PIPELINE FAULT-CROSSING DESIGN STRATEGY

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SUMMARY

This paper presents the elements in a pipeline fault-crossing design strategy for the case where the likelihood of large fault offsets at the pipeline crossing during the design life is low. Where acceptable risk of pipeline rupture has not been defined, it is recommended that the design decision be fundamentally based upon an economic analysis, to achieve minimum total cost during the design life, as well as other considerations. An outline of the strategy is given.

INTRODUCTION

Although an active fault crossing is the greatest seismic hazard for oil and natural gas transmission pipelines, they have been specifically designed for this hazard only in recent years (Refs. 1, 2 and 3). A decision to use special fault-crossing designs for pipelines should consider fault activity, length of fault-crossing zone, rupture consequences, environmental impacts, exposure to other hazards and cost.

Two approaches to the design of a pipeline crossing an active fault or active fault zone can be considered for the situation where the probability of large fault displacements during the design life is low. The first approach, often voiced by regulatory requirements, is deterministic and requires a design to resist pipeline failure resulting in rupture caused by fault displacements expected to occur during the design life. For example, the federal stipulations governing the Trans Alaska Pipeline system (Ref. 4) state that where the pipeline crosses an active fault zone, the pipeline shall as a minimum be designed to resist failure resulting in leakage from two feet of horizontal and/or vertical fault displacement. The second method, and the one coming more into use, is probabilistic. It requires accepting a low risk of pipeline rupture and the associated consequences, and taking steps to minimize them.

Strategy Choice

In situations where the probability of fault movement is comparable to the level selected for design for other hazards such as ground shaking, or where in populated areas even a low level of risk cannot be accepted, the deterministic method is appropriate. On the other hand, when the probability of fault movement during the design life is very small, for example, an order of magnitude less than the ground shaking hazard and in remote areas where the consequences of fault-induced rupture are not great, the probabilistic approach appears to be preferable.

When the probability of fault movement is between these two bounds, the

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fault-crossing design decision should be fundamentally based upon a cost analysis as well as consideration of the consequences of pipeline rupture and associated impacts particular to specific fault-crossing designs.

In many cases the probabilistic approach is applicable and preferable. It requires a probabilistic assessment of the several fault parameters, the most important of which is the probability of occurrence of fault movements of various amounts of displacement at the pipeline crossing during the design life.

Ideally, given such a fault-hazard assessment, the total probability of occurrence of all amounts of fault movement at the pipeline can be compared with the acceptable risks previously established for the project for other natural and man-made hazards. On this basis it may be possible to show that the fault-displacement risk is acceptable and needs no further consideration in design. In this situation, however, measures need to be taken to minimize the consequences of rupture including the following: 1) Development of an emergency response plan, 2) Stockpiling of repair materials, 3) Use of heavy wall, high-toughness pipe at the fault crossing to reduce the possibility of pipe rupture and minimize its effects should it occur, and 4) Placement of mainline block valves on either side of the fault-crossing zone with automatic, remote shutoff capabilities.

If it is shown that the fault displacement risk in unacceptable, or if no definition of acceptable risk has been established, additional evaluation to properly select a design mode for the fault crossing is warranted. The following sections address the essential elements of such an evaluation as might be applied to an oil or gas transmission pipeline.

FAULT-CROSSING DESIGNS

For a given fault offset, the probability of rupture for buried pipe depends upon the burial depth, fault-crossing geometry, type and strength of surrounding soil and pipe material properties. In most soils (other than rock or well-bonded frozen soils in arctic areas) conventional pipe burial and favorable fault-crossing geometry can be shown to accommodate fault offsets of several feet without rupture (Ref. 3). At increased burial depths and in rock cuts conventional pipe burial has reduced capacity to withstand fault offset and, in extreme conditions, has essentially no such capacity. In these cases, special fault-crossing design modes may be considered such as (Ref. 5):

- Placement of pipe in an aboveground embankment constructed of low-strength soil

- Placement of pipe in an oversized ditch surrounded by low-strength, crushable material or selected backfill with enhanced slip planes

- Burial of pipe within a sacrificial culvert or oversize conduit

- Placement of pipe on aboveground sliding supports.

It should be noted that the cost of constructing sacrificial culverts or conduits can be quite high since they are sized internally to accommodate the pipe with sufficient free rattle space to allow for fault displacement. In fact, any special fault-crossing mode is generally more costly than conventional burial, although special design modes will reduce the probability of pipeline rupture given a fault offset. Further, the environmental consequences may be more severe for the aboveground modes than is the risk of rupture for a buried mode, even with no consideration given to fault design capability. These issues are discussed in later sections.

In order to select a design mode for a fault crossing, it is first necessary to estimate the conditional probability of pipeline rupture for various amounts of fault movement for all fault-crossing modes considered appropriate. Because analytical or test data do not currently exist to accurately define such probability estimates for all conditions, the values may be determined qualitatively by judiciously assessing how well each fault-crossing mode would perform relative to a conventionally buried pipeline. To account for uncertainties in this assessment, both best-estimate and upper-bound conditional rupture probabilities should be determined for later use in a sensitivity evaluation.

The product of the fault displacement probability and the conditional rupture probability is equal to the probability of pipeline failure during the design life for each fault-crossing mode considered, including conventional burial. If the pipeline crosses more than one active fault or fault zone, the total probability for more than one occurrence of pipeline rupture from all fault movements during the design life should be evaluated and factored into the evaluations. The pipeline failure probability as computed above for each fault-crossing mode is used in the cost analysis described next.

COST ANALYSIS

The cost of each fault-crossing design alternative, including conventional burial, is determined and should include the total cost of construction and those costs associated with the occurrence of a fault-induced pipe rupture during the design life. For the comparative cost analysis, each special fault-crossing design is evaluated on the basis of total added cost (above a no-mitigation design case) equal to the cost of construction of the mitigative design plus the present value of future fault-induced probabilistic losses arising from pipeline repair, revenue loss and gas loss minus the corresponding costs for a no-mitigation design. The analysis should include growth, inflation and discount rates. Losses may be assumed to be equally likely to occur in any year of the design life. Repair costs include field mobilization and demobilization of crews, equipment and materials; excavation or removal of ruptured pipe; replacement, welding, inspection, purging and equalizing pressure of the pipe; removal and replacement of culvert or conduit, embankment or aboveground structure, if necessary; backfilling; and restoration.

The present value of each of the probable losses (PVL) due to fault movement may be determined using an approach suggested by Oppenheim (Ref. 6), modified to account for growth rate, as follows:

$$PVL = AEL\ (P) \sum_{i=1}^{t} (1 + GR)^{i}\ (1 + MARR)^{-i}$$

where: AEL = annual expected loss = loss/design life in years,
i = index over each year of pipeline life,
GR = annual growth rate associated with a loss,
MARR = discount rate or expected rate of return,
t = pipeline design life in years, and
P = probability of pipe rupture in t years.

A cost comparison is then made between construction cost plus the PVL of each loss, evaluated for conventional burial and each special fault-crossing design mode under consideration. Assuming the conventional burial and all of the mitigative designs evaluated are otherwise acceptable, the lowest total cost design is preferable.

Cost Sensitivity

Before drawing hard conclusions from such analyses, studies should be conducted to assess the sensitivity of the results for realistic ranges of the important input variables such as probability of occurrence of the loss; initial construction costs; and general growth, inflation and discount rates. Factors affecting the probability of occurrence of the loss include the following:

- Probability of occurrence of the fault movement
- Uncertainty of best-estimate conditional rupture probabilities
- Burial depth
- Percentage of the pipeline alignment surrounded by high-strength material such as well-bonded frozen soil in arctic areas or bedrock
- Spacing of fault-crossing isolation valves.

The results of the cost analysis previously outlined will tend to show that conventional pipe burial for fault crossing is preferable when: 1) The length of a fault-crossing zone is great (on the order of several miles), which dramatically increases the construction cost differentials between conventional burial and special fault-crossing designs, and 2) The probabilities of pipe rupture are sufficiently small, which reduces the influence of the probable losses. The length of the fault crossing can be great where the definition of the fault location is uncertain. In this case, construction costs tend to dominate over PVL costs. For well-defined, very short fault-crossing zones, the length of fault crossing becomes much less critical to the outcome of the cost analysis.

CONSEQUENCES OF FAULT-CROSSING DESIGNS

In addition to the cost analysis, the selection of a fault-crossing design mode should consider the other consequences of constructing the alternative modes. This evaluation might be considered in three categories: 1) Public safety effects, 2) Environmental effects, and 3) Susceptibility to other hazards.

A qualitative approach can be used to make the comparison between the various fault-crossing modes in each of these categories. This can be done by first evaluating the consequences associated with each design mode and then ranking the various design modes relative to each other with respect to each consequence. Factors to consider in this evaluation are discussed in the following paragraphs.

Safety Consequences

The major effect on the health and safety of the public due to rupture of an oil or gas pipeline is the release of contents within a localized area. However, the same amount of product will be released for any of the fault-crossing modes. Hence, all modes are considered to have an equal impact from a health standpoint due to pipe rupture.

The rupture of a gas pipeline requires the consideration of safety aspects. Both pipe whip, caused by a sudden release of pressure, and the possibility of fire need to be considered for the various fault-crossing modes. The degree of overburden or aboveground structure restraint and potential for flying debris should be assessed for each of the fault-crossing modes with their varying degree of restraint capability including modes which use sacrificial culverts or conduits. These evaluations should also recognize the remoteness of the pipeline alignment and the potential numbers of the public which may be exposed to the hazards should a pipe rupture occur.

Environmental Consequences

The environment may be affected by the various modes of fault-crossing by their influence on drainage patterns, visual impact, requirements for mineral materials and the need for greater restoration. The various fault-crossing modes will require differing quality and amounts of mineral materials, both for embankment and backfill and for concrete aggregates. Additional drainage culverts may be required for embankment modes in order to maintain drainage patterns and allow for fish passage. The extra width of backfill area should also be considered as it affects surface drainage.

The rupture of an oil pipeline presents additional considerations, especially in environmentally sensitive areas. Impacts on fish, wildlife and plant life should be assessed for each of the fault-crossing modes with their varying ability to mitigate the release of or otherwise confine the spread of oil.

Other Hazards

Depending on the fault-crossing mode adopted, the pipeline will be subjected to other natural or man-made hazards. These include:

- Vehicle impact, including accidental collisions by construction equipment, automobiles and aircraft

- Vandalism and sabotage

- Foundation failures, including, for example, stability problems caused by liquefaction and slope instability.

All buried modes are preferable with respect to both vehicular collision, vandalism and sabotage. The location of the pipeline has low visibility and the pipe itself is inaccessible to vehicles. An aboveground embankment mode has greater visibility and may be more susceptible to vandalism or sabotage. It may also be possible for heavy construction equipment to damage the pipeline. The pipe placed on aboveground supports is highly visible, which will increase its exposure to vandalism, sabotage and vehicle impact.

Liquefaction and slope stability problems, if any, will most probably be induced by a seismic event and will tend to have an equally detrimental effect on any fault-crossing mode. Furthermore, slope stability and liquefaction problems induced by seismic events could have more effect on the pipeline behavior than a fault movement.

MITIGATION MEASURES

If the results of the cost and consequence analyses described in the foregoing favor crossing the fault or fault zone with conventional pipe burial, measures should be taken to mitigate potential damages and losses. These might include:

- Use of heavy wall, high-toughness pipe

- Installation of fault zone isolation valves

- Automatic line break controls

- Minimum burial depth in the fault zone

- Offsetting the pipeline alignment from nearby structures and public-use areas in the fault zone

- Emergency repair plan

- Seismic monitoring system

Some, if not all, of these measures might well be considered for modes other than conventional pipe burial.

CONCLUSIONS

Special fault-crossing designs can greatly minimize, but not completely eliminate the possibility of fault-induced pipe rupture or damage during the design life because of possible uncertainties in fault zone definition, fault movement parameters and the reliability of the designs themselves. Accordingly, in remote areas where the likelihood of large fault movements at a pipeline crossing during the design life is low, the final decision to construct special fault crossings or the selection of a specific fault-crossing mode should be fundamentally based upon the results of the economic analysis described with lesser consideration given to the results of the consequence analysis. In cases where the economic analysis yields no clearcut benefit between candidate fault-crossing modes, the decision should be based upon the consequence analysis.

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