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SEISMIC RETROFIT DESIGN OF WATER PIPELINES CROSSING THE HAYWARD FAULT

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ABSTRACT

The Hayward Fault, having a high probability of incurring a Richter magnitude 7 and above earthquake, can cause severe earthquake damage on fault-crossing pipelines. To ensure uninterrupted water supply, the City and County of San Francisco has initiated a preliminary study on seismically retrofitting two existing pipelines across the Fault. The study investigated site-specific design issues such as pipes' supports, joints, orientations and fault types. Based on these design criteria, three seismic rehabilitation schemes of buried and uncovered pipelines with and without special expansion joints were developed and evaluated. The analysis indicated that either a buried or an exposed pipeline with specially designed expansion joints/flexible couplings can reliably withstand a major earthquake.

KEYWORDS

fault crossing design, Hayward Fault, water pipelines, buried pipelines, pipeline orientation, pipe supports, pipeline design, expansion joints, flexible couplings, redundancy design.

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. A major portion of the aqueduct is the 45.9-km (28.5-mi) long Coast Range Tunnel. From its west end, four Bay Division Pipelines (BDPL) convey water by gravity flow to the Pulgas Tunnel which in turn conveys water to the City's terminal reservoirs.

BDPL's #1 and #2, both 56.3 km (35 mi) long and within the same right-of-way, cross the San Francisco Bay at the Dumbarton Strait. Most of BDPL #1 (completed in 1925) is a riveted pipeline with a 152-cm (60-in) diameter. BDPL #2 (completed in 1936) is largely a 168-cm (66-in) diameter pipeline. Both pipelines cross the Hayward Fault, and each has two expansion joints near the Fault.

BDPL's #3 and #4, both 54.7 km (34 mi) in length, were completed in 1956 and 1973 respectively, and routed through the south end of the San Francisco Bay to the Pulgas Temple. These pipelines are a combination of riveted steel, welded steel, and steel-cylinder reinforced concrete. Because all four BDPL's cross the Hayward Fault (Fig. 1), their alignments are strategically separated to reduce the probability of simultaneous water loss due to damage caused by earthquakes and other causes.

As 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 (Working 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 the pipelines. The first phase of the project is to develop a conceptual design for BDPL's #1 and #2 at the Hayward Fault crossing, and is the focus of this paper. This paper first discusses design issues specific to the two pipes and their sites. It then presents three seismic retrofit schemes based on these design issues. In the end, the paper summarizes preliminary design results and discusses how they can be extended.

DESIGN ISSUES

Design issues specific to the two pipelines under study are: (1) the direction and dimension of fault displacements during a Maximum Credible Earthquake (MCE), (2) orientation of the pipes with respect to the fault line, (3) special site conditions, (4) joints used to accommodate fault displacements, i.e., expansion-contraction joints and flexible couplings (5) design redundancy, and (6) other special design criteria. These six design issues are discussed in detail in the following sections.

(1) Direction and Dimension of Fault Displacements

The severity of earthquake damage on a fault-crossing pipe depends on the type of fault involved. Based on a fault's geometry and its direction of relative slip, there are three fault types: dip-slip, strike-slip, and oblique faults. The Hayward is an example of the second type. It is primarily a right-lateral strike-slip fault with minor vertical displacement.

The 1868 earthquake on the Hayward Fault has an approximate magnitude of 7, and a reported maximum offset of 0.9 m (3 ft.). For a magnitude-7.5 Hayward earthquake, the maximum offset is projected to be 3 m (10 ft.), based on the postulated scenario given by California Division of Mines and Geology (Steinbruge, *et al.*, 1987). The average displacement, prevalent throughout the fault rupture, is estimated to be 1.5 m (5 ft.). Also expected is some vertical displacement. This 7.5 Hayward earthquake is used as the MCE for the preliminary study.

(2) Orientation of the Pipes with Respect to the Fault Line

The orientation of a pipeline across a right-lateral strike-slip fault is the angle measured clockwise from the original pipeline position to the fault line. When a pipe's orientation ranges from 0 to slightly greater than 90 degrees, a fault movement will make the pipe elongate between anchors, and cause axial tensile strain in the pipe. For orientations greater than about 95 degrees, the pipe will be shortened, and the resulting compressive strain causes local wrinkling (Kennedy, *et al.*, 1977).

A preliminary study indicates the orientation between the Hayward Fault and the two pipelines under study is approximately 70 degrees. Field inspection of their expansion joints confirms that they are under tension.

(3) Special Site Conditions

Past earthquakes indicated that site conditions such as topography, geography, terrain and soil, have great influence on seismic damage sustained by pipes (Wang *et al.* 1985).

At the Hayward Fault site, the following potential problematic conditions have been identified: (a) slope stability problems due to small hills, (b) liquefaction potential due to possible high water table, (c) congested urban area, (d) possible highway crossing due to the fault zone extension, and (e) environmental issues such as a flood channel nearby. These conditions dictate that some portion of the pipe be placed above ground and some portion below ground. Consequently, study on both placement schemes is required.

(4) Expansion-Contraction Joints and Flexible Couplings

Two types of mechanical joints or couplings can be used in a fault-crossing pipe. The first type is a combination of an expansion-contraction joint with one or two sleeve couplings as shown in Figure 2. It is typically used by steel pipes to relieve stress and strain caused by temperature variations. It can be also used to accommodate fault creep movements at a fault crossing. The expansion-contraction joint can take up to 25 cm (10 in) longitudinal movement in an axial direction of the pipe, but not angular deflection. The sleeve coupling, on the other hand, can accommodate an angular deflection up to 2.5 to 3 degrees for pipes with diameters between 152 cm (60 in) and 168 cm (66 in). Combining the two allows both axial and rotational movements for the pipe.

The second type of joint is a flexible expansion joint which is originally designed for ductile steel pipes (Figure 3). The flexible expansion joint is a proprietary design and can be modified for use with welded steel pipe. It consists of one to three sleeves for expansion and contraction, and one or two ball joints for rotation. Each sleeve has the capacity for 25-cm (9.8 in) expansion and 10-cm (3.9 in) contraction. The ball joint can withstand a maximum offset angle of 11 degrees.

Multiple joints of both types can be used by BDPL's #1 and #2 across the Hayward Fault to withstand the anticipated impact of the Fault's surface rupture. However, at present the flexible expansion joint can not be used directly by BDPL #2 of 168-cm diameter which exceeds the joint's maximum fitting size of 152 cm.

(5) Design Redundancy

So far, design of fault-crossing pipes has relied on strain capacity of the pipe and/or mechanical joints for earthquake resistance. It has not been tested by nature. As a result, redundancy and contingency plans should be developed to minimize the disruption of water services. Possible redundancy options are construction of an additional pipeline, replacement of an existing pipe with multiple smaller ones, and/or installation of shutdown valves with or without T connections outside the fault zone.

(6) Other Special Design Criteria

In addition to the design criteria discussed above, the following factors for the pipe are considered: (a) buried depth, (b) anchor length, (c) internal pressure including hydrodynamic and water hammer pressure, (d) aging characteristics, (e) corrosion, and (f) cost of the seismic upgrade. Also considered is soil strength and its dynamic soil resistance and damping characteristics.

SEISMIC RETROFIT DESIGN SCHEMES

Based on the design criteria discussed above, three different new pipes have been investigated to replace an existing section of BDPL #1 in the Fault zone. These new pipes are made of welded steel as it has been shown that welded steel pipes outperform pipes made of riveted steel and other materials during recent earthquakes (Wang, 1985; Katayama and Isoyama, 1980). Specifically, the three schemes for the new welded pipes are: (1) a new buried pipeline; (2) a new buried pipeline with seismic expansion joints and flexible couplings; and (3) an uncovered new pipeline with seismic expansion joints and flexible couplings. In addition, automatic shut-off valves will be placed outside the Fault zone. In analyzing behavior of these new pipes during an MCE, only the horizontal fault displacement is considered in order to simplify the analysis procedure. Note that the analysis procedure developed for BDPL #1 is also applicable to BDPL #2 as the two BDPL's are similar.

Scheme 1: A New Buried Pipeline

The first scheme replaces a portion of the riveted steel pipe in the Fault zone with a new welded steel pipe with expansion joints designed for seismic creep. The new pipe is back filled with medium sand.

The new pipe's behavior during an MCE was analyzed with the assumption that the expansion joints had reached their maximum capacity. As a result, the pipeline behaves like a continuous pipe. Based on the theory developed by Newmark and Hall (1975), a continuous pipe responds to fault motion through axial motion only, not through any lateral restraint posed by soil. Their theory provides a lower-bound estimate of strain in the pipeline. For instance, an MCE with a 3-m (10-ft.) horizontal fault offset produces plastic deformation in approximately 90 m (300 ft.) of the pipeline. The expansion joints designed for seismic creep alone are not adequate for such length of pipe's plastic deformation. Specially designed expansion joints are needed, and are described in the following two schemes.

Scheme 2: A New Buried Pipeline with Seismic Expansion Joints/Flexible Couplings

In the second scheme, the new 90-m (300-ft.) welded steel pipe is fitted with expansion joints and flexible couplings that are specially designed for the MCE. These joints are placed at both ends of the new 90-m pipeline. The 90-m length is determined by fault zone width and plastic deformation length computed from Scheme 1.

Assuming an inflection point at the pipe/fault crossing intersection, a half model was developed to analyze the interaction among the pipe, the soil, the expansion joints, and the flexible couplings (Fig. 4). This half model uses finite-element analysis in which the pipe is modeled as elastic beam elements, expansion joints and flexible couplings as gap elements, and soil as spring elements. The spring elements for soil are a combination of non-linear axial springs and transverse horizontal springs. What is not considered by this model is soil's vertical resistance force. Values of the axial springs, representing the friction between the pipe and its surrounding soil, are derived from pile shaft load transfer theory. Values of the transverse horizontal soil springs, which model lateral soil resistant forces, are determined from the Trautmann and O'Rourke's procedure (1983). Based on these analyses, soil load-deformation curves for medium sand were generated as shown in Fig. 5.

The preliminary analysis indicated that part of the pipeline would experience plastic deformation for the 3-m (10-ft.) horizontal fault movement of an MCE. The plastic deformation arises, in part, from lateral soil resistance forces. That is, the analysis is sensitive to the value of transverse horizontal soil springs used. It requires further studies on soil properties and acceptable plastic deformation behavior in order to adopt this scheme for final design.

Scheme 3: An Uncovered Pipeline with Seismic Expansion Joints and Flexible Coupling

Instead of being buried as described in Schemes 1 and 2, the pipeline in Scheme 3 is placed above ground, in an open trench, and/or inside a concrete box (Fig. 6) as dictated by the site condition, i.e. road and flood channel crossings. In addition, it can be constructed on sliding supports that reduce lateral restraints on the pipe. This scheme, may be preferred to two earlier schemes because it does not have the disadvantage of the uncertainties in seismic analysis as buried pipelines (Gooding, 1985).

The critical elements in this design are the longitudinal expansion joints and flexible couplings which will theoretically relieve all the pipe's stresses and strains caused by a fault displacement. The required extension length for an expansion joint can be calculated using the O'Rourke and Trautmann's equation (1981) with a fault displacement of 3 m (10 ft.) of an MCE as an input. The computed result of approximately 1070 mm (42 in.) can be accommodated by a pair of expansion joints each placed at one end of the 90-m (300-ft.) new pipeline. The required rotation at the location of an expansion joint is approximated by assuming that the pipeline undergoes a rigid body rotation pivoting at the flexible coupling. This will result in a rotation of 4.8 degrees which can be taken care of by constructing two flexible couplings or one (or two) ball joint next to each expansion joint.

In this design scheme, pipe supports shall be carefully designed to allow maximum freedom of movement for the pipe. Anchor blocks may be needed to resist unbalanced forces. If a concrete box is used to house the pipeline, special attention is required on designing the box's seismic joints.

SUMMARY AND CONCLUSIONS

This paper presents seismic design issues and retrofit schemes on upgrading two existing pipelines across the Hayward Fault. Specific design issues considered are that the Hayward Fault is mainly a strike-slip fault and the orientation of two pipelines with respect to the Fault are such that its movements cause tension in the pipes. To relieve such tension, specially designed expansion joints and/or sleeve couplings are required. Also considered and evaluated is the above-ground and below-ground placement of the pipes due to site conditions of the Fault zone. In addition, shutdown valves outside the Fault zone could be installed for redundancy design.

Based on these design criteria, three seismic retrofit schemes have been developed and investigated to replace each of the two pipes: a buried steel pipeline, a buried and an uncovered pipeline with special expansion joints and flexible couplings. The preliminary analysis indicated that either a buried or an exposed pipeline with specially designed expansion joints/flexible couplings is a viable solution. However, complete design requires further studies on soil properties, fault zone width, pipe's plastic behavior, sliding supports, anchor blocks, concrete boxes, and cost-benefit analysis.

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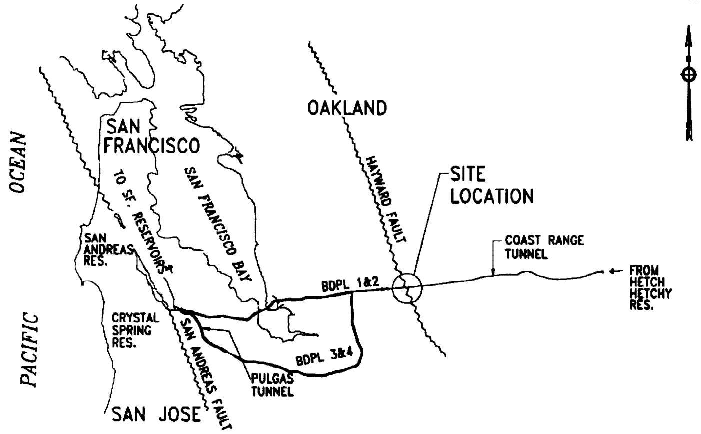

FIGURE 1. LOCATION OF THE SITE

N.T.S.

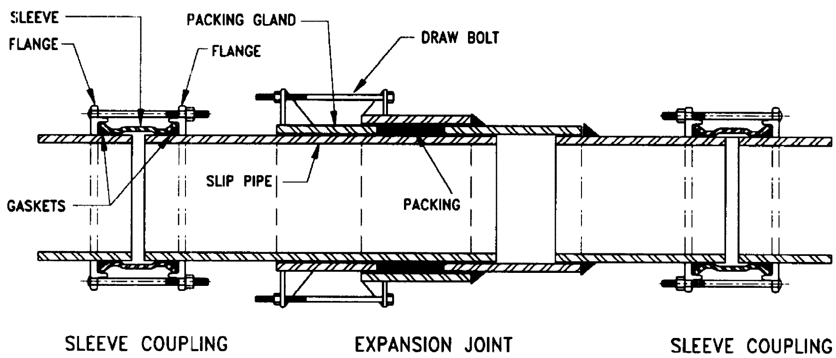

FIGURE 2. SCHEMATIC DRAWING OF COMBINATION OF EXPANSION JOINT AND SLEEVE COUPLINGS

N.T.S.

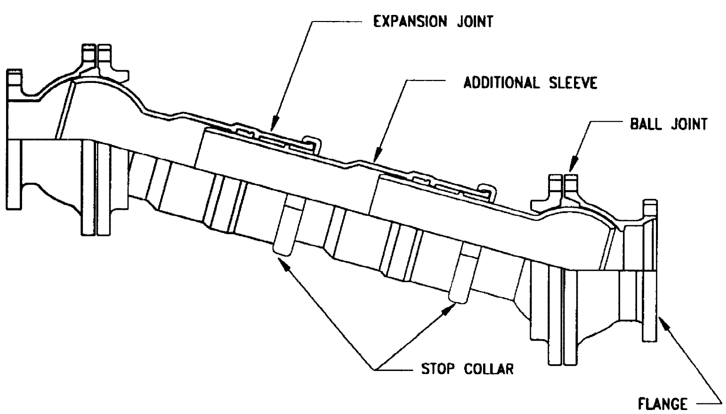

FIGURE 3. FLEXIBLE EXPANSION JOINT

(COURTESY OF EBBA IRON)

N.T.S.

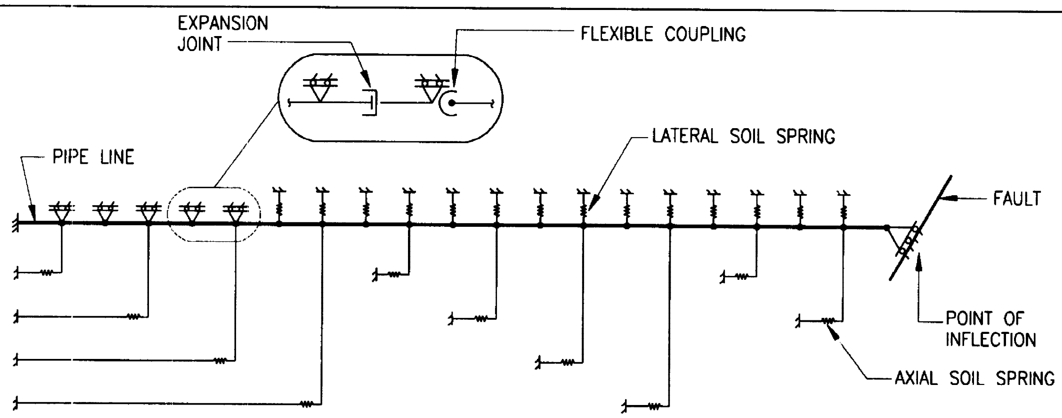

FIGURE 4. FINITE ELEMENT MODEL OF PIPELINE SUBJECTED TO FAULT MOVEMENT
N.T.S.

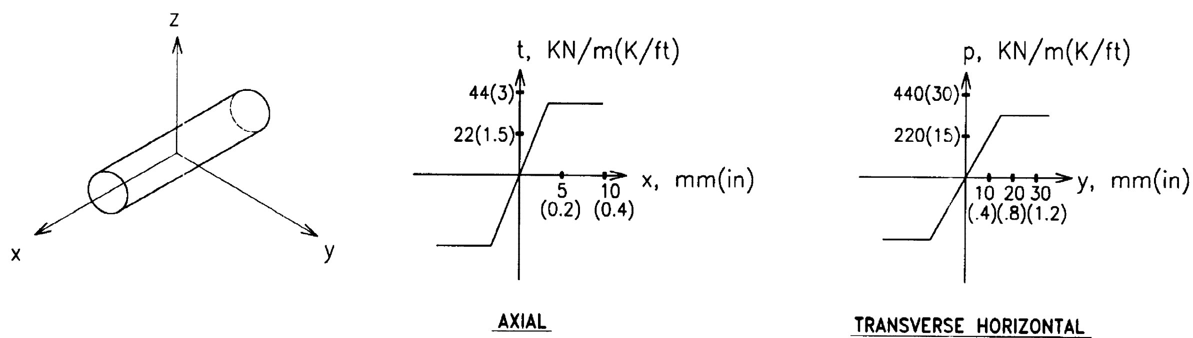

FIGURE 5. SIMPLIFIED SOIL LOAD – DEFORMATION CURVES
N.T.S.

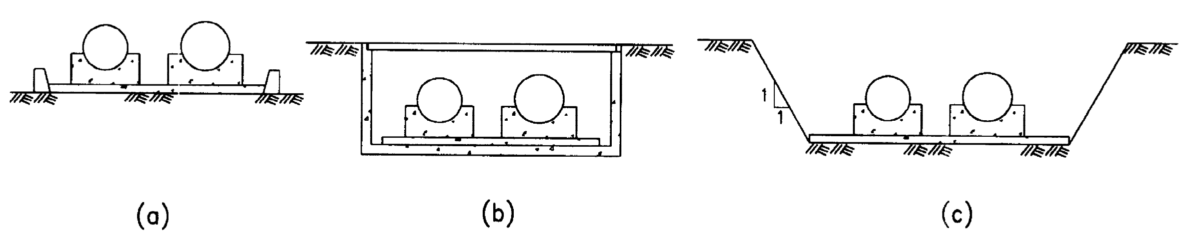

FIGURE 6. PROPOSED PIPE SUPPORT CONFIGURATION FOR SCHEME 3
N.T.S.