ALTERNATIVE STUDIES OF WATER TRANSMISSION PIPELINES CROSSING THE HAYWARD FAULT

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ABSTRACT:

The Bay Division Pipelines (BDPLs) Nos. 3 and 4 are vital components of the San Francisco Public Utilities Commission's (SFPUC's) transmission system that delivers water from Hetch Hetchy Reservoir in Yosemite National Park to the San Francisco Bay Area. The pipelines cross three traces of the Hayward Fault, which is capable of producing a magnitude 7.25 earthquake and over 6 feet of horizontal fault offset. The alignment of the SFPUC pipeline right-of-way is such that offset of the fault will produce compression in the 78-inch and 96-inch-diameter pipelines. A large earthquake on the Hayward Fault would almost certainly rupture both BDPLs 3 and 4 causing localized flooding and loss of water supply to the San Francisco Bay Area. Adding to the complexity of the project, the fault crossing is located in a highly congested and trafficked area at the intersection of the Interstate 680 freeway and Mission Boulevard in Fremont, California. This unusual situation of large-diameter pipelines constrained by local right-of-way restrictions to a compression fault crossing requires a unique solution to mitigate the danger. Nine alternatives were developed to address the situation considering cost, constructability, seismic reliability, operations and maintenance, environmental and governmental permitting, and community impact. The goal of the alternative studies is to yield a solution that provides a high level of survivability and operability after a major earthquake and constructability within a confined construction area, while minimizing disruption to the community, traffic, and water delivery.

KEYWORDS: Pipeline, fault crossing, California, seismic design

1. INTRODUCTION

Much of the population of California live close to the plate boundary of the Pacific and North American Plates. This plate boundary is characterized most notably by the dominant San Andreas Fault zone, but in the San Francisco Bay Area in Northern California, there are a number of major faults generally trending SE-NW including the San Andreas, Hayward, and Calaveras faults. Total movement of the Pacific plate relative to the American Plate over all the faults is estimated by the USGS to be, on average, approximately 40 mm per year, right lateral. This movement is achieved by creep and the inevitable fault offsets associated with seismic events.

1.1 Hetch Hetchy Water System

The supply of water to a significant population (2.4 million) in the Bay Area, including those residing in San Francisco and the South Bay Cities, is drawn from Hetch Hetchy reservoir in the High Sierras some 150 miles to the east, and is transported through hydro power plants, tunnels and pipes to the Bay Area through a system initially completed in 1932. Downstream of the west portal of Irvington Tunnel which transports the water into Fremont from the Sunol valley, the conduit separates into the four Bay Division Pipelines (BDPLs.) Two pipelines (BDPLs 1 and 2) are oriented directly west to cross the San Francisco Bay. The other two pipelines (BDPLs 3 and 4) head south and skirt the south bay, eventually rejoining BDPLs 1 and 2 on the peninsula.

1.2 Rehabilitation Program

Commencing in the late 1990s, the increasing awareness of the dependency of the Bay Area economy on the Hetch Hetchy system, and the greater appreciation of the seismic risks in the Bay Area drove the SFPUC to instigate planning for upgrading its delivery facilities to ensure the continuity of supply after a projected major seismic event in the region. This planning led to the formulation of the Water System Improvement Program which is currently moving from the planning stage into full implementation. The probability of a major seismic event has been estimated, by a 2008 working group convened under the auspices of the USGS, as 63% in the next thirty years (a slight increase from previous projections in 2002). In the case of an event on the Hayward fault, and the associated fault rupture, the calculated probability is 31%. The estimated damage (not including fire losses) resulting from loss of water supply after a fault movement of the Hayward has been assessed at US$ 17 billion (2001 dollars). The SFPUC is therefore attempting to ensure that, after an event, the level of service goal, of "winter's day demand for 70% of the turnouts within 24 hrs" can be met.

2. DESCRIPTION OF PROJECT SITE AND EXISTING FACILITIES

The pipelines are so vulnerable at the various fault crossings that there never any doubt that upgrading at the crossings would be a vital part of the program, but it was discovered that to achieve the level of service goal, it was not necessary to upgrade all pipes at each crossing. Although all four pipelines traverse the Hayward fault, and strengthening is being undertaken at both fault crossings, the crossing that is the subject of this paper is that of BDPL 3 and 4, which is a particularly difficult configuration and location.

2.1 Site Challenges

The first difficulty of the BDPL 3 and 4 crossing is that the pipelines cross the Hayward fault, which could offset over 6 ft at this location, at an unfavorable angle. The pipelines are at an angle of 45 degrees, but at an orientation that induces compression during fault creep and after a fault rupture. In fact, SFPUC has already installed slip joints on the existing pipes to relieve some of the compression due to creep. It is well understood that crossing a fault in an orientation such that tension is induced in the pipeline is more easily achieved and desirable. The design challenge of addressing compression at this location is further compounded by three conditions.

First, the Hayward fault at the crossing location has three distinct traces (A, B and C) although the central trace (B) is expected to demonstrate the majority of the slip.

Second, the urbanization of the Bay Area has resulted in residential home construction right up to the limits of the 80 foot right of way – allowing no room to design a conventional "zig-zag" arrangement similar to the Denali crossing, without condemnation of multiple residential (single family) properties.

Third, the crossing of the main fault trace by the pipelines occurs underneath the northern side of a major "cloverleaf" intersection on I-680, one of the most heavily trafficked freeways in the Bay Area. Even the secondary road that intersects the freeway carries heavy commuter traffic to and from Silicon Valley and Oakland. The SFPUC pipes were in place before the freeway and the intersection were constructed

2.2 Existing Conditions

The two BDPLs of 78 and 96-inch-diameter cross eight lanes of I-680, four lanes of the secondary route and three freeway on-ramps. In addition they cross an open-channel creek as well as a creek in culvert that was rerouted when the freeway interchange was constructed. There are also various utilities including large diameter local water lines in the vicinity.

The 78-inch BDPL 3 is for most of its length a reinforced concrete cylinder pipe. Under the open-channel creek and at Trace B, BDPL 3 is welded steel pipe. BDPL 4 is 96-inch diameter and consists of pre-stressed concrete cylinder pipe for most of its length. However, the section that crosses the creek and Traces A and B of the fault is welded steel pipe. Three segments of corrugated metal pipe (CMP) to house a future possible third transmission pipeline were installed under the I-680 intersection when the freeway was constructed. These CMPs are 114 inches inner diameter.

A site plan showing the existing pipes and the fault traces is shown in Figure 1.

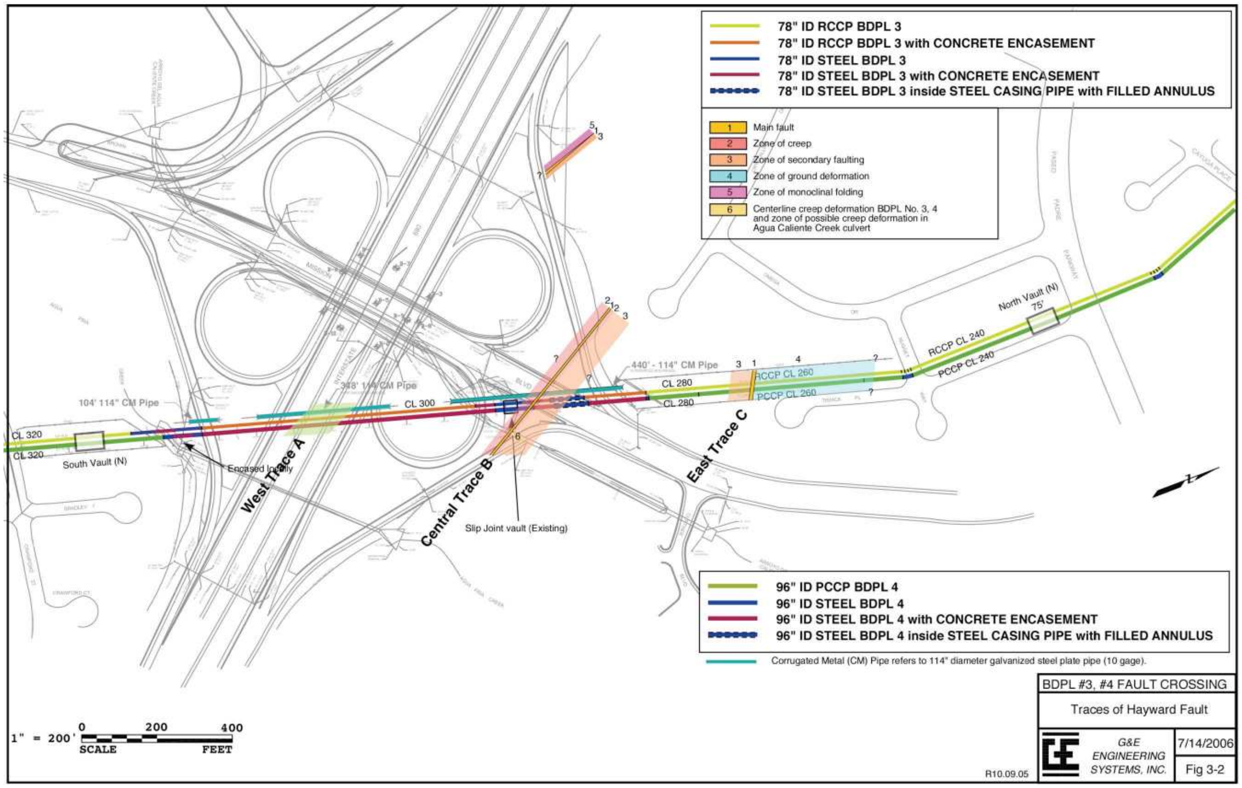

Figure 1. Map of Project Site and Hayward Fault Traces

2.3 First Phase

The first phase (Phase A) of the project has already been completed, and includes two new valve vaults, one on either side of the Hayward Fault trace, containing crossover pipes and isolation valves. This will allow for isolation of any broken pipe after an earthquake, and rerouting of the flow past a single pipe break at the fault. The valves will also enable easier construction of Phase B of the project which is the seismic upgrade of the pipelines between the valve vaults.

3. SEISMIC HAZARDS

The site lies along the active Hayward fault zone, which is a major right-lateral strike-slip fault that extends from San Pablo Bay on the northwest to the City of Fremont on the southeast. The fault zone is divided into southern and northern rupture segments.

A comprehensive geotechnical investigation was performed between 2003 and 2004. It included detailed field exploration, laboratory testing, literature surveys and seismic hazard analysis. Seven geotechnical borings were drilled to depths from about 46 to 70 below the ground surface. Nine cone penetrometer tests were performed and five fault trenches excavated. The study confirmed the existence of the three Holocene active traces at the location of the pipelines: Traces A, B and C (Fig. 1). Because of the well-developed deformation zone, the strong geomorphic expression and the manifestation of the creep along the Central trace (B), it is determined that a large percentage of fault displacement will likely occur on the Central trace. In 2008, a probabilistic fault displacement hazards analysis (PFDHA) based on the methodology for probabilistic seismic hazard analysis (Cornel, 1968) was performed to confirm the expected magnitude of the fault movements.

From this second study, it is determined that for the maximum magnitude earthquake, the 50th percentile (median) estimate of total horizontal displacement ranges from 2-3/4 to 4-1/4 feet while the 84th percentile (median-plus-one standard deviation) estimate of maximum total horizontal displacement ranges from 6-1/2 to 10 feet. For the 975-year return period earthquake, the 97.5th percentile (median-plus-two standard deviations) estimate of maximum horizontal displacement is about 6.3 ft. Given a scenario of simultaneous rupture on all three traces, the distribution of the total horizontal displacement among the three traces at the crossing will be 80 percent to the Central trace, 15 percent to the West trace, and 5 percent on the East trace. The vertical fault displacements are estimated as follows: a 2:3 vertical to horizontal (V:H) ratio for West trace, a 1:1 V:H ratio for the East trace, and zero vertical for the Central trace. For the design of pipelines, the SFPUC General Seismic Design Requirements (SFPUC, 2006) recommends the use of 975-year return period earthquake. Using the SFPUC requirements and a conservative approach (the full horizontal offset may occur at Central trace), the following design fault displacements were recommended:

Central trace (B): horizontal = 6.5 feet, vertical = 0 ft
West trace (A): horizontal = 1.0 ft, vertical = 0.7 ft
East trace (C): horizontal = 0.5 ft, vertical = 0.5 ft

Other geotechnical hazards including creep, seismic ground motion, soil liquefaction and landslides were evaluated. The long-term creep rate at the Central trace is 6mm/yr. The peak ground acceleration for a Maximum Earthquake is estimated at 0.87g. The procedure recommended by the National Center for Earthquake Engineering Research (Youd etal. 2001) was used to evaluate liquefaction potential. The potential for significant liquefaction at site was found to be very low. Consequently, the damage to the pipelines is very low. The site ground surface slopes are generally relatively flat with an average inclination of 2 to 3 percent. The calculated static factor of safety is greater than 15 or more. Therefore, the landslide potential along the pipelines is low.

4. ALTERNATIVES

An alternatives analysis was conducted as part of the planning effort for this project. Nine alternatives were developed in response to this problem considering cost, constructability, seismic reliability, operations and maintenance, environmental and governmental permitting, and community impact. The alternatives range from a do-nothing approach to a full replacement of the pipelines across the fault zone and are described more fully in the following sections.

The alternatives were evaluated considering the project objectives which are: 1) to mitigate within budget constraints the catastrophic failure of the existing pipelines, the resulting inundation of the neighboring residences and businesses, and the possible erosion and failure of I-680 and secondary roadway; and 2) to meet the SFPUC's water delivery goals after an earthquake.

4.1 Alternative 1 Do Nothing

Alternative 1 is the "do nothing" alternative. It essentially consists of the recently installed isolation valve vaults on either side of the Hayward Fault. Although Alternative 1 is low cost as well as low impact, it does not meet the goals of the project.

4.2 Alternative 2 Bypass Pipe

Alternative 2 consists of the installation of a 48-inch bypass pipe between the two new isolation valve vaults. The bypass pipe would be installed within the three existing CMP sections under the existing highway and roadway. The fault-crossing concept consists of the thick-walled steel pipe accommodating fault offset by compressing and moving laterally at the three fault traces. At Traces A and B, the pipe would be supported on sliding supports within the larger CMP segments. At Trace C where less fault offset is expected, the pipe would flex and move within engineered backfill.

This alternative has relatively low cost and few constructability issues as the need for traffic rerouting is eliminated by placing the new pipe within the existing CMP sections under I-680 and the secondary roadway. A 48-inch pipe also fulfills the immediate post-earthquake water delivery goals. However, this alternative does not upgrade either of the existing pipelines which will most likely fail and cause flooding of the intersection, and need to be repaired after an earthquake. This alternative also assumes the thick-walled steel pipe would be capable of withstanding extremely high compressive strains during the fault offset. As a result, this alternative is classified as reliable only for lesser fault offsets and not the full design fault offset.

4.3 Alternatives 3, 4 and 5 Zig-zag Pipes

Alternatives 3, 4 and 5 are variations of the “zig-zag” arrangement used in the Denali Fault crossing of the 48-inch Alyeska oil pipeline in Alaska which withstood the 14 feet of fault offset from a M7.9 earthquake in November 2002. The existing pipelines would be replaced with two new steel pipes in an underground concrete vault of ample width to allow an initial “zig-zag” or “S” shape arrangement of the pipes on sliding supports. In a fault offset, the pipes would accommodate the compression through axial and lateral movement and elastic deformation.

Alternative 3 consists of the underground vault and “zig-zag” of the pipelines spanning across all three traces of the fault including under I-680. Alternative 4 consists of a shorter vault and “zig-zag” spanning over only Traces B and C with the addition of the 48-inch bypass pipe described in Alternative 2. Alternative 5 consists of the shorter vault with a steel liner to retrofit the existing BDPL 3 under I-680 at Trace A. The existing BDPL 4 is steel pipe at that location and is expected to perform satisfactorily at Trace A.

An advantage of the “zig-zag” concept is that it was tested and proven in the Denali quake of 2002. Another advantage is that it allows the replacement of the two pipelines without reducing their sizes or capacities. The disadvantage of the concept is that the width of the vault must be wide enough to house a “zig-zag” configuration that allows the pipes to remain in the elastic deformation range. This required inside width of 120 feet exceeds the 80-foot SFPUC right-of-way and implementation would require acquisition and demolition of at least seven private residences. The public controversy and cost of the land acquisition and relocation and the legal and political implications are considered the fatal flaws of the “zig-zag” alternatives.

4.4 Alternatives 7 and 8 Emergency Bypass Pipe

Alternatives 7 and 8 both employ the concept of an emergency bypass pipe system which would require manpower to connect and/or lay portable pipe after a fault rupture has damaged the existing pipes. Alternative 7 consists of installing a 48-inch bypass pipe similar to Alternative 2 from the two isolation valve vaults to either side of Trace B, ending in outlet manifolds. After a fault rupture, emergency crews would lay portable pipe across Trace B connecting from manifold to manifold. The disadvantages of this alternative are that there will be no water supply after an earthquake until the connection is made and the water supply would be limited by the size of the portable pipes. Alternative 7 would likely not satisfy the post-earthquake water delivery goals.

Alternative 8 includes the full 48-inch bypass pipe from vault to vault of Alternative 2 with provisions for an emergency bypass across Trace B. Isolation valves and outlet manifolds would be installed on the pipe on either side of Trace B to allow connection of portable pipes. Alternative 8 would enable continuous water supply through the 48-inch pipeline after a lesser fault offset. Should a major fault offset occur at Trace B which damages the 48-inch pipeline, the water can be diverted through the emergency bypass. Again, the water supply would be limited by the size of the portable pipes and post-earthquake water delivery goals would likely not be met.

4.5 Alternative 6 Bypass Pipe and Retrofit of Existing Pipes

The components of Alternative 6 are the 48-inch bypass pipe of Alternative 2 and a retrofit of the existing pipelines using steel liners and ball and slip joints. Steel liners would be installed in BDPL 3 at Trace A and Trace C and in BDPL 4 at Trace C. Retrofitting the existing pipes with steel liners was found to be insufficient at Trace B where the expected fault offset is greatest. Therefore, to the south of Trace B, an underground concrete vault with an open end would be installed to house a new flexible assembly on each existing pipe. Each flexible assembly would consist of two ball joints with a 34-foot long slip joint in between that would enable each pipe to rotate and compress to accommodate a fault offset at Trace B. The purpose of the vault is to protect the flexible assemblies and provide the required space for them to move freely during a fault rupture. Because the length of the vault is limited by the width of the roadway median to avoid construction in the roadway, one end is left open to allow lateral movement of the pipes to continue unrestricted into the buried portions under the roadway.

Some advantages of Alternative 6 are estimated construction costs within the project budget, phased construction in which at least two of the three pipes (bypass and BDPLs 3 and 4) remain in service, and limited traffic relocation for construction. However, the perceived advantages of this alternative are outweighed by the disadvantages. As mentioned previously, further review concluded that the bypass pipeline would be reliable only for minor fault offsets at Trace B. Moreover, the short vault with an open end introduces several issues. The first issue is that the short length of the vault restricts the location of the ball and slip joints to south of Trace B rather than a more ideal condition of straddling the fault trace. A second issue is that the stresses and forces from the fault offset would be transferred by the existing pipes under the roadway to the ball and slips joints south of the fault trace. Leaving these pipes in place without any mechanism to address fault movement means consequently accepting existing steel grades, unknown workmanship, changes over time due to aging, and quality of welds. In addition, the open end of the vault will be subject to the ground rupture and attendant soil instability which may lead to failure of the roof and walls of the vault and collateral damage to the pipes.

Alternative 6 was eliminated due to the above design flaws. However, it introduced the concept of installing ball and slip joints in the pipelines within an underground vault to accommodate the large fault offset at Trace B. This concept is the basis for the chosen alternative (Alternative 6A) that was subsequently developed to address the issues with the original Alternative 6.

5. SELECTED ALTERNATIVE

5.1 Alternative 6A Concept

The basic concept of Alternative 6A is to replace the 78-inch and 96-inch diameter BDPLs 3 and 4 with new steel pipes of the same diameter in the Hayward Fault zone. Across the secondary roadway and Trace B, the two new pipes would be housed within individual underground concrete vaults. Each vault would be approximately 19-feet wide by 15-feet tall by 400-feet long. The vault would be designed to “fail” during a fault offset in a controlled articulated manner to protect the pipeline from the surrounding soil in the rupture zone and to provide “rattle” space for the pipelines to move.

Just inside either end of the vaults, a ball and slip joint would be installed in each of the pipelines to allow both rotation and compression of the pipe to accommodate the fault offset. The pipelines would be necked down to either 66 or 72-inch diameter inside the tunnel to minimize the incremental increase in size beyond the largest size of ball and slip joint currently available (60-inch diameter.) Inside the vaults, the pipelines would be supported on sliders to allow additional movement. An illustration of the concept is given in Figure 2.

At Trace A under I-680, the new pipelines would be installed within oversized conduits to accommodate movements resulting from the smaller anticipated fault offset at that location. The new BDPL 3 will be installed in the empty existing 114-inch CMP. An additional 120-inch diameter pipe casing will be jacked under I-680 to house the new BDPL 4. At Trace C in the SFPUC right-of-way, the new pipelines can be buried in “soft” backfill or possibly wrapped in fabric to allow slip between the pipe and the soil.

There are two key advantages of Alternative 6A. Compared to Alternative 6, Alternative 6A has significantly longer vaults that span the entire Trace B fault zone to control and accommodate the deformation in the pipelines. This translates to more control and significantly less uncertainty in the performance of the pipelines at Trace B. Stresses in the pipelines are expected to remain in the elastic range. The vaults respond to fault movement by absorbing compression and lateral offset without damaging the pipelines inside. Alternative 6A explicitly addresses controlled failure by creating a longitudinally segmented vault that will fail at or near the fault rupture in compression as well as shear across its transverse joints. As the joints are successively offset with respect to each other in the zone of concentrated fault movement, the vault will adjust to the ground deformation without impairing the pipeline within.

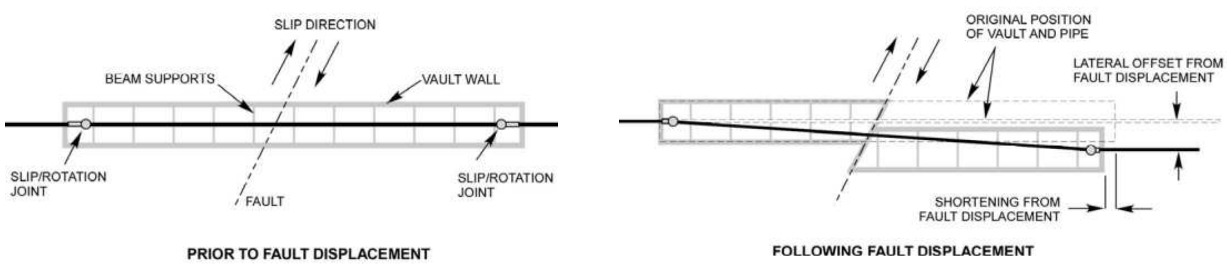

Figure 2. Selected Alternative Fault-Crossing Concept

5.2 Jacking vs. Cut and Cover Construction

Originally, to minimize traffic impacts, the construction method for the concrete vault was to jack box segments from either side of the road. This method introduced inherent complexities since the box segments had to be of certain length and strength to be jacked. The articulation joints would have to be cut and widened after the box is in place. In addition, the boxes would be jacked under existing major utilities in the roadway and the proposed 400-foot drive exceeds known experience with respect to length by about 40 feet.

Consideration of these issues led to negotiations with the California Department of Transportation (Caltrans) to employ cut-and-cover construction through the freeway on-ramps and roadway. The proposed method of traffic relocation is to install temporary bridges on the on-ramps and roadway to allow traffic to continue above while excavation and construction of the concrete vault takes place below. In that way, the concrete vault can be installed in precast segments with the joints in their final configuration.

5.3 Laboratory Testing

As Alternative 6A includes innovative concepts that have not been completely tested in an earthquake, it will be advantageous to conduct scaled tests to confirm behavior, assess in detail the interaction among different components, and optimize the longitudinal separation of joints. Large-scale (not full scale) tests are feasible and will be performed in a shear box using joint configurations that are promising to verify the soil-structure interaction of the longitudinally segmented vault with transverse joints

As part of the design of this project, large-scale tests of the vault are planned to be conducted at Cornell University in Ithaca, New York. The tests will include four 1/10 scale models of the concrete vaults and one

1/5 scale model. Possible testing parameters include the design width of the joints, the spacing of the joints and length of the vault sections, the orientation of the joints whether parallel to the fault (at 45 degrees to the pipe) or perpendicular to the pipes, and the type of backfill required (whether soft or conventional) around the vault.

In addition, the ball and slip joints required for the project are 10 to 20% larger in diameter than those currently available on the market. As a result, the first of these joints will be tested in the factory to verify rotation and compression capacity and behavior in a simulated fault offset.

6. CONCLUSION

Extensive alternative studies and input from industry experts have led to a seismic upgrade concept that meets the unique challenges of this project. The compression crossing of large-diameter pipelines across a major fault zone in a congested urban area has been successfully addressed at a conceptual level. The next steps of the project are to verify the components of the innovative concept by laboratory testing and to begin developing the design details of the articulated vault and the pipeline. Major effort will also be required to coordinate with Caltrans and utility agencies to develop acceptable plans to relocate traffic and utilities during construction, and to support the review process and obtain all necessary permits. This exciting project will continue to provide challenges at every stage through design, permitting, and into construction.

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