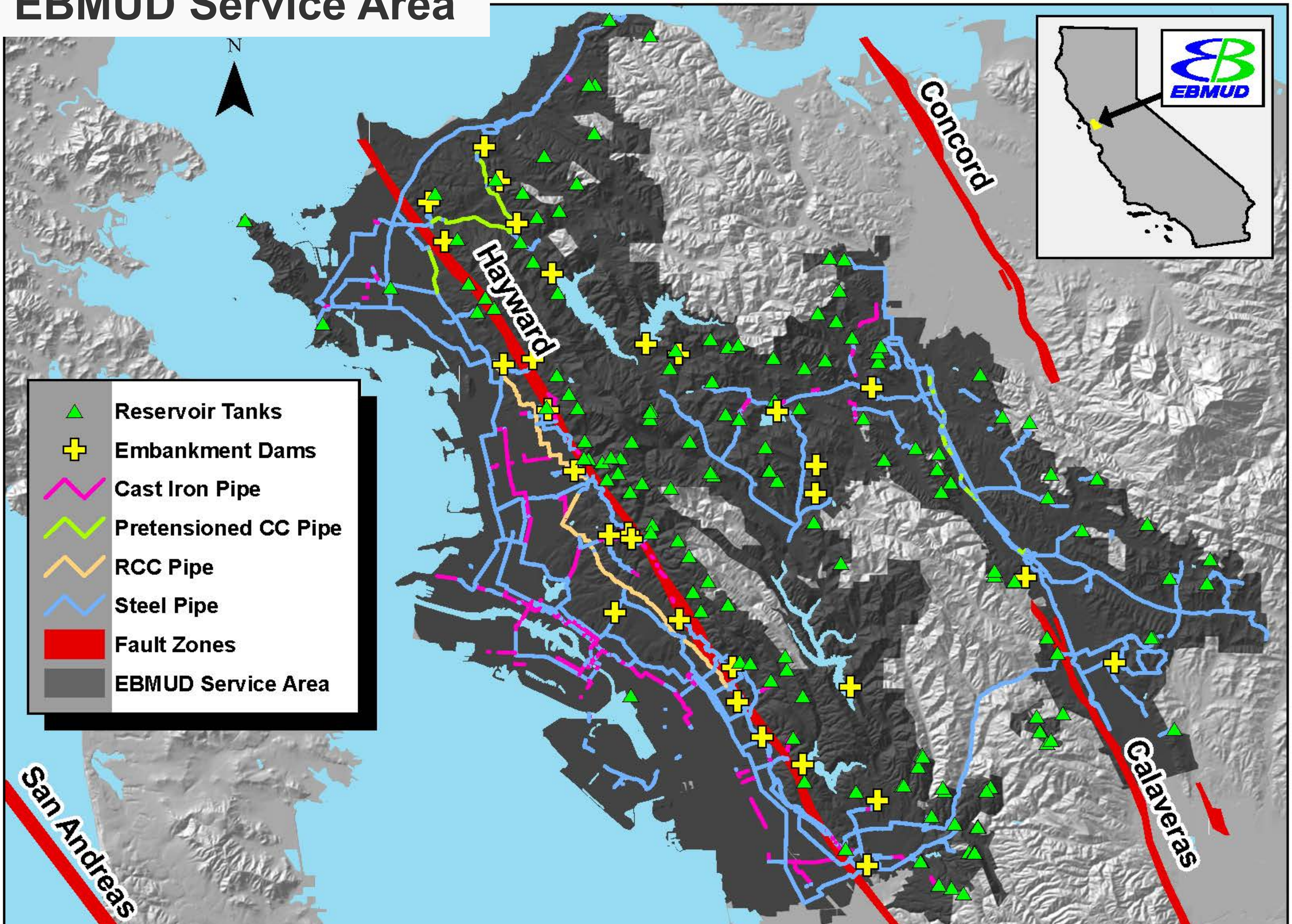
EAST BAY MUNICIPAL UTILITY DISTRICT

Main Shock and Aftershock Impact to Water System Fragility

Of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines

Yogesh Prashar, Roberts McMullin, Andrea Chen, Xavier Irias

EBMUD Service Area



EBMUD System

EBMUD

Damage Prediction Models

28 Embankment Dams

21 Open Cut Dams
7 Supply Reservoir Dams

147 Tank Reservoirs

86 Steel Tanks
58 Concrete Tanks
4 Wood Tanks

360 Miles Large Diameter Pipelines

295 miles of Steel
40 miles of Cast Iron
14 miles of Reinforced CC
11 miles of Pretensioned CC

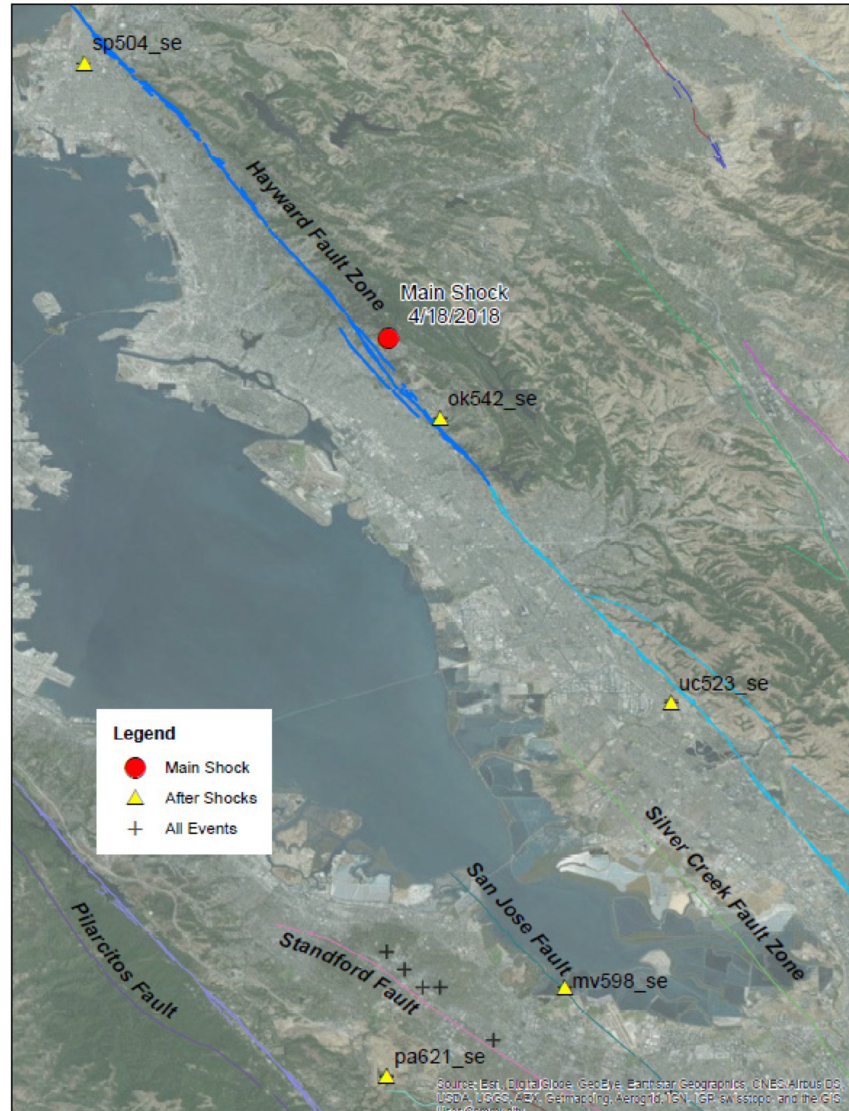
FEMA

MARCONi

Scenario Events

EBMUD

No.	Scenario	Abbrev.
1	Main Shock Mw 7.05	MS705
2	Aftershock 1 Mw 5.20	UC523
3	Aftershock 2 Mw 5.40	OK542
4	Aftershock 3 Mw 6.20	PA621
5	Aftershock 4 Mw 6.00	MV598
6	Aftershock 5 Mw 6.40	CU640



Main Shock Event
Mw 7.05

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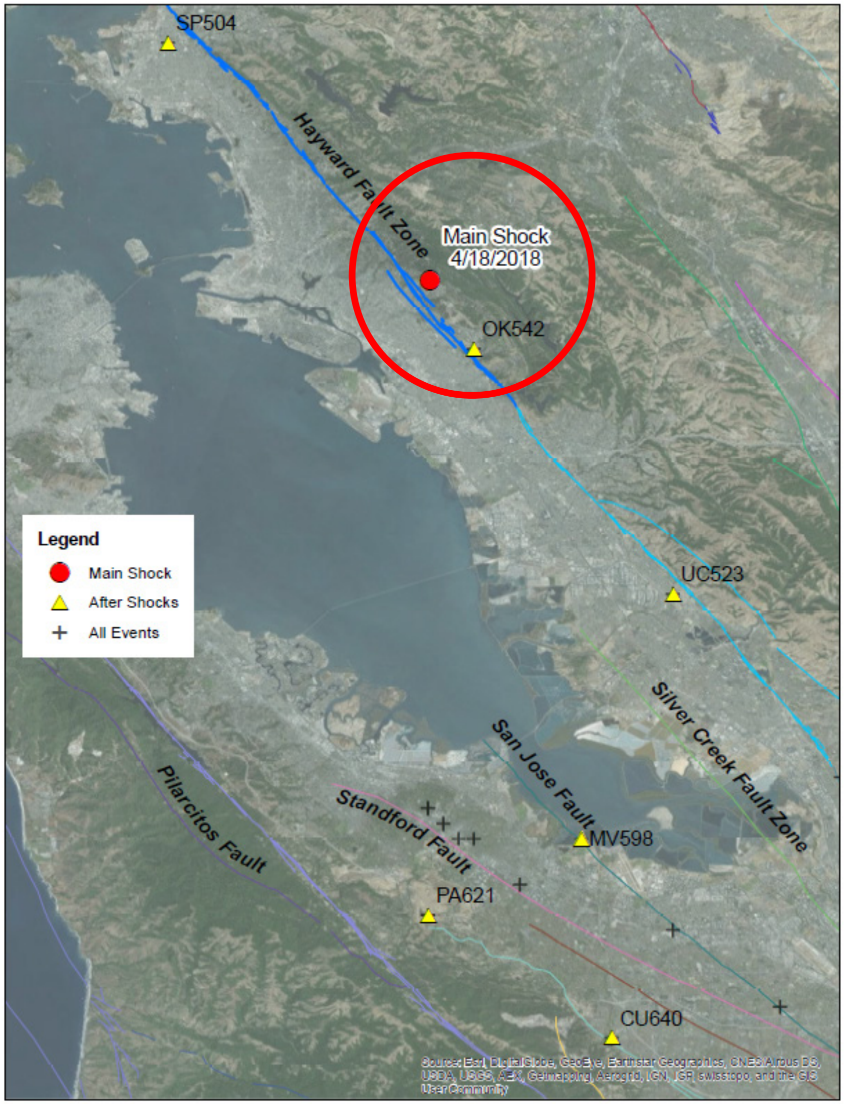
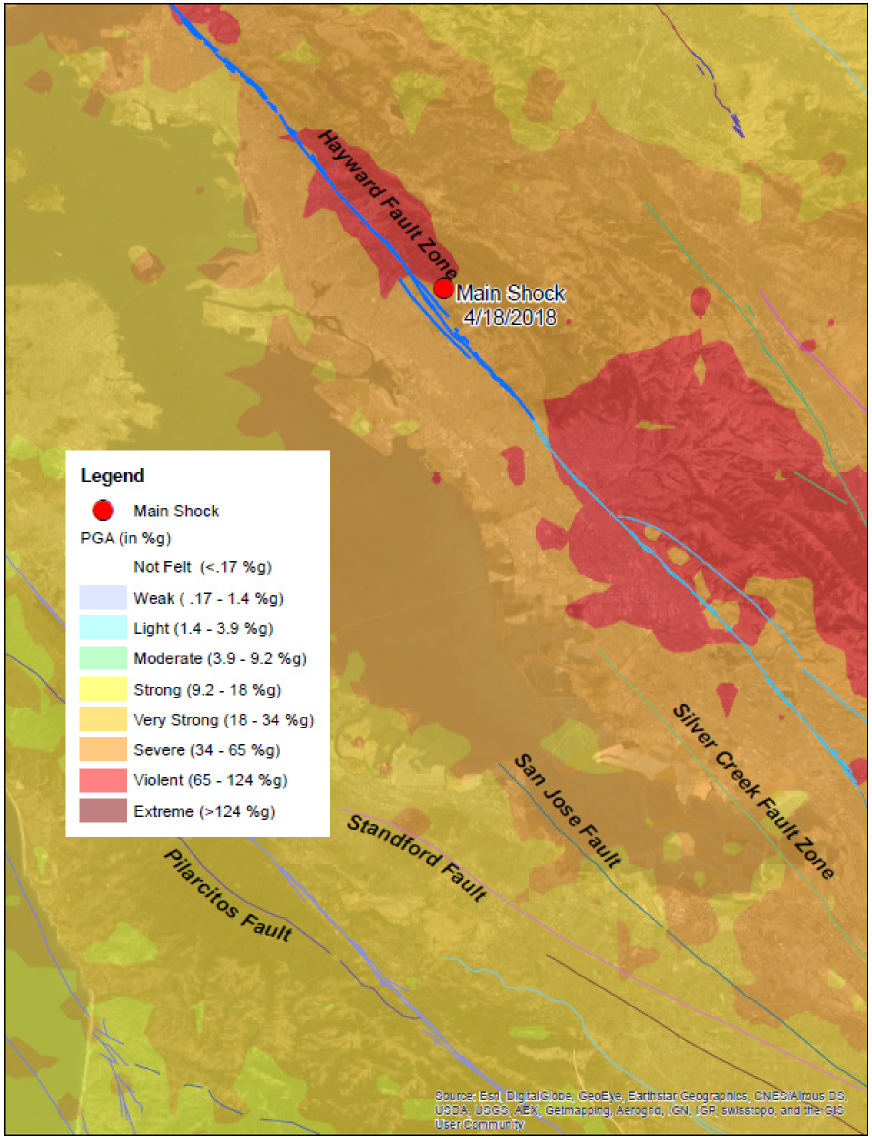
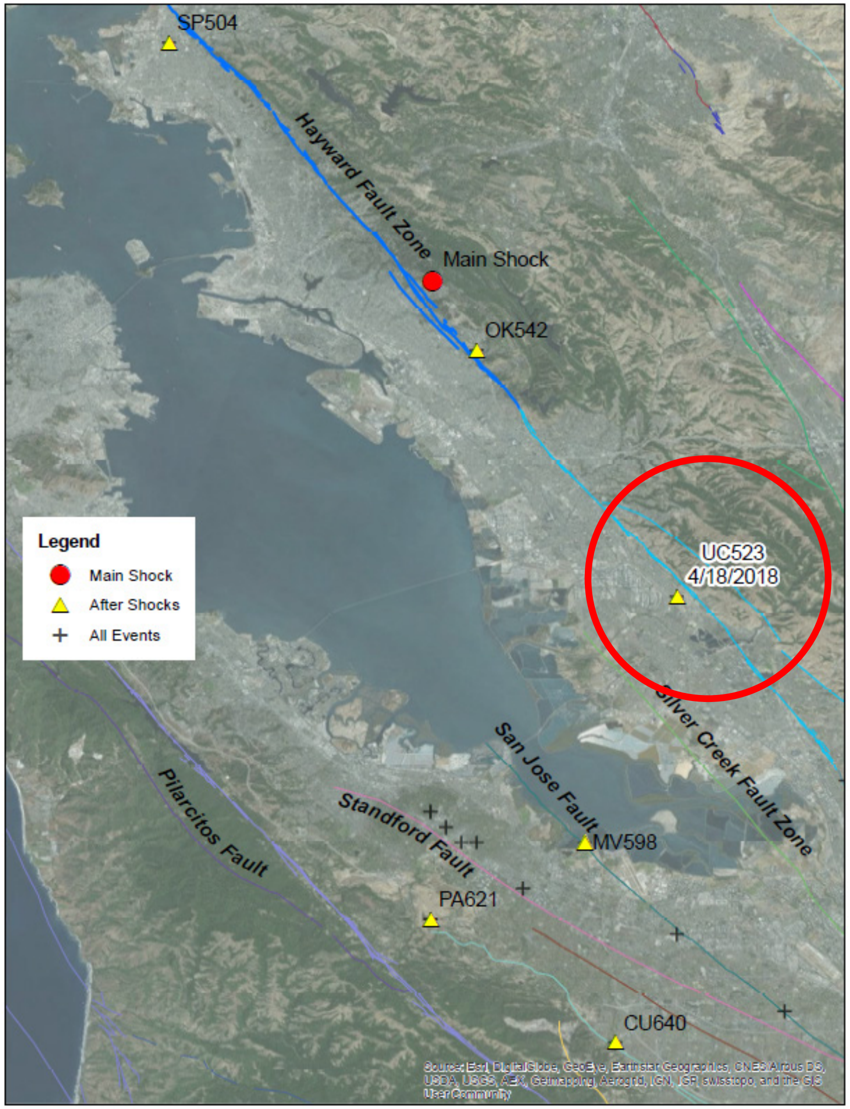
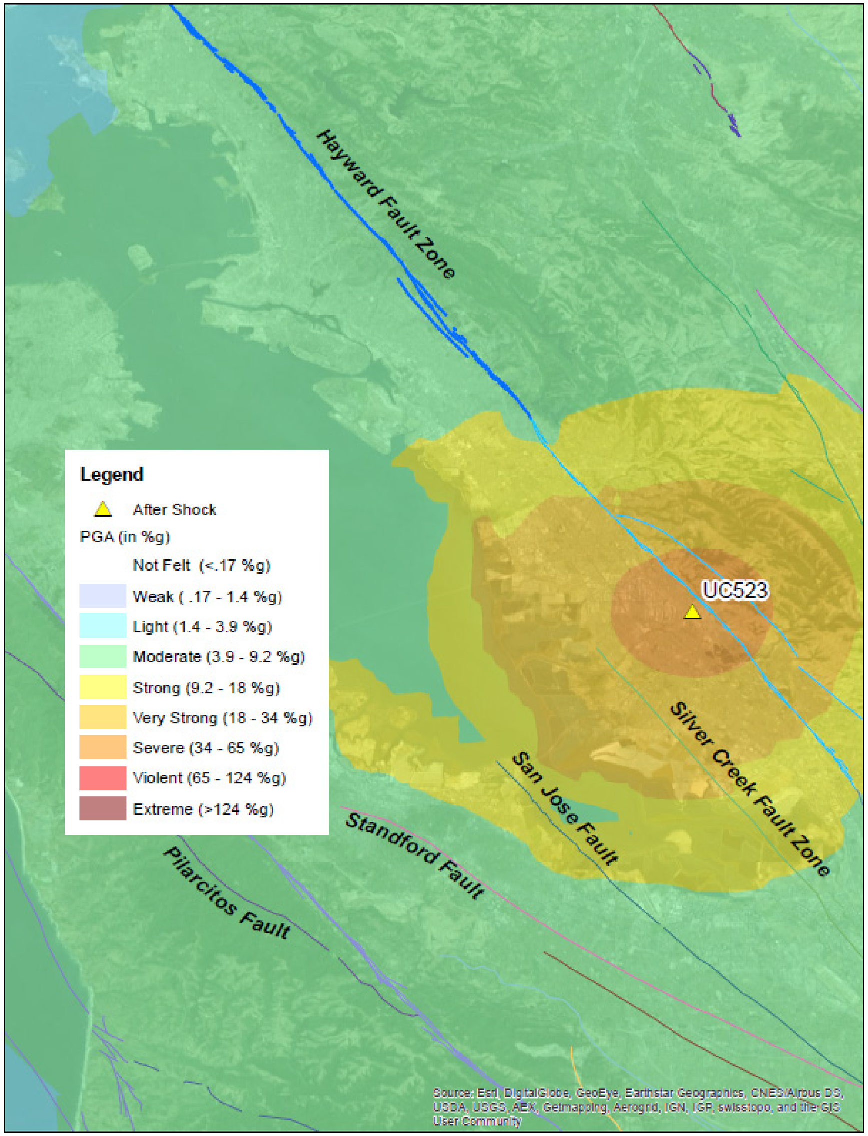


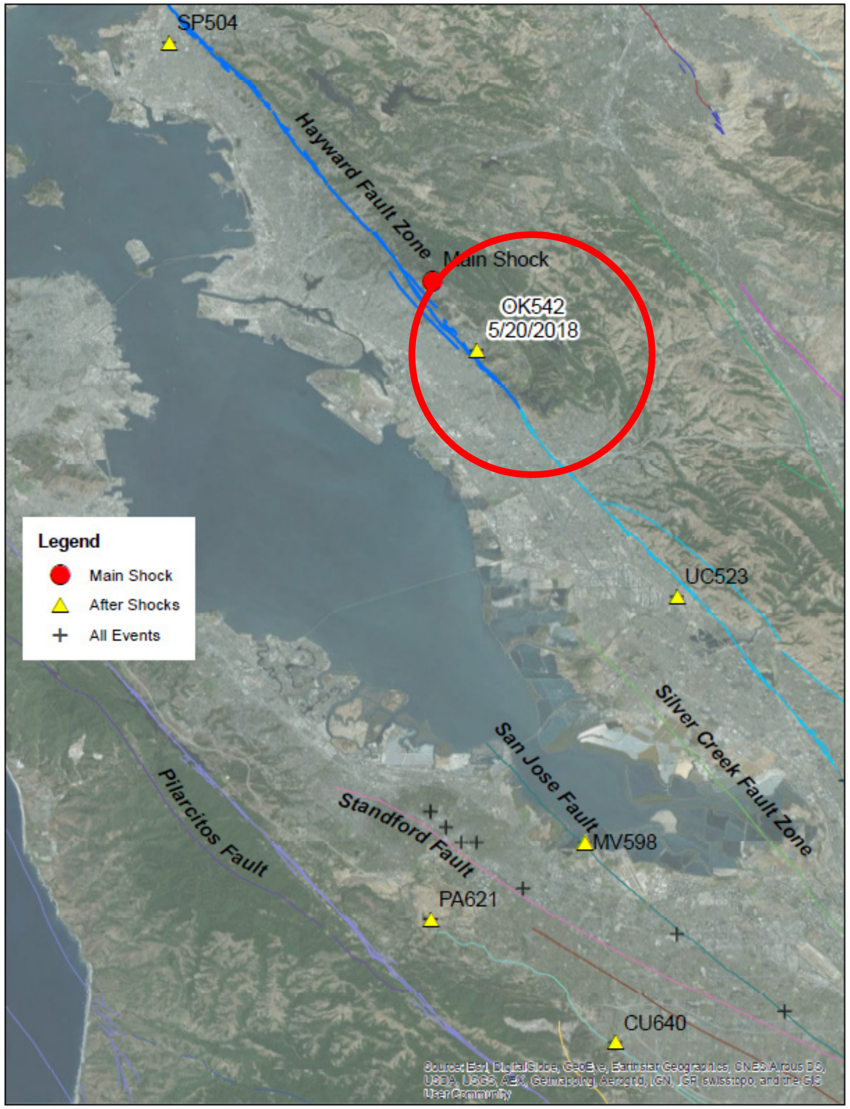


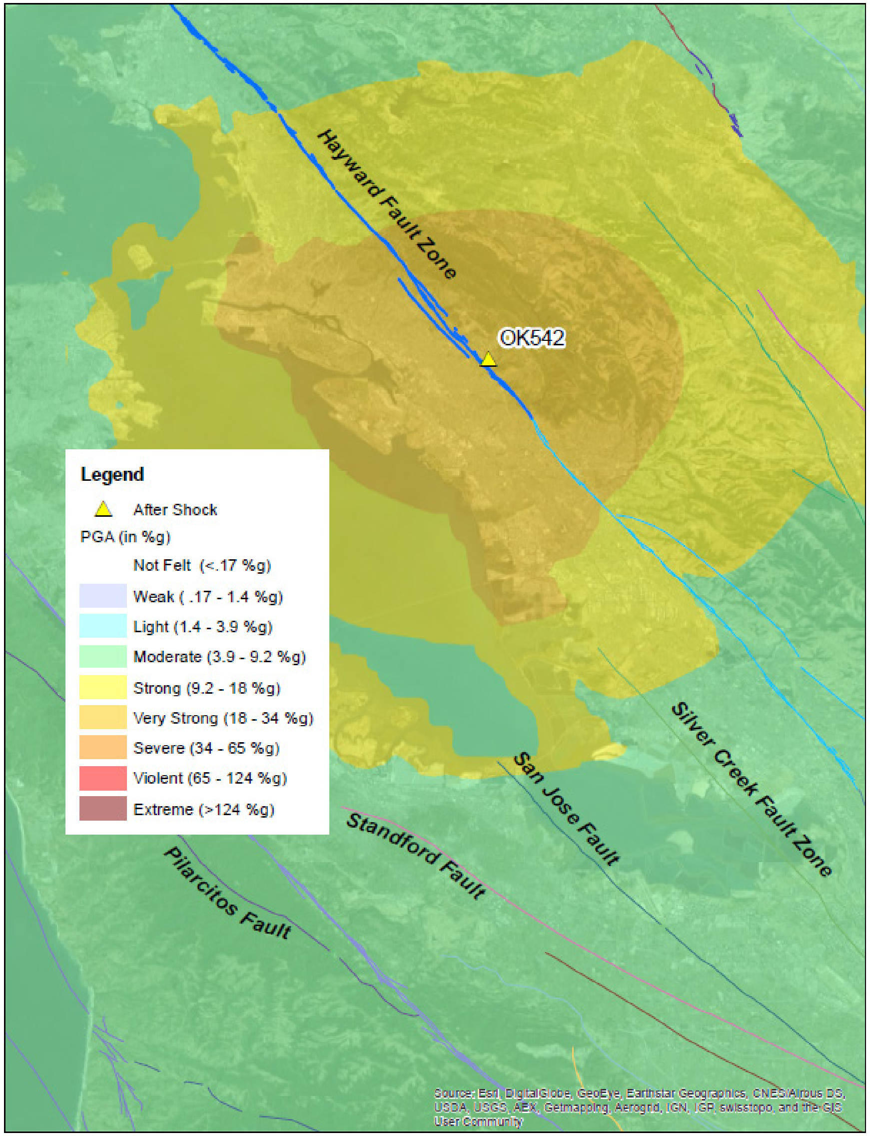
Aftershock 1 - UC523
Mw 5.2



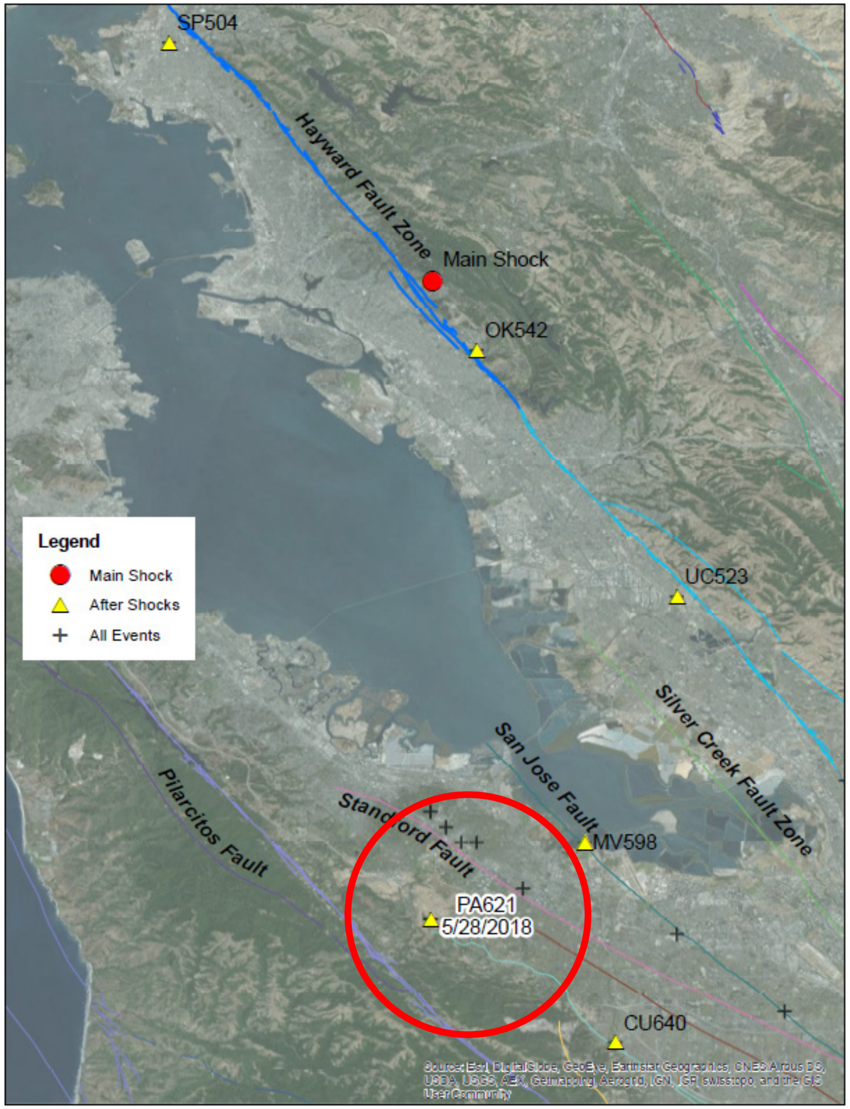


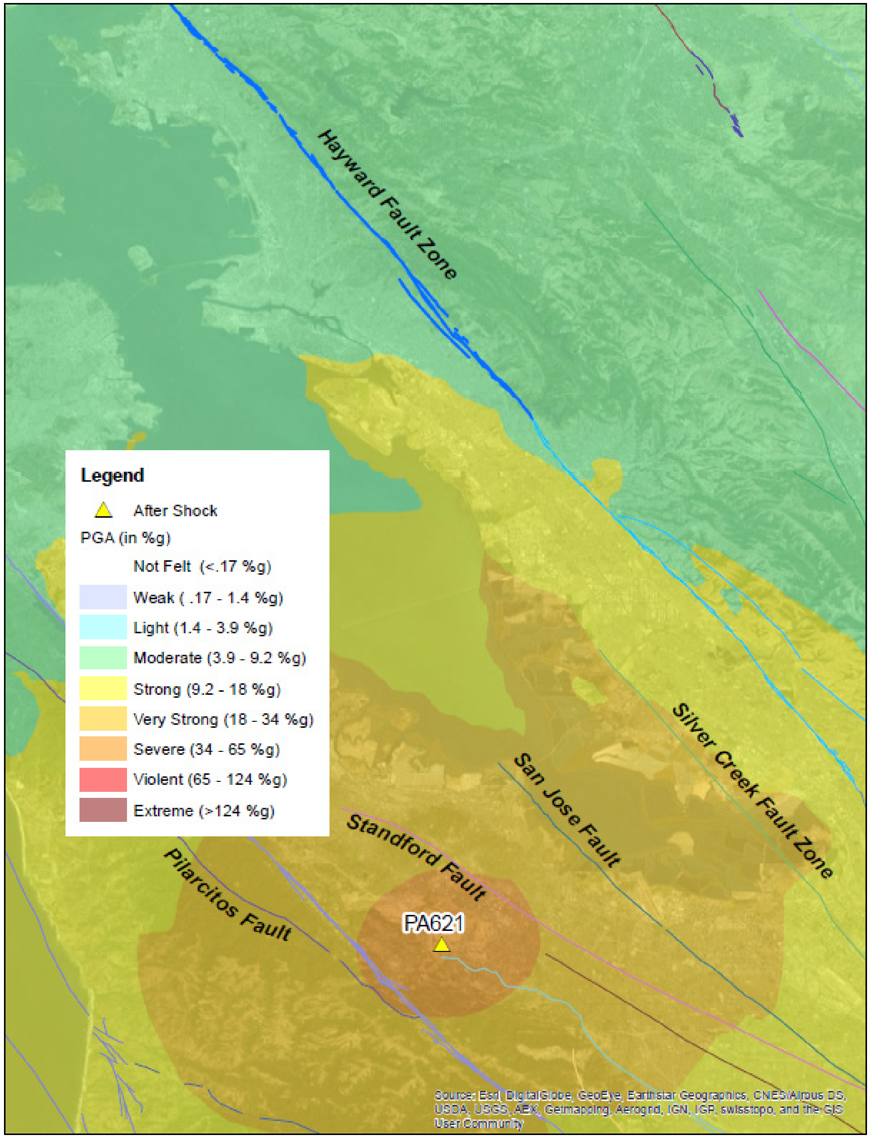
Aftershock 2 - OK542
Mw 5.4



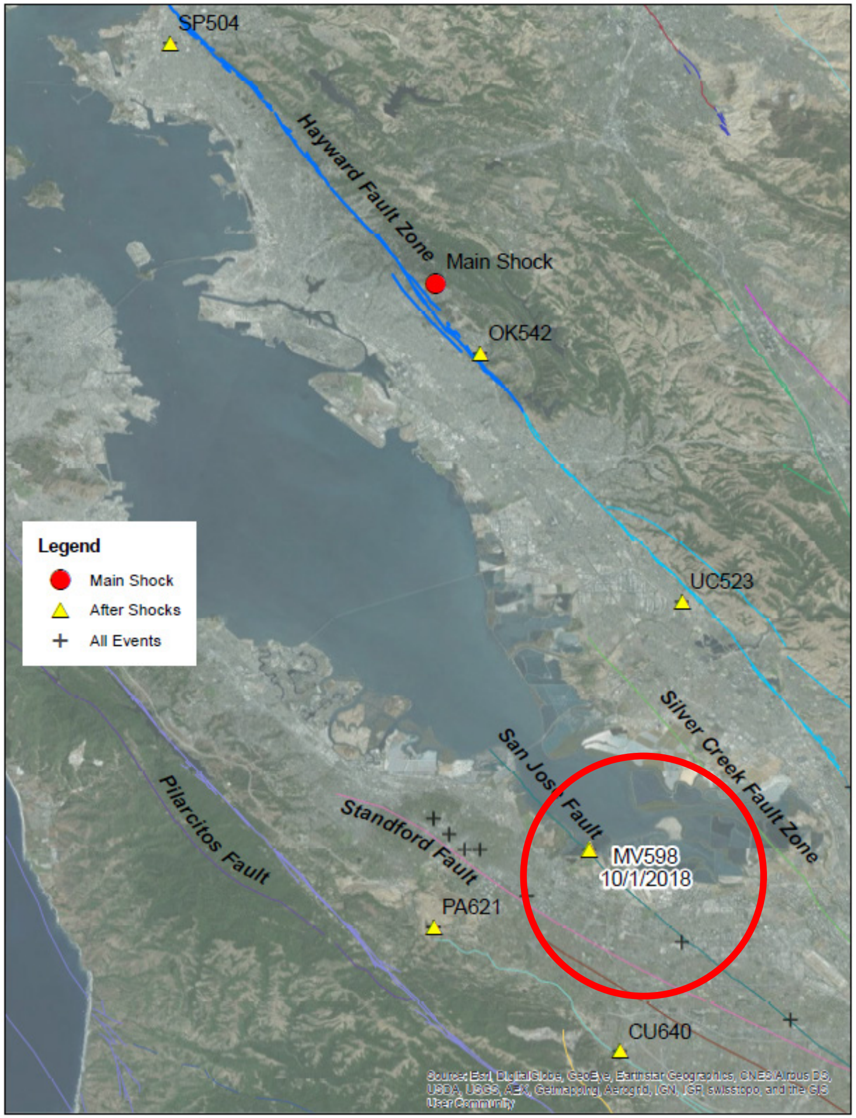


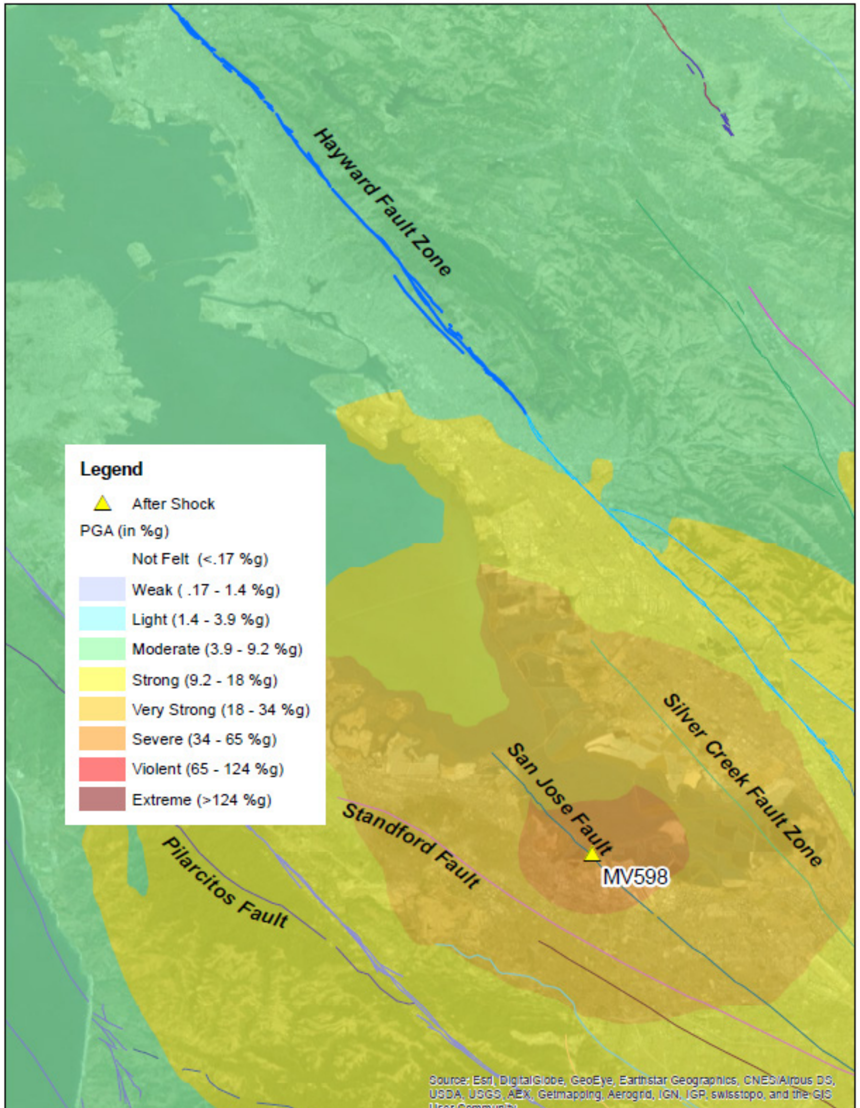
Aftershock 3 - PA621 Mw 6.2



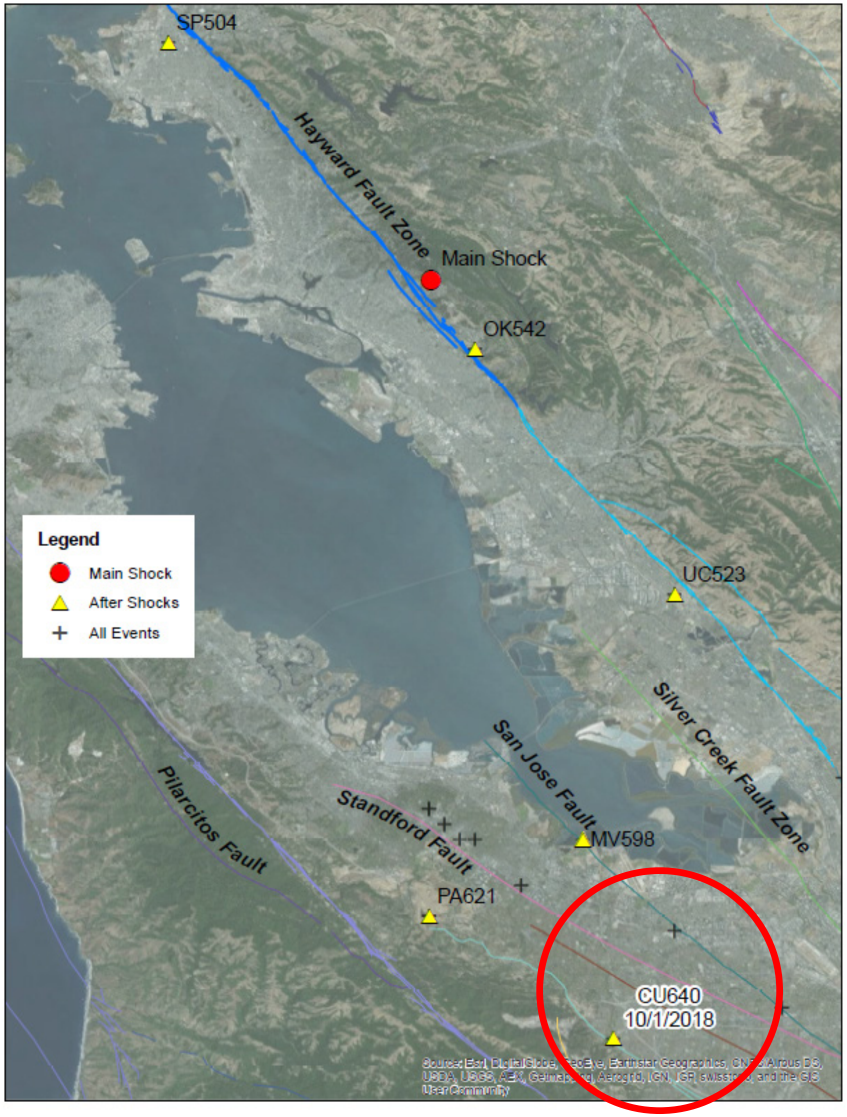


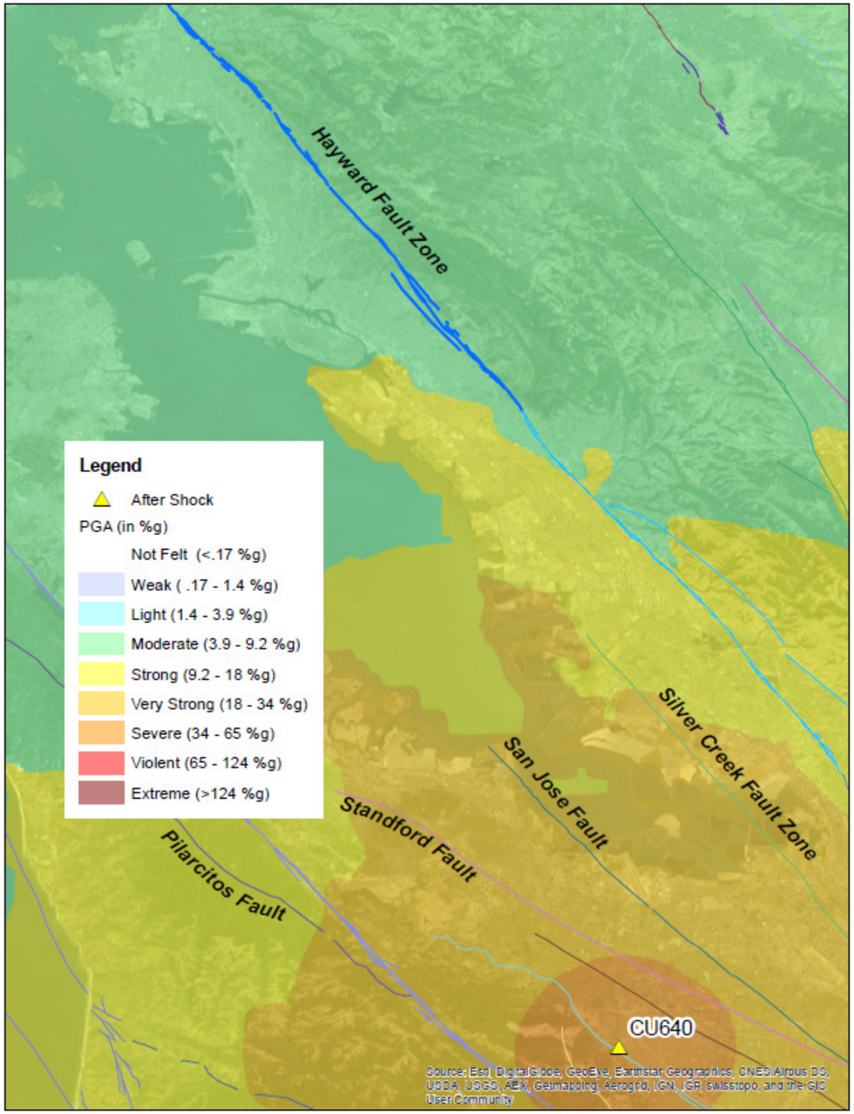
Aftershock 4 - MV598
Mw 6.0



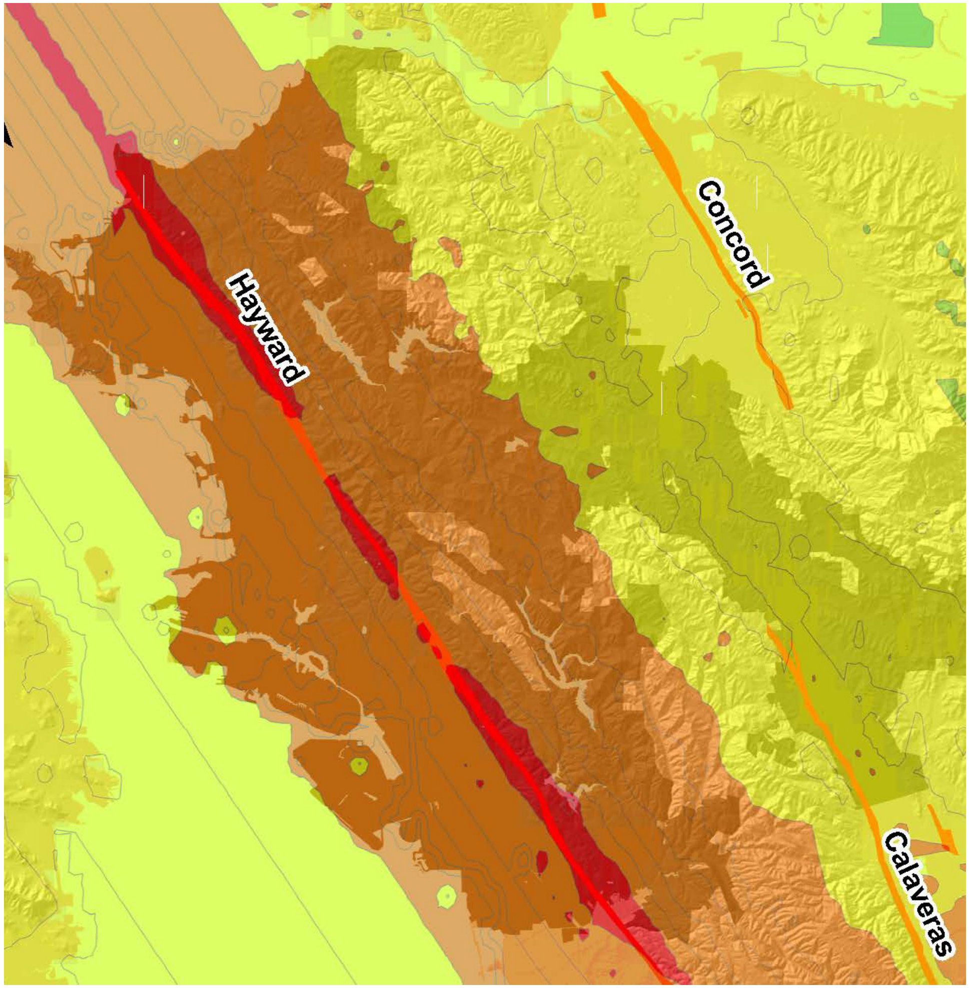


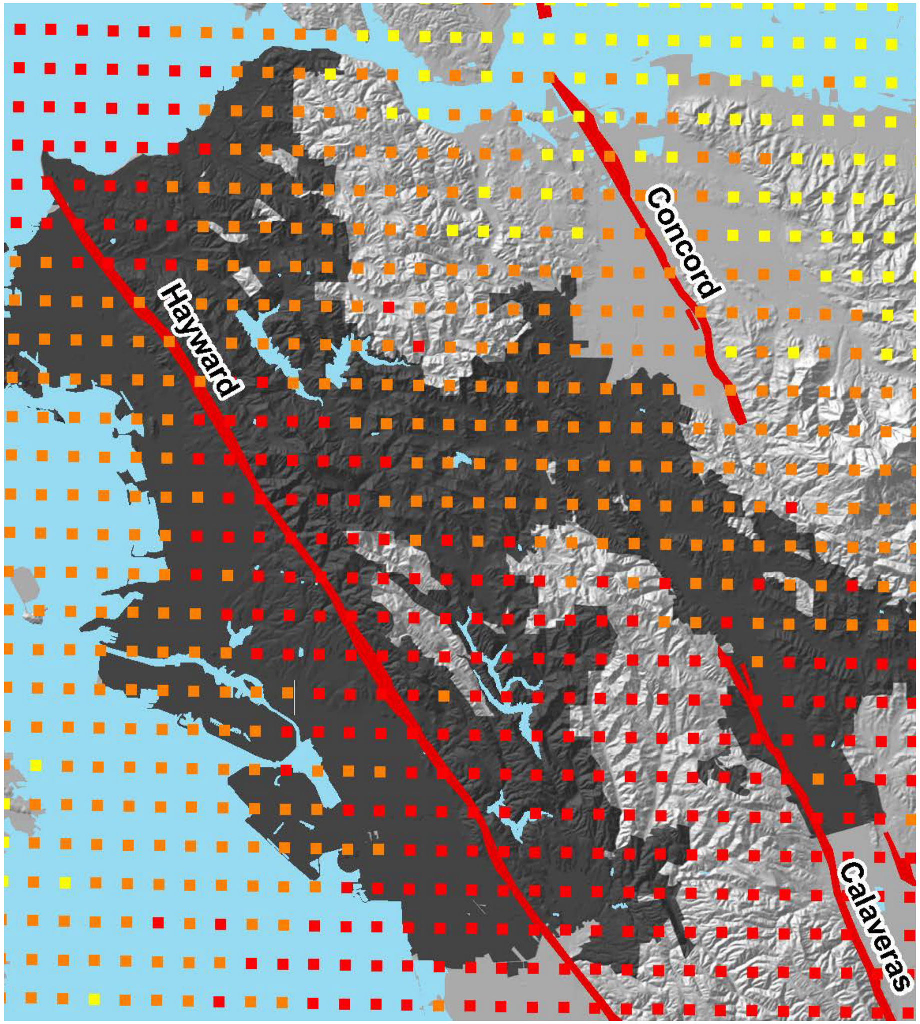
Aftershock 5 - CU640
Mw 6.4





Methodology – Scenario Event





Collapse Capacity Reduction

AMERICAN SOCIETY OF CIVIL ENGINEERS

Collapse Fragility of Steel Structures Subjected to Earthquake Mainshock-Aftershock Sequences

Yue Li, M.ASCE[1]; Ruiqiang Song, S.M.ASCE[2]; and John W. Van De Lindt, M.ASCE[3]

Abstract: This paper investigates the collapse probability of mainshock-damaged steel buildings in aftershocks, as an essential part of developing a framework to integrate aftershock seismic hazard into performance-based engineering (PBE). Analytical studies were conducted utilizing structural degradation models derived from existing publicly available NEEShub data. During earthquake events, aftershocks have the potential to cause severe damage to buildings and threaten life safety even when only minor damage is present from the mainshock. While aftershocks are normally somewhat smaller in magnitude, their ground motion intensity is not always smaller. Aftershocks may have a higher peak ground acceleration than the mainshock, even longer duration, and significantly different energy content as a result of the change in their location relative to the site. To date, the description of seismic hazard in PBE has not included the probability of aftershocks. In this study, the structural degradation model of a four-story code-compliant steel moment-resisting frame is calibrated using existing publicly available NEEShub data. Three approaches to generate collapse fragility for the steel building that sustain a certain state of damage from a mainshock are used to investigate the effect of damage states from mainshocks on the structural collapse capacity. It is found that structural collapse capacity may reduce significantly when the building is subjected to a high intensity mainshock. As a result, the structure is likely to collapse even if only a small aftershock follows the mainshock. In addition, the effects of mainshock records, fault types and spectral shapes of aftershocks on the structural collapse capacity, are evaluated, respectively. DOI: 10.1061/(ASCE)ST.1943-541X.0001019. © 2014 American Society of Civil Engineers.

Author keywords: Aftershock hazard; Collapse risk; Degraded system; Earthquake damage; Fragility; Performance-based engineering; Reliability; Steel structures; Structural safety and reliability.

Introduction

During earthquake events, it is not uncommon to observe aftershocks following a mainshock. On April 11, 2012, a M8.6 earthquake struck Indonesia, followed by several strong aftershocks with the largest measured at M8.2 just over two h later (USGS 2012). After the 2011 Great Tohoku earthquake in Japan, 588 aftershocks with M5.0 or greater were recorded with 60 aftershocks being over M6.0 and three over M7.0 (USGS 2011). In the 24 h following the M8.8 earthquake in Chile on February 27, 2010, approximately 90 aftershocks with magnitudes equal to or larger than 5.0 were recorded by the USGS (2010). The Wenchuan earthquake occurred on May 12, 2008 with a magnitude of M7.9. By September 8, 2008, there had been 42,719 total aftershocks, of which 34 were from M5.0 to M5.9, and eight were from M6.0 to M6.5(RMS 2008). These strong aftershocks contributed to the collapse of many of the buildings that sustained damage from the mainshock, causing even more loss of life. More than 70,000 people lost their lives in the Wenchuan earthquake and its aftershocks. In addition, the economic loss was estimated to be around $150 billion (RMS 2008). There have also been occurrences of several large earthquakes, seemingly related, but not necessarily aftershocks. For example, consider the series of large earthquakes, known as the New Madrid Earthquakes of 1811–1812, which included three earthquakes ranging from M8.1–M8.3 that caused extensive damage as a result of all three earthquakes.

A mainshock may trigger aftershocks along the fault very far away from the mainshock center (Alliard and Léger 2008; Yeo and Cornell 2009). The delay between a mainshock and the largest aftershock can range between several minutes to months. The delay is difficult to predict, while magnitudes of aftershock are relatively easy to predict (Scholz 2002). In general, the occurrence rate decreases as time goes by after the mainshock. The magnitude of an aftershock is usually less than the mainshock, but the aftershock may have a higher peak ground acceleration (PGA) than the mainshock, even longer duration, and different energy content (Li et al. 2012). This combination of a mainshock and aftershocks would require structures to dissipate more energy.

Aftershocks have the potential to cause severe damage to buildings and threaten life safety even when only minor or no damage is present from a mainshock. Particularly, buildings with deteriorated or degraded structural properties are more susceptible to damage. In the 1999 Taiwan Chi-Chi earthquake, a gas station collapsed in an aftershock after it had sustained damage in the mainshock (Lew et al. 2000). A M7.1 earthquake hit New Zealand's second largest city, Christchurch on September 4, 2010. After 5 months, a M6.3 aftershock occurred on February 22, 2011. This sequence resulted in 185 deaths and approximately US$15 billion rebuild costs (Parker and Steenkamp 2012). Fig. 1 compares the peak interstory drifts of a steel building (described in the following section of this paper and used throughout as an example) from the mainshock and

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Collapse Capacity Reduction

Collapse Capacity Reduction After Main Shock	
Structure has Minor Damage	0%
Structure has Moderate Damage	13%
Structure has Severe Damage	40%

Collapse Capacity Reduction After Random Aftershocks	
Structure has Minor Damage	0%
Structure has Moderate Damage	14%
Structure has Severe Damage	53%

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%

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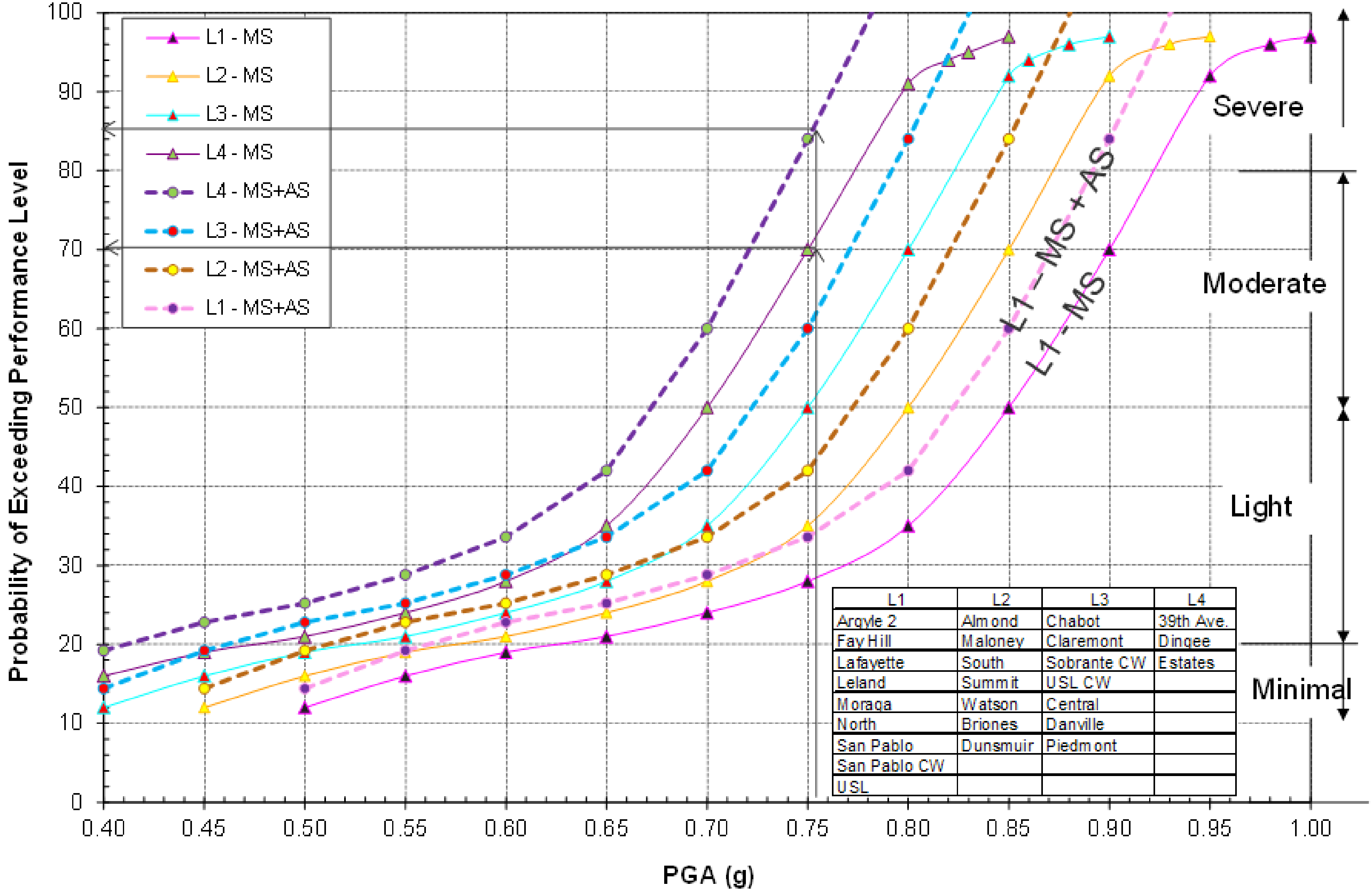
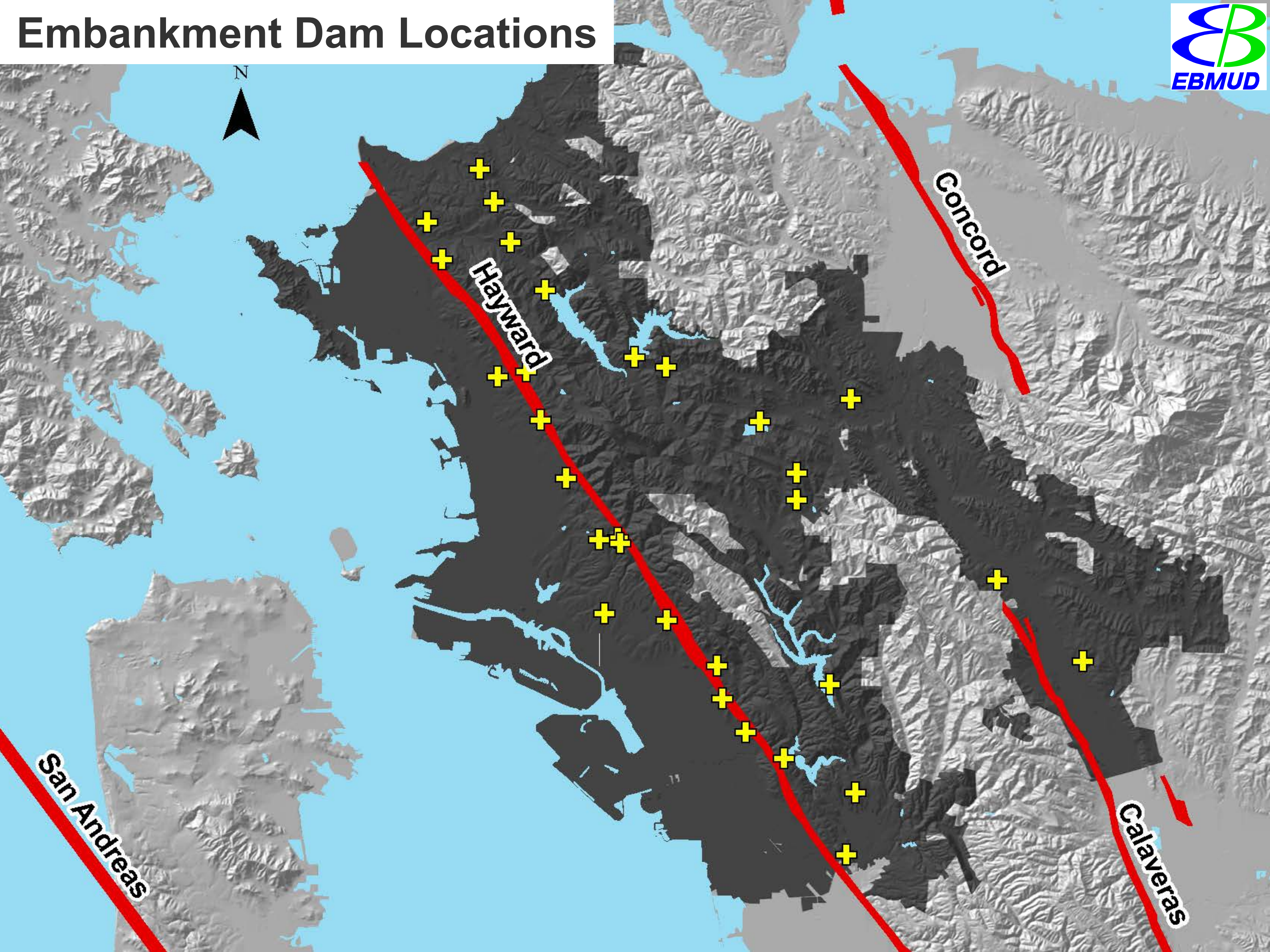
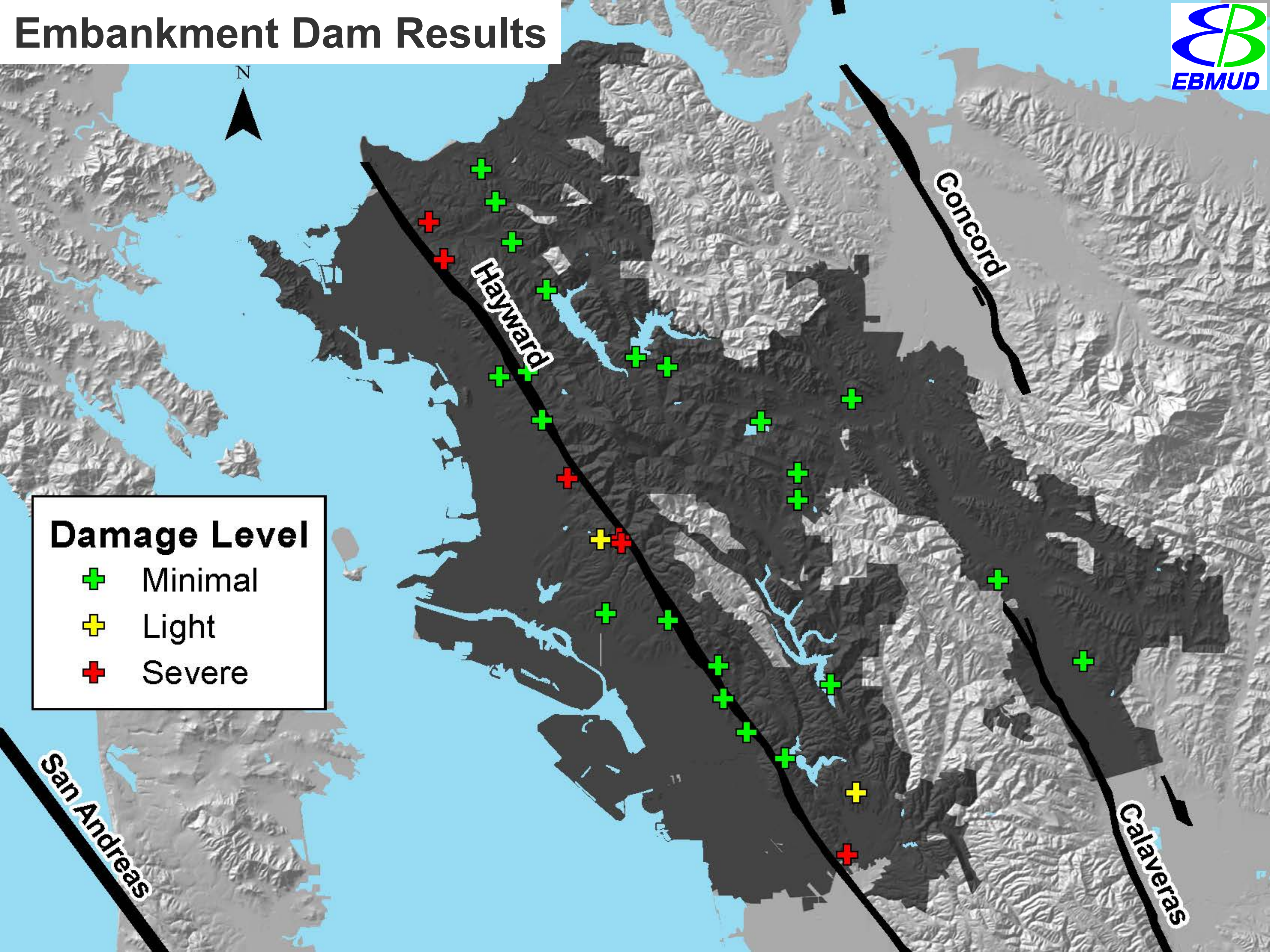
Embankment Dam Fragility Limits



Embankment Dam Locations



Embankment Dam Results



Embankment Dam Damage Summary

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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

Tank Reservoir Fragility Limits

EBMUD

HAZUS-MH MR3

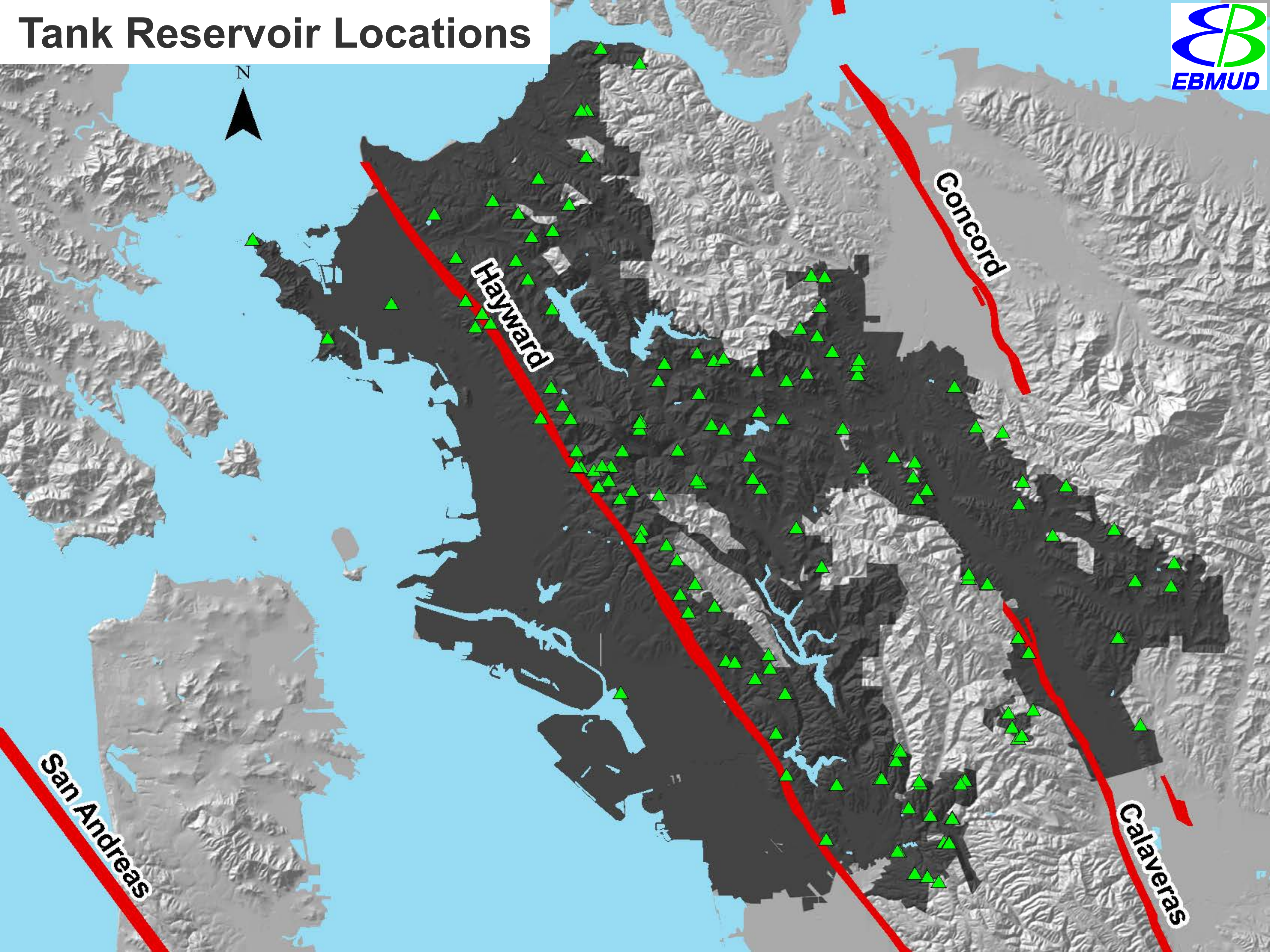
Technical Manual

Developed by:

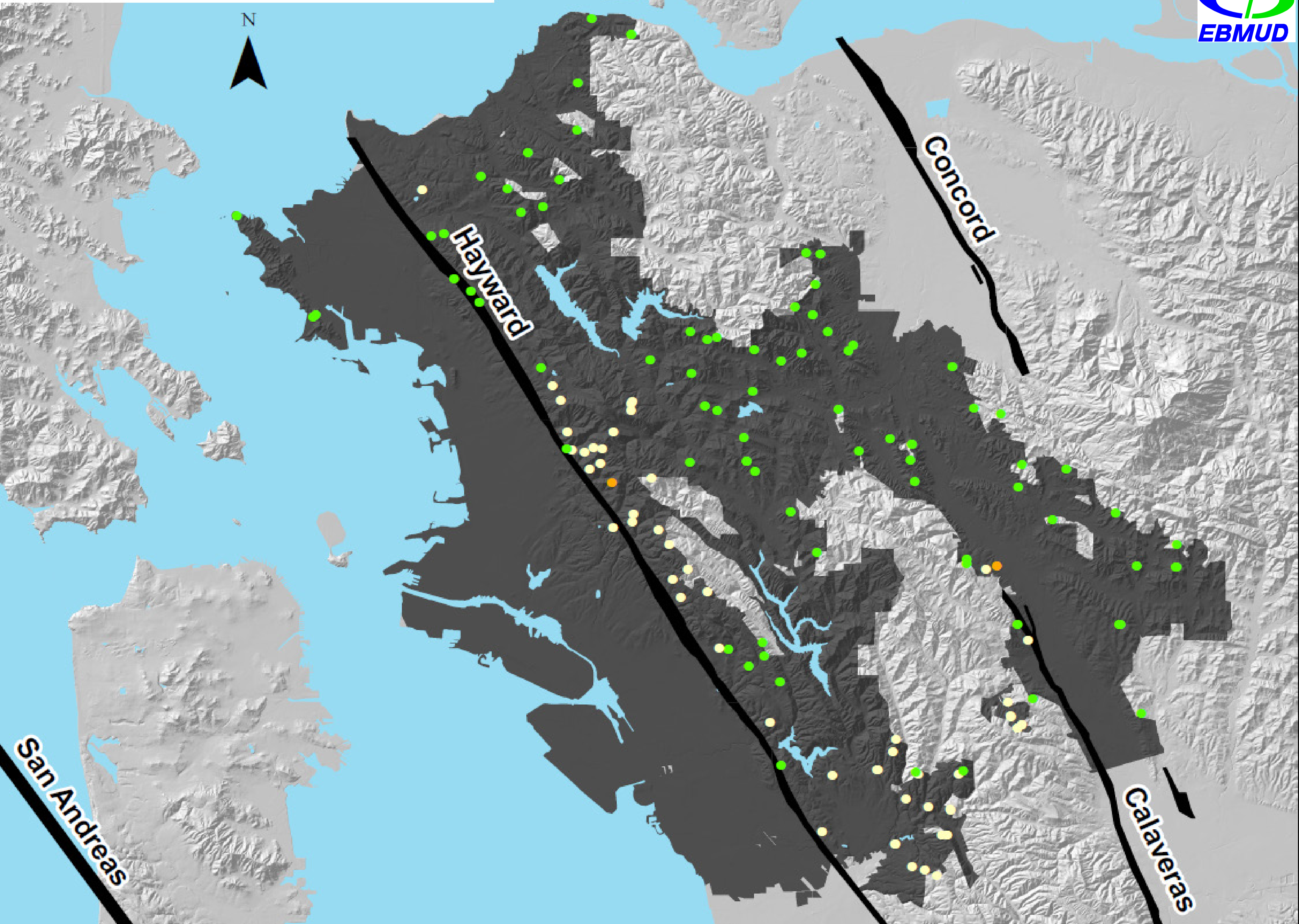
Department of Homeland Security
Emergency Preparedness and Response Directorate
FEMA
Mitigation Division
Washington, D.C.

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

Tank Reservoir Locations



Water Tanks - Main Shock Event



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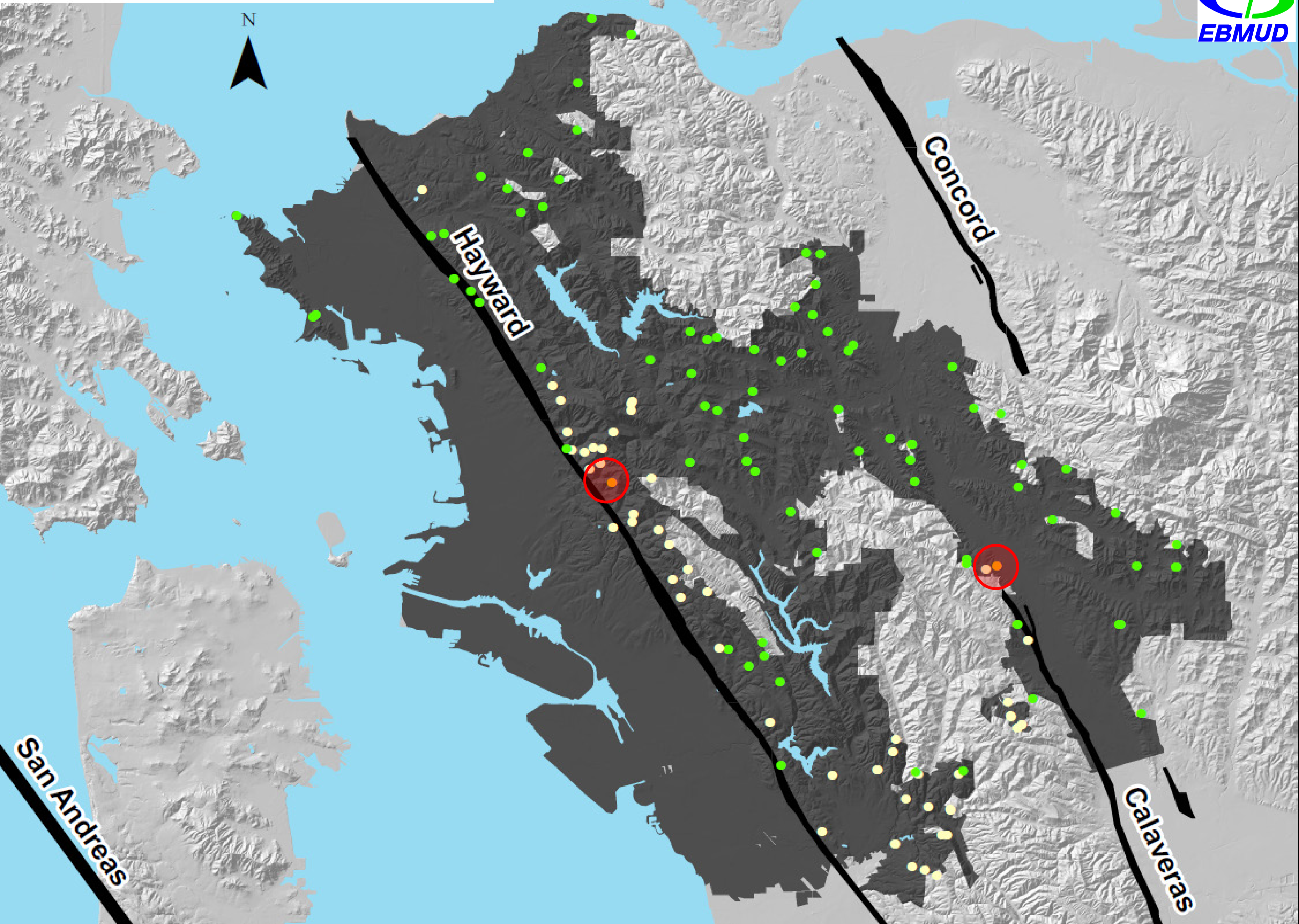
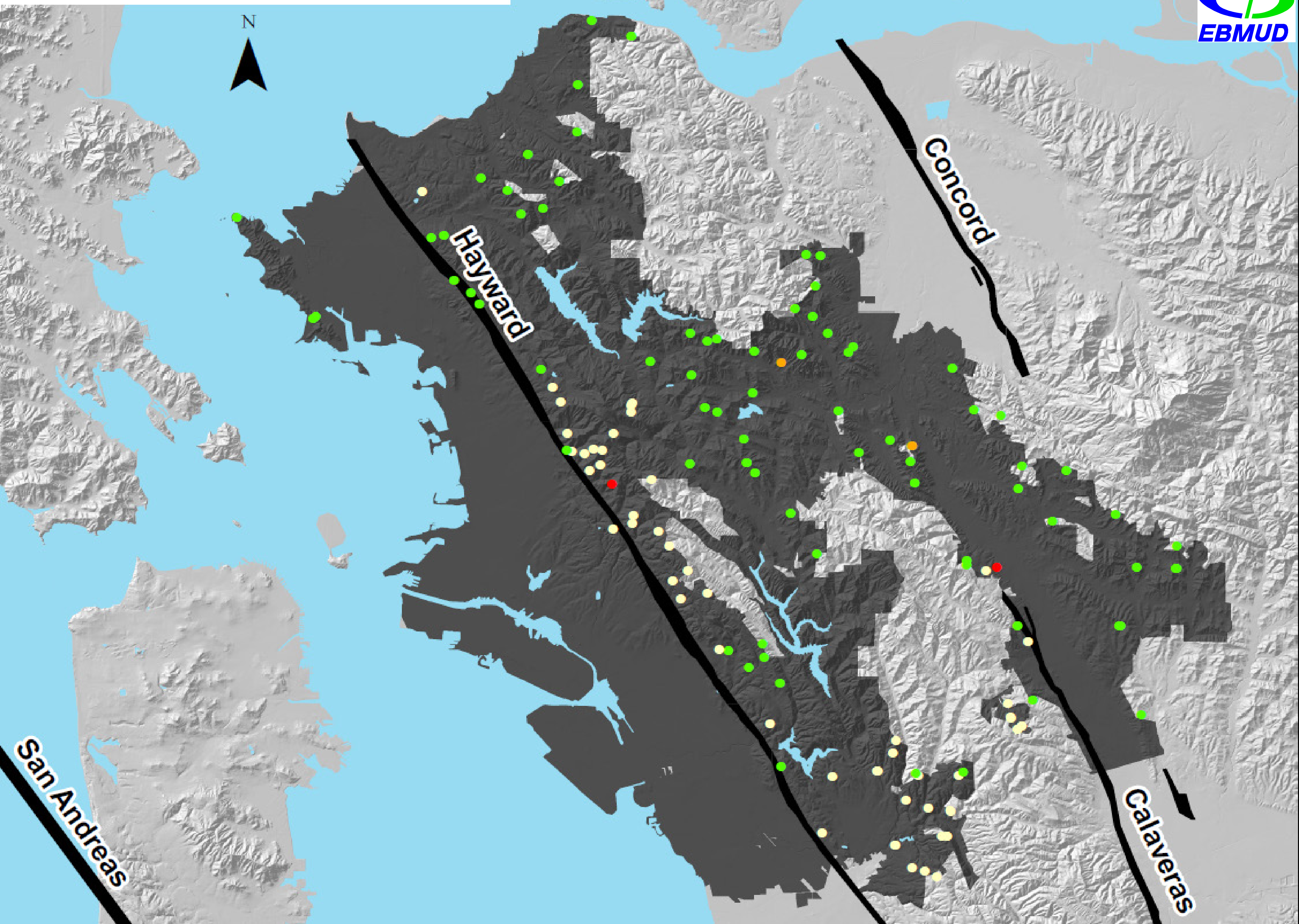


Water Tanks - After Shock Events



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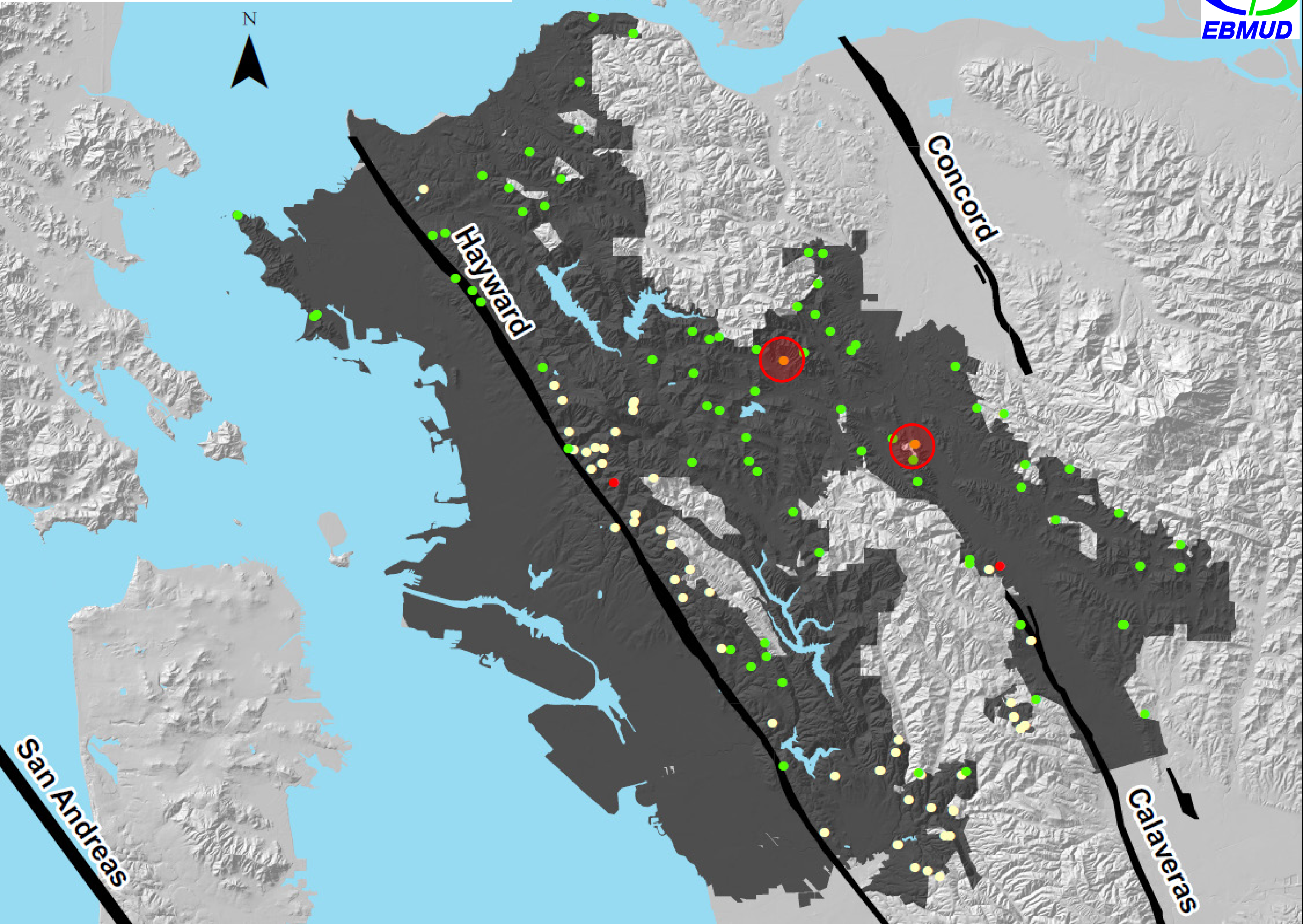
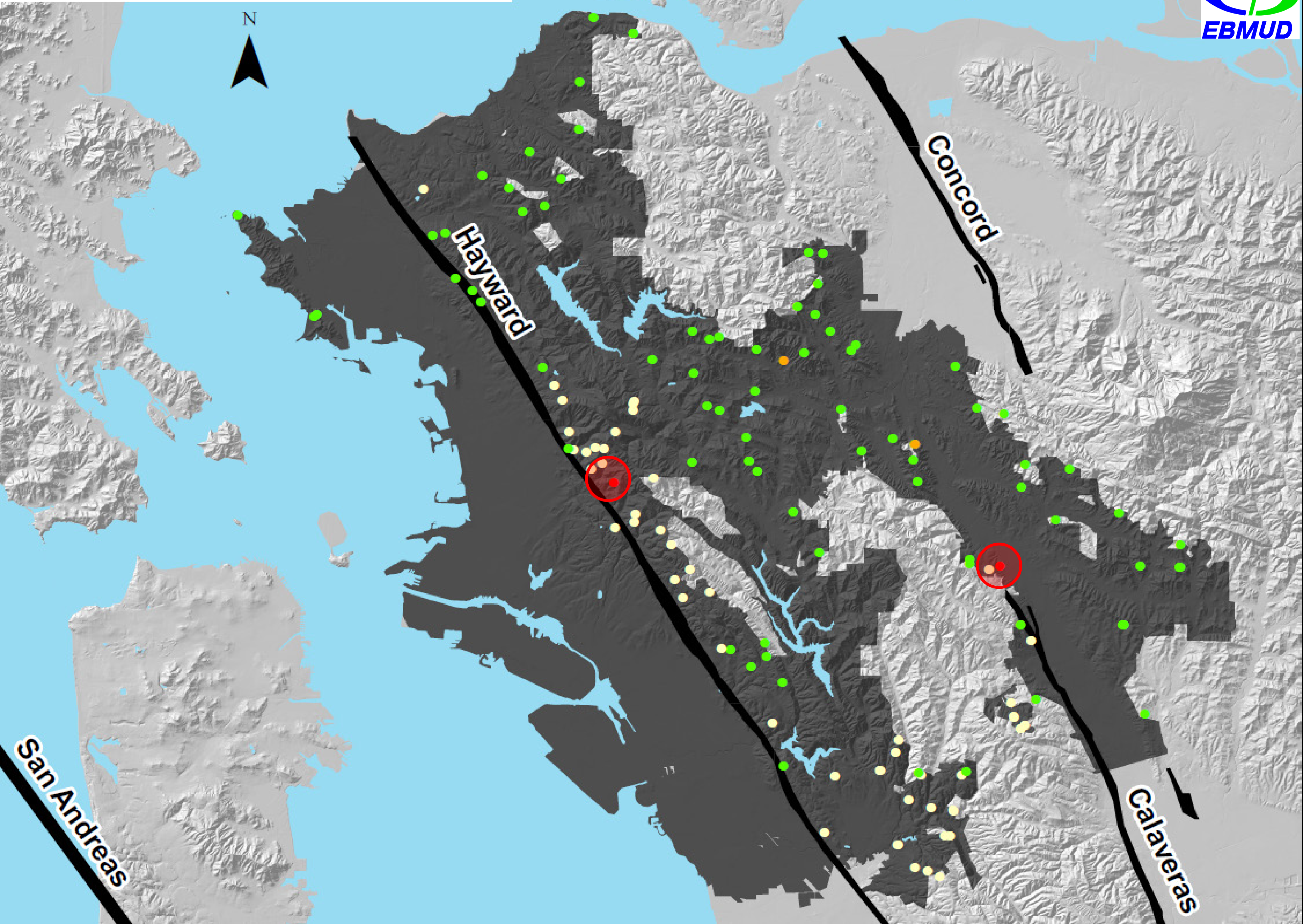


Water Tanks - After Shock Events



Tank Reservoir Damage Summary

EBMUD

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%

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%

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%

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%

Tank Reservoir Damage Summary

EBMUD

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%

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%

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%

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%

ALA Vulnerability Functions

EBMUD

AmericanLifelinesAlliance

A public-private partnership to reduce the risk to utility and transportation systems for natural hazards

Hazard	Vulnerability Function	Lognormal Standard Deviation, β	Comment
Wave Propagation	RR=0.00187 * PGV	1.15	Based on 81 data points of which largest percentage (38%) was for CI pipe.
Permanent Ground Deformation	$RR=1.06 * PGD^{0.319}$	0.74	Based on 42 data points of which largest percentage (48%) was for AC pipe.

Notes
1. RR = repairs per 1,000 of main pipe.
2. PGV = peak ground velocity, inches/second.
   PGD = permanent ground deformation, inches.
3. Ground failure mechanisms used in PGD formulation: Liquefaction (88%); local tectonic uplift (12%).

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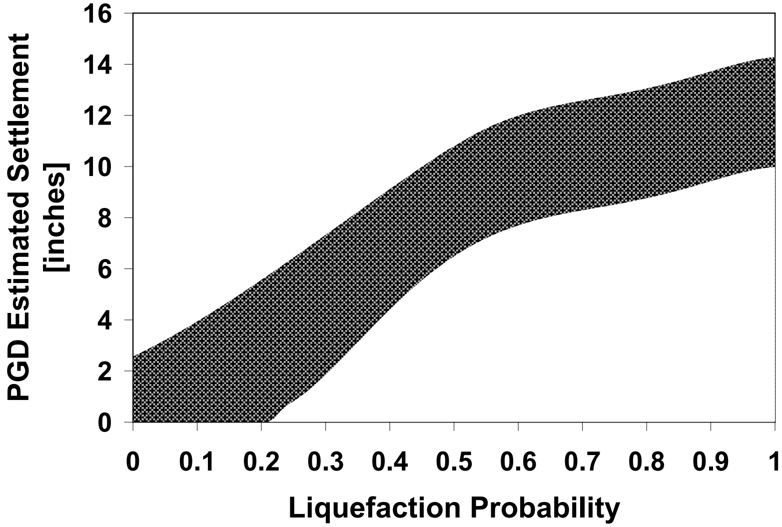
Pipeline Fragility Limits Landslide

USGS Holzer Liquefaction Potential Index



USGS Witter Liquefaction Susceptibility

Susceptibility Category	PGA(t)
Very High	0.09g
High	0.12g
Moderate	0.15g
Low	0.21g
Very Low	0.26g
None	N/A

Relative Susceptibility	Settlement (inches)
Very High	12
High	6
Moderate	2
Low	1
Very Low	0
None	0

Pipeline Fragility Limits Liquefaction

HAZUS-MH MR3

Technical Manual

Developed by:

Department of Homeland Security
Emergency Preparedness and Response Directorate
FEMA
Mitigation Division
Washington, D.C.

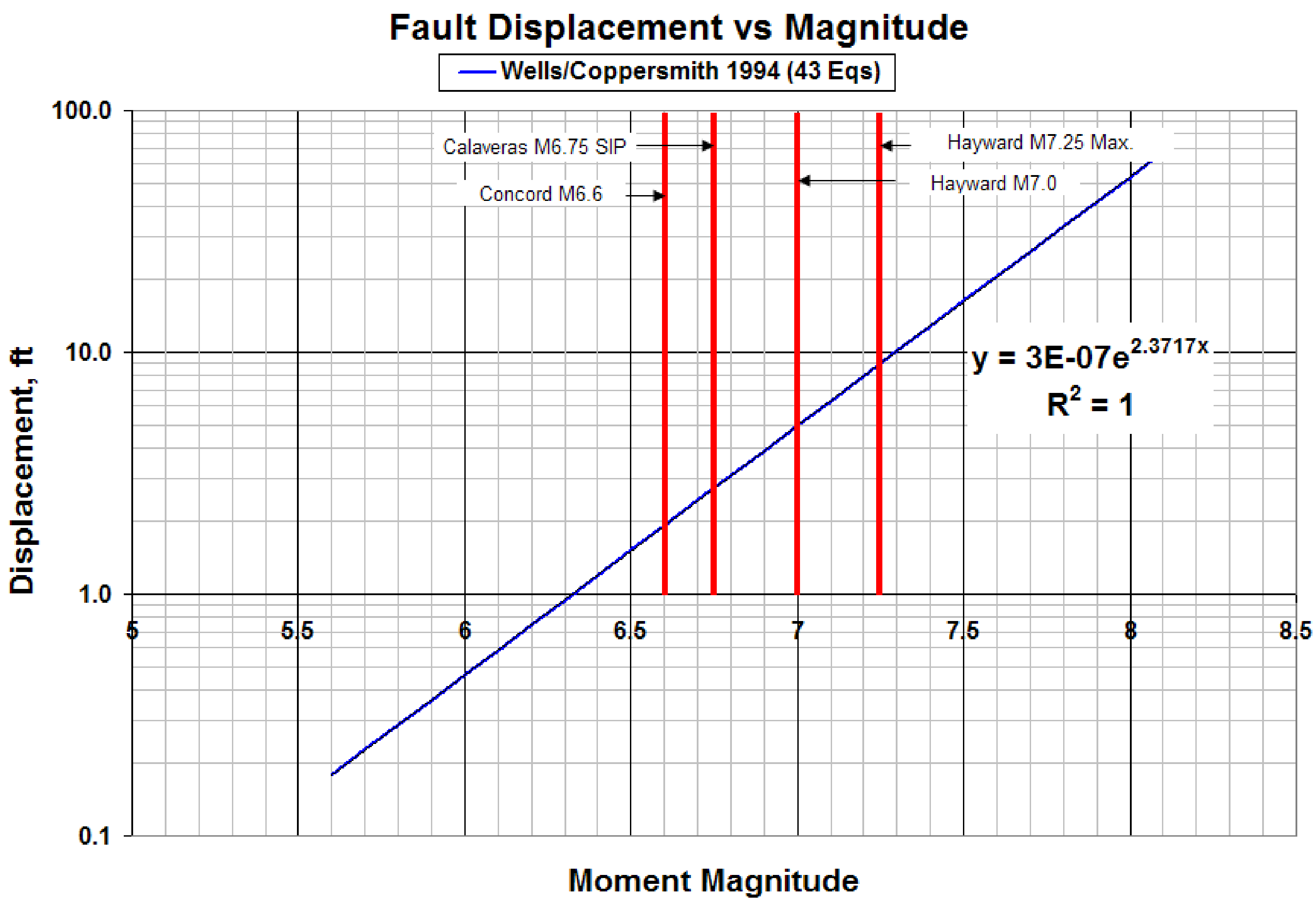
CGS Wills Landslide Susceptibility

$$\log D_N = -2.710 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.335}\left(\frac{a_c}{a_{max}}\right)^{-1.478}\right] + 0.424M \pm 0.454,$$

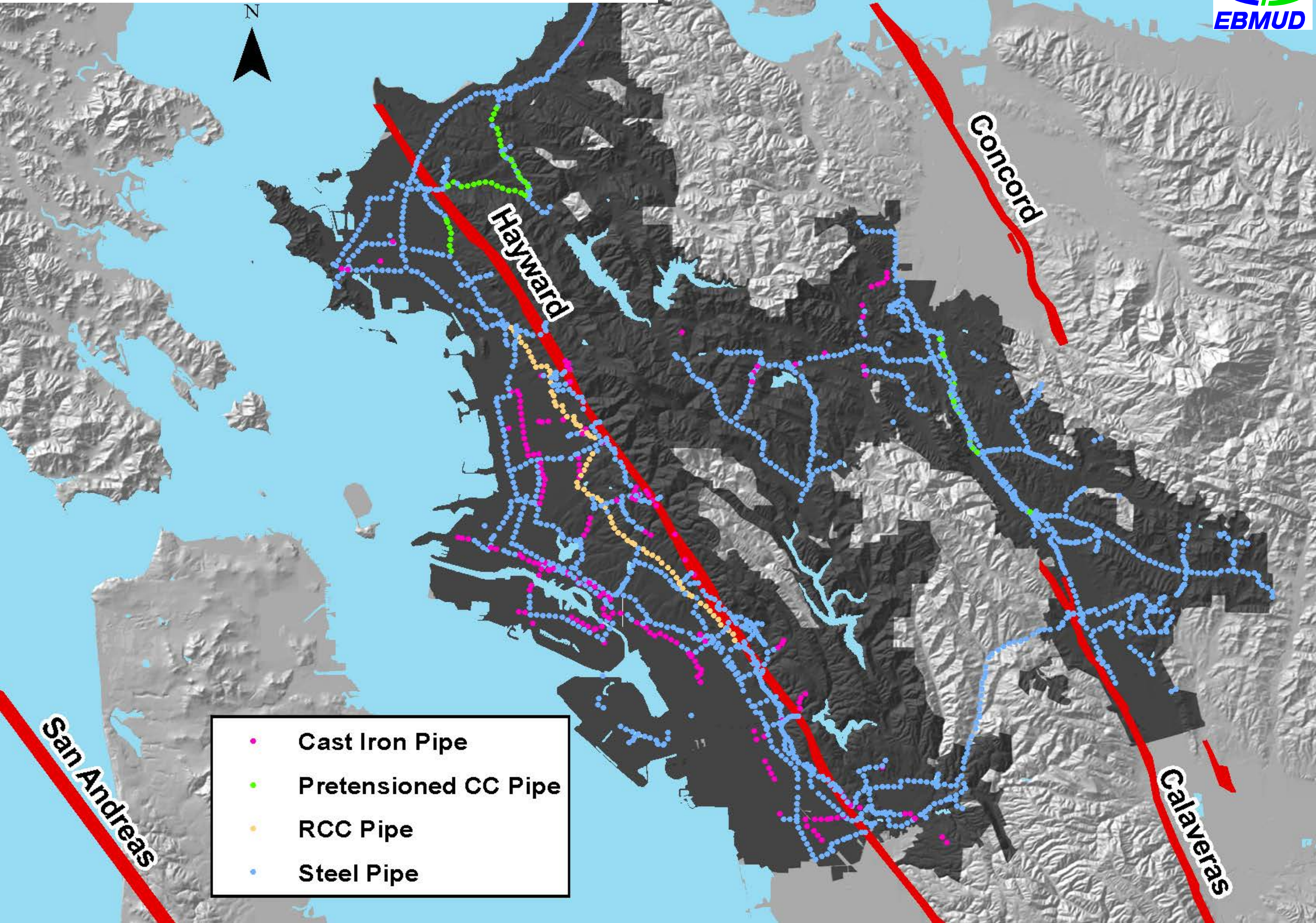
Susceptibility Category	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Critical Accelerations (g)	None	0.60	0.50	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05

Pipeline Fragility Limits
Fault Displacement

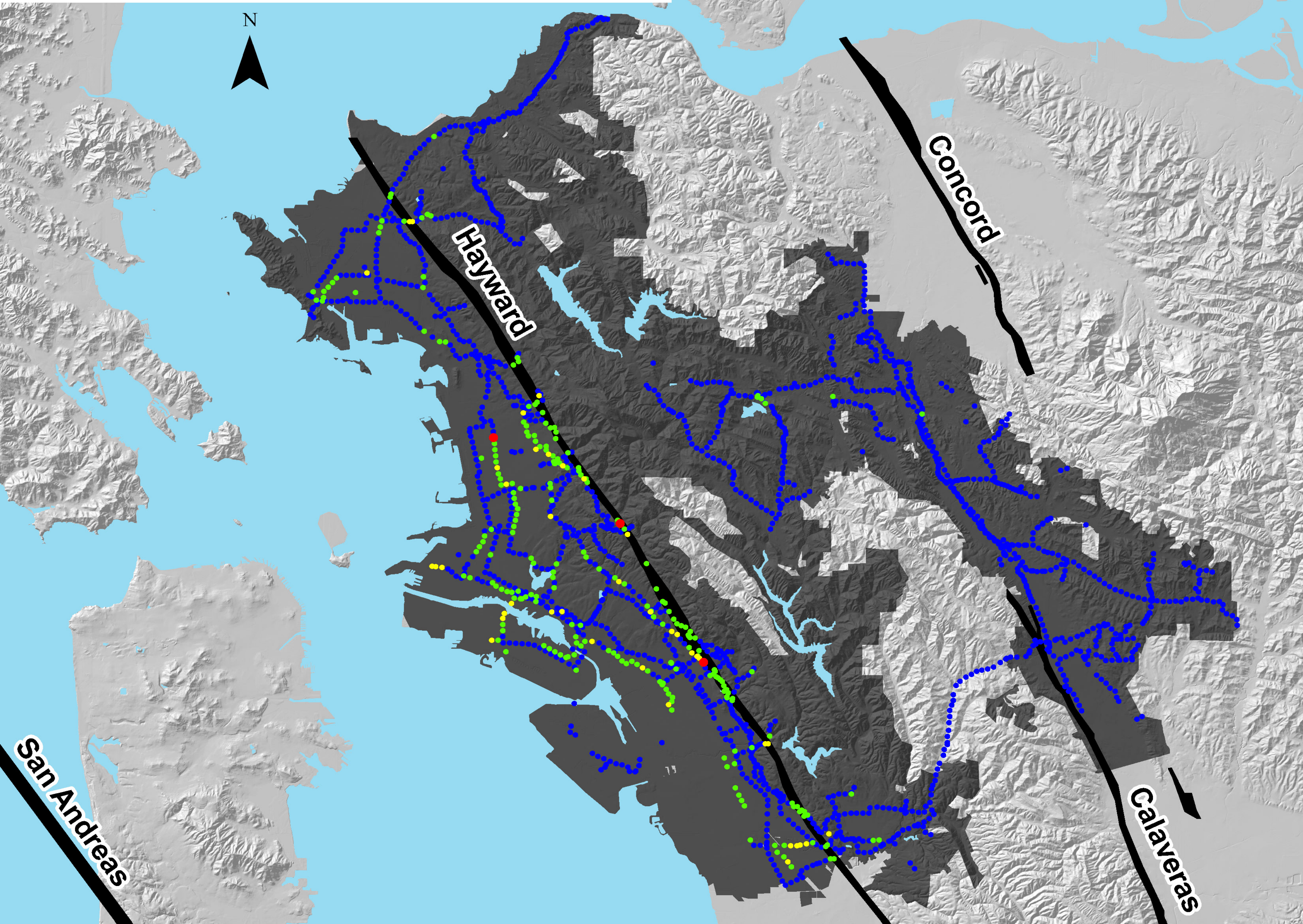
CGS Alquist-Priolo Fault Zones



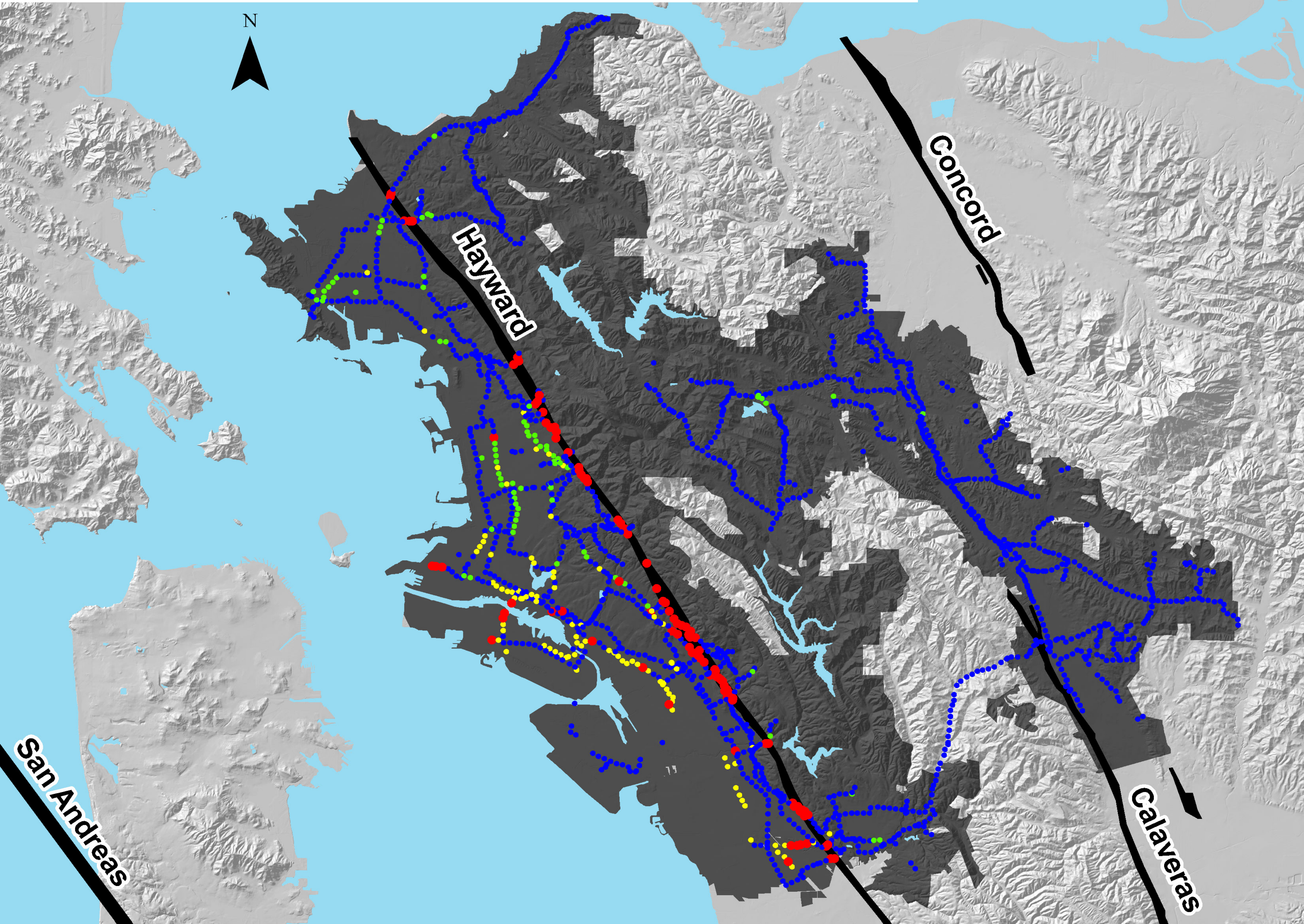
Large Diameter Pipelines



Large Diameter Pipelines - Main Shock Event



Large Diameter Pipelines - Main Shock and After Shock Events



Large Diameter Pipeline Results

EBMUD

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%

Large Diameter Pipeline Results

EBMUD

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%	17%	0%	5%	4%	4%	4%	35%

Thank You!

ありがとう
ございました!

Thank You!

謝謝!

Questions?

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