understanding of the BC GAS system, these pipelines are also expected to be critical to maintaining gas service.

Further investigation and analysis to quantify the seismic hazard at these locations could be carried out to better define the relative risks and to assist in planning and scheduling remedial action. Alternatively, the existence of a significant seismic hazard could be accepted and steps put into motion to avoid the hazard, or minimize the potential impact. The following actions could be considered to minimize the effect of the seismic hazard at these locations:

1. Consider mitigation measures, such as ground improvement, to reduce or eliminate the risk at the most critical sites. The Fraser and River gate stations are two such critical sites. Alternatively, relocate Fraser and River gate stations to avoid potentially large lateral spread displacements near the river bank.

3. Examine temporary operations measures that could increase gas supply in emergency situations (e.g., boosting pressure in certain intermediate pressure lines that still have gas supply)

8.4.3 Gas Supply to BC GAS

The main gas supply to the Vancouver region is provided by the West Coast Energy pipeline. Efforts should be taken to contact West Coast Energy and determine what provisions they have taken to identify hazards to their pipeline (both seismic and non-seismic) and their plans for responding to the presence of those hazards.

10. Byrne, P.M. 1991. A model for Predicting Liquefaction-Induced Displacement, Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 7.14, pp. 1027-1035.

11. Byrne, P.M., Jitno, H., and Salgado, F. 1992. Earthquake Induced Displacements of Soil-Structures Systems, in Proceedings: Tenth World Conference, Earthquake Engineering, July 19-24, 1992, Madrid, Spain, A.A. Balkema, Rotterdam, Brookfield, 1992, pp. 1407-1411.

12. Earthquake Design in the Fraser Delta (1991), Task Force Report, June 1991.

13. Finn, W.D. Liam, Yogendrakumar, M., Yoshida, N., and Yoshida, H. 1986. TARA-3: A Program to Compute the Response of 2-D Embankments and Soil Structure Interaction Systems to Seismic Loadings, Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

14. Hamada, M., and O'Rourke, T.D. (editors) 1992. Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes: Japanese Case Studies, Technical Report NCEER-92-0001, Vol. 1, National Center for Earthquake Engineering Research, State University of New York at Buffalo.

15. Honegger, D.G., 1990, "MIGHTY OAK Structures Experiments to Investigate Tunnel Liner Design and Conduit Performance at Fault Crossings," National Technical Systems, NTS 1553.

16. Kennedy, R.P., A.W. Chow and R.A. Williamson, 1977, "Fault Movement Effects on Buried Oil Pipeline," Journal of the Transportation Engineering Division, ASCE, vol. 103, no. TE5.

17. Meyersohn, W.D. and T.D. O'Rourke, 1991, "Pipeline Buckling Caused by Compressive Ground Failure During Earthquakes," Proceedings, Third Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, San Francisco California, Technical Report NCEER-91-0001,

18. National Aeronautics and Space Administration (NASA), 1968, "Buckling of Thin-Walled Circular Cylinders, " NASA Space Vehicle design Criteria (Structures), NASA SP-8007.

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Huntindon Gate Station (Cont.)			
Uninterruptable Power Supply	Unanchored.	Moderate to High	Important
Meter Cabinet	Unanchored.	Moderate to High	Maintenance
Natural Gas Cylinder	Restrained with only one chain.	Moderate to High	Maintenance
Gravitometer Building	None (metal building).	Low	N/A
Generator and Workshop Building	None (metal building).	Low	N/A
Workshop Storage	Spillage of stored items and/or cabinet tip-over.	High	N/A
Air Compressor in Workshop	Unanchored.	Low to Moderate	Maintenance
Chemical Building Barrel Storage	Tip-over and spillage of chemical storage barrels.	High	Maintenance
Chemical Storage Building	None (metal building).	Low	Maintenance
"New" Control Building	CMU building.	Low	N/A
Raised Floor in Control Building	Raised floor is unbraced.	Moderate	Important
Telemetry Cabinets in "New" Control Building	Unanchored.	High	Important
Generator in "New" Control Building	Unanchored.	Moderate	Important
Battery Stand	Unanchored.	High	Important
Heater in "New" Control Building	Unanchored.	Low to Moderate	Important
Water Heater in "New" Control Building	Unanchored.	Moderate to High	Maintenance
Communications Equipment Building	None (metal building).	Low	N/A
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
McDermot Gate Station			
Regulator Building	None (metal building).	Low	N/A
Regulator Building Meter Stand	Breakage of attached tubing possible from movement of meter.	Low to Moderate	Maintenance
Barrels	Unrestrained.	Moderate to High	Maintenance
Notes: None			
Yarrow Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Some bolt nuts are missing, and some bolt shafts do not extend up enough to be nutted.	Moderate	Maintenance
Notes: None			
Atchelitz Gate Station			
Regulator Building	Brick masonry building.	Low	N/A
Heater and Heater Meter	Unanchored.	Moderate to High	
Notes: None			
Chilliwack Gate Station			
Regulator Building	CMU building.	Low	N/A
Piping Outside of Regulator Building	Pipe supports are unstable with respect to lateral loads.	High	Maintenance
Control System Panels (Odorant Housing Cover)	Resistance of stand to lateral loads is questionable.	Moderate	Maintenance
Heater	Unanchored.	High	Important
Electrical Cabinet Building	CMU building.	Low	N/A
Electrical Cabinets	Unanchored. One cabinet is on rollers.	High	Important
Air Cooler	Rests unanchored on a cabinet.	High	Maintenance
Notes: None			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Rosedale Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand in Regulator Building	Movement of stand could sever attached tubing.	Low to Moderate	Maintenance
Heaters	Failure of support pedestals possible.	Low to Moderate	Important
Notes: None			
Agassiz Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand in Regulator Building	Movement of stand could sever attached tubing.	Low to Moderate	Maintenance
Heater Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate to High	Important
Filter	Unanchored.	Low	Important
Notes: None			
Hope Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate to High	Important
Odorizer Distribution Panel	Odorant injection stand movement may sever odorant injection piping.	Low to Moderate	Maintenance
Notes: None			
Latimer Gate Station			
CMU Walls	If walls fell, CMU blocks could damage gate station compound. See CMU building discussion.	Low	Critical
Heater and Heater Meter	Bolt nuts are not tight on heater anchorage. Heater meter rests on wood blocks on an unanchored table.	Low to Moderate	Maintenance
Notes: None.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Alexander Gate Station			
Regulator Building	Metal building on skids. Skid is probably unanchored. Building movement and damage to building contents may be possible.	Low	Critical
Heater	Anchored, but bolt nuts are missing.	Moderate	Maintenance
Notes: None			
Fort Langley Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Unanchored.	Moderate	Important
Notes: None			
McKay Gate Station			
Notes: No buildings or apparent deficiencies.			
Ferguson Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Heater is unanchored. Heater meter is supported by wood blocks.	Moderate	Important
Notes: None			
Coquitlam Gate Station			
Regulator Building	CMU building.	Low	N/A
Control Building	CMU building.	Low	N/A
Power Supply and Other Cabinets	Unanchored. Some cabinets are on rollers.	Moderate to High	Important
Gas Cylinder Storage	Some cylinders are completely unrestrained. Other cylinders are restrained with only one chain.	High	Maintenance
Methanol Barrel	Sits on unanchored saddle frame.	Moderate to High	Maintenance

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Coquitlam Gate Station (Cont.)			
Storage Building	Brick masonry building.	Low	N/A
Material Storage in Storage Building	Unanchored and/or unrestrained storage of materials.	High	Maintenance
Heaters	Heaters rest on unanchored rails.	Moderate	Important
Heater Building	Reinforced concrete building.	Low	N/A
Fire Extinguisher Stand	Timber stand is flexible and may also be weak.	Low to Moderate	Maintenance
Notes: None			
Barnett Gate Station			
Heater	Heater is unanchored. Heater meter rests on wood blocks on an unanchored table.	Moderate	Important
Barrel (Unknown Contents)	Barrel rest on timber blocks.	Low to Moderate	Maintenance
Notes: There is a retaining wall (unknown vulnerability) above the Barnett Gate Station.			
Westwood Gate Station			
Notes: Westwood Gate Station is essentially a valving station with no apparent deficiencies or buildings.			
Eagle Mountain Gate Station			
Regulator Building	None (metal building).	Low	N/A
Power Control Cabinets	Two clip-angle connections for one cabinet were observed. Other cabinets appeared to be unanchored.	Moderate to High	Important
Computer and Printer	Unanchored.	Moderate to High	Important
Notes: Eagle Mountain Gate Station is located on a cut into a hillside. There is a large rock retaining wall on the uphill side of the station. At the time of the site visit, construction was still in progress.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Anmore Gate Station			
Note: The Anmore Gate Station is a simple station without any buildings or apparent deficiencies.			
IOCO Gate Station			
Heater	Unanchored. The front legs extend about 2 inches beyond the edge of the concrete pad.	Moderate	Important
Note: The IOCO Gate Station is located on a cut in a hillside.			
Burrard Thermal Gate Station			
Gas Metering Station	CMU building.	Low	N/A
Electrical/Power Cabinets	Cabinets are unanchored. Some cabinets are on rollers.	Moderate to High	Important
Regulator Building	Reinforced concrete building.	Low	N/A
Filter	Unanchored.	Low	Important
Pipe Stands in Regulator Building	Some pipe stands are on wood blocks. Some pipe stands are threaded into unanchored channel sections.	Low to Moderate	Maintenance
Generator Building	CMU building.	Low	N/A
Fuel Tank	Angle leg supports are probably inadequate.	Moderate	
Barrels	Unrestrained.	Moderate	Maintenance
Heaters, Heater Filters, and Motors	Bolts or bolt nuts are missing on heater anchors. Unanchored filters and motors rest on wood blocks that sit on unanchored tables.	Low to Moderate	Maintenance
Heater Area Pipe Supports	Wood blocks are used for pipe supports.	Low	Maintenance
Notes: The Burrard Thermal Gate Station is located on a cut in a hillside on the bank of Burrard Inlet.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Trenton Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater Meter	Meter is supported by a wood block that rests on an unanchored table.	Low to Moderate	Maintenance
Valve and Piping Support Stands	Unanchored.	Low to Moderate	Maintenance
Notes: None			
Pitt Meadows Gate Station			
Regulator Building	None (metal building).	Low	N/A
Filter	Unanchored.	Low	Important
Heater	Unanchored.	Moderate	Important
Notes: None			
Hammond Gate Station			
Regulator Building	None (metal building).	Low	N/A
Pipe Stands	One stand is free to move and others are unanchored.	Low	Maintenance
Heater	Unanchored.	Moderate	Important
Notes: None			
Haney Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand	Flexibility of stand may result in displacements that sever attached tubing.	Low	Maintenance
Filter	Unanchored.	Low	Important
Heater Battery	Rests on unanchored stand.	Moderate to High	Maintenance
Control Panel	Flexibility of panel may result in displacements that sever attached tubing.	Low to Moderate	Maintenance
Notes: It could not be determined if the heater was anchored.			

Table 7.2

Summary of Potential Ground Shaking Vulnerabilities at BC GAS Aboveground Facilities Identified in Table 7.1

Description	Concern	Seismic Vulnerability for 1 in 2000 Year Earthquake Hazard	Potential Operational Impact
Albion Gate Station			
Regulator Building	None (metal building).	Low	N/A
Meter Stand	Flexibility of stand may result in displacements that sever attached tubing.	Low to Moderate	Maintenance
Notes: None			
Mission Gate Station			
Regulator Building	None (metal building).	Low	N/A
Heater	Bolt nuts are loose or missing.	Low to Moderate	Maintenance
Notes: Filter is unanchored and is supported by only one leg. Because filter center of gravity is near the same height as the attached piping, it is probably OK.			
Goudy Gate Station			
Pipe Support Stands	Pipe support stands are unanchored and movable.	Low to Moderate	Maintenance
Notes: None			

Table 7.3

Aboveground Facilities with Concerns for Continued Function for Earthquake Hazards Having Annual Exceedance Probabilities of 0.05% (1 in 2000)

FACILITY	RATING	CONCERNS
Fraser	Low	Severe lateral spread deformations Possible impact of loss of telemetry information
Lattimer	Low	Impact of block wall on aboveground equipment
Pattullo	Low	Transitory ground motions Foundation instability from ongoing settlement
River	Low	Severe lateral spread deformations
Alexander	Moderate	Possible flange leaks at heater
Benson	Moderate	Possible flange leaks at filter and adjacent regulator
Bradshaw	Moderate	Piping configuration at heater may induce leakage
Burrard Thermal	Moderate	Unknown function of unanchored electrical cabinets
Chilliwack	Moderate	Possible flange leaks at heater
Coast Meridian	Moderate	Possible flange leaks at heater and filter
Eagle Mountain	Moderate	Unknown function of unanchored electrical cabinets
Haney	Moderate	Possible flange leaks at heater and regulator
Huntingdon	Moderate	Potential vulnerabilities of control equipment
Johnston	Moderate	Possible flange leaks at heater
King	Moderate	Possible flange leaks at heater
Otter	Moderate	Unanchored building skids may allow building to shift
Richardson	Moderate	Unanchored frame supporting piping may be inadequate
Riverside	Moderate	Possible flange leaks at heater
Tynehead	Moderate	Possible flange leaks at heater

8. RECOMMENDATIONS

Our findings have identified approximately 27 km of pipeline and 19 components of aboveground facilities as likely to have annual probability of failure greater than the 1 in 2000 chance established at the outset of the project. While, we do not believe that our results should be the sole basis for initiating major system modifications, the methodology is believed to reliably present the relative risk among different portions of the BC GAS system.

8.1 General Recommendations

The following general recommendations provide for a multi-tiered approach to improving the seismic reliability of the BC GAS pipeline system. These recommendations fall into three categories:

1. Activities that can be carried out immediately to eliminate seismic vulnerabilities with minor capital expenditure

2. Further investigations to better define the level of risk and potential mitigative measures

3. Long term planning for future system modifications

8.2 Near Term Recommended Activities

Although we feel that major upgrades of the BC GAS pipeline system should not be based solely on this risk assessment report to prioritizing efforts, we do recommend that certain upgrades and investigation be taken in the near term that can provide measurable benefits at low cost.

8.2.1 Upgrade of Aboveground Facility Components

Recommended upgrades for aboveground facilities relate to assuring adequate anchorage of electrical and mechanical equipment. Nearly all of the items identified in the aboveground facility review (see Attachment 4), pertain to unanchored or questionably anchored equipment. While perhaps not essential to maintaining gas supply under emergency conditions, improving equipment performance can reduce post-earthquake repair costs. It is our experience that a considerable amount of damage can be prevented with a relatively low investment.

Equipment upgrades can be carried out as part of a maintenance activity with very little engineering support required. This is especially true for the BC GAS facilities for which there are a great number of similar components. To implement such a maintenance activity, it is necessary to provide facility maintenance personnel with sufficient information to allow them to identify potential deficiencies and alternatives for correcting suspected deficiencies. In our experience, this information is best transmitted in the form of standard equipment anchorage requirements. These requirements typically associate minimal anchorage (e.g., bolt, weld, expansion anchor) with various equipment parameters such as plan dimension, height, and weight. An effective aid in carrying out these minor upgrades is to provide field personnel with simple screening charts and diagrams that graphically relate anchorage requirements to equipment configurations. The absence of detailed engineering input is offset by conservatism in the anchorage requirements.

If such a facility upgrade program is carried out, we believe that all of the aboveground facilities identified as having a "Moderate" chance for maintaining continued service can be placed in the "High" category.

8.2.2 Investigations of BC GAS System Operation

The findings from our assessment of the BC GAS pipeline system have been prioritized in terms of risk for failure. For planning future modifications, it is most important to further prioritize the likely points of failure in terms of the importance for maintaining a minimum level of system function. This requires a systems analysis to assess gas supply to key service areas. From discussions in the working group meeting of July 21, 1993, it is our understanding that BC GAS intends to incorporate the information presented in this report into such an analysis.

8.2.3 Modify Walls at Latimer Station

The block wall barriers at the Latimer Station should be modified such that they are no longer a falling hazard. The modification may consist of strengthening the wall, providing protective covering for fragile components, or removing the block walls.

8.2.4 Detailed Review of the Huntingdon Gate Station

Proper function of the control equipment at the Huntingdon Gate Station is essential for supplying gas to the BC GAS system. A thorough review of the structures, electrical equipment and mechanical equipment should be performed to assure high capacity for earthquake ground shaking forces. The review should include identification of critical relays and other gas control switching components. Electrical power and signal transmission equipment (including conduit and cable trays) are other important facility components that may be required to function immediately after an earthquake.

8.3 Site-Specific Risk Assessment

Once a systems analysis has prioritized portions of the system to be considered for upgrade, it is recommended that a more site specific review be performed at the identified locations. This detailed assessment is recommended for the most critical portions of the system regardless of the seismic risk ranking determined in this study. Possible refinements include use of more representative soil strength parameters, incorporation of site specific information on topography and stratigraphy, and site specific estimates of liquefaction susceptibility. Information necessary to refine the assessment of risk for certain high priority locations can also be used in the development and assessment of proposed upgraded configurations.

8.3.1 Specific Recommendations for Additional Hazard Investigation

The relatively high risk assigned to certain pipeline configurations was significantly influenced by what are believed to be conservative assumptions in the risk assessment. For these locations, additional investigation to determine the site specific hazard is considered worthwhile. Key questions to be answered by the additional investigation are the likelihood of liquefaction and the potential ground deformations relative to the pipeline alignment. These investigations might require site specific soil borings, testing to characterize the strength of site soil deposits, and analytical evaluation of ground deformation and pipeline response.

Five locations (ranged 6 through 10) are recommended for additional site specific evaluation:

1. North Vancouver near the Second Narrows bridge
2. Near the Fort Langley gate station
3. Near the Hammond gate station
4. Near the Metro Gas Center
5. In West Vancouver near the Capilano River

Recommendations for further evaluation are based on a qualitative assessment of potential conservatism in assessing of risk and the potential for identifying alternatives to lower the estimated risk. Two outcomes are anticipated from the site specific evaluations. A lower risk of rupture may be determined resulting in a change in priority of the site in question. A site specific evaluation may also provide the basis for recommended alteration of the pipeline alignment to lower seismic hazards to an acceptable level.

8.3.2 Review Bridge Crossings

The Mission, Pattullo and Second Narrows bridges are used by BC GAS to cross rivers. The performance of these bridges should be assessed to better define the risks to the BC GAS pipelines. This may include independent analyses or simply monitoring the activities of the BC Ministry of Transportation.

8.4 Recommendations for Future Planning of Pipeline System Modifications

8.4.1 High Risk River Crossings

Many of the high risk locations identified in the seismic risk assessment are at river crossings which was not unexpected. Portions of the pipeline system determined to be at greatest risk include the 20-inch and 24-inch transmission pipelines in the vicinity of the crossings f the north and south arms of the Fraser River and the Pattullo site. From our understanding of the BC GAS system, these pipelines are also expected to be critical to maintaining gas service.

Further investigation and analysis to quantify the seismic hazard at these locations could be carried out to better define the relative risks and to assist in planning and scheduling remedial action. Alternatively, the existence of a significant seismic hazard could be accepted and steps put into motion to avoid the hazard, or minimize the potential impact. The following actions could be considered to minimize the effect of the seismic hazard at these locations:

1. Consider mitigation measures, such as ground improvement, to reduce or eliminate the risk at the most critical sites. The Fraser and River gate stations are two such critical sites. Alternatively, relocate Fraser and River gate stations to avoid potentially large lateral spread displacements near the river bank.

2. Accept possible pipeline rupture at Fraser and River gate stations and provide alternate pipeline supply to the Metropolitan Vancouver. This could be accomplished by crossing the Fraser River north of Ferguson gate station. The length of pipeline crossing infirm ground is minimized by following this route. The alternate route will require a combination of new transmission pipelines and additional intermediate pressure pipelines to provide system redundancy. Detailed investigation of the river crossing and the expected response of the pipeline is recommended prior to proceeding with this high-cost activity.

3. Relocate or provide site stabilization of the Pattullo gate station. The structure at Pattullo is believed to be founded on piles while the buried piping is not. This piping is likely to be stressed due to ongoing ground settlement. If site stabilization or relocation is not possible in the near term, it is recommended that the station piping be modified by routing as much piping as possible on the surface with provisions for accommodating future ground settlement.

These activities are major projects and require considerable planning, supported by necessary site specific information The recommendation for providing alternate supply lines to Metropolitan Vancouver entails great expense and needs to be studied with consideration of future gas demand, right-of-way access and capital budget availability.

8.4.2 Emergency Planning

Emergency planning is a key element in the response to seismic hazards that has not been addressed in this risk assessment. Consideration should be given to operational actions that might be taken in the event of disruption in the main gas supply to minimize the impact on area inhabitants. Some actions that may be considered include the following:

1. Shutdown of major industrial customers and largely non-residential areas to preserve some heating capacity

2. Coordination with other governmental and utility agencies to develop an emergency energy response plan for the public in the event of a major earthquake

3. Examine temporary operations measures that could increase gas supply in emergency situations (e.g., boosting pressure in certain intermediate pressure lines that still have gas supply)

8.4.3 Gas Supply to BC GAS

The main gas supply to the Vancouver region is provided by the West Coast Energy pipeline. Efforts should be taken to contact West Coast Energy and determine what provisions they have taken to identify hazards to their pipeline (both seismic and non-seismic) and their plans for responding to the presence of those hazards.

9. REFERENCES

1. Armstrong, J.E. 1976. Surficial Geology, Mission, West of Sixth Meridian, British Columbia, Geological Survey of Canada, Map 1485A, Scale: 1: 50,000, Printed by the Surveys and Mapping Branch of GSC, 1980.

2. Armstrong, J.E. 1977. Surficial Geology, Chilliwack (West Half), West of Sixth Meridian, British Columbia, Geological Survey of Canada, Map 1487A, Scale: 1: 50,000, Printed by the Surveys and Mapping Branch of GSC, 1980.

3. Armstrong, J.E., and Hicock, S.R. 1976a. Surficial Geology, Vancouver, British Columbia, Geological Survey of Canada, Map 1486A, Scale: 1: 50,000, Printed by the Surveys and Mapping Branch of GSC, 1979.

4. Armstrong, J.E., and Hicock, S.R. 1976b. Surficial Geology, New Westminster, West of Sixth Meridian, British Columbia, Geological Survey of Canada, Map 1484A, Scale: 1: 50,000, Printed by the Surveys and Mapping Branch of GSC, 1980.

5 ASCE, 1984, Seismic Design Guidelines for Oil and Gas Pipeline Systems, Gas and Liquid Fuels Lifelines Committee.

6. Audibert, J.M.E. and K.J. Nyman, 1977, "Soil Restraint Against Horizontal Motion of Pipes," Journal of the Geotechnical Division, ASCE, vol. 103, no. GT10.

7. Audibert, J.M.E., Lai, N.W. and Bea R.G., 1978, "Design of Pipelines-Sea Bottom Loads and Restraints," Pipelines in Adverse Environments, New Orleans, Louisiana, ASCE, vol. 1.

8. Bartlett, S.F., and Youd, T.L. 1992. Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spreads, Technical Report NCEER-92-0021, National Center for Earthquake Engineering Research, State University of New York at Buffalo.

9. Bouwkamp, J.G. and R.M. Stephan, 1973, "Large Diameter Pipe Under Combined Loading," ASCE Journal of Transportation Engineering, Vol. 99, No. TE3.

10. Byrne, P.M. 1991. A model for Predicting Liquefaction-Induced Displacement, Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 7.14, pp. 1027-1035.

11. Byrne, P.M., Jitno, H., and Salgado, F. 1992. Earthquake Induced Displacements of Soil-Structures Systems, in Proceedings: Tenth World Conference, Earthquake Engineering, July 19-24, 1992, Madrid, Spain, A.A. Balkema, Rotterdam, Brookfield, 1992, pp. 1407-1411.

12. Earthquake Design in the Fraser Delta (1991), Task Force Report, June 1991.

13. Finn, W.D. Liam, Yogendrakumar, M., Yoshida, N., and Yoshida, H. 1986. TARA-3: A Program to Compute the Response of 2-D Embankments and Soil Structure Interaction Systems to Seismic Loadings, Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

14. Hamada, M., and O'Rourke, T.D. (editors) 1992. Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes: Japanese Case Studies, Technical Report NCEER-92-0001, Vol. 1, National Center for Earthquake Engineering Research, State University of New York at Buffalo.

15. Honegger, D.G., 1990, "MIGHTY OAK Structures Experiments to Investigate Tunnel Liner Design and Conduit Performance at Fault Crossings," National Technical Systems, NTS 1553.

16. Kennedy, R.P., A.W. Chow and R.A. Williamson, 1977, "Fault Movement Effects on Buried Oil Pipeline," <u>Journal of the Transportation Engineering Division</u>, ASCE, vol. 103, no. TE5.

17. Meyersohn, W.D. and T.D. O'Rourke, 1991, "Pipeline Buckling Caused by Compressive Ground Failure During Earthquakes," <u>Proceedings, Third Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction</u>, San Francisco California, Technical Report NCEER-91-0001,

18. National Aeronautics and Space Administration (NASA), 1968, "Buckling of Thin-Walled Circular Cylinders, " NASA Space Vehicle design Criteria (Structures), NASA SP-8007.

19. Newmark, N.M., and W.J. Hall, 1975, "Pipeline Design to Resist Large Fault Displacement," Proceedings, U.S. National Conference on Earthquake Engineering, Ann Arbor, Michigan, EERI.

20. O'Rourke, T.D., and Hamada, M. (editors) 1992. Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes: United States Case Studies, Technical Report NCEER-92-0002, Vol. 2, National Center for Earthquake Engineering Research, State University of New York at Buffalo.

21. Prevost, J.H. 1981. DYNA-FLOW: A Non-linear Transient Finite Element Analysis Program, Report No. 81-SM-1, Department of Civil Engineering, Princeton University, Princeton, N.J.

22. Rowe, R.K. and E.H. Davis, 1982, "The Behavior of Anchor Plates in Clay," Geotechnique, vol. 32, no. 1.

23. Sorenson, J.E., R.E. Mesloh, E. Rybicki, A.T. Hopper, and T.J. Atterbury, 1970, "Buckling Strength of Offshore Pipelines," Summary Report, Volume I, for Offshore Pipeline Group, Battelle Memorial Institute.

24. Southwell, R.V., 1914, Philosophical Transactions, Royal Society, London, Series A. vol. 213.

25. Tokimatsu, K., and Seed, H.B. 1987. Evaluation of Settlements in Sands due to Earthquake Loading, Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 8, pp. 861-878.

26. Trautmann, C.H. and T.D. O'Rourke, 1983, "Behavior of Pipe in Dry Sand Under Lateral and Uplift Loading," Geotechnical Engineering Report 83-6, Cornell University, Ithaca, New York.

27. Vesic, A.S., 1969, "Breakout Resistance of Objects Embedded in Ocean Bottom," Paper presented at the ASCE Ocean Engineering Conference, Miami Beach.

28. Youd, T.L., and Perkins, D.M. 1978. Mapping of Liquefaction-induced Ground Failure Potential, Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT4, pp. 433-446.

Appendix B

Low Pressure Replacement Project Cost - Low Estimate (5 km company install)	2006			2007			2008			2009			Total Activity	Rationale
Line Item	Base Year Unit Cost*	Quantity (units of main, services or meters)	Item Cost for 2006	Unit Cost (Base Year plus x % inflation)	Quantity (units of main, services or meters)	Item Cost for 2007	Unit Cost (Base Year plus y % inflation)	Quantity (units of main, services or meters)	Item Cost for 2008	Unit Cost (Base Year plus z% inflation)	Quantity (units of main, services or	Item Cost for 2009		
Project Management														
Project Management	500	240	140000	500	180	90000	500	90	45000	500	0	0		300 workdays at $500 per day per year. 80% first year, then 60%, then 30%. 20k in YR 1 for regulatory and public communication
Training & Evaluation	500	80	40000	510	40	20400	520.2	40	20808	530.604	0	0		Instructor initially provides training and qualification course and then continuing refresher and evaluation.
Mains														
Company office labour - mains plan	16.2	23600	382320	16.524	35200	581644.8	16.85448	36200	610132.176	17.1915696	0	0	95000	Office planning work as has occurred in the past. Labour inflated 2% per year.
Company field labour - mains and services inspect	160000	1	160000	163200	1	163200	166464	1	166464	169793.28	0	0		DM1 to provide system control. Wage rate inflated 2% per year
Company field labour - mains install	41.85	5000	209250	42.687	5000	213435	43.54074	5000	217703.7	44.4115548	0	0		Company install labour if used. 2% inflation applied.
Contract labour - gas mains install	35.5725	18600	661648.5	37.351125	30200	1128003.975	39.21868125	31200	1223622.855	41.17961531	0	0		Gas contract labour resources, inflation held to 5% per year due to long term contract. Could be as high as 10% per year per BC trades advise. 15% CONTRACTOR ADVANTAGE APPLIED TO BASE RATE.
Contract labour - other	58.05	23600	1369980	60.9525	35200	2145528	64.000125	36200	2316804.525	67.20013125	0	0		Contract labour resources, inflation suggested be 5% per year. Could be as high as 10% per year per BC trades advise
Materials - mains	18.9	23600	446040	19.278	35200	678585.6	19.66356	36200	711820.872	20.0568312	0	0		Materials inflated at 2% per year.
Services & Meter Sets														
Company office labour - services plan	135	1763	238005	137.7	2832	389966.4	140.454	2505	351837.27	143.26308	0	0	7100	Office planning work as has occurred in the past. Labour inflated 2% per year.
Permits	120	176.3	21156	120	283.2	33984	120	250.5	30060	120	0	0		10% of services will require housepiping altered. No inflation applied to permit cost.
Company field labour - meter sets	160000	0.666666667	106666.6667	163200	0.666666667	108800	166464	0.666666667	110976	169793.28	0	0		Senior CS 1 alters housepiping and sets all meter sets; 2/3 of year, wages inflated 2% per year
Company field labour - services relations	80000	1	80000	81600	1	81600	83232	1	83232	84896.64	0	0		IC1 to maintain customer relationship in field
Company field labour - services install	348.75	310	108112.5	355.725	310	110274.75	362.8395	310	112480.245	370.09629	0	0		Company install labour if used. 2% inflation applied. # est'd from 0.062 per/metre of main
Contract labour - gas services install	296.4375	1453	430723.6875	311.259375	2522	784996.1438	326.8223438	2195	717375.0445	343.1634609	0	0		Gas contract labour resources, inflation held to 5% per year due to long term contract. Could be as high as 10% per year per BC trades advise. 15% CONTRACTOR ADVANTAGE APPLIED TO BASE RATE.
Contract labour - other	483.75	1763	852851.25	507.9375	2832	1438479	533.334375	2505	1336002.609	560.0010938	0	0		Contract labour resources, inflation suggested be 5% per year. Could be as high as 10% per year per BC trades advise
Materials - services	157.5	1763	277672.5	160.65	2832	454960.8	163.863	2505	410476.815	167.14026	0	0		Materials inflated at 2% per year.
Materials - Low clearance regulators	83	528.9	43898.7	84.66	849.6	71927.136	86.3532	751.5	64894.4298	88.080264	0	0		30% of services will require low clearance regulators, 2006 incremental of $83. 2% inflation applied to incremental value.

Materials - Electrofusion PTT	21	1453	30513	21.42	2522	54021.24	21.8484	2195	47957.238	22.285368	0	0		Electrofusion to be used by contractor to connect services to mains. 2% inflation applied to incremental value.
Stations														
Company field labour - station removal	6000	5	30000	6120	10	61200	6242.4	9	56181.6	6367.248	0	0	24	Company labour to stop off, remove station and then rehabilitate ground. Inflation of 2% per year.
Surface Rehabilitation - station removal	9000	5	45000	9450	10	94500	9922.5	9	89302.5	10418.625	0	0		Materials used to rehabilitate. Higher than normal inflation due to local construction; 5% per year.
Total Budget														
Calendar Year			**$5,673,838**			**$8,705,507**			**$8,723,132**			**$0**	**$23,102.5**	**X 1000**

Regulatory Alignment									
Mains			$3,229,239			$4,910,397			$5,246,548
Services			$2,017,878			$3,314,298			$3,059,361
Meters			$171,721			$214,711			$205,930
Other Costs			$255,000			$266,100			$211,292
Total			**$5,673,838**			**$8,705,507**			**$8,723,132**
Unit Price for Mains			$136.83			$139.50			$144.93
Unit Price for Services			$1,144.57			$1,170.30			$1,221.30
Unit Price for Meters			$97.40			$75.82			$82.21
Unit Price for "Other Costs"			$0.04706			$0.03153			$0.02482

		Rounded off Figures for CPCN
Mains	$13,386,184	**13386.2**
Services	$8,391,537	**8391.5**
Meters	$592,363	**592.4**
Other	$732,392	**732.4**
Total check	$23,102,477	**23102.5**
Stn lab	147381.6	
Stn land	228802.5	
Total stns	376184.1	**376.2**
Other remainder		**356.2**
		732.4

AFUDC Calculation		6.00%			6.00%			6.00%	
Spending	Spending	AFUDC	Total	Spending	AFUDC	Total	Spending	AFUDC	Total
January	$0	$0	$0	$0	$0	$0	$0	$0	$0
February	$0	$0	$0	$0	$0	$0	$0	$0	$0
March	$14	$2,837	$570,221	$14	$4,353	$874,904	$14	$4,362	$876,675
April	$14	$5,688	$1,143,293	$14	$8,727	$1,754,182	$14	$8,745	$1,757,733
May	$14	$8,553	$1,719,230	$14	$13,124	$2,637,857	$14	$13,150	$2,643,196
June	$14	$11,433	$2,298,047	$14	$17,542	$3,525,950	$14	$17,578	$3,533,087
July	$14	$14,327	$2,879,758	$14	$21,983	$4,418,484	$14	$22,027	$4,427,427
August	$14	$17,236	$3,464,378	$14	$26,445	$5,315,480	$14	$26,499	$5,326,239
September	$14	$20,159	$4,051,921	$14	$30,930	$6,216,961	$14	$30,993	$6,229,545
October	$14	$23,097	$4,642,402	$14	$35,438	$7,122,950	$14	$35,509	$7,137,367
November	$14	$26,049	$5,235,835	$14	$39,968	$8,033,469	$14	$40,048	$8,049,728
December	$12	$29,016	$5,832,233	$11	$44,520	$8,948,537	$16	$44,610	$8,966,653
Total	$138	$158,395	$5,832,233	$137	$243,030	$8,948,537	$142	$243,521	$8,966,653
Cummulative	$138	$158,395	$5,832,233	$275	$401,425	$14,780,770	$417	$644,946	$23,747,423

AFUDC Calculation Assumptions:

Each year's spending is capitalized at the end of the year

Spending occurs from February to December each year and the costs are spread evenly over the 10 months.

Appendix B2
Vancouver LP Replacement CPCN
Project Costs by Phases

Phase 1			**Capital Expenditure**		Asset	CapEx
1.0 Dunbar		**2006**	**2007**	**2008**	Retirement	Total
	Mains	$3,229,235	$613,800	$0		
	Services	$2,017,877	$1,284,989	$0		
		$5,247,112	$1,898,789	$0		
	Meters Sets	$171,716	$83,250	$0		
		$171,716	$83,250	$0		
	Other Costs	$255,010	$62,494	$0		
		$255,010	$62,494	$0		
1.0 Dunbar Total		**$ 5,673,838**	**$ 2,044,533**	**$ -**		**$7,718,372**
	Retirement Value	$ (300)	$ (200)	$ -	**$ (500)**	

Phase 2			**Capital Expenditure**		Asset	CapEx
2.0 Kerrisdale		**2006**	**2007**	**2008**	Retirement	Total
	Mains	$0	$4,045,500	$0		
	Services	$0	$1,888,864	$0		
		$0	$5,934,364	$0		
	Meters Sets	$0	$122,373	$0		
		$0	$122,373	$0		
	Other Costs	$0	$190,969	$0		
		$0	$190,969	$0		
2.0 Kerrisdale Total		**$ -**	**$ 6,247,707**	**$ -**		**$6,247,707**
	Retirement Value	$ (100)	$ (300)	$ -	**$ (400)**	

Phase 3			**Capital Expenditure**		Asset	CapEx
3.0 Marpole		**2006**	**2007**	**2008**	Retirement	Total
	Mains	$0	$251,100	$2,927,626		
	Services	$0	$140,436	$1,630,436		
		$0	$391,536	$4,558,062		
	Meters Sets	$0	$9,098	$109,750		
		$0	$9,098	$109,750		
	Other Costs	$0	$12,632	$115,864		
		$0	$12,632	$115,864		
3.0 Marpole Total		**$ -**	**$ 413,266**	**$ 4,783,677**		**$5,196,943**
	Retirement Value	$ -	$ (500)	$ -	**$ (500)**	

Phase 4			**Capital Expenditure**		Asset	CapEx
4.0 UBC		**2006**	**2007**	**2008**	Retirement	Total
	Mains	$0	$0	$869,592		
	Services	$0	$0	$1,025,892		
		$0	$0	$1,895,484		
	Meters Sets	$0	$0	$69,056		
		$0	$0	$69,056		
	Other Costs	$0	$0	$48,764		
		$0	$0	$48,764		
4.0 UBC Total		**$ -**	**$ -**	**$ 2,013,304**		**$2,013,304**

	Retirement Value	$ -	$ (300)	$ (300)	$ **(600)**

Phase 5		**Capital Expenditure**			Asset	CapEx
5.0 Riley Park		**2006**	**2007**	**2008**	Retirement	Total
	Mains	$0	$0	$1,449,320		
	Services	$0	$0	$403,029		
		$0	$0	$1,852,349		
	Meters Sets	$0	$0	$27,129		
		$0	$0	$27,129		
	Other Costs	$0	$0	$46,652		
		$0	$0	$46,652		
5.0 Riley Park Total		**$ -**	**$ -**	**$ 1,926,131**		**$1,926,131**
	Retirement Value	$ (50)	$ (300)	$ (400)	$ **(750)**	

Total CapEx All Phases		**Capital Expenditure**				
LP Replacement Project		**2006**	**2007**	**2008**		
	Mains & Services	**$ 5,673,838**	**$ 8,705,506**	**$ 8,723,112**		**$23,102,456**
	Asset Retirement	**$ (450)**	**$ (1,600)**	**$ (700)**	**$ (2,750)**	

Total Operating Savings	**Operating Savings**		
LP Replacement Project	**2006**	**2007**	**2008**
	25%	**50%**	**75%**
Service Delivery Improvements	**$ 135,000**	**$ 135,000**	**$ 135,000**
Reduced Station Operating Costs	**$ 62,600**	**$ 62,600**	**$ 62,600**
	$ 49,400	**$ 98,800**	**$ 148,200**

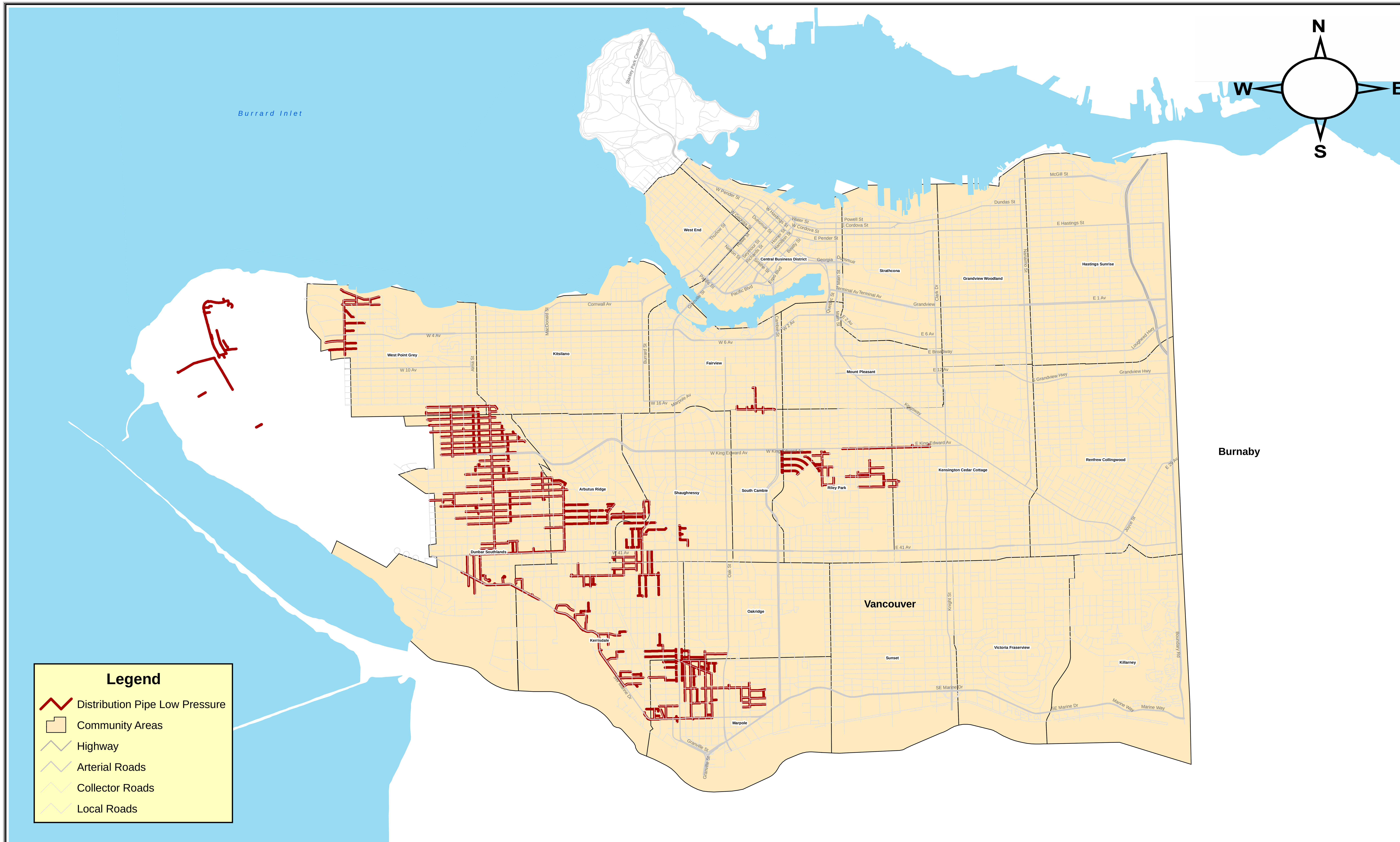
Notes:

1) Please note that a minor variance of $20 is acknowledged between this model and the Final Project Estimate.
This variance is due to rounding.

Appendix C

Low Pressure System - Vancouver

Terasen



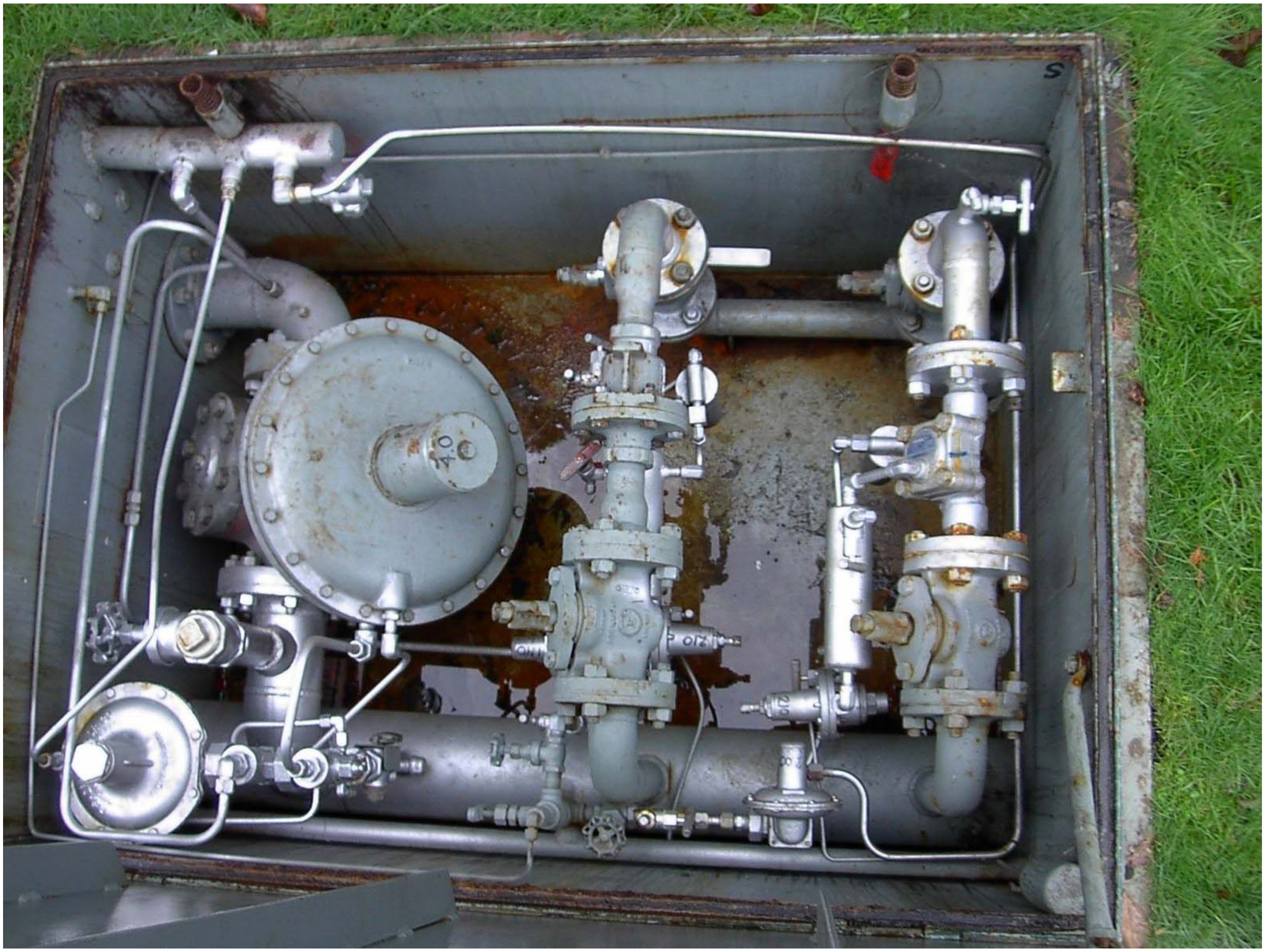
Date: 2006/04/06

X:\Projects\Update_Cathodic_Protection_Status

Appendix D

Appendix E

Typical Congested LP Station



Typical Easy Access DP Station