ASSESSING VULNERABILITY OF BC GAS PIPELINES TO LATERAL SPREAD HAZARDS

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ABSTRACT

A systematic review of seismic risks was performed for the BC GAS Lower Mainland natural gas transmission system using a probabilistic approach to define potential earthquake hazards and pipeline response. Potentially liquefiable deposits were identified and mapped into a Geographical Information System (GIS) Lateral spread displacements were made based on the methodology of Bartlett and Youd. There are two very unique features of the BC GAS study First, finite element analyses were used to define pipeline vulnerability Second, published data on lateral spread displacements were used to estimate the likelihood of lateral spreading at specific pipeline locations This study highlights research needs to define lateral spread hazard and is believed to be a model for future seismic risk studies of pipeline systems

INTRODUCTION

A systematic review of seismic risks was completed for the BC Gas Lower Mainland natural gas distribution system. 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 scope of the pipeline review included transmission and large diameter (greater than NPS 8) intermediate pressure pipelines. All of these pipelines are considered modern steel (post-1950 construction) and are fabricated with full penetration butt-welded joints 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 annual exceedance probability for disruption in the natural gas supply of 0 05% was assigned as an acceptable level of risk

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. They also suffer from an inability represent variation in pipeline performance with diameter, wall thickness or material yield strength. As a result, 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. A further inadequacy in past studies is their inability to identify specific locations of pipeline damage Because of these limitations, past evaluations of earthquake performance of buried pipelines only have merit when one is interested in knowing general information such as the total number of repairs They are totally inadequate for studies of system performance

Recognizing that past methodologies were incapable of providing the information desired by BC Gas, pipeline vulnerability was based on numerous detailed analysis 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

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.

SEISMICITY OF STUDY REGION

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 Three basic sources of earthquakes affect 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 To avoid overly conservative estimates of failure probabilty, median estimates of seismic hazard were used This was a departure from the standard practice in the NBCC which uses ground motions estimated at one standard deviation above the mean.

Probabilistic ground motions 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. Estimates of potential lateral spread deformations were obtained using a method based upon the correlation of data from past earthquakes (Bartlett and Youd, 1992) Input required for estimating potential lateral spread displacements on a regional basis included earthquake magnitude, epicentral distance and general soil properties.

Lateral spread movement associated with liquefaction is the principal seismic hazard to the pipelines. Wave propagation and local subsidence was eliminated early in the program as significant seismic hazards because of their inability 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

APPROACH TO EVALUATION OF PIPELINE RISK

The approach used to assess the BC Gas pipeline system incorporated 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 is described below.

1. Identify portions of the pipeline alignment for which the slopes of the terrain are greater than 0 5%

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

3 Assign 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 (annual exceedance probability of 0.002, 0 001, or 0 0005), determine the mean lateral spread displacement.

5 Compute the probability that spread displacement or spread length will exceed the failure criteria determined in Step 3.

6 Adjust the probability computed in Step 5 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 4 through 6 for the remaining levels of seismic hazard

8 Estimate the cumulative probability of failure by adding the products of the failure probabilities at various levels of earthquake hazard and the level of earthquake hazard

9 Prioritize the locations identified in Step 2 according to the failure probability computed in Step 8

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.

CHARACTERIZATION OF LATERAL SPREAD DEFORMATIONS

A key challenge to the BC Gas study was the definition of lateral spread movements in a fashion suitable for use with the analytical pipeline vulnerabilities The author knows of no 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

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 Hamada and O'Rourke (1992)

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 duration of strong shaking that bound those considered applicable for the source mechanisms used to generate ground shaking hazard estimates for the BC Gas study 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 Hamada and O'Rourke (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 Hamada and O'Rourke (1992) was susceptible to lateral spread movement
3. Large changes in displacement vector direction were indications of lateral spread boundaries

The scope of the BC Gas study did not permit a thorough assessment of the potential impact of these assumptions The author is hopeful that this paper will spur other investigators to critically examine practical representation of lateral spread hazards necessary for regional risk evaluations

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 Hamada and O'Rourke (1992), it was used to temper judgments on the location of lateral spread boundaries. No attempt was made to characterize patterns in the Hamada and O'Rourke (1992) maps. The pattern of movement within the lateral spread is nearly always a minor issue. This is based on past analytical experience with site specific evaluations of pipeline response to imposed ground deformations.

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.

Measurement of Lateral Spread Dimensions

To test the potential uses of previously mapped displacement data, measurements were first collected from mapped displacements along the Shinano River between the Bandai Bridge and Sekiya-Cho. An example of the determination of lateral spread dimensions from the Hamada and O'Rourke (1992) report is provided in Figure 1 The results were plotted in histogram format as shown in Figure 2 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. A total of 156 lateral spread zones were identified. When the measurements from these additional data sources were examined, their distribution(Figure 3) 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.

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 4. 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

Estimates of Lateral Spread Coverage

Even in areas experiencing severe lateral spread damage, there is a considerable area in which lateral spread movements are 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)

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. An upperbound estimate of lateral spread area was related to measured longitudinal and transverse spread dimensions using assuming a rectangular spread shape

$$A_{LS} = L_T * L_L \tag{1}$$

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 the BC Gas study, a 50% reduction to 17% was assumed

PIPELINE VULNERABILITY

The finite element computer code ANSYS (a product of Swanson Analysis Systems, Inc) was used to perform analyses for the BC Gas pipeline risk assessment. The analysis approach is discussed in detail in numerous references including ASCE (1984) and Honegger (1991, 1992). Pipeline configurations for which vulnerability relationships were computed are illustrated in Figure 5

The analyses produced a wealth of information regarding pipeline response to ground deformations. A typical plot of strain variation for a 24-inch ell configuration is shown in Figure 6 In all cases, significant pipeline strains are limited to within 50 feet of the application of relative ground deformation, an elbow or a tee Interpretation of the analysis results was greatly simplified by examining only the point of greatest pipeline strain. A consequence of this approach was that supplemental information that might have led to better extrapolation of vulnerabilities to non-analyzed conditions was not reviewed in detail. This was not felt to be a detriment to the risk assessment since extrapolation was only necessary for 5 of 26 configurations. Four of these cases only involved extrapolation to account for a different soil type

Soil Resistance Representations in the Analyses

In a regional assessment, such as the one performed for the BC Gas system, there is considerable uncertainty with respect to assigning soil properties. The range of soil loading relationships for the general soil classifications identified for the BC Gas system are illustrated in Figures 5 and 6. These relationships were estimated using the approaches outlined in ASCE (1984) with the following general assumptions:

1 The coefficient of earth pressure at rest was equal to 0 7 for all cases

2 3 feet of soil cover exists in all cases

3 Soil density was assumed to be representative of unsaturated soil

4 All pipelines are buried with relatively dense sand backfill

Assumptions 1, 3, and 4 were believed to be conservative. Assumption 2 was only expected to be violated at river crossings where much deeper cover exists. However, other conditions assumed for the river crossings result in an overestimate of soil strength and were believed to compensate for any unconservatism regarding the depth of soil cover

For the analyses, soil resistance relationships were simplified by the use of only three relationships. For axial restraint, only dense sand backfill was assumed For lateral restraint, two soil restraint relationships were assumed. These were labeled Soil Type I and Soil Type II Soil Type I was assumed to be representative of the more competent materials in the region. Soil Type II was assumed to be representative of the poorer soil deposits consisting of weak clayey silts and peat deposits

Criteria for 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.

For the BC Gas study, we were interested in realistic estimates for relating analytical strains to pipeline rupture. A review of numerous studies and experimental investigations revealed very little useful information on pipeline rupture criteria (ASCE, 1984, Bouwkamp and Stephan, 1973, Meyersohn and O'Rourke, 1991, Meyersohn, 1991, NASA, 1968, Sorenson et al, 1970;) For the BC Gas study, a very simple criterion was used based upon recommendations in ASCE (1984) that compressive strains be kept below about 1/4 to 1/3 the value given by Southwell (1914)

$$\varepsilon_c < 0.6\, t/R \tag{2}$$

where:

ε_c = theoretical compressive strain for onset of wrinkling
t = pipe wall thickness
R = pipe radius

Equation 2 was used to represent the median value of longitudinal compressive strain associated with pipeline rupture Strains corresponding to 10% and 90% likelihood of rupture were assumed to be equal to 1/3 and 2 times the value given by equation 2, respectively.

Analyses were not performed for the case of a straight run of pipeline subjected to relative ground deformation in a direction parallel to the pipeline Instead, estimates of pipeline capacity were made by computing the length of lateral spread movement necessary to produce various stress levels in the pipeline Stress levels of σ_y, $1.5\sigma_y$, and $2\sigma_y$ were assumed to correspond to 10%, median and 90% chances of pipeline rupture, respectively A similar approach was taken for analyses in which longitudinal soil loading on the pipeline was modeled as a force acting on an ell or tee The force associated with pipeline rupture was converted to an equivalent length of pipeline subjected to longitudinal soil movement using the appropriate axial soil resistance relationship

CONCLUSIONS

The approaches outlined above were successfully employed in the evaluation of the BC Gas transmission pipeline system We were able to rank specific segments of the pipeline system and identify the basis for specific vulnerabilities. Results from the study are being used to prioritize allocation of resources for seismic improvement measures and to augment system planning.

The rupture criteria used in the BC Gas study resulted in the determination that nearly all pipelines could withstand at least 4 meters of lateral movement in a straight configuration This conclusion was partially tested following the study when a non-seismic ground failure in the vicinity of one pipeline produced approximately 3 5 meters of lateral ground movement over approximately 30 meters of pipe length. No leakage occurred in the pipe.

Because of the lack of existing methodologies to provide sufficient practical information, several unique approaches were developed during the project The most important technical by-product of the BC Gas study was the utilization of mapped ground deformation information to quantify lateral spread hazard in a manner that is practical for use in a risk assessment. It is estimated that most other investigations of lateral spread risk for regions without previous evidence of lateral spread movement may overestimate the likelihood of occurrence by a factor of 3 to 6.

Development of the methodology used in the BC Gas study was driven by the need to provide needed information to a client There is clearly a need for more investigation to understand the impact of assumptions used in the study and improve upon the simplified approaches taken. It is hoped that more research resources will be directed to the refinement of the methodology described in this paper

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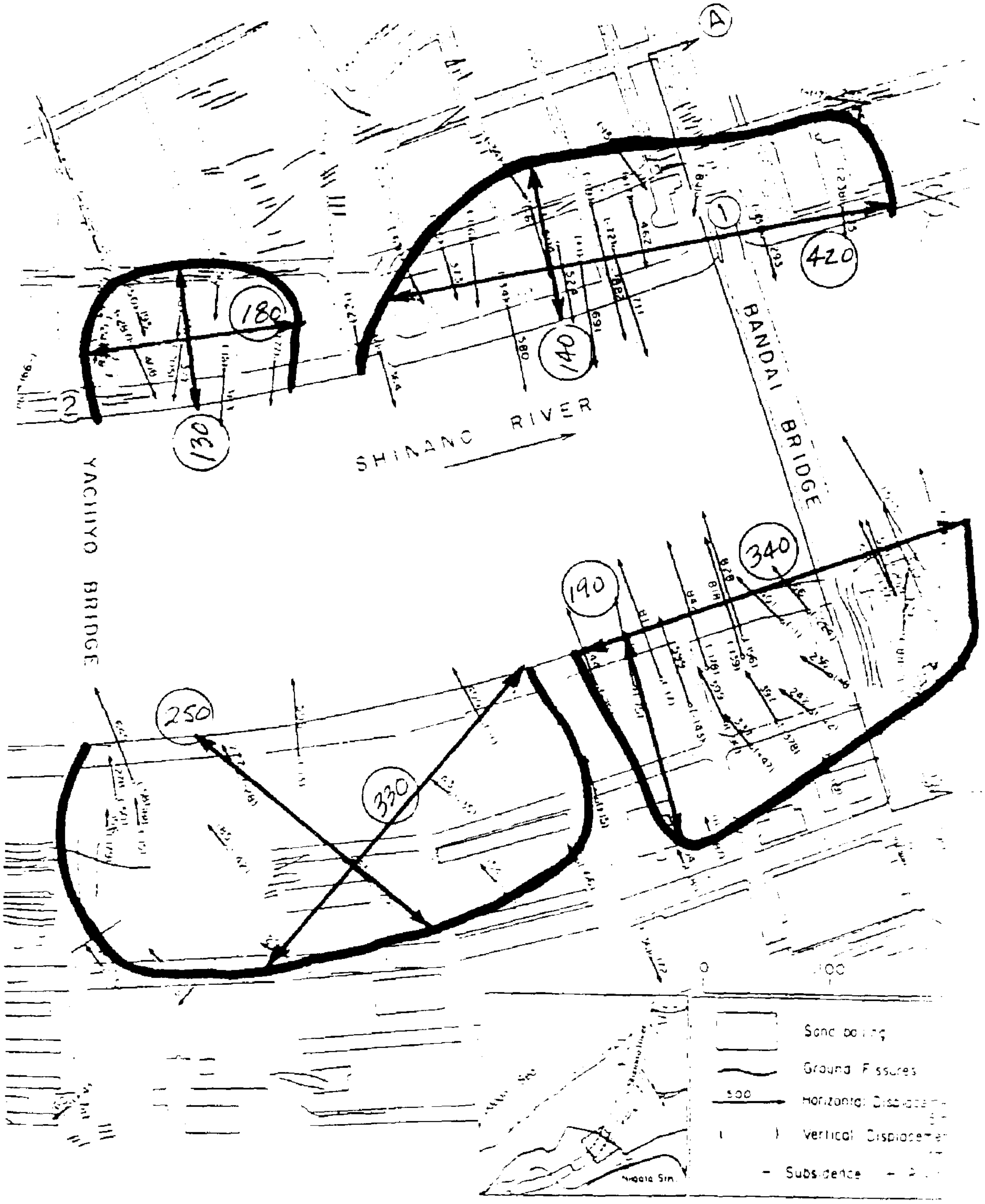

Figure 1: Example Extraction fo Lateral Spread Information

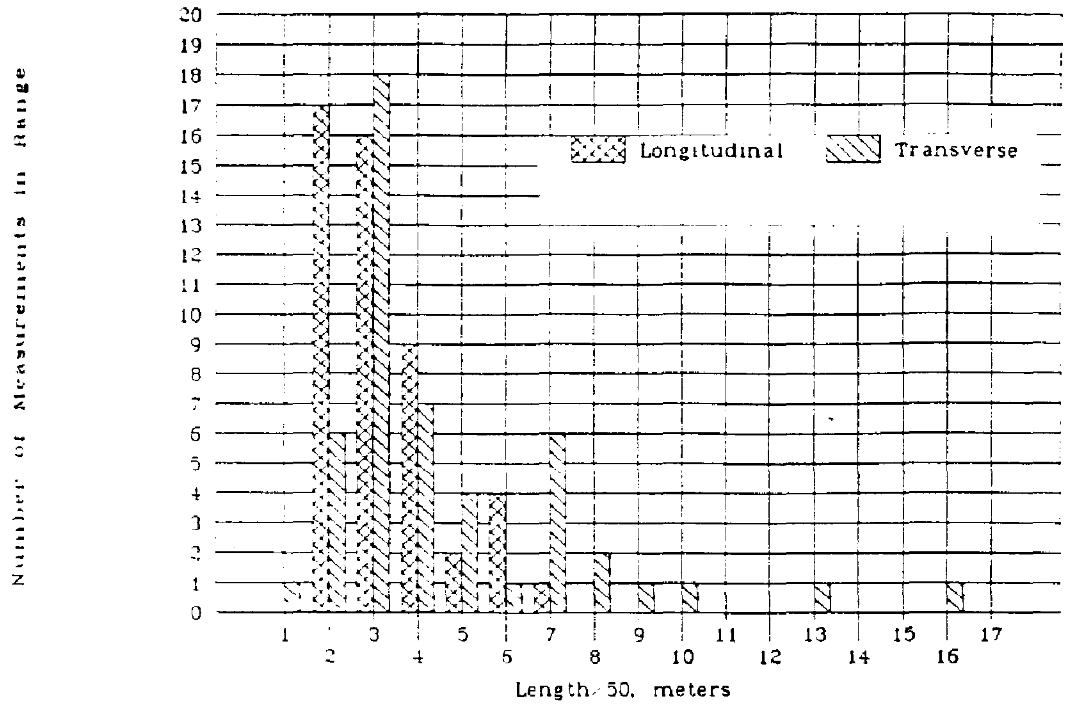

Figure 2: Distribution of Lateral and Transverse Dimensions for 50 Lateral Spread Zones

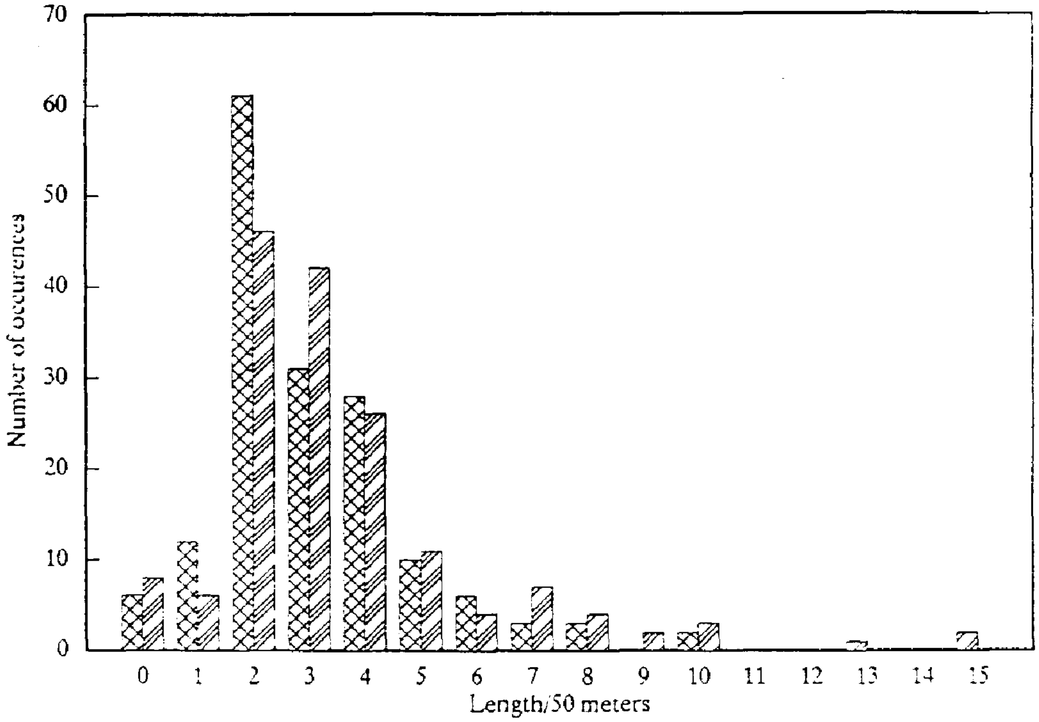

Figure 3: Distribution of Lateral and Transverse Dimensions for 150 Lateral Spread Zones

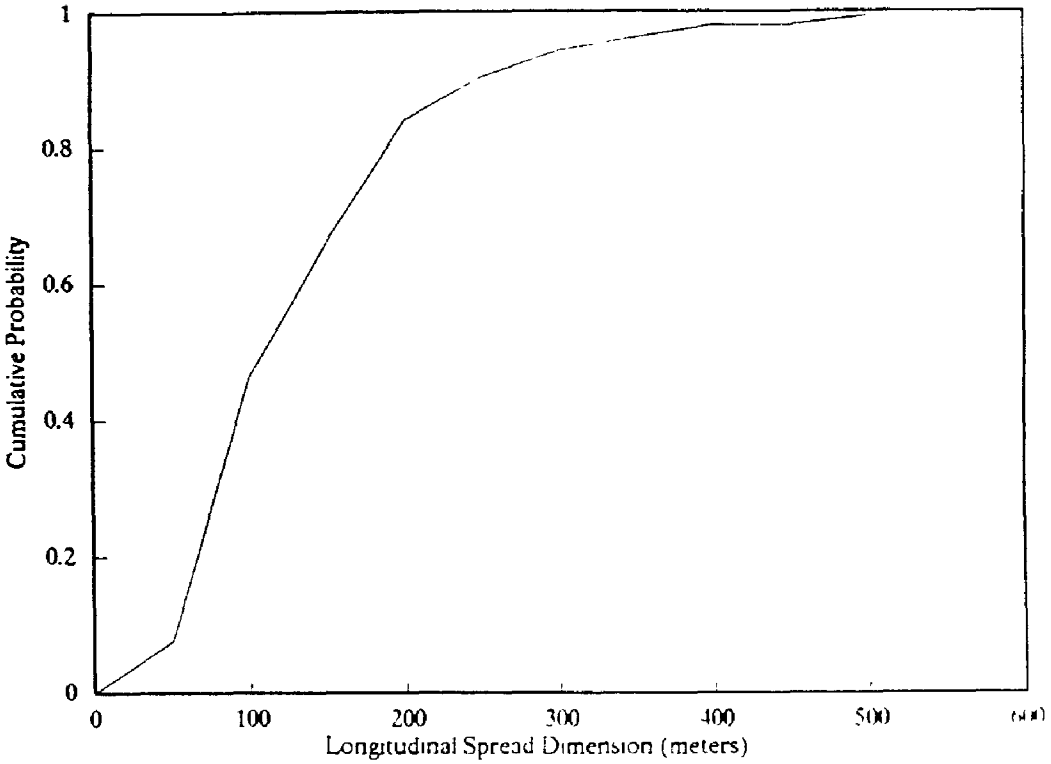

Figure 4: Probabilistic Density Function for Lateral Spread Longitudinal Dimension

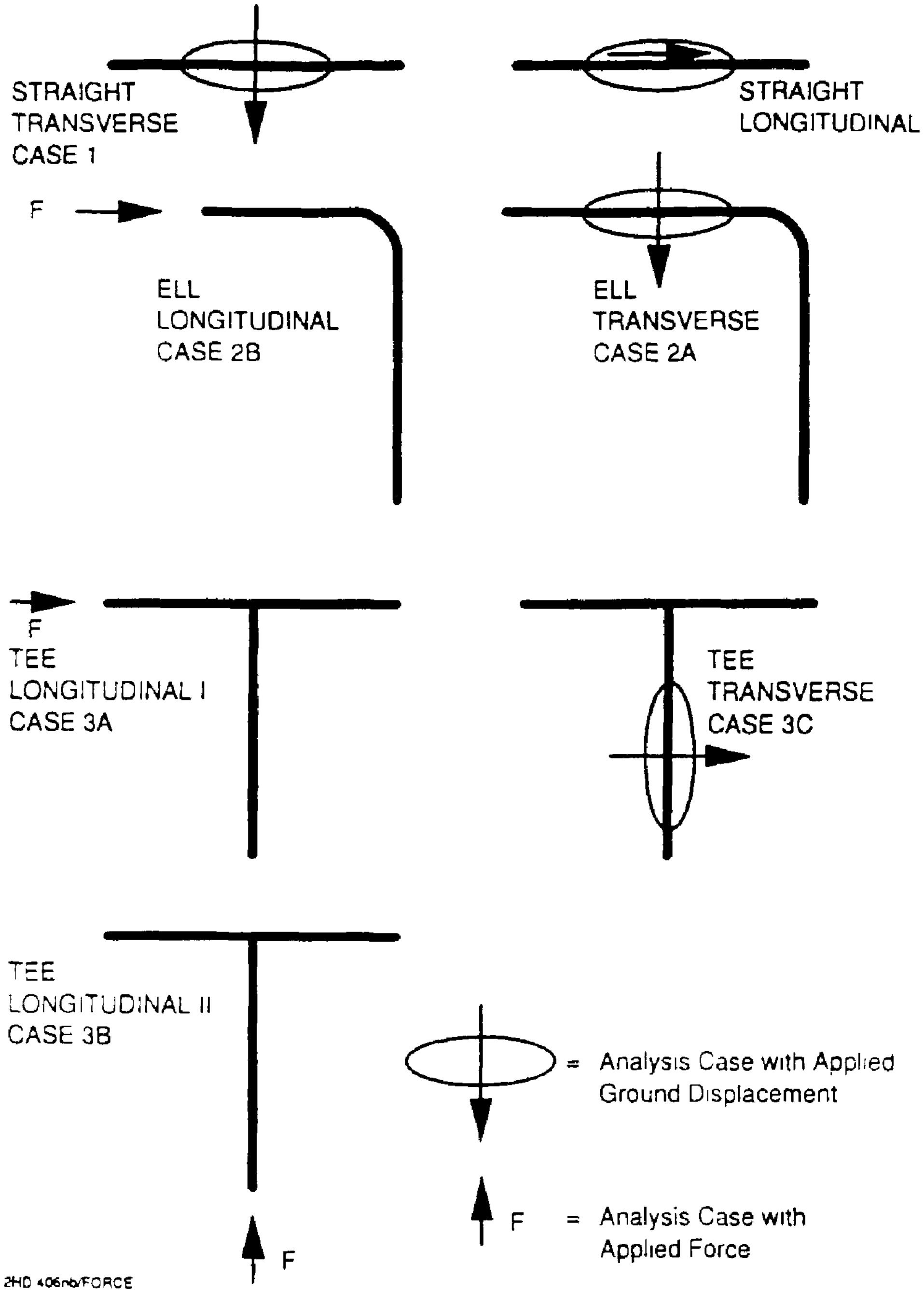

Figure 5: Pipeline Configurations Analyzed for BC Gas Study

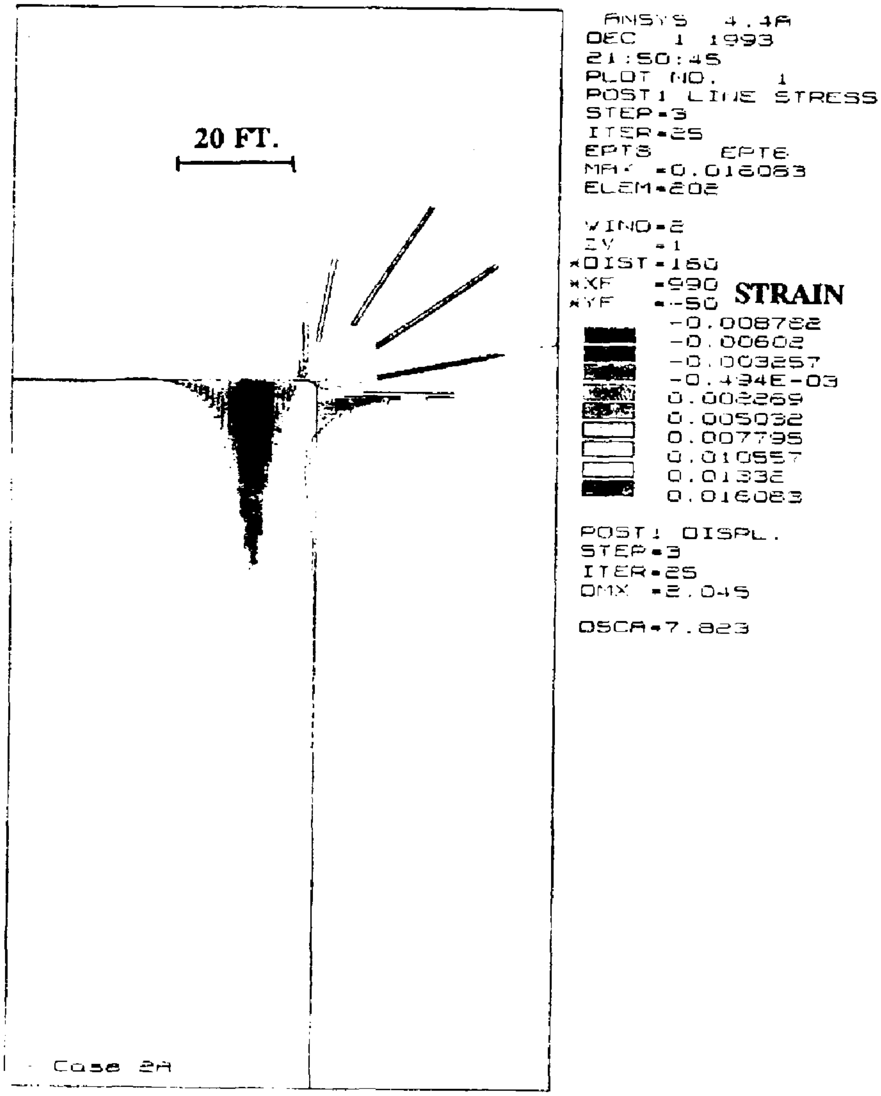

Figure 6: Example of Analysis Output for 24-inch Diameter Ell Configuration