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Main Shock and After Shock Impact to Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines

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ABSTRACT

The East Bay Municipal Utility District (EBMUD) is a major water utility providing drinking water to over 1.4 million people on the eastern side of the San Francisco Bay Area. The EBMUD water system comprises approximately 144 storage tanks, 132 pumping plants, 22 active dams, 7 water treatment plants, 6760 km of treated water distribution and transmission pipelines, and 270 miles of raw water aqueducts. The EBMUD service area encompasses over 331 square miles of varying topography. EBMUD has created a damage prediction model to aide in the rapid fragility assessment of all critical infrastructure, which can reduce recovery time.

The published document entitled “Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines” (Prashar, et al. August 2012) provides the introductory framework to this paper. Estimating the level of ground shaking at any particular site is the critical input in developing the expected performance of any given structure. Forecasting aftershock levels at sites of critical facilities will assist in establishing the likelihood of further damage to our facilities and guide response and recovery decisions. The damage prediction models provide results for the water system components of EBMUD’s water system.

This paper discusses the development of the damage prediction models for EBMUD’s water system for embankment dam reservoirs, tank reservoirs, and large diameter pipelines; damage results related to the two Hayward Fault scenario earthquake and aftershock events; and the next steps for damage prediction to increase robustness in the water system. A revised approach to developing a more comprehensive EBMUD infrastructure risk model is presented. The probability of failure is revisited in this approach of considering the contribution of aftershocks in rapid modeling of infrastructure fragility.

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INTRODUCTION

About EBMUD

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.4 million people on the eastern side of the San Francisco Bay. The EBMUD water system comprises approximately 144 supply reservoirs, 132 pumping plants, 22 embankment dams, 7 water treatment plants, 6760 km of treated water distribution and transmission pipelines, and 435 km of raw water aqueducts.

Figure 1 shows EBMUD's service area which encompasses over 860 square kilometers of varying topography. With such a large water system to manage and operate in an area prone to destructive earthquakes, emergency response can be an overwhelming task following an earthquake. As a result, EBMUD created damage prediction models to prioritize field inspections of the water system and help accelerate emergency response and recovery time.

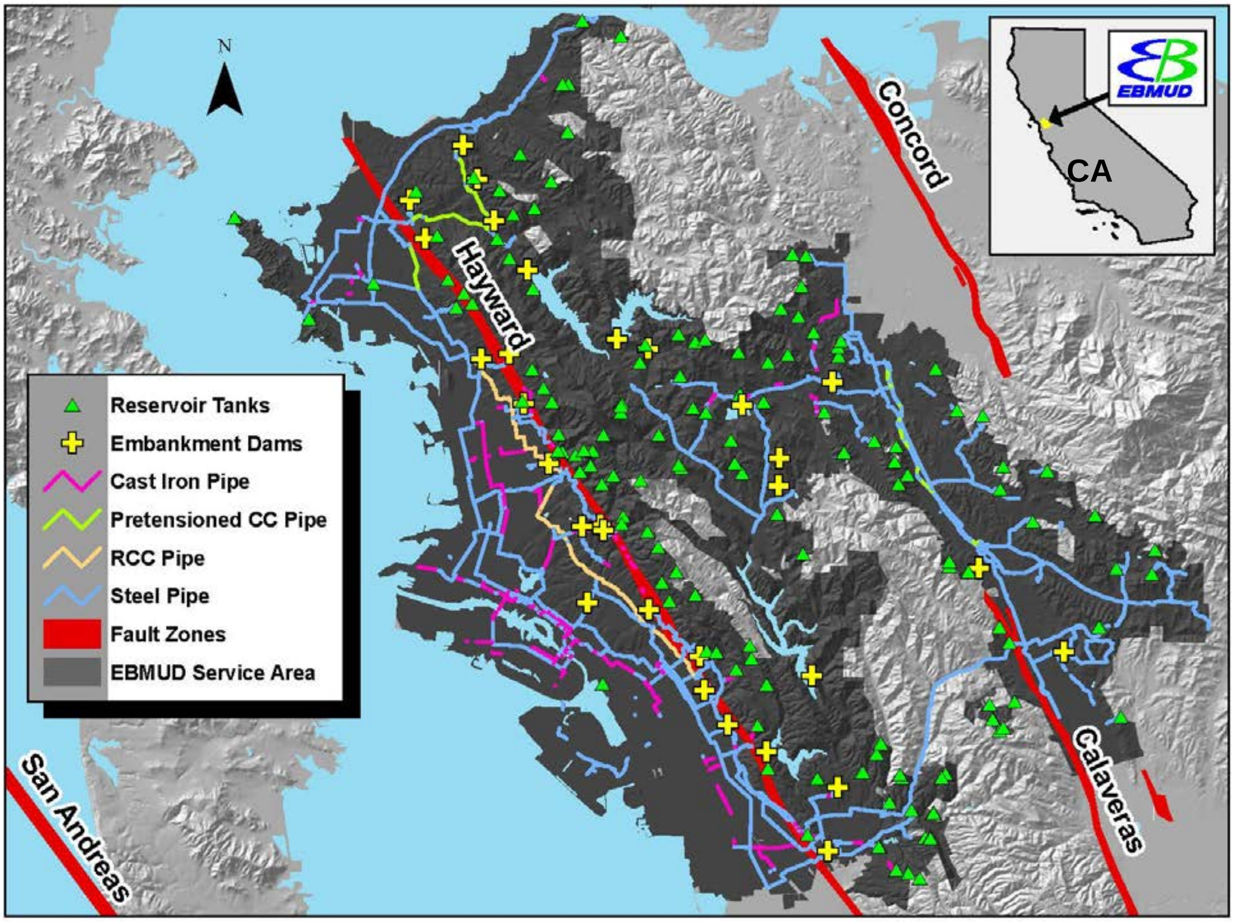


Figure 1: EBMUD Location Map

Background

The published document entitled “Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines” [5] provides the introductory framework to this paper. Estimating the level of ground shaking at any particular site is the critical input in developing the expected performance of any given structure. United States Geological Survey (USGS) provides computational tools in developing these estimates of ground motions. Additionally, spreadsheet tools containing the Next Generation Attenuation relationships can be calculated to estimate ground motions based on earthquake magnitude, distance, and shear wave velocity. Fortunately for EBMUD, the USGS has developed a revised set of specific scenario events [16] for the rupture of the Hayward Fault which is the main fault of concern in the service area. This study relied on using GIS as an evaluation tool by injecting scenarios and extracting strong ground motions (acceleration, velocity) parameters at specific sites. The site-specific results were evaluated and are presented below for District Dams, tanks and large diameter pipelines.

USGS Earthquake Scenario Events

A scenario represents one realization of a potential future earthquake by assuming a particular magnitude, location, and fault-rupture geometry and estimating shaking using a variety of strategies. In planning and coordinating emergency response, utilities, local government, and other organizations are best served by conducting training exercises based on realistic earthquake situations—ones similar to those they are most likely to face. ShakeMap Scenario earthquakes can fill this role. They can also be used to examine exposure of structures, lifelines, utilities, and transportation corridors to specified potential earthquakes. A ShakeMap earthquake scenario is a seismic map based on with an assumed magnitude and location, and, optionally, specified fault geometry.

The Hayward-Rodgers Creek fault system has the highest probability (33%) for a large rupture (Mw>6.7) on the major faults in the region [16]. For the Haywired study, the USGS developed a 2-year aftershock sequence scenario, and ran thirteen different aftershock sequence models and selected one with 175 aftershocks Mw>4, and 16 aftershocks Mw>5, and then moved the modeled aftershocks on to actual faults in the San Francisco Bay Region. Figure 2 shows the location of the main shock and significant aftershocks within EBMUD service area.

Main and Aftershocks

EBMUD downloaded data from the USGS ShakeMap website for the Hayward M_w 7.05 scenario event for the main and 16 aftershocks. Figure 2 presents the scenario events in the vicinity of our service area. For modeling purposes we only used 5 aftershock events listed below. Scenario earthquakes are based upon an approach that assumes a particular fault or fault segment will rupture over a certain length relying on consensus-based information about the potential behavior of the fault. For historic events, the actual rupture dimensions may be constrained based on existing observations or models. Second, estimate ground motions at all locations in a chosen region surrounding the causative fault. These earthquake scenarios are not earthquake predictions.

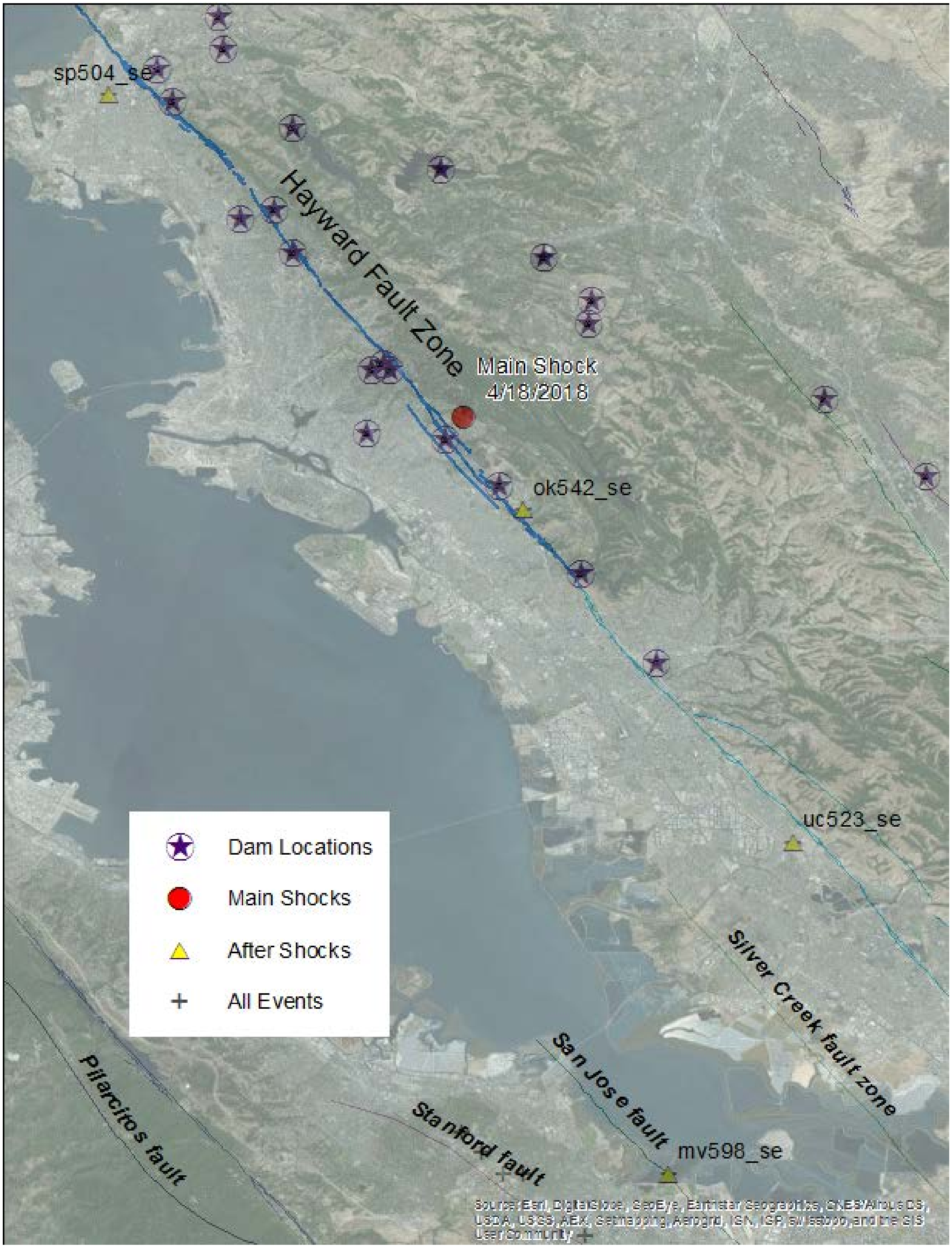


Figure 2: USGS Main and Aftershock Model [16, 17]

The scenario earthquakes given on the Northern California ShakeMap website represent 34 possible future earthquakes in the greater San Francisco Bay Area as determined by the USGS-led Working Group on California Earthquake Probabilities. This Working Group (WG02) concluded that the likelihood of one or more large (M>=6.7) earthquakes in the San Francisco Bay region in the next 30 years is 62%. Table 1 presents the Main shock and 5 aftershocks available through USGS [18]. The Scenario ID's used in this study are: 1-MS705, 17-UC523, 8-OK542, 13-PA621, 7-MV598, and 3-CU640. These scenarios were used in reservoir and structural assessment of District facilities and are used throughout the remainder of the report.

TABLE 1: EBMUD SELECTED MS AND MS+AS SCENARIO

USGS #	Scenario_ID	Event	Mw	Date of Exercise	Lat	Long	Depth_KM
1	Main Shock	Main Shock - Scenario	7.05	18-Apr-18	37.805	-122.179	8.0
3	cu640_se	Cu640 Scenario	6.40	1-Oct-18	37.310	-122.060	15.4
7	mv598_se	Mv598 Scenario	6.00	1-Oct-18	37.440	-122.080	11.3
8	ok542_se	Ok542 Scenario	5.40	20-May-18	37.760	-122.150	8.4
13	pa621_se	Pa621 Scenario	6.20	28-May-18	37.390	-122.180	19.0
15	sp504_se	Sp504 Scenario	5.00	19-Apr-18	37.960	-122.350	2.6
17	uc523_se	Uc523 Scenario	5.20	18-Apr-18	37.600	-122.020	2.6

EMBANKMENT DAMS

Figure 1 shows EBMUD's 22 dam reservoirs denoted as yellow crosses, along with major active faults. As the figure presents, most of the dam reservoirs are near the Hayward Fault. The embankment dams were previously evaluated and published in the paper titled: "Developing Embankment Dam Fragilities for Emergency Modeling and Response for 22 EBMUD Reservoirs." [5]

Overview

To develop the dam fragility curves, EBMUD engineers first estimated the crest settlement during the postulated seismic shaking for each dam. Next, the settlement estimate was divided by the dam height to provide an estimate of axial compressive strains induced within the dam during or following an earthquake. The percent settlement magnitude was used as a proxy to establish the performance/fragility of the dam. Based on the percent settlement strain for the EBMUD dams, four performance classes were established. Newmark double integration procedure was used to determine the settlement of a dam for varying peak ground acceleration (PGA) values and the result was a fragility curve that models the performance of the dam for recorded ground motions.

The fragility evaluations resulted in estimated crest settlement versus varying peak ground accelerations for each embankment, which were used as a baseline to establish the relative rankings for each dam. The final modeling step uses the USGS input scenario events to calculate the level of fragility. The scenario event shape files were input into ArcGIS and ground motion parameters were extracted and tabulated for each reservoir, tank, and pipeline locations.

Damage Model Development

Tables 2A and 2B present the four reservoir dam class categories corresponding to four performance (fragility) level limits for the main shock alone (MS) and for the main shock plus aftershocks (MS+AS). It can be seen that values corresponding to the low and high ranges for the various levels of dam classes correspond to the axial strain values. The performance levels are simply related to percent settlement values assuming 5% is a maximum value. Figure 3 (following page) shows how the individual dams were categorized, which were based on the settlement percent shown for each dam. These varying performance levels were used to develop the four dam classes.

TABLE 2A: DAM CLASS FRAGILITY LIMITS – MS ONLY

Fragility	Limit 1 (L1)		Limit 2 (L2)		Limit 3 (L3)		Limit 4 (L4)	
	Low	High	Low	High	Low	High	Low	High
Minimal	0	0.63	0	0.58	0	0.53	0	0.48
Light	0.63	0.85	0.58	0.8	0.53	0.75	0.48	0.7
Moderate	0.85	0.93	0.8	0.88	0.75	0.83	0.7	0.78
Severe	0.93	-	0.88	-	0.83	-	0.78	-

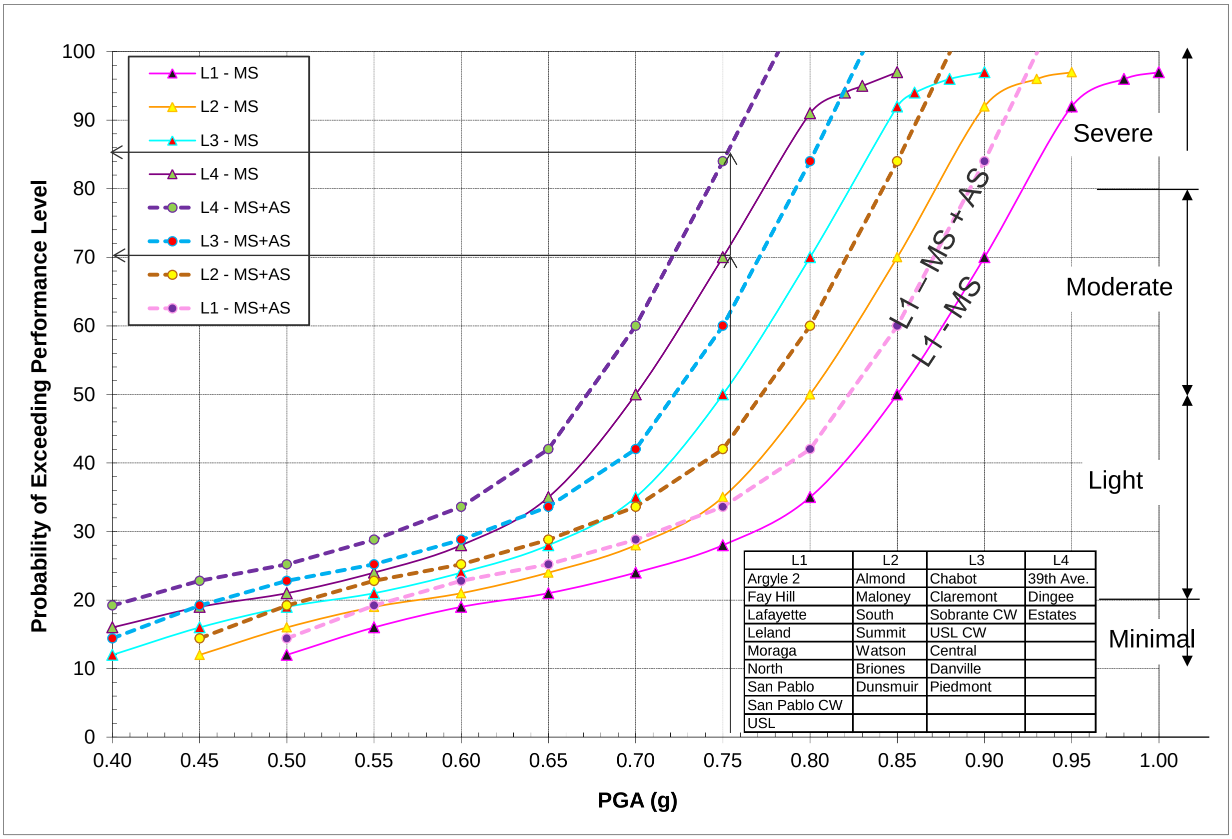
TABLE 2B: DAM CLASS FRAGILITY LIMITS – MS + AS

Fragility	Limit 1 (L1)		Limit 2 (L2)		Limit 3 (L3)		Limit 4 (L4)	
	Low	High	Low	High	Low	High	Low	High
Minimal	0	0.57	0	0.52	0	0.46	0	0.42
Light	0.57	0.83	0.52	0.78	0.46	0.73	0.42	0.68
Moderate	0.83	0.89	0.78	0.84	0.73	0.79	0.68	0.74
Severe	0.89	-	0.84	-	0.79	-	0.74	-

The fragility for each dam was developed based on the shape of curves shown in Figure 3. Additional details of the background and approach are provided in Ref No. 5, and 6.

Damage Model Results

Tables 2A and B show the qualitative performance limits for dams, which were extracted from Figure 3. In addition, Tables 2A and B shows the definition of failure/damage versus PGA. The four classes will have four different ranges of damage: L1, L2, L3, and L4. Figure 3 shows a second set of curves representing the MS + AS that were developed by assuming a 20% capacity reduction (accounting for temporary loss of shear strength) following the main shock. The 20% strength loss of geo-materials is a standard practice in geotechnical engineering and is considered appropriate for these set of simplified assumptions and purposes intended. Future such studies may consider delve into additional details on this approach and explore the possibility of dam-specific strength reductions to account for site-specific properties.



L1	L2	L3	L4
Argyle 2	Almond	Chabot	39th Ave.
Fay Hill	Maloney	Claremont	Dingee
Lafayette	South	Sobrante CW	Estates
Leland	Summit	USL CW	
Moraga	Watson	Central	
North	Briones	Danville	
San Pablo	Dunsmuir	Piedmont	
San Pablo CW			
USL			

Figure 3. Fragility Limits for 4 Different Levels (L1, L2, L3, L4) of Dam

TABLE 3: MS AND MS +AS SCENARIO RESULTS

Dam No.	RESERVOIR	Reservoir Classes	PF - MS (%)	Damage Level	PF - MS+AS (%)	Damage Level	MCE Site PGA (g)	Damage Level MS	Damage Level MS+AS
14	39th Ave.	L4	16.0	Minimal	19.2	Minimal	0.80	Severe	Severe
20	Almond	L2	24.0	Light	28.8	light	0.78	light	Moderate
30	Argyle 2	L1	21.0	Light	25.2	light	0.86	Moderate	Moderate
15	Briones	L2	12.0	Minimal	14.4	Minimal	1.00	Severe	Severe
00	Central	L3	16.0	Minimal	19.2	Minimal	0.71	light	light
05	Chabot	L3	12.0	Minimal	14.4	Minimal	1.05	Severe	Severe
01	Claremont	L3	35.0	Light	42.0	light	1.00	Severe	Severe
28	Danville	L3	16.0	Minimal	19.2	Minimal	0.65	light	light
03	Dingee	L4	16.0	Minimal	19.2	Minimal	1.00	Severe	Severe
18	Dunsmuir	L2	16.0	Minimal	19.2	Minimal	1.09	Severe	Severe
09	Fay Hill	L1	10.0	Minimal	12.2	Minimal	0.57	Minimal	light
02	Lafayette	L1	16.0	Minimal	19.2	Minimal	0.60	Minimal	light
21	Leland	L1	8.0	Minimal	10.0	Minimal	1.19	Severe	Severe
24	Maloney	L2	16.0	Minimal	19.2	Minimal	0.85	Moderate	Severe
22	Moraga	L1	9.0	Minimal	11.0	Minimal	0.66	light	light
27	North	L1	12.0	Minimal	14.4	Minimal	0.87	Moderate	Moderate
06	San Pablo	L1	13.0	Minimal	15.2	Minimal	1.00	Severe	Severe
29	San Pablo CW	L1	9.0	Minimal	11.0	Minimal	0.75	light	light
23	Sobrante CW	L3	24.0	Light	28.8	light	0.83	Severe	Severe
17	USL CW	L3	35.0	Light	42.0	light	0.80	Moderate	Severe
31	Upper San Leandro	L1	35.0	Light	42.0	Light	1.02	Severe	Severe
33	Watson	L2	19.0	Minimal	22.8	Light	0.76	light	light

Table 3 presents the dam damage level results. Evaluation of all embankments for MS only and MS+AS levels, all of the facility's damage levels were Minimal to Light. The revised fragility curves (Tables 2A and B), were compared against one another using the Maximum credible earthquake (MCE) based site specific peak ground acceleration. As anticipated the damage levels for our reservoirs were higher when considering the MS +AS scenario case.

RESERVOIR TANKS

Overview

EBMUD currently has 144 water distribution tank reservoirs in service, consisting of 58 concrete tanks, 4 wood tanks, and 82 steel tanks. The types of concrete tanks in EBMUD's system include cable stressed, reinforced buried, wire stressed, bar stressed, and reinforced concrete tanks. EBMUD's steel tanks include welded and bolted tanks. EMBUD's wood tanks are made of redwood. All of EBMUD's steel and concrete tanks have been retrofitted to have a positive connection between the tank wall and supporting concrete ring wall. Therefore, the steel and concrete tanks were assessed under the classification of anchored tanks.

For the main shock event, tanks were assessed using fragility relationships developed by HAZUS [6]. Tanks were assessed after each subsequent aftershock event by shifting the HAZUS curves by approximations developed by Li, et al. [15].

Damage Model Development

EBMUD developed a prediction model to estimate damage to distribution reservoirs experiencing a local magnitude scenario seismic event and subsequent local aftershock seismic events. The prediction model required the collection of EBMUD GIS data for the reservoir location (longitude and latitude), classification (capacity and anchorage) of the tanks, and the PGA for the scenario earthquake event.

Damage to a water storage tank has been predicted using fragility curves. For this study, fragility curves are based on the probability of reaching or exceeding different damage states for a given level of PGA. Main shock damage states describing the level of damage to each of the water storage tanks have been defined by Table 8.9 of the HAZUS-MH-MR3 Technical Manual. Table 4 summarizes the damage state versus PGA for the steel, concrete, and wood tanks considered.

TABLE 4. WATER ON-GROUND STORAGE TANKS DAMAGE ALGORITHMS

Damage	Anchored Concrete Tank	On-Ground Anchored Steel Tank	On-Ground Wood Tank
	Median PGA (g)	Median PGA (g)	Median PGA (g)
Slight/Minor	0.25	0.30	0.15
Moderate	0.52	0.70	0.40
Extensive	0.95	1.25	0.70
Complete	1.64	1.60	0.90

Aftershock damage states describing the level of damage to each of the water storage tanks have been defined by shifting the median PGA of the HAZUS curves for each damage state. The amount of shifting is dependent on the damage level to the tank after the previous event. The approximated percent reduction in the tank's seismic collapse capacity was determined by incremental dynamics analysis (IDA). The collapse capacity losses used in this study were approximated by Li, et al. [15] and are summarized in the tables below. Table 5 and 6 shows how much the collapse capacity of a tank could be reduced after a seismic event.

TABLE 5. WATER TANK COLLAPSE CAPACITY REDUCTIONS

Damage	Main Shock	Aftershock
Minor :	0%	0%
Moderate :	13%	14%
Extensive/Complete :	40%	53%

TABLE 6. CUMULATIVE COLLAPSE CAPACITY

Damage	Before	Main Shock	Aftershock				
			1	2	3	4	5
Minor	100%	100%	100%	100%	100%	100%	100%
Moderate	100%	87%	75%	64%	55%	48%	41%
Extensive/Collapse	100%	60%	28%	13%	6%	3%	1%

For example, before an earthquake event, we can assume that a reservoir will have 100% of its collapse capacity, as it has not sustained any structural damage. After the main event, a reservoir that sustains moderate damage will have a remaining structural collapse capacity of 87%. Each subsequent aftershock event will further reduce the structural collapse capacity by 14% if the damage level remains in the Moderate range or by 54% if the damage increases to the "Extensive/Complete" level.

Damage Model Results

EBMUD executed the damage prediction model using the six scenario events – one main shock event, followed by five aftershock events. Tables 7 through 10 presents the predicted number of damaged tanks for each damage state. 94% of EBMUD's tanks are expected to withstand the scenario events and suffer a level of damage that causes minor or no loss of contents.

TABLE 7. TANKS WITH NO/SLIGHT/MINOR DAMAGE

TYPE	**MS705**	**UC523**	**OK542**	**PA621**	**MV598**	**CU640**
STEEL	53	53	53	53	53	53
CONC.	26	26	26	26	26	26
WOOD	2	2	2	2	2	0
TOTAL	81	81	81	81	81	79
% OF ALL TANKS	56%	56%	56%	56%	56%	55%

TABLE 8. TANKS WITH MODERATE DAMAGE

TYPE	**MS705**	**UC523**	**OK542**	**PA621**	**MV598**	**CU640**
STEEL	25	25	25	25	25	25
CONC.	30	30	30	30	30	30
WOOD	1	1	1	1	1	1
TOTAL	56	56	56	56	56	56
% OF ALL TANKS	39%	39%	39%	39%	39%	39%

TABLE 9. TANKS WITH EXTENSIVE DAMAGE

TYPE	**MS705**	**UC523**	**OK542**	**PA621**	**MV598**	**CU640**
STEEL	0	0	0	0	0	0
CONC.	1	1	1	1	1	0
WOOD	1	1	1	1	0	2
TOTAL	2	2	2	2	1	2
% OF ALL TANKS	1.4%	1.4%	1.4%	1.4%	0.7%	1.4%

TABLE 10. TANKS WITH COMPLETE DAMAGE

TYPE	**MS705**	**UC523**	**OK542**	**PA621**	**MV598**	**CU640**
STEEL	0	0	0	0	0	0
CONC.	0	0	0	0	0	1
WOOD	0	0	0	0	1	1
TOTAL	0	0	0	0	1	2
% OF ALL TANKS	0%	0%	0%	0%	0.7%	1.4%

LARGE DIAMETER PIPELINES

Overview

EBMUD operates approximately 580 km of large diameter pipelines. These pipelines include 50.8 cm (20-inch) and larger diameter welded steel pipe, 91.4 cm (36-inch) and larger reinforced concrete cylinder pipe, 40.6 cm (16-inch) and larger diameter cast-iron pipe, and 50.8 cm (20-inch) and larger pre-tensioned concrete cylinder pipe.

Damage Model Development

EBMUD developed a damage prediction model to estimate the number of pipe repairs using empirical vulnerability formulations and specific hazard settlement relationships. The damage model followed a three step approach, as presented below:

a. Assemble EBMUD and seismic GIS Data;
b. Define scenario earthquake events; and
c. Estimate pipeline fragility.

The 360 miles of large diameter pipelines were processed into midpoints representing 1,000-foot pipe segments. Using a point, rather than a polyline, simplified the GIS processing of spatial data. Figure 1 presents a GIS map of the large diameter pipeline study area showing fault lines and symbology for cast iron, RCC (reinforced concrete cylinder), Pretensioned CC (concrete cylinder), and S (steel) pipe materials.

The seismic hazards evaluated in the damage prediction model included ground shaking, liquefaction, landslide, and fault rupture. EBMUD collected the latest GIS data from USGS and CGS to incorporate in the model. Refer to the Yogesh papers [6] and [7] for a detailed explanation of each seismic hazard and description of the model input metrics.

The pipeline damage model used empirical formulas developed by the ALA Seismic Fragility Formulation for Water Systems [14]. The damage model provided output in terms of repairs per 1,000 feet of pipeline using PGV, PGD, and fault offset input data. EBMUD selected pipe characteristic constants based on the pipe material and joint types. Welded and riveted steel, as well as pre-tensioned concrete cylinder pipe were modeled as continuous pipe. All remaining large diameter pipeline materials (cast iron and reinforced concrete) were modeled as segmented pipe. For a more detailed explanation of the damage prediction model, specifically the calculation of PGD, see references [6] and [7].

Damage Model Results

EBMUD executed the damage prediction model using the main shock and five aftershock scenarios. Tables 11 through 15 present the number of repairs computed for each pipe material type, seismic hazard, total damage, and percent of total pipe segments damaged. Where: C (cast iron), L (reinforced concrete cylinder), T (pretensioned concrete cylinder), S1 (steel riveted joints < 1950), S2 (steel welded joints between 1950 and 1970), S3 (steel welded joints >1970), and R/Segment (repairs per pipe segment or 1,000 feet of modeled large diameter pipe).

TABLE 11. REPAIRS DUE TO GROUND SHAKING

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0
T	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	0	0	0	0	0	0	0
%	0%	0%	0%	0%	0%	0%	0%

TABLE 12. REPAIRS DUE TO LIQUEFACTION

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	120	0	77	0	0	0	197
L	28	0	7	0	0	0	35
T	3	0	0	0	0	0	3
S1	36	1	19	1	0	1	58
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	187	1	103	1	0	1	293
%	10%	0%	5%	0%	0%	0%	15%

TABLE 13. LANDSLIDE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	27	0	0	0	0	0	27
L	18	0	0	0	0	0	18
T	0	0	0	0	0	0	0
S1	9	0	0	0	0	0	9
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	54	0	0	0	0	0	54
%	3%	0%	0%	0%	0%	0%	3%

TABLE 14. FAULT RUPTURE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	9	0	0	9	9	9	36
L	4	0	0	4	4	4	16
T	0	0	0	0	0	0	0
S1	24	0	0	24	24	24	96
S2	36	0	0	36	36	36	144
S3	8	0	0	8	8	8	32
TOTAL	81	0	0	81	81	81	324
%	4%	0%	0%	4%	4%	4%	17%

TABLE 15. TOTAL DAMAGE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	156	0	77	9	9	9	260
L	50	0	7	4	4	4	69
T	3	0	0	0	0	0	3
S1	69	1	19	25	24	25	163
S2	36	0	0	36	36	36	144
S3	8	0	0	8	8	8	32
TOTAL	322	1	103	81	81	82	671
%	17%	0%	5%	4%	4%	4%	35%

CONCLUSIONS

Embankment Dams

The above approach of categorizing 22 dams into fragility classes enables EBMUD emergency response team to prioritize an emergency response approach. Rapid prediction allows EBMUD emergency response efforts staff on the most important facilities. Mobilizing properly trained staff to the facilities in a timely basis could even help prevent impending failures. This approach can easily be duplicated by other public agencies in seismically active areas where critical infrastructure is geographically spread out. The assessment for these 22 dams was completed primarily for emergency response purposes. It should be noted that all EBMUD dams have been evaluated using current design standards and have been found to be safe under the postulated shaking.

Reservoir Tanks

The ability to predict the relative likelihood of damage to tanks within EBMUD's extensive system of distribution reservoirs enables EBMUD to prioritize the emergency response approach. The damage modeling also helps to ensure that enough water is available for emergency response purposes, such as fire-fighting and supplying emergency response efforts. This study found that 94% of the distribution tanks are predicted to remain functional and in-service after the considered earthquake and aftershocks. Using these damage predictions can help EBMUD prioritize which tanks to send emergency responder and repair crews to following a seismic event.

Large Diameter Pipelines

No repairs were computed for the ground shaking seismic hazard, which confirms historical pipeline damage. Liquefaction damaged 187 (10%) pipe segments during the main shock and 293 (15%) total pipe segments with the combined aftershocks. Landslide damage included 54 (3%) pipe segments with the main shock. And, fault rupture accumulated 81 (4%) segment repairs during the main shock and 324 total pipe segments following the combined aftershocks. The segmented pipes (cast iron and reinforced concrete pipe) showed high levels of damage. The fault rupture accounted for the most damage to the large diameter pipelines.

The main shock and combined aftershocks damaged 322 and 349 pipe segments, respectively. A total of 671 pipe segments or 35% of the total pipe segments are estimated to be damaged after both the main shock and aftershocks.

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