Mitigating Risk to Underwater Crossings to Improve Water Supply Reliability: Two Case Studies

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ABSTRACT

Isolated segments of the East Bay Municipal Utility District's (EBMUD) raw water aqueducts and large diameter transmission pipelines are at risk of breaking as a result of seismically-induced liquefaction at underwater crossings, which may significantly limit potable water supply for EBMUD's 1.4 million customers in the San Francisco East Bay Area. This paper examines two case studies that highlight alternative approaches that can be used to mitigate risk of failure: the first considers potential levee failures in the Sacramento-San Joaquin Delta (Delta), as a result of a low-probability seismic event that could result in structural damage to EBMUD's raw water aqueducts at river crossings; the second considers failure of transmission pipes that supply potable water to Alameda Island, a city of about 80,000 residents that depends solely on underwater pipeline crossings for its water supply.

The first case study is Mokelumne Aqueduct No. 3, a major pipeline that crosses three rivers. While the probability of seismic damage is relatively low, as Aqueduct No. 3 was seismically retrofitted in 2003, the consequence is high because the pipeline is a major supplier to 1.4 million customers. To mitigate the risk of structural failure to Aqueduct No. 3, and to the other older and nonretrofitted Mokelumne Aqueduct Nos. 1 and 2, EBMUD installed cross connections among these three raw water aqueducts at both ends of the Delta to allow damaged sections to be bypassed. To further mitigate the risk to its raw water supply, EBMUD developed a repair plan and approach that identifies how raw water service could be restored within 6 months, utilizing a bypass scheme of floating in-place and sinking to the river bottom six 32-inch diameter high density polyurethane bypass pipes, and by connecting these pipes to Mokelumne Aqueduct No. 3 using manifolds on both sides of the river.

The second case study involves treated water pipelines supplying water to Alameda, an island with no water storage facilities. Four underwater pipeline crossings currently supply water to the island including some 16- to 24-inch diameter cast iron pipes installed between 1918 and 1946, located in potentially liquefiable soil with a high likelihood of failure. Results of a Crossings Master Plan study determined that failure of any one of the crossings could lead to a reduction in the level of service to Alameda Island, and recommended three new 24-inch diameter pipeline crossings and in-street pipelines connecting the new crossings to existing transmission pipelines.

This paper summarizes the process used to assess the vulnerability of underwater crossings for these two case studies and identifies mitigation strategies to improve water supply reliability considering both the likelihood and consequence of failure. This includes process used to evaluate underwater crossing alternatives, considering various alignment options and construction methods including micro-tunneling, horizontal directional drilling, and float-and-sink, as well as other criteria including cost, constructability, survivability, speed of repair, and environmental factors. The process used to select an alignment and construction method for the first Alameda crossings replacement is discussed, including design details to reduce potential for differential settlement.

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INTRODUCTION

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.4 million customers on the eastern side of the San Francisco Bay. The EBMUD water system is comprised of 167 reservoirs, 132 pumping plants, 29 embankment dams, 5 water treatment plants, 90 miles (145 kilometers) of raw water aqueducts, and approximately 4,200 miles (6,800 kilometers) of treated water distribution and transmission pipelines. Figure 1 presents EBMUD's water supply infrastructure and service area.

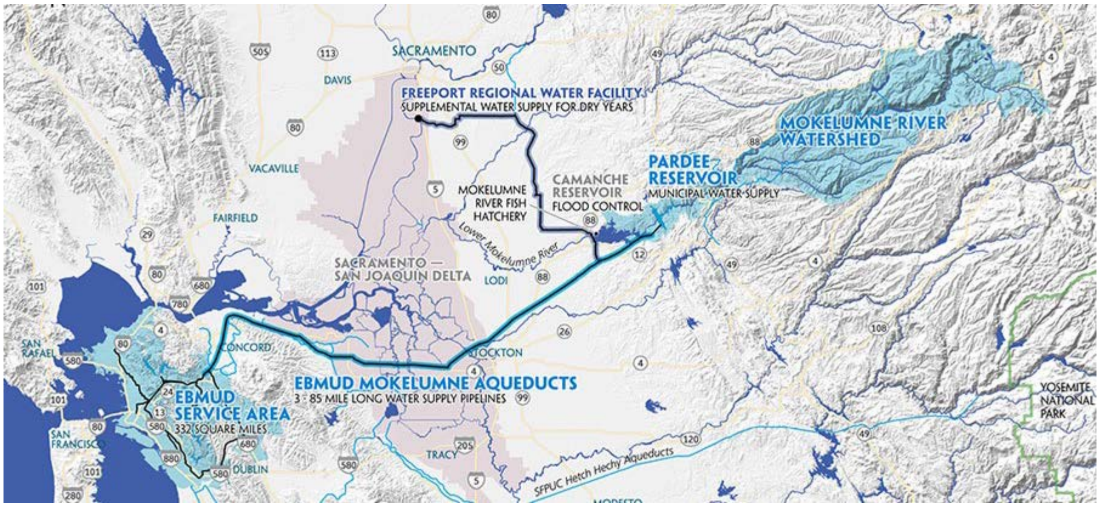

Figure 1: Map of EBMUD Water Supply and Service Area

Completed in 2007, EBMUD's $189 million Seismic Improvement Program (SIP) retrofitted 13 building structures, 70 storage reservoirs, 130 pumping plants, 5 water treatment plants, 56 pipeline fault crossings, 18 upgrades in areas of landslides and liquefaction, and 8 transmission system upgrades. These upgrades included $55 million for transmission system and $50 million in fault crossings improvements to meet various service level goals. The seismic improvement philosophy was to upgrade critical links for overall system performance, rather than fix every component of the system that could be damaged [1].

EBMUD's SIP, however, proved too costly to replace the nearly 2,400 miles of cast iron and asbestos cement pipes. Results of a recent study indicate that an earthquake sequence that begins with a Hayward Magnitude (M_w) 7.0 rupture of the Hayward Fault and 16 M_w 5.0+ aftershocks would cause on the order of 5,500 breaks and leaks that would take up to about 6 months to repair [2]. These estimates are consistent with results of EBMUD's 1994 SIP studies, which indicated that the extent of damage to distribution pipelines as a result of a M_w 7.0 earthquake would include more than 4,000 leaks and breaks, and that nearly 90% of the pipe damage would result from breaks in cast iron and asbestos cement pipe [3]. A majority of these breaks and leaks are expected to occur on smaller diameter (<300 mm) distribution pipes located in paved streets, which are relatively more accessible by emergency repair crews.

Of particular concern are breaks or leaks that could occur to underwater transmission pipeline (≥ 20-inch or 500mm in diameter) crossings that could take months to repair and could significantly impact EBMUD's water supply after an earthquake. This paper examines two such underwater crossings and discusses the approaches that EBMUD adopted to mitigate the risk of failure: the first is a “low risk, high consequence” example that considers potential levee failures in the Sacramento-San Joaquin Delta (Delta) from a low-probability seismic event that could cause structural damage to EBMUD’s raw water aqueducts at river crossings; the second is a “high risk, high consequence” example that considers failure of transmission pipes that supply potable water to Alameda Island, a city of about 80,000 residents that depend solely on underwater pipeline crossings for its water supply.

SEISMIC SETTING

The highly active Hayward Fault dominates EBMUD’s risk profile. This fault, capable of earthquakes of M_w 7.25, has produced major earthquakes on average every 140 years, with the last damaging earthquake occurring in 1868. According to the United States Geological Survey (USGS), the overall probability of a magnitude 6.7 or greater earthquake in the Bay Area in the next 30 years is 63%. The earthquake probability is highest for the Hayward Fault system, at 31%. As shown in Figure 2A, EBMUD’s service area is bifurcated by the Hayward fault, and dozens of critical facilities are located within a few hundred meters of the Hayward Fault.

Beyond the Hayward Fault, several other faults threaten EBMUD’s system, ranging from the larger San Andreas Fault in the west, the Calaveras and Concord Faults in the east, and the Central Valley fault in the Delta (see Figure 2B). The two case studies in this paper consider an earthquake event from the Central Valley Thrust Fault or the Midland Fault Zone, which could impact the Mokelumne Aqueducts at river crossings in the Delta, and an M_w 7.0 event on the Hayward fault, which could impact pipeline estuary crossings that provide water to the island of Alameda.

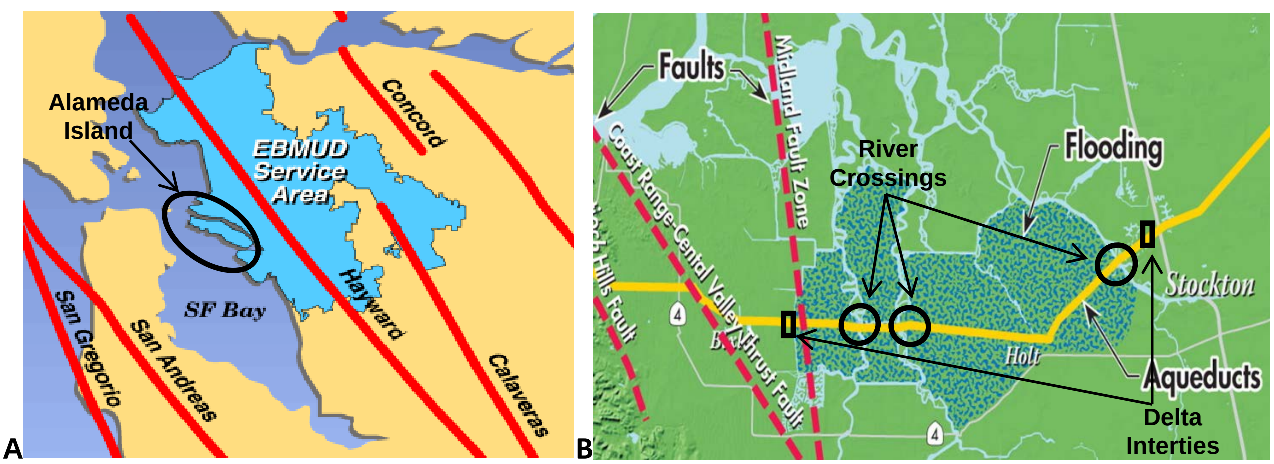

Figure 2: Fault Maps for EBMUD Service Area & Aqueducts in Delta Region

VULNERABILITY ASSESSMENT

Pipelines are susceptible to damage or failure as a result of seismic hazards like ground failure and ground motion. Ruptures or severe distortions of pipelines most often arise from fault movements, landslides, liquefaction, loss of support, or differential motion at interfaces [4]. The consequence of a pipeline failure, as a result of a seismic hazard, depends on a number of factors, including reparability (i.e. time to repair and restore service), level of service impacts, and customer

criticality, just to name a few. Failure of an underwater pipeline crossing presents a significant challenge in terms of damage assessment, accessibility, time to complete repairs, and cost.
The risk and consequence of a liquefaction-induced failure of underwater crossings located in the Delta and in Alameda vary significantly:

- **Low Risk, High Consequence Example -- Mokelumne Aqueduct No. 3 River Crossings:** While the risk of a liquefaction-induced failure of Aqueduct No. 3 is considered low, the consequence of such a failure is considered to be high if repairs cannot be completed within 6 months.
- **High Risk, High Consequence Example – Alameda Transmission Pipelines Estuary Crossings:** The risk of failure of three out of four in-service underwater estuary crossings to Alameda is considered to be high, and the consequence is considered relatively high as well.

These two case studies consider the seismic risk, consequence of failure, and the different strategies that EBMUD adopted to mitigate the risk and consequence of failure.

Case Study 1: Low Risk, High Consequence of Damage to a Raw Water Supply System

The Mokelumne Aqueducts consist of three large diameter pipelines of up to 87-inches (2,200 mm) in diameter that are the sole water supply to 1.4 million people in Northern California. EBMUD relies on these three aqueducts for its raw water supply, which are most vulnerable when they are above ground and cross the Delta. Natural Delta hazards include potential levee failures, flooding, land subsidence, and liquefaction. In 2017, EBMUD developed a strategy to determine how to protect its aqueducts in the Delta. This study evaluated hazards and risks to the aqueducts and alternative options to mitigate those hazards and risks [5].

As part of its SIP, EBMUD evaluated alternatives to seismically upgrade eight miles of elevated pipe, five miles of buried pipe, and three river crossings in the Delta region. The largest and newest of its three aqueducts, Mokelumne Aqueduct No.3, was upgraded to withstand a magnitude 6.7 earthquake. Upgrades included reinforcing levees and strengthening pipe joints at three river crossings. The two older and smaller of the three aqueducts, Aqueducts Nos. 1 and 2, were not seismically retrofitted and, therefore, have a much higher risk of failure in the Delta in the event of a large earthquake compared to Aqueduct No. 3.

<u>Aqueduct No. 3 River Crossing Alternative Repair Study</u>

Despite these seismic upgrades, which were completed in 2003 at a cost of $38 million, there remains a risk that Mokelumne Aqueduct No.3 could break or leak as result of liquefaction-induced levee failure at one of the river crossings, as a result of an earthquake with a return period greater than 500 years. While the probability of such an event is low, the consequence would be significant if repairs cannot be completed within 6 months, which is equivalent to EBMUD’s terminal raw water storage capacity.

To address that risk, EBMUD conducted a study that outlined the initial response and provided conceptual repair plans in the event of a major failure of Mokelumne Aqueduct No. 3 [6].

A major aqueduct and river crossing failure is defined as severe damage with all three aqueducts being severed and water flow interrupted. The study concludes that conventional repair methods for a major river crossing failure, using sheeting and trenching, would take approximately 8 months to complete. An 8-month return-to-service period was deemed unacceptable because the District’s current terminal storage cannot sustain customer demands for longer than 6 months. Additional conceptual design work was, therefore, undertaken to explore alternative repair methods that could result in a 6-month return-to-service. The resulting mitigation measures and conceptual plans that were developed are discussed in more detail in the next section of this paper under "Mitigation Strategies."

Delta Interconnections

Given the high probability of Aqueducts Nos. 1 and 2 suffering significant structural damage in the Delta from a catastrophic earthquake, EBMUD developed plans to interconnect all three of its aqueducts. In 2012, the District completed a $15 million project to interconnect its aqueducts on either side of the Delta. This will allow EBMUD to use surviving portions of Aqueducts Nos. 1 and 2 outside of the Delta to increase the raw water supply that can be delivered through Aqueduct No. 3 following an emergency. As shown in Table 1, these interconnections will allow EBMUD to significantly increase the flow of raw water that can be delivered to EBMUD's service area after an emergency.

TABLE I: Aqueduct Flow Capabilities With and Without Delta Interconnections

	Aqueducts In-Service			**Total Water Supply (MGD)**	
Condition	**No. 1**	**No. 2**	**No. 3**	**Pumped**	**Gravity**
Normal Operations	Yes	Yes	Yes	326	196
Delta Emergency (w/o Interties)	No	No	Yes	172	107
Delta Emergency (w/ Interties)	*Partial*	*Partial*	*Yes*	*256*	*166*

Case Study 2: High Risk, High Consequence of Damage to a Distribution System

Alameda is an island with no water storage facilities that relies on four underwater pipeline crossings for its water supply. Three of these crossings are cast iron pipes (installed between 1918 and 1946) located in potentially liquefiable soil, and have a high risk of failure that could result in a reduction in the level of service to Alameda. A Crossings Master Plan study evaluated failure of any one of the crossings and recommended three new 24-inch diameter pipeline crossings and in-street pipelines connecting the new crossings to existing transmission pipelines.

During an earthquake event, the risk to pipeline failure is the presence of young bay mud (YBM) and liquefiable soils. YMB is soft, unconsolidated silty clay, which is saturated with water. YBM has a low likelihood of liquefaction but remains a seismic hazard due to high seismic shaking amplification; the stresses associated with this amplification can rupture a pipeline that traverses through or above YBM. Liquefiable soils and artificial fill are present throughout the Oakland-Alameda estuary and are both susceptible to liquefaction. Lateral spreading during liquefaction can stretch the pipeline to the point of breakage.

Three of the four in-service crossings have severe risk of failure caused by a seismic event based on subsurface soil types, potential for liquefaction, shaking amplification, and the pipeline depth and alignment relative to these soil types. Two of these pipeline traverse through loose and liquefiable sandy layers in the submarine portion and through artificial fill at the approaches, putting these pipeline at high risk of later spreading and pipe failure. These pipes also traverse YBM at the approaches, which can undergo large amplifications of seismic-induced shaking and break pipe during a seismic event. Though information is limited for the third pipe, a sand layer appears to be in both approaches and can pose a risk to liquefaction and lateral spreading. In addition, liquefaction risk cannot be ruled out. The fourth crossing is at low risk of failure from a seismic event since it is embedded deep in relatively stable soil and traverses mostly through a silty clay layer, which does not pose a high risk to the pipeline.

MITIGATION STRATEGIES

Case Study 1: Low Risk, High Consequence of Damage to a Raw Water Supply System

As previously discussed in this paper, EBMUD completed a study and developed conceptual design work to explore alternative repair methods that would result in a 6-month return-to-service in the unlikely event of a major aqueduct failure. This study evaluated different alternatives and presented a conceptual design that focused on the use of non-conventional construction methods using High Density Polyethylene (HDPE) pipe for repair of a major river crossing failure at Old, Middle, and/or San Joaquin River.

Multiple joint-failures constitute a major failure of Mokelumne Aqueduct No. 3 at a river crossing. The Mokelumne Aqueduct No. 3 seismic upgrades completed in 2003 involved reinforcing the pipe joints at all three river crossings, which significantly reduced the potential for a major river crossing failure. Based on the seismic analyses performed during the upgrade evaluations, it is not expected that joints will fail during the 500-year design earthquake [6]. At worst, it was estimated that there would be no more than 3 failed joints, one for each river crossing, as a result of a 500-year event. This type of failure would be considered relatively *minor* and would likely involve repairs using conventional construction methods that could be completed within 6 months. The probability of a *major* failure at a river crossing is considered low and is not expected during the 500-year design earthquake.

A detailed plan was developed to address the low probability/high consequence event of having a *major* river crossing failure of Mokelumne Aqueduct No. 3. The goal was to determine if repairs could be completed within 6 months following a major event in order to restore raw water capacity to 174 MGD. As discussed below, it is estimated that a temporary repair could be accomplished within 6 months by floating in place and sinking to the river bottom a total of six 32-inch (800 mm) diameter HDPE pipes, and by connecting these HDPE pipes to the existing Aqueduct No. 3 using manifolds on both sides of the river. The HDPE pipe repair concepts and details are illustrated on Figure 3, and are discussed in more detail below.

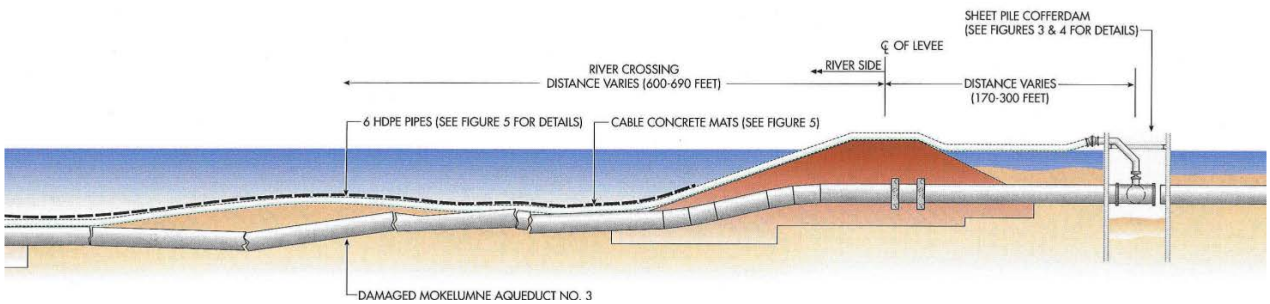

Figure 3: Aqueduct No.3: HDPE Temporary Float and Sink River Repair Concept

EBMUD developed a construction schedule for completing a river crossing repair using this method with input from contractors and the HDPE pipe distributor and manufacturer. Based on this detailed schedule analysis, EBMUD estimates that repair work could be completed and temporary service could be restored within 6 months (approximately 25.5 weeks).

This estimated repair timeline includes 1.5 months for damage assessment, preliminary design, and contract negotiations, 2.5 months for material acquisition, and 3 months for construction (some tasks have to be done concurrently, adding up to 6 months to return Aqueduct No. 3 to service). This timeline assumes use of two construction crews to install the cofferdam/manifold on both sides of the river at the same time, and includes installation of approximately 1,300 feet of HDPE pipe between connections. The schedule analysis also incorporates the estimated duration and interdependencies of various tasks required to complete an emergency river crossing repair.

Conceptual Design Details and Construction Sequence

The design concept for river crossing repair (illustrated in Figures 3 and 4) includes installing a manifold and connecting six 32-inch diameter HDPE pipes, with pipe diameter ratio (DR) of 9 (252 psi pressure rating), to the buried aqueduct at the levee. Manifolds would be connected to the existing buried portion of the aqueduct and installed as close as possible to the edge of the levees to reduce the lengths of HDPE pipes required for repair.

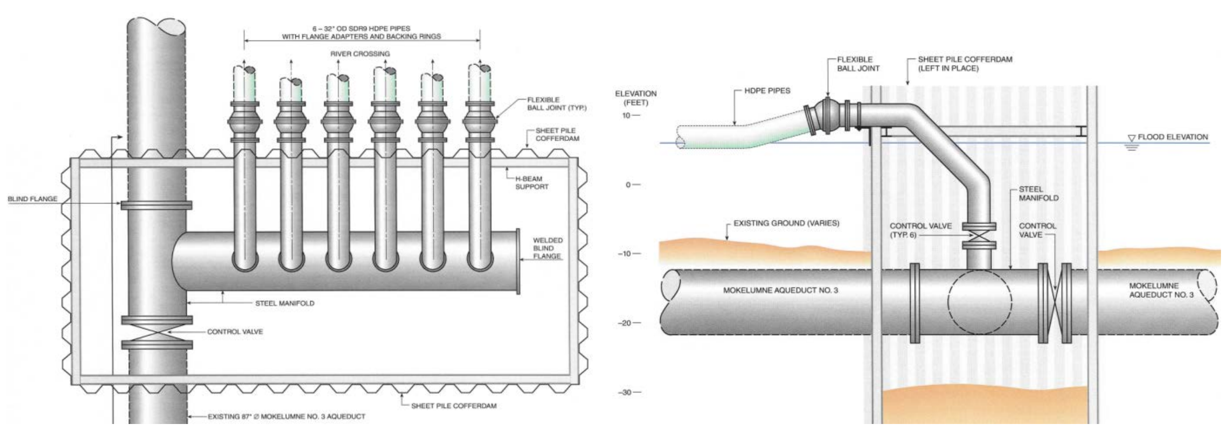

Figure 4: Aqueduct/HDPE Pipe Manifold, Levee Connection Detail: Plan & Section

The anticipated construction sequence for repairing river crossings with HDPE pipes using the "float and sink" method would be as follows.

1. Install a sheet pile cofferdam on each side of the river banks, as illustrated in Figures 3 and 4.

    a. Dewater and excavate to expose the existing aqueduct inside the cofferdam.

    b. Remove a section of the aqueduct and connect the pre-fabricated manifold and connection fittings.

    c. Deliver HDPE pipes to a designated staging area where fusion of the pipes, storage of materials, and other logistic will take place.

    The fusion of pipe joints is a process that could be done on barges, should the entire area near a river crossing failure be flooded.

2. Float the entire length of the assembled HDPE pipe into position.

3. Place pre-cast concrete ballast blocks at predetermined spacing and fill the entire length of HDPE pipe with water to sink the assembled pipe to the bottom of the river. The pipe could be arranged either in single, twin or triple line configurations. The ballast blocks may be installed on shore or on the water (on a low-profile barge), depending on the contractor's preference and any environmental restrictions in effect at the time of repair.

4. Perform the placement of the pipe in a controlled fashion, with marine surveyors directing the alignment and position of each pipe prior to sinking a segment of pipe, to ensure that it falls within the designated alignment/corridor.

5. Continue this process until all six HDPE pipe segments are placed in their proper location.

6. Place cable concrete mats on top of the HDPE pipe at the river bottom to protect the installed pipes from damage.

7. Install earth anchors, if needed, to keep the concrete mats in place.

8. Connect the 32" diameter HDPE pipes to the manifolds at aqueduct (see Figure 4).

9. Flush the HDPE pipes and restore service for Mokelumne Aqueduct No. 3.

Case Study 2: High Risk, High Consequence of Damage to a Distribution System

<u>Master Planning Efforts</u>

Water service to the City of Alameda (Alameda) is provided by four existing underwater pipeline crossings at three separate locations between the City of Oakland (Oakland), Alameda Island, and North Bay Farm Island (see Figure 5). Failure at any of the three crossing locations could lead to a reduction in the level of service for existing customers and potentially reduce the available water supply to Alameda Island and North Bay Farm Island.

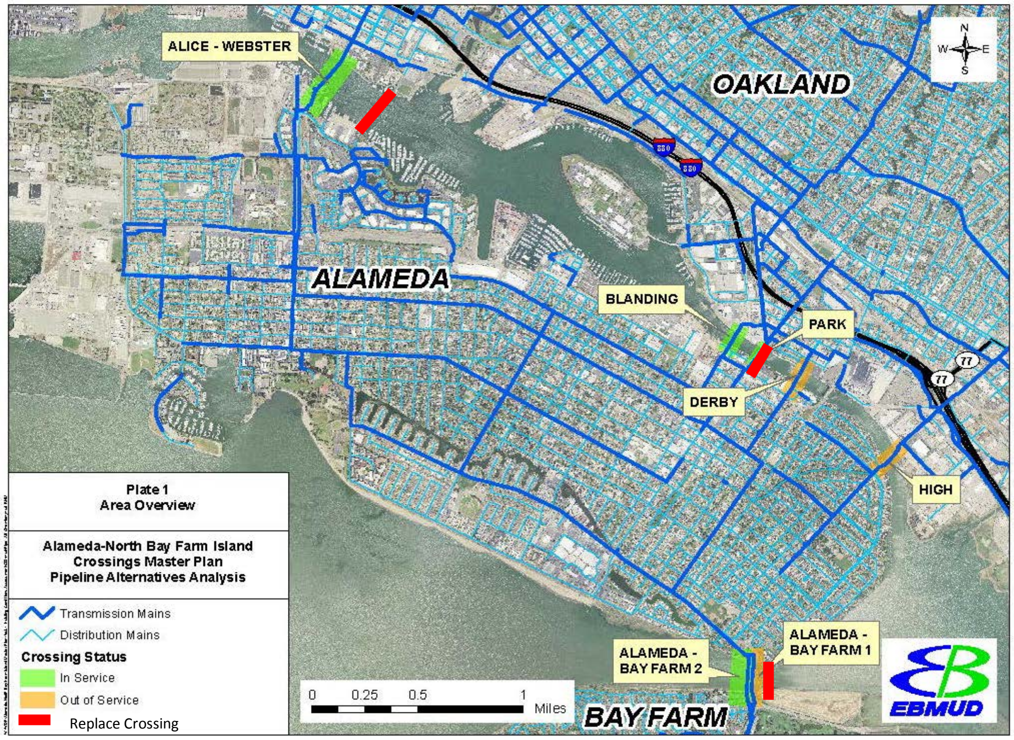

Figure 5: Alameda Crossings. Map Showing All Estuary Crossing Locations

In 2014, EBMUD completed the Alameda-North Bay Farm Island Crossings Master Plan, which recommended three new 24-inch (600 mm) diameter submarine pipeline crossings to be installed using horizontal directional drilling (HDD) and associated 24-inch, in-street pipelines connecting the crossings to existing transmission pipelines. EBMUD's goal is to replace three of the four existing pipeline crossings within the next 6 years to improve the long-term reliability and redundancy of the water distribution system, meet existing and future water needs, and facilitate future repair and maintenance [7].

The master planning effort, which was initiated in 2013, identified the need for three new crossings and replacement of in-street pipelines located in potentially liquefiable soil, to create a network of seismic-resilient pipes to improve the reliability of the water supply system to Alameda:

- **Crossing No. 1, Oakland Inner Harbor:** Approximately 10,500 feet of in-street pipeline in Oakland and on Alameda Island, and approximately 1,800 feet of underwater pipeline crossing.
- **Crossing No. 2, San Leandro Bay Channel:** Approximately 4,200 feet of in-street pipeline on Alameda Island and Bay Farm Island, and approximately 1,400 feet of underwater pipeline crossing.
- **Crossing No. 3, Tidal Canal:** Approximately 3,800 feet of in-street pipeline in Oakland and Alameda Island and approximately 1,400 feet of underwater pipeline crossing.

The approximate locations of these three replacement crossings are shown on Figure 5. The overall project scope will include abandoning existing crossings as these new crossings are constructed. EBMUD recently completed the planning effort, including an Environmental Impact Report (EIR) for all three crossings, and is currently proceeding with the design for the first crossing replacement, Crossing No. 1, which is shown in Figure 6A. Crossing No. 1 includes installation of 1,800 feet of

24-inch (600 mm) HDD pipeline under the Oakland Inner Harbor estuary, and 10,500 feet of connecting 24-inch (600 mm) pipeline on each side of the estuary, to replace in-street pipeline located in potentially liquefiable soil in Oakland and Alameda (see Figure 6B), for an estimated total cost $15 million. Crossing No.1 is scheduled for completion in 2020 and construction for Crossing Nos. 2 and 3 are currently scheduled for completion by 2023.

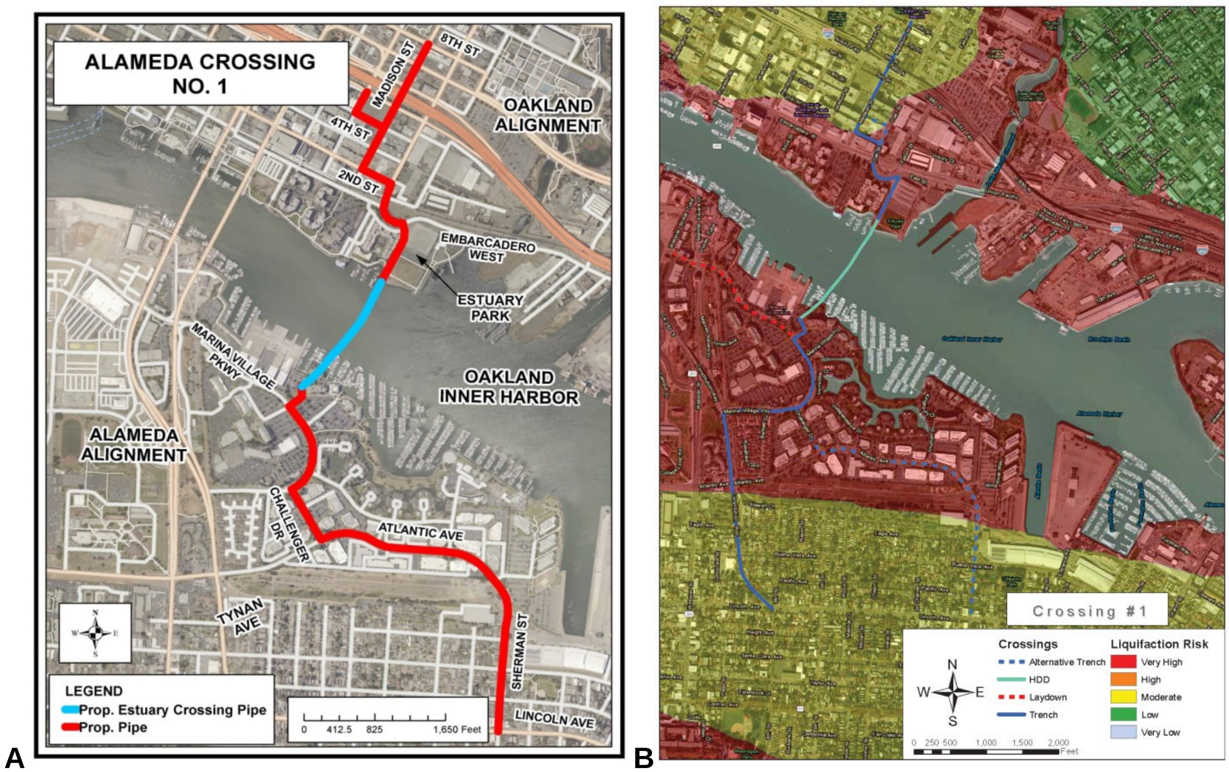

Figure 6: Alameda Crossing No. 1 New Crossing Location & Extent of Liquefaction

<u>Alternatives Evaluation</u>

Eleven alternative alignments were identified, as part of the Master Plan and EIR analyses, based on the need for adequate construction staging, length of the underwater crossing, and close proximity to the existing distribution grid and backbone piping on both sides of the crossing. These alignments were narrowed down to four preferred alignments based on construction accessibility on both sides, distance of additional piping needed to connect to a reliable transmission main, geology and geotechnical considerations, and construction costs.

Multiple design and construction approaches were developed for each of the four preferred alignments with the goal of maximizing survivability and minimizing repair-related water service outages attributable to a major seismic event. Microtunneling and HDD were identified as the two most feasible trenchless construction methods for the crossings. To avoid unstable ground conditions, deeper underwater pipeline crossings are needed, so both construction methods were developed to be in the deeper, more stable ground conditions.

Microtunneling consists of a jacking shaft from which the microtunneling boring machine (MTBM) and casing are advanced to a receiving shaft for retrieval of the MTBM. The shaft depths were selected to place the underwater tunnels below the fill and YBM and into the deep stable soils not prone to liquefaction. Three concepts for the water main riser pipe through the shaft to the surface connection were explored, including concrete encasements, structural backfill, and free-standing. These alternatives were evaluated based on protection against failure versus ease of access for future maintenance.

HDD is a three-stage construction method which originates from the surface. A U-shaped pilot hole is drilled, reamed and enlarged to the required size, and the carrier pipe is pulled into the hole. The depth of the crossing is dictated by the clearance requirements of the water body and to locate the crossing within a particular suitable soil horizon.

Design Details

The entry and exit angles will be 10-15 degrees. Oversized conductor casings are required at each end of the HDD to control fluid pressures to prevent hydraulic fracturing to the surface. The conductor casing is installed using pipe ramming up to 200 feet in length. Based on a 15-degree entry angle, the casing would reach a depth of 50 feet, which is the approximate boundary between liquefiable and non-liquefiable soils. The entry and exit pits will be located at least 200 feet onshore to allow installation of 200-foot conductor casings and associated ground improvements before the pipeline is under the estuary.

In order to ensure the HDD crossing is housed in non-liquefiable soils from surface to surface, ground improvements via jet-grouted columns will be incorporated as part of EBMUD's design to support the conductor casings in the liquefiable soils. These jet-grouted columns are 8 feet (2,400 mm) in diameter and spaced approximately 20-feet center-on-center. The conceptual design detail developed to reduce potential for differential settlement due to liquefaction, is shown in Figure 7.

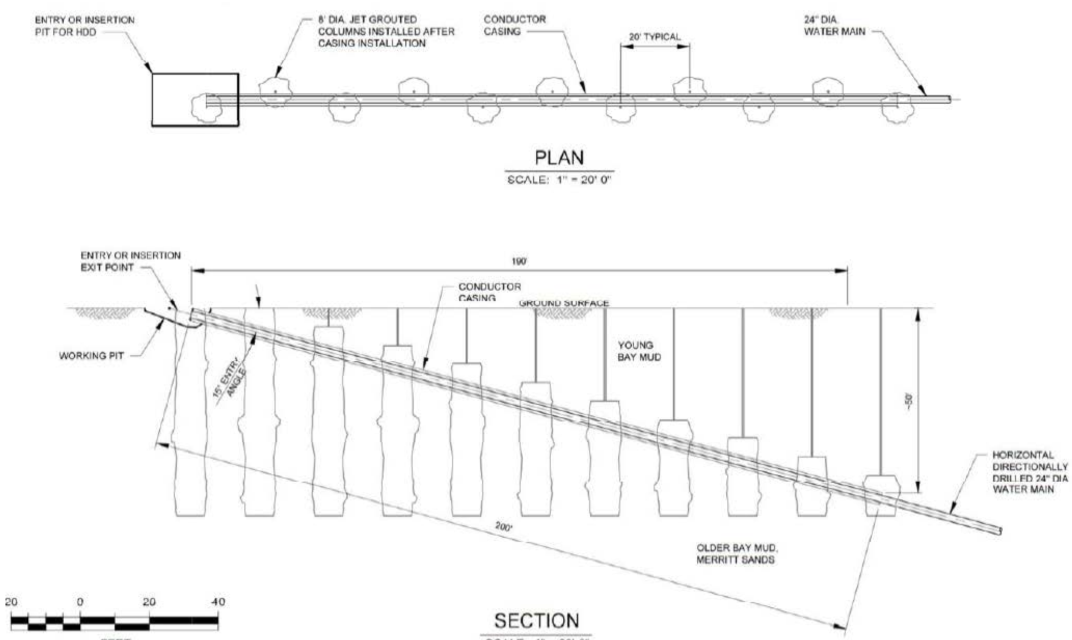

Figure 7: Jet-Grouting Support Concept for HDD Crossing No. 1

CONCLUSIONS

This paper summarizes the process EBMUD used to assess the risk and consequence of breaks to isolated segments of large diameter underwater pipeline crossings as a result of seismically-induced liquefaction, and the alternative approaches that can be used to mitigate the risk of failure.

In the first case study, a low-probability seismic event that would result in the failure of all three raw water aqueducts is considered. For this scenario, EBMUD adopted a two-pronged mitigation strategy that relied on the use of (1) interconnections at both ends of the Delta to allow damaged sections to be bypassed in the event of a failure of one or both of EBMUD's oldest and most vulnerable aqueducts, and (2) six HDPE bypass pipes installed using a "float and sink" method, and connected by manifolds on both sides of the river, which could be installed in the event that EBMUD's newest and most robust aqueduct suffers significant damage at a Delta river crossing.

The second case study considers a high-probability seismic event that could result in the failure of three of the four in-service estuary crossings that the Island of Alameda solely depends on for its potable water supply. Given the relatively high risk and consequence of such an event, which could reduce service to about 80,000 residents, EBMUD completed a Master Plan assessing the reliability and redundancy of the water supply and distribution system for Alameda and initiated the design to replace the first of three new crossings. A detailed analysis and evaluation of alternatives was used to select the location, installation method, and design details for the first crossing and connecting pipelines. The use of an HDPE pipeline, installed using HDD with conductor casings and jet-grouted columns to reduce potential for differential settlement in liquefiable soils, was ultimately selected as the preferred option. Crossing No.1 is currently in design and scheduled for completion in 2020 and construction for Crossing Nos. 2 and 3 are currently scheduled for completion by 2023.

This paper demonstrates the different approaches that can be considered and the advantages of adopting significantly different mitigation strategies that take into account the likelihood and consequence of failure of underwater pipeline crossings. In a "low risk, high consequence" scenario, water agencies should consider the use of alternative construction methods, such as "floating and sinking" HDPE pipelines in place, to restore temporary service while permanent repairs or replacement of a failed crossing can be completed. In a "high risk, high consequence" scenario, water agencies should consider underwater crossing alignment options and construction methods, such as micro-tunneling and HDD, given cost, constructability, survivability, speed of repair, and environmental factors.

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