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ABOVEGROUND SEISMIC RETROFIT SCHEMES OF WATER PIPELINES CROSSING THE HAYWARD FAULT

Luke CHENG[1]

SUMMARY

Large abrupt differential ground movements at a water pipeline crossing of an active fault have the potential of causing the most severe earthquake damages on the pipeline. To mitigate potential earthquake damages, the City and County of San Francisco has conducted a seismic study on upgrading two large-diameter pipelines crossing the Hayward Fault, one of the major faults in Northern California, which is capable of generating a Richter Magnitude 7+ earthquake. This paper discusses various seismic upgrade methods covering both buried and aboveground pipelines with an emphasis on the aboveground pipeline schemes. In addition, it presents geotechnical findings of the site, methods for analysing the aboveground pipelines, and cost comparisons among identified viable schemes.

INTRODUCTION

The City and County of San Francisco owns and operates the Hetch Hetchy Aqueduct to bring water from the Sierra Nevada mountains to San Francisco and its peninsula cities. In the west of the Hetch Hetchy water system, there are four Bay Division Pipelines (BDPL) which cross the Hayward Fault in the City of Fremont before reaching the San Francisco peninsula.

Since the Hayward Fault is predicted to have 23% to 28% probability of incurring an earthquake of a Richter Magnitude 7 and above before the year 2020 [Work Group, 1990], it is essential that these pipelines withstand such a big earthquake to ensure reliable water supply. To this end, the City has initiated a project to seismically upgrade BDPL Nos. 1 and 2. At the Hayward Fault crossing, BDPL No. 1 (completed in 1925) is a riveted steel pipeline with a 152-cm (60-in) diameter. BDPL No. 2 (completed in 1936) is a 168-cm (66-in) diameter welded steel pipeline. This paper presents various seismic upgrade schemes for these two pipelines with an emphasis on the aboveground pipeline alternatives.

GEOTECHNICAL STUDY FINDINGS

BDPL No. 1 and 2 at the Hayward Fault are currently below ground, and each has two expansion joints near the fault. From 1996 through 1998, geotechnical studies, test programs and analyses were performed to establish the basic design parameters for the seismic retrofit of these pipelines [Geomatrix, 1998]. The main findings of the study are summarised below.

Faulting

Zones of active fault creep and subsidiary faulting were established for the possible fault rupture region (Figure 1). The zone of active creep, where the most significant displacements are most likely to occur, is about 6 meters

[1] *Utilities Engineering Bureau, City and County of San Francisco, San Francisco, CA 94103 USA Email: lcheng@puc.sf.ca.us*

(20 feet) wide. The zone of subsidiary faulting extends another 4.6 meters (15 feet) on each side of the creep zone and may extend twice that distance to the west.

Design Earthquakes

Two levels of earthquake loading are defined for the purpose of the seismic evaluation and retrofit design: Maximum Earthquake and Probable Earthquake. The Maximum Earthquake (ME) represents an upper level that is unlikely to be exceeded during the remaining life of the pipelines. The lower level, Probable Earthquake (PE), represents an event most likely to occur during the pipeline's life.

Based on extensive studies, the horizontal displacements of 1.5 meters (5 feet) and 3 meters (10 feet) are recommended for design considerations under the PE and ME respectively. It is further recommended that the vertical fault displacement be assumed to be equal to 10% of the corresponding horizontal fault displacement.

Horizontal and vertical design response spectra of ground motions for the PE and ME were also developed. The ME spectra are shown in Figure 2.

Geotechnical Hazards

The liquefaction and the landslide potential were studied. They are not considered significant hazards to the pipelines.

Parameters for Soil-Pipeline Interaction Modelling

Per ASCE guidelines [ASCE, 1984], the study developed site specific values of the soil loading and restraint relationships (i.e. elasto-plastic soil springs) used to analyze pipelines subject to large relative ground movements.

BURIED PIPELINE SEISMIC RETROFIT DESIGN SCHEMES

Based on the geotechnical information above, two major types of seismic retrofit schemes, buried pipelines and aboveground pipelines, were investigated. This section presents the study results of buried pipeline retrofit schemes, whereas the next section presents those of aboveground pipelines. All these seismic retrofit schemes include a fail-safe system consisting of valves, outlet manifolds, concrete vault boxes and flexible hoses. The fail-safe system will be activated in case the pipe breaks. The valve will shut off the water supply temporarily. Subsequently, the pipe will be reconnected by the flexible hoses at the outlet manifolds.

Five alternatives of buried pipeline retrofit schemes were studied and are presented below.

Alternative BP1 - In Place Upgrade of BDPL No. 2

In this alternative, all existing girth joints near the fault are straightened to be as strong as the main body of the pipe. This would involve welding interior butt straps to the interior of the pipe. Also, the pipe is stiffened to limit the effects of ovalization. In addition, the existing expansion joints are welded closed.

Alternative BP2 - Partial in Place Upgrade of BDPL No. 2

The upgrades include only welding the existing expansion joints closed and stiffening the pipe to limit the effects of ovalization.

Alternative BP3 - Flexible Joint Upgrade

This alternative examines the use of either (1) the ball joint and extension hardware manufactured by EBAA or others (Figure 3) or (2) the flexible coupling and expansion joint (Figure 4). Various combinations of different locations and number of joints were investigated. None of the combinations were found to be satisfactory.

Alternative BP4 - Full Upgrade in Place with New Trench Backfill

In addition to using the upgrade scheme described in Alternative BP1, this alternative replaces the existing native soil backfill with pea gravel backfill.

Alternative BP5 – New Pipelines in Trench

The pipelines are replaced with a new thicker-walled, butt-welded pipe. Near the fault crossing, the new pipe is backfilled with pea gravel.

Among the five buried pipeline alternatives described above, Alternative BP5, new pipelines in trench, is recommended. It provides very good performance for both the PE and ME even though it has a higher cost due to the use of new pipes.

ABOVEGROUND PIPELINE SEISMIC RETROFIT DESIGN SCHEMES

Three alternatives are available for aboveground pipelines to resist the fault movement. These are (1) continuous pipeline, (2) pipeline with flexible coupling and extension joint, and (3) pipeline with the ball joint and extension hardware manufactured by EBAA or others. All schemes require the pipe to be supported by concrete or steel pipe supports that are spaced at a 6-meter (20-foot) interval, which is the standard spacing for the existing aboveground BDPL. These pipe supports should allow the pipe to move both longitudinally and transversely. One of the proposed concrete supports meeting the above criteria is shown on Figure 5.

The site conditions limit the length of the aboveground pipelines. At the east and west ends of the pipelines, the pipelines are bounded by two major four-lane roads. At the east end where the pipelines cross the road, there is a flood channel. At the west end, the pipelines are encased in concrete. Along the south side of the pipelines, the ground slopes upward toward a residential neighbourhood.

Alternative AP1 – Continuous Aboveground Pipelines

A continuous aboveground pipeline means an aboveground pipeline without any flexible joints between two anchor points. The anchor points can be provided by concrete encasement, soil, anchor blocks or properly designed concrete vault boxes.

When subject to either the PE or the ME, the pipeline with any aboveground length will reach beyond its elastic limit from tensile strain alone. To stay within the allowable strain range, the aboveground pipeline length has to be about 110 or 145 meters (360 or 480 feet) for the PE or ME respectively. For such lengths, the thermal movements are in the range of ±5 cm. (2 in.). Since this movement can cause local compressive strain which is a constant problem, additional mitigation measures are required. One mitigation measure uses a cover structure for the continuous aboveground pipeline. The other is to create bents or loops along the pipeline to release the temperature load. The first measure of using a cover structure may be very expensive since the cover needs to be designed to accommodate the anticipated fault movement in order not to damage the pipeline during an earthquake. The second measure requires additional space, which the site does not have. As a result, a continuous aboveground pipeline is not considered as a viable solution.

Alternative AP2 – Aboveground Pipelines with the Flexible Coupling and Expansion Joint

For this alternative, flexible joints are placed at the two ends of an aboveground pipeline just before the anchor points. The flexible coupling is a Bolted Sleeve Type Coupling (BSTC) which consists of a center sleeve (middle ring), two end rings (followers), two wedge-shaped gaskets and a set of fasteners (bolts and nuts). The BSTC can accommodate angular deflection, and a very small amount of expansion or contraction about 1 cm. (3/8 in.). For a 168-cm. (66-in.) diameter pipe, its allowable deflection is up to 2.5 to 3 degrees. The expansion joint is a Mechanical Expansion-Contraction Joint (MECJ) which consists of a body, slip pipes, packing chambers, and end ring(s). The MECJ provides only expansion and contraction, and has no provision for allowing angularity between pipes. The joint can be made for 60-cm. (24-in.) longitudinal movement. When combining BSTC and MECJ, the joint will allow both the longitudinal and angular movements.

This system has the advantage of being inexpensive. Specifically, a BSTC costs about US$5,000 and a MECJ costs about US$10,000. In addition, these joints can be repaired easily. The system has the disadvantage of having a relatively small rotation capacity that results in requiring a longer aboveground pipe. Furthermore, its BSTC is relatively weak. The gasket in the BSTC can handle, without failure, gradual movement such as temperature, but may fail if subject to rapid movement. To the author's knowledge, it has not been used for accommodating sudden large fault displacements.

Alternative AP3 – Aboveground Pipelines with Ball Joint and Expansion Hardware

This alternative ultilizes the ball joint and expansion hardware manufactured by EBBA or others. The hardware is available for pipes with a diameter up to 152 meters (60 inches). It consists of one sleeve for expansion and a ball joint for rotation. The sleeve has the expansion capacity of up to 60 cm. (24 in.) while the ball joint can be designed to withstand a maximum offset angle of 10 degrees. This joint hardware allows much larger angular deflections. Its one-piece construction may withstand rapid movements resulting from major earthquakes. However, this joint is expensive. Each unit costs about US$170,000 to US$200,000 vs. US$15,000 for the one consisting of a flexible joint and coupling. In addition, if the unit fails, it might be very difficult to repair.

ANALYSIS METHODS AND PROCEDURES

This section describes analysis methods and procedures for buried and aboveground pipelines with an emphasis on the aboveground pipelines.

Buried Pipelines

The buried pipelines were analysed by the finite element methods [Row, 1988]. A 430-meter (1,400-foot) long pipeline beam model was developed and analysed by G&E Engineers [G&E, 1998]. This length is required to capture the pipe's behaviour beyond the fault zone. The pipe and the soil are represented by three-dimensional non-linear elements. The ground displacement input includes two horizontal and one vertical directions. A three-dimensional shell model was also developed to capture the oval effects. The analysis results show that, with a new pipe of a 2-cm. (3/4 in.) thickness, the maximum tensile and compressive strains are +2.2% and –0.10% during the PE. These values are within the allowable +5% and –0.40%. By extrapolation, the new pipe will meet the ME criteria [G&E, 1998].

Aboveground Pipelines

Only the analysis methods for pipelines with flexible joints are presented here since the continuous pipeline option is not considered feasible as discussed in Section 4.1. The analysis consists three parts: (1) determining the required aboveground pipeline length, (2) studying the pipe's behaviour in response to the support reactions, and (3) computing the dynamic behaviour of the pipeline during an earthquake.

Pipeline Length

The required aboveground length of the pipeline with flexible joints is determined by the fault displacement, the angle between the pipeline and the fault, and the allowable slip and the limiting angle of rotation at the flexible joint. Using the method suggested by O'Rourke and Trautmann [O'Rourke and Trautmann, 1981], the required aboveground pipeline length is 92 meters (300 feet) and 46 meters (150 feet) for the pipe with flexible coupling and expansion joint, and the pipe with ball joint and expansion hardware, respectively.

Pipeline Behaviour in Response to Support Reactions

When the aboveground pipeline is subject to the fault displacement, it experiences forces at the pipe support locations. The forces come from the friction either (1) between the pipe and the pipe support if there is no restraint between the pipe and its support and the support is fixed to the ground or (2) between the support and the ground if the pipe is tied to the support and the support is free to move on the ground. Modelling both kinetic and static friction forces, a three-dimensional beam model representing the pipeline was developed to determine the support reactions and the resulting pipe forces and moments. The analysis result shows that the pipe's flexure and shear stresses are within the elastic range. This is true for both the AP2 and AP3 schemes.

Dynamic Behaviour

Similar to a structure, the dynamic behaviour of an aboveground pipeline in response to an earthquake is characterised by its dynamic parameters. In general, the analysis of aboveground elements or structures is carried out using the concept of the design or response spectrum [Hall and Newmark, 1977]. Our study used analysis procedures based on the Newmark and Hall method [Newmark and Hall, 1973], the same method as used in designing the Trans-Alaska Pipeline [Newmark, 1975]. The site spectra used by our study were developed by Geomatrix Consultants [Geomatrix, 1998].

The proposed aboveground BDPL was modelled by three-dimensional beam elements representing the pipe with intermediate supports spacing at 6 meters (20 feet) on centre (Figure 6). The two end supports are either pinned or on the roller to model the expansion joints. The intermediate supports have lateral and vertical restraints but are free to move along the axial direction of the pipeline. Since the response spectrum analysis can not include the sliding effects, this model assumes the resulting support reactions would not exceed the static friction force at the supports and no support movement occurs. Fortunately, none of the analyses showed the reaction forces exceed the calculated static friction forces. Furthermore, all the pipe stresses are within the elastic range.

COST COMPARISON OF RETROFIT SCHEMES

This section presents the cost estimates of the three recommended retrofit schemes: (1) new buried pipeline in trench, (2) aboveground pipelines with the flexible coupling and expansion Joint, and (3) aboveground pipelines with ball joint and expansion hardware.

The costs of three recommended retrofit schemes are shown in Table 1 below. The numbers shown in the table do not reflect the actual construction cost and are for comparison purpose only. To be consistent, the cost estimates include the installation of new pipelines and the fail-safe system (manual valves, outlet manifolds, concrete vault boxes and flexible hoses) for all three schemes. This table shows that cost estimates for the three schemes are comparable, and are within 20% of one another. The first scheme was chosen by the City of San Francisco with the added consideration that a buried pipeline is less vulnerable to sabotage and easier to maintain.

Table 1: Cost of Retrofit Schemes

Retrofit Scheme	Cost
New buried pipelines in pea gravel trench	US$4,047,000
Aboveground pipelines with flexible coupling and expansion joint	US$4,010,000
Aboveground pipelines with ball joint and expansion hardware	US$4,667,000

CONCLUSIONS

This paper presents various seismic retrofit schemes for upgrading two existing pipelines across the Hayward Fault. The retrofit schemes studied include both buried and aboveground pipeline alternatives. To aid the analysis of the retrofitted pipelines, a geotechnical study was conducted at the site, which includes faulting, design earthquakes, geotechnical hazards and parameters for soil-pipeline interaction modelling.

Based on the geotechnical inputs, analyses were done for both buried and aboveground pipeline schemes. The analysis of an aboveground pipeline included the determination of the aboveground pipe length, pipeline behaviour due to support reactions, and the dynamic behaviour of the pipe. The study indicated that a buried pipe or an aboveground pipeline with specially designed flexible joints is a viable solution. The specially designed flexible joint is either a flexible coupling and extension joint, or a ball joint and extension hardware manufactured by EBAA or others. The cost estimates for these three schemes are comparable, and are within 20% of one another.

8. ACKNOWLEDGEMENTS

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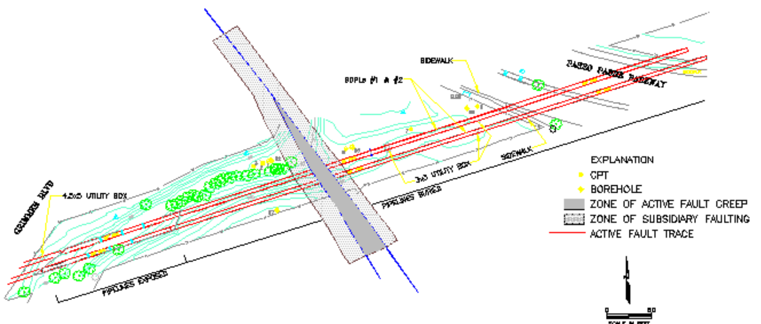

FIGURE 1 SITE PLAN SHOWING FAULT ZONES
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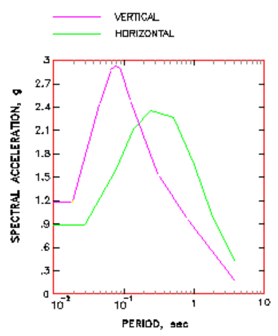

FIGURE 2 RESPONSE SPECTRA FOR MAXIMUM EARTHQUAKE (ME)
N.T.S.

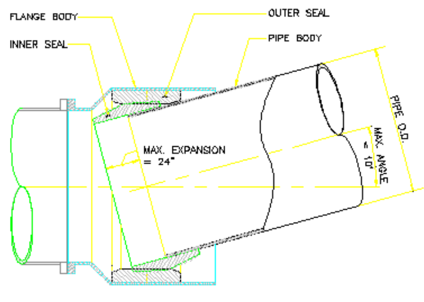

FIGURE 3 PORPOSED EBBA EXPANSION/BALL JOINT
N.T.S.

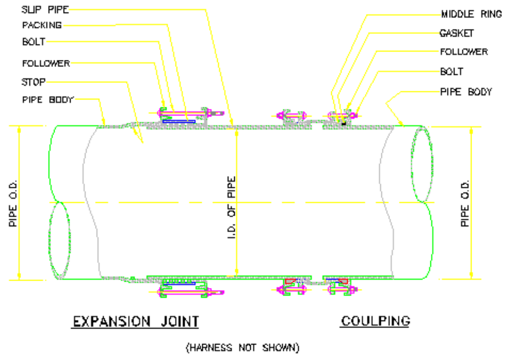

FIGURE 4 PROPOSED COUPLING/EXPANSION JOINT
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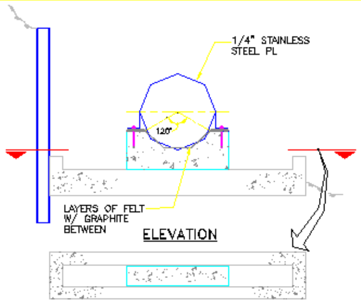

FIGURE 5 CONCRETE PIPE SUPPORT
N.T.S.

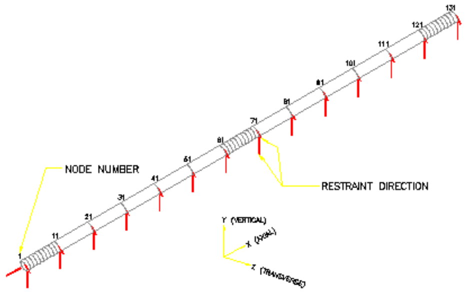

FIGURE 6 COMPUTER MODEL FOR DYNAMIC ANALYSIS
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