SAN FRANCISCO EARTHQUAKE STUDY
HAYWARD FAULT (MAGNITUDE 7.0) SCENARIO

June 2016

NATIONAL PROTECTION AND PROGRAMS DIRECTORATE

OFFICE OF CYBER AND INFRASTRUCTURE ANALYSIS

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EXECUTIVE SUMMARY

The U.S. Department of Homeland Security Office of Cyber and Infrastructure Analysis (DHS/OCIA) manages the advanced modeling, simulation, and analysis capabilities of the National Infrastructure Simulation and Analysis Center (NISAC). OCIA–NISAC analyzed the impacts to the Dams Sector, the Highway Infrastructure and Motor Carrier Subsector, and the Water and Wastewater Systems Sector after a scenario 7.0 magnitude earthquake strikes the Hayward-Rodgers Creek Fault system in the San Francisco Bay Area.

The results of this analysis show a strong earthquake will likely cause significant damage to critical infrastructure in the area affecting 547 dams or water control structures, render approximately 300 roadway segments unusable, and cause damage to 172 water and wastewater treatment systems.

The scenario earthquake will likely cause damage to 154 dams in the area. Seven of the dams will likely experience Extensive or Complete damage. The Ward Creek Dam, which is used for flood control, is likely to incur Complete damage. Extensive damage to the James H. Turner Dam poses the greatest risk to downstream population.

The earthquake will cause damages to many road segments, bridges, and tunnels in the area. As a result, travel times on these roadways and others will increase significantly. Multiple areas on freeways such as I–680, I–880, and I–580 will have the highest above normal traffic volumes. Several bridges on these freeways will also likely incur Extensive damage. Tunnels in the area will likely have less damage with bores in the Caldecott Tunnel on State Route 24 experiencing only Moderate damage.

The earthquake is likely to affect water and wastewater services. The Alameda County Water District is likely to experience the most substantial impacts to water treatment systems. Alameda and Contra Costa County wastewater treatment plants are likely to experience the worst impact.

KEY FINDINGS

- **Although ground shaking from the scenario earthquake would occur throughout the San Francisco Bay Area and surrounding regions, the most significant impacts would occur around the Hayward Fault line and regions corresponding to high liquefaction and landslide susceptibility.**
- **Five high-hazard dams and one significant-hazard dam are likely to suffer Extensive damage. The Ward Creek Dam, used for flood control, is likely to incur Complete damage. Of the seven Extensively to Completely damaged dams, the James H. Turner Dam poses the greatest risk to downstream population.**
- **The scenario earthquake damages bridges, tunnels, and roadways disrupting traffic at numerous locations throughout San Francisco and the surrounding area. Damaged road segments on high-traffic-volume roads under normal conditions are very likely to disrupt traffic volumes and patterns as traffic is rerouted to compensate. In addition to interrupting traffic, losing a roadway bridge can adversely affect other infrastructure: electrical, communication, and additional connections across the span.**
- **The scenario earthquake is likely to significantly affect water delivery to consumers. The Hetch Hetchy Aqueduct supplies about 85 percent of San Francisco's water supply. This aqueduct separates into four distinct Bay Division Pipelines at Fremont, California. All of these pipelines cross the Hayward Fault, and they are likely to experience significant damage. The majority of San Francisco consumers will not have water if these pipelines are out-of-service.**

- **The Alameda County Water District is likely to experience the most substantial impacts to water treatment systems. The Mission San Jose Treatment Plant is likely to be out-of-service until major repairs are completed. Extensive damage to the Sobrante and Upper San Leandro water treatment plants in the East Bay Municipal Utility District will likely put these plants out-of-service.**
- **The wastewater treatment plants that serve Alameda and Contra Costa Counties are likely to experience the worst impact. Five wastewater treatment plants in these counties are likely to sustain Complete damage. Five wastewater treatment facilities serving Marin, San Mateo, Santa Clara, Solano, and Sonoma Counties are likely to experience Complete damage, rendering them out-of-service.**

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SCOPE

The U.S. Department of Homeland Security/Office of Cyber and Infrastructure Analysis (DHS/OCIA), National Infrastructure Simulation and Analysis Center (NISAC) San Francisco Earthquake Hayward Fault study analyzed the impacts of a scenario earthquake on the Dams Sector, the Highway Infrastructure and Motor Carrier Subsector, and the Water and Wastewater Systems Sector in the area. Additional infrastructure sectors were beyond the scope of this study.

OCIA–NISAC intends for this analysis to inform all stakeholders who support development of earthquake hazard mitigation strategies and preparedness planning measures and to increase the awareness of response and recovery efforts. In addition, OCIA-NISAC intends this analysis to provide timely and defensible consequence modeling to DHS and National Infrastructure Protection Plan security partners.

OVERVIEW

The San Francisco Bay Area is home to approximately 7.2 million people and vast critical infrastructure. This area is subject to frequent earthquakes of varying size and intensity because it sits on several faults.

Since 1968, three earthquakes have occurred in the San Francisco Bay Area with a magnitude 6.80 or higher. The October 21, 1968, magnitude 6.8 earthquake struck the San Francisco Bay area on the Hayward Fault. The April 18, 1906, magnitude 7.7 Great San Francisco earthquake and the October 17, 1989, magnitude 6.9 Loma Prieta Earthquake struck the area on the San Andreas Fault.[1]

The scenario for this report assumes a 7.0 magnitude earthquake occurs in the Hayward-Rodgers Creek Fault system in early April at 4 p.m. Pacific Standard Time. The earthquake epicenter (N37.80, W122.18) is in Crestmont, California, approximately 5 miles west of Oakland, California, at a depth of 4.97 miles. Based on modeling results and evolving earthquake theories, the scientists at the U.S. Geological Survey (USGS) concluded that a 63-percent probability exists of at least one magnitude 6.7 or higher earthquake striking one of the seven main fault systems in the San Francisco Bay Area in the next 30 years. The USGS model lists the Hayward-Rodgers Creek Fault system as having the highest probability of an earthquake at 31 percent.[2]

EARTHQUAKE AND LIQUEFACTION METRICS TERMINOLOGY

Earthquakes can present several hazards to a region, including ground shaking, liquefaction, landslides, and tsunamis, depending on area geography. These primary hazards can often produce secondary hazards such as ruptured utility lines, fallen buildings, hazardous spills, damaged surface transportation segments, and fires.[3] The following provides a brief description of the primary hazards and their impacts:

- Ground shaking—vibration of the ground during an earthquake. It can trigger other hazards such as liquefaction and landslides. Most earthquake damage results from the shaking caused by seismic waves passing beneath buildings, roads, and other structures. For example, ground shaking may cause exterior building walls to crumble injuring people, blocking sidewalks and streets, and bringing down utility lines.[4]
- Liquefaction—the way in which wet granular soils change from a solid state to a liquid state during ground shaking. This results in a loss of soil strength and the ability to support weight, which can undermine the foundations and supports of buildings, bridges, pipelines, and roads, causing them to sink into the ground, collapse, or dissolve.[5]

[1] U.S. Geological Survey, "Earthquake Glossary," http://earthquake.usgs.gov/learn/glossary/, accessed 26 February 2016.
[2] Earthquake Safety.com, Bay Area earthquake hazards, "Forecasting California's Earthquakes," www.earthquakesafety.com/earthquake-faults.html, accessed 23 March 2015.
[3] Cascadia Regional Earthquake Workgroup, "From Ground Shaking to Tsunamis: Earthquake Hazards," www.crew.org/earthquake-information/earthquake-hazards, accessed 29 April 2015.
[4] Ibid.
[5] Ibid.

- Landslides—earthquakes can trigger landslides, especially in areas with water-saturated soils. Landslides may result in falling rocks and debris that collide with people, buildings, and vehicles. They can also block roads and disrupt utility lines.[6]

The USGS Earthquake Hazards Program produces ShakeMaps that provide near real-time maps of ground motion and shaking intensity following an earthquake. Figure 1 shows the peak ground acceleration on the Hayward-Rodgers Creek fault for a magnitude 7.0 earthquake. Figure 2 shows the landslide susceptibility. Figure 3 shows the liquefaction susceptibility. The following provides brief definitions of the data provided in these maps:[7]

- Peak ground acceleration—the maximum acceleration that any point on the ground would experience. The units are in G-force (gravity). For example, if a 100-pound rock receives a 50-pound shaking force, it has a peak ground acceleration of 0.5 (50 percent) or half of a G-force; that is, half of its weight.
- Peak ground velocity—the maximum speed that a point on the ground would achieve from ground shaking in an earthquake. Units are in centimeters per second.
- Spectral acceleration—the maximum horizontal acceleration that a point on the ground would experience at a particular frequency. This acceleration is approximately what is experienced by a building as modeled by a particle on a massless vertical rod having the same natural period of vibration as the building.
- Liquefaction susceptibility—the likelihood of soils behaving as a fluid-like mass during an earthquake. As mentioned above, liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Surface geology and the degree of water saturation determine the local susceptibility to liquefaction.
- Landslide susceptibility—the likelihood of a potentially damaging landslide occurring in the area due to earthquake or other seismic activity.

[6] Cascadia Regional Earthquake Workgroup, "From Ground Shaking to Tsunamis: Earthquake Hazards," www.crew.org/earthquake-information/earthquake-hazards, accessed 29 April 2015.
[7] U.S. Geological Survey, "Earthquake Glossary," http://earthquake.usgs.gov/learn/glossary, accessed 23 April 2015.

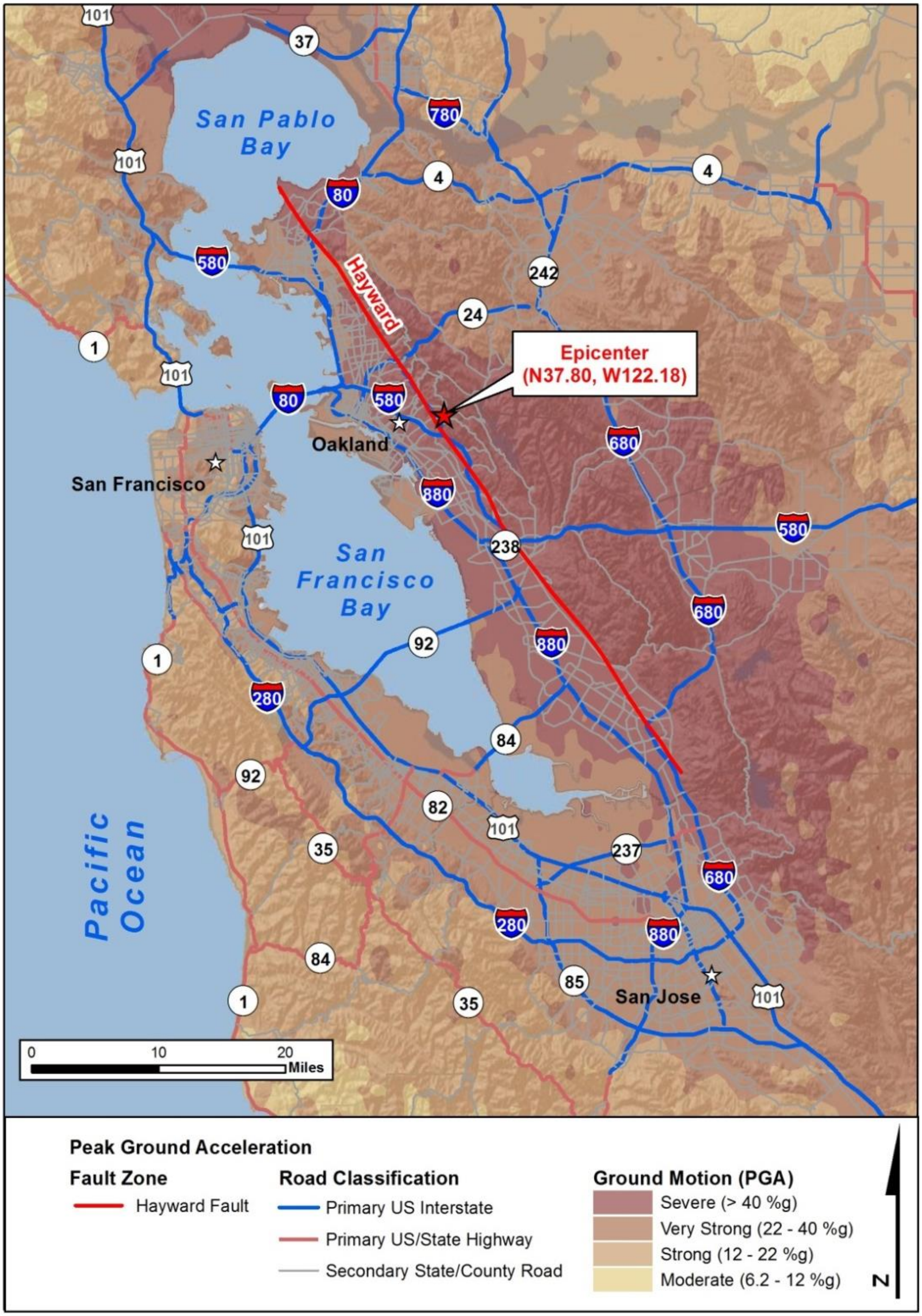

FIGURE 1—PEAK GROUND ACCELERATION, HAYWARD-RODGERS CREEK FAULT

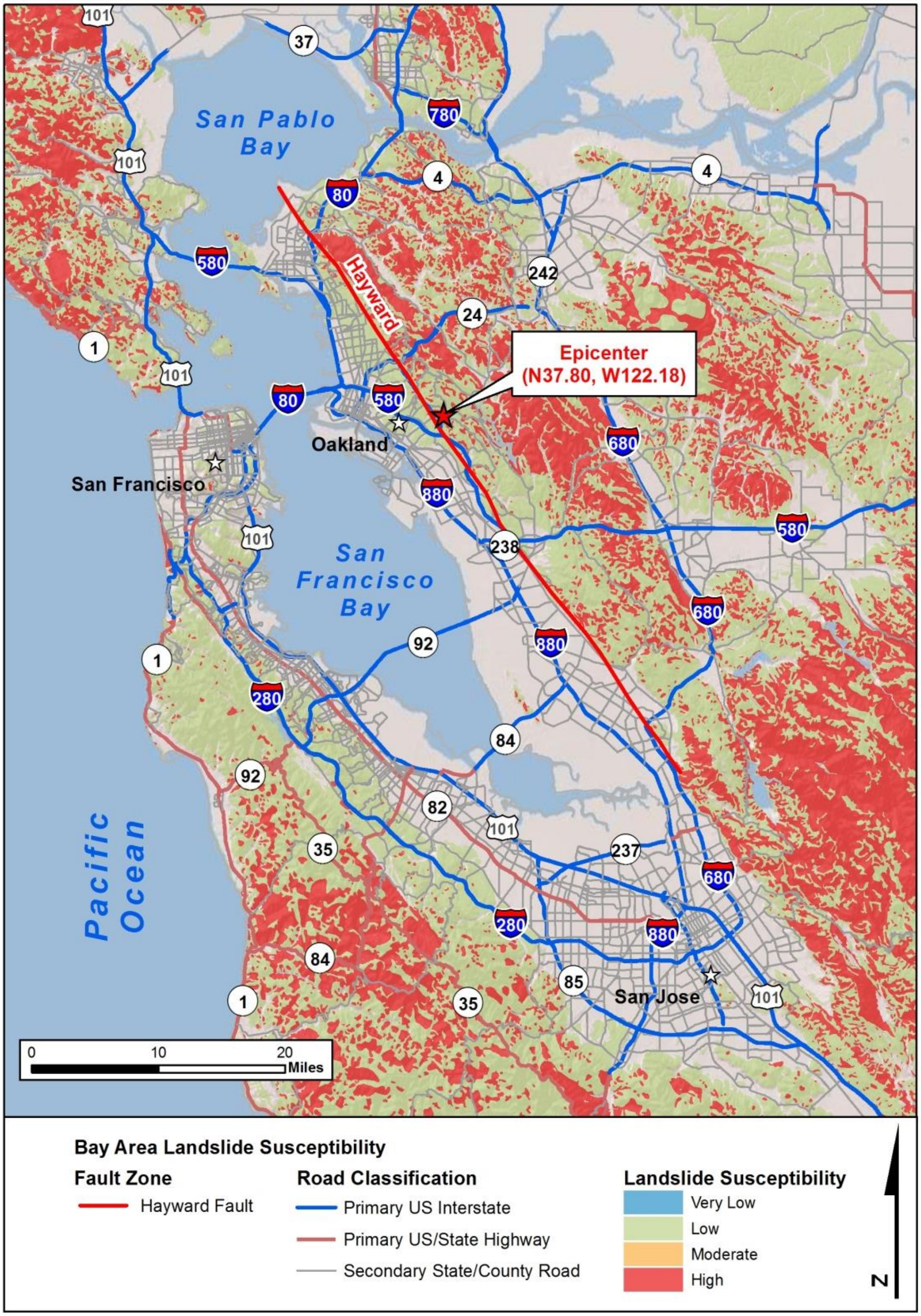

FIGURE 2—LANDSLIDE SUSCEPTIBILITY, HAYWARD-RODGERS CREEK FAULT

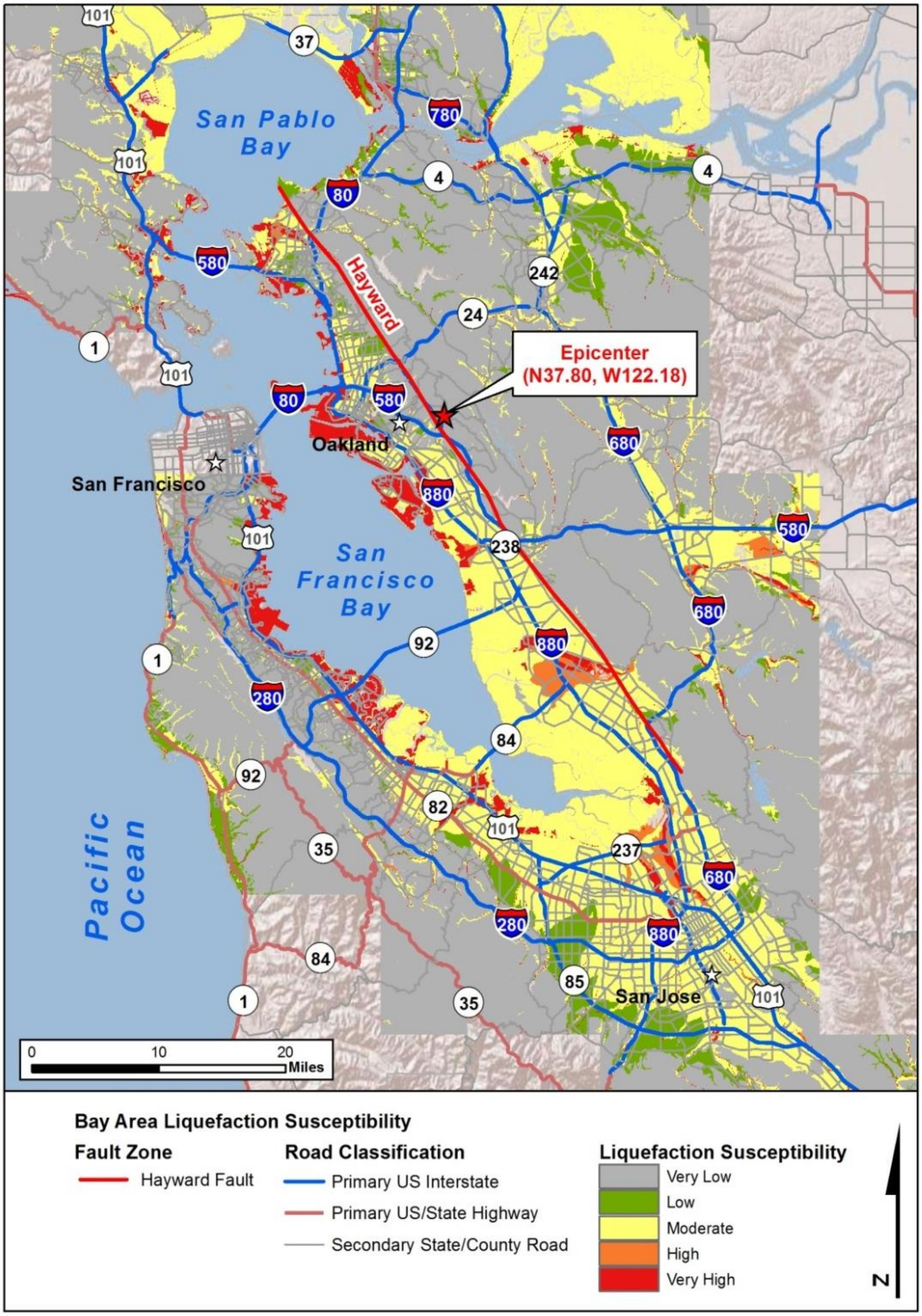

FIGURE 3—LIQUEFACTION SUSCEPTIBILITY, HAYWARD-RODGERS CREEK FAULT

ANALYSIS RESULTS

Although ground shaking from the scenario earthquake would be felt throughout the San Francisco Bay Area and surrounding regions, a majority of the impacts to critical infrastructure are in the region surrounding the Hayward Fault line and areas corresponding to high liquefaction and landslide susceptibility levels. See Appendix A for a discussion on the methodologies used for this analysis.

ANALYSIS RESULTS–DAMS

The scenario earthquake is likely to affect 547 dams or water control structures identified in the National Inventory of Dams (NID).[8] Table 1 provides the characteristics of various damage states for dams, along with damage state descriptions.[9]

TABLE 1—DAMAGE CATEGORIES AND DESCRIPTIONS FOR DAMS[10]

Damage State	Damage Description
Complete	Major widespread damage resulting in the facility possibly being demolished or total destruction of the majority of the facility
Extensive	Extensive damage requiring major repair
Moderate	Significant localized damage of many components warranting repair
Slight	Limited-to-significant localized damage of some components generally not requiring repairs
None	No damage to components

Direct earthquake effects resulting from peak ground acceleration are likely to range from Slight damage to Complete damage to 154 dam structures located within the scenario impact area. Six dam structures are likely to have Extensive damage. The Ward Creek dam is likely to incur Complete damage.

Table 2 provides a summary of the earthquake-induced expected damages to the dam structures within the region, along with a summary of the National Inventory of Dams Dictionary (NIDD) hazard classifications. The NIDD hazard classification levels indicate the potential hazard to the downstream area resulting from the failure or misoperation of the dam facility.[11]

- Dams classified as high hazard are structures in which failure or misoperation would probably cause the loss of human life.
- Significant-hazard dams are structures in which failure or misoperation probably would not result in loss of human life; however, economic loss, environmental damage, disruption to lifeline facilities, or other significant damage would likely occur. Significant-hazard dams are often located in predominantly rural or agricultural areas, but could be located in populated areas with significant infrastructure.[12]

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[8] U.S. Army Corps of Engineers, CorpsMap, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12:, accessed 29 April 2015.
[9] Federal Emergency Management Agency, "Hazus 2.1 Technical and User's Manuals, Earthquake Model Technical Manual, Section 3.2.3," www.fema.gov/media-library/assets/documents/24609, accessed 7 April 2015.
[10] Lin, L., J. Adams, "Probabilistic Method for Seismic Vulnerability Ranking of Canadian Hydropower Dams," (paper presented at the Canadian Dam Association Annual Conference, St. John's, NL, Canada, September 22–27, 2007).
[11] National Inventory of Dams Database Data Dictionary, https://ire.org/media/uploads/files/datalibrary/samplefiles/National%20Inventory%20of%20Dams/DATADICT02.txt, accessed 7 April 2015.
[12] Ibid.

TABLE 2—SUMMARY OF EXPECTED DAMAGE STATES FOR DAMS AND NID HAZARD CLASSIFICATIONS

Damage State	Number of Dams	NID Hazard Classification		
		High	Significant	Low
Complete	1	1	0	0
Extensive	6	5	1	0
Moderate	42	36	4	2
Slight*	105	70	27	6
None**	393	149	119	112
Total	547	261	151	120

* Two slightly damaged dams within the region did not contain NID hazard classification.
** Thirteen undamaged dams within the region did not contain NID hazard classifications.

Table 3 provides a list of dams, with dam purpose, that are likely to be Extensively or Completely damaged under this earthquake scenario.[13] This table also shows the county location, hazard classification, and purposes for each of the dams in the significant or high-hazard categories, based on data provided in the 2013 NID database.

TABLE 3—AFFECTED DAMS; EXTENSIVE OR COMPLETE EXPECTED DAMAGE STATES

Dam Name	County	Damage State	Hazard Classification	Dam Purpose
Ward Creek	Alameda	Complete	High	C
James H. Turner	Alameda	Extensive	High	S
San Lorenzo Creek	Alameda	Extensive	High	C, R
Cull Creek	Alameda	Extensive	High	C, R, S
Danville	Contra Costa	Extensive	High	S
Almond	Alameda	Extensive	High	S
Shinn Pond	Alameda	Extensive	Significant	S

Purpose Codes: C—Flood control and storm water management R—Recreation S—Water supply

Figure 4 shows the locations of Extensively or Completely damaged dam structures, relative to peak ground acceleration. These damage states are color-coded and included in the figure legends. Based on the severity of damage estimated for these dams, structural failure could pose a significant threat to downstream populations, critical infrastructure, and economic activity. The recent drought conditions in California, starting in 2012, have led to lower than usual water levels in the upstream reservoirs so these downstream impacts are likely to be lower than OCIA–NISAC would normally expect.[14]

[13] National Inventory of Dams Database Data Dictionary, https://ire.org/media/uploads/files/datalibrary/samplefiles/National%20Inventory%20of%20Dams/DATADICT02.txt, accessed 7 April 2015.
[14] Brekke, D., April Drought Update: How Do the Reservoirs Look? Low, and Getting Lower, April 14, 2015, http://ww2.kqed.org/news/2014/12/15/its-raining-so-how-do-those-reservoirs-look, accessed 23 April 2015.

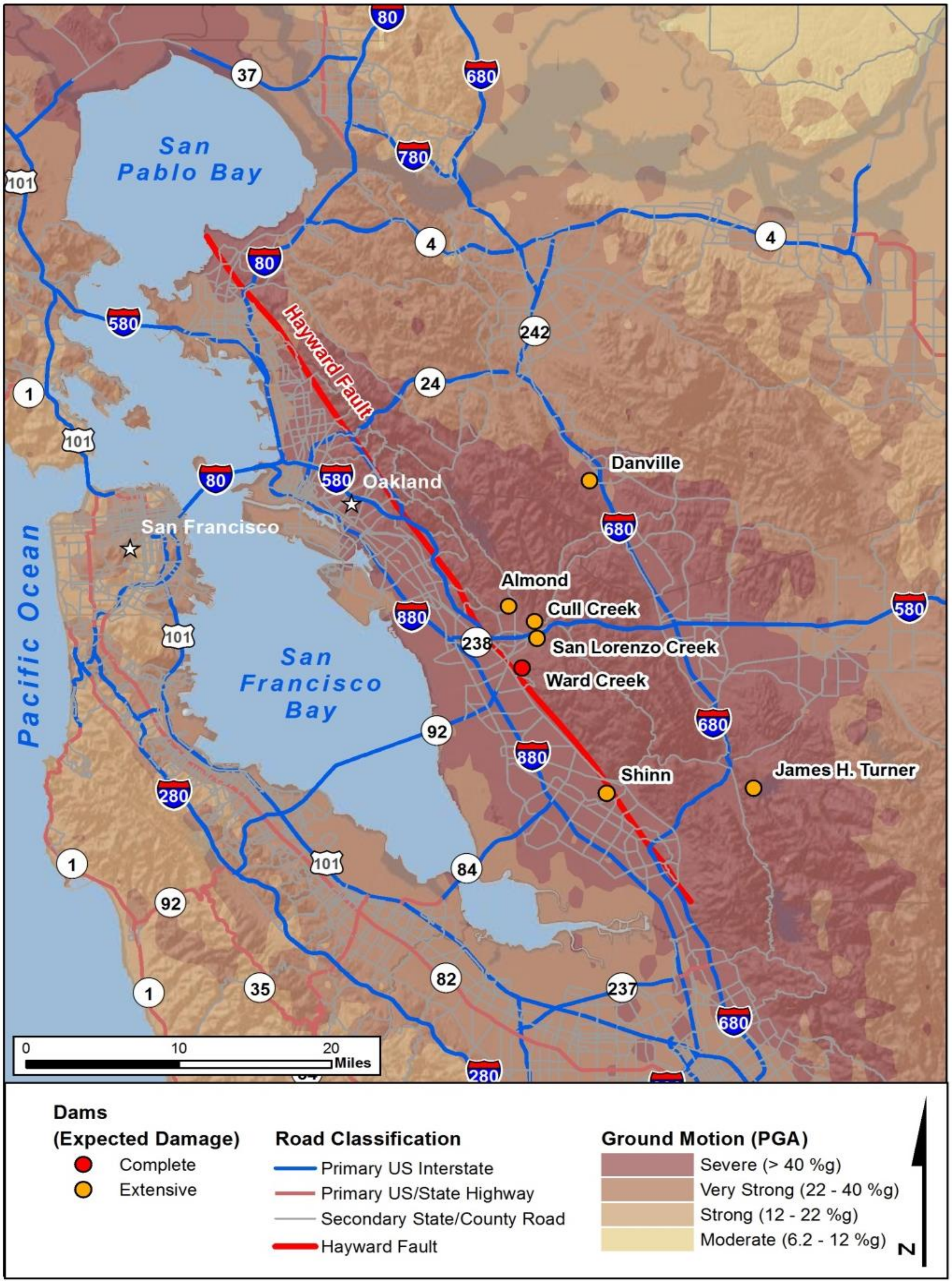

FIGURE 4—SAN FRANCISCO BAY AREA DAM FACILITIES; EXTENSIVE OR COMPLETE EXPECTED DAMAGE STATES

WARD CREEK DAM

Ward Creek Dam, which provides flood control and storm water management, is a compacted earth-filled structure located approximately 0.5 miles from the corner of Mission Boulevard and Pinedale Court in Hayward, California. This embankment dam has a maximum storage capacity of 220 acre-feet and a hydraulic head of approximately 60 feet.[15] This dam provides flood control and storm water management.

This dam experiences Complete damage from the scenario earthquake. If the dam is retaining a significant level of water at the time of failure, loss of life could occur because the Mission-Foothill neighborhood and Highway 238 (Mission Boulevard) lie downstream. OCIA–NISAC expects the downstream inundation area to be relatively small at this time, due to the 2015 drought conditions in California and the reservoir design capacity.

JAMES H. TURNER DAM

The James H. Turner Dam is a 193-foot-high, 2,160-foot-long compacted earth-filled structure that impounds the San Antonio Reservoir.[16] Located approximately 1 mile upstream of San Antonio Creek's confluence with Alameda Creek, it is approximately 2.5 miles southeast of the town of Sunol, California. The James H. Turner Dam is designed with a maximum storage capacity of 50,650 acre-feet; sedimentation has reduced the reservoir's maximum capacity to approximately 49,500 acre-feet.[17]

This dam experiences Extensive damage from the scenario earthquake. A catastrophic failure of this dam would generate a significant flood wave. Sunol is located immediately downstream from the San Antonio Reservoir, so a dam failure would likely result in loss of life and disruptions to I–680 and Highway 84. Because of the size of this reservoir, the downstream inundation area is likely to be significant.

SAN LORENZO CREEK DAM

San Lorenzo Creek Dam is a 65-foot-high, 385-foot-long compacted earthen dam that impounds Don Castro Reservoir.[18] Located near the boundary between Hayward and Castro Valley, this dam is used for recreation, flood control, and storm-water management.

This dam experiences Extensive damage from the scenario earthquake. A catastrophic failure of this dam would render it unable to manage storm water runoff or control flooding and could generate a flood wave that results from the release of up to 380 acre-feet (normal storage) of water. Normal storage, in acre-feet, is the total storage space in a reservoir below the normal retention level, including dead and inactive storage and excluding any flood control or surcharge storage.[19] Because of the 2015 drought conditions in California, OCIA–NISAC expects the total risk area to be localized within the steep slopes surrounding the downstream riverbed below the dam.

CULL CREEK DAM

Cull Creek Dam is a 55-foot-high, 440-foot-long compacted earthen embankment dam that impounds Cull Canyon Lake. [20] Located near the corner of Heyer Avenue and Cull Canyon Road in Castro Valley, California, this dam is used for recreation, water supply, flood control, and storm water management. The NID data indicate that the normal storage level for this dam is approximately 524-acre-feet.[21]

This dam experiences Extensive damage from the scenario earthquake. Because of the 2015 drought conditions in California and the water-level restrictions behind this dam, OCIA–NISAC expects the inundation risk area

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[15] U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12, accessed 29 April 2015.
[16] U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12, accessed 29 April 2015.
[17] Alameda Creek Watershed Streams and Reservoirs, www.sf-planning.org/Modules/ShowDocument.aspx?documentid=8000, accessed 20 April 2015.
[18] U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12, accessed 29 April 2015.
[19] Ibid.
[20] Ibid.
[21] Ibid.

following a potential breach of this dam to be localized within the slopes surrounding the downstream riverbed below the dam.

DANVILLE DAM

The Danville Dam is a compacted earth-fill embankment that is approximately 765-feet long and 75-feet high.[22] This dam, with a normal storage of 45 acre-feet, supplies water to the East Bay Municipal Utility District.[23]

This dam experiences Extensive damage from the scenario earthquake. Although drought conditions have severely affected reservoir water levels in the area, a dam breach would pose a substantial threat to downstream residential neighborhoods surrounded by Highland Drive and West-East Prospect Avenue, Green Valley Creek, Interstate 680, and Town and Country Drive.[24]

ALMOND DAM

The Almond Dam embankment, which surrounds the Almond Reservoir, is a compacted earth-fill embankment. It is approximately 30-feet high and 1,040-feet long and has a normal storage of 20 acre-feet. The dam provides water to the East Bay Municipal Utility District.[25]

This dam experiences Extensive damage from the scenario earthquake. A breach at this dam could pose a substantial threat to downstream residential neighborhoods.[26]

SHINN POND DAM

The Shinn Pond Dam is a 25-foot-high and 700-foot-long earthen embankment that impounds Shinn Pond.[27] The dam is located in Fremont, California, just west of Niles Community Park and adjacent to the Quarry Lakes Regional Recreation Area. The ponds and lakes in the area are used for groundwater recharge, recreation, and water supply.[28]

At Quarry Lakes, the Alameda County Water District operates several interconnected recharge ponds, including Shinn Pond, on the north and south side of the Alameda Creek Flood Control Channel. Diversion pipelines that pass under the flood control levees are used to divert water from Alameda Creek to these surroundings ponds. The diverted water flows into adjacent Quarry Lakes.

This dam experiences Extensive damage from the scenario earthquake. Downstream impact to residential and commercial areas is likely to be minimal because of lower than usual water levels caused by the 2015 drought conditions. Depending on where the damage occurs on the Shinn Pond Dam, disruption to the Fremont line tracks of the Bay Area Rapid Transit (BART) system is possible.

ANALYSIS RESULTS—TRANSPORTATION SYSTEMS

OCIA–NISAC analyzed the impacts of the scenario earthquake on roads and their associated bridges and tunnels.

ROADWAYS

The roadway portion of the earthquake scenario analysis estimated the impact of the scenario earthquake on roadway traffic, including disruptions and the resulting changes in traffic patterns and flows. OCIA–NISAC first

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22 U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12, accessed 29 April 2015.
23 Ibid.
24 Town of Danville, Hydrology and Water Quality, www.danville.ca.gov/WorkArea/DownloadAsset.aspx?id=7979, accessed 29 April 2015.
25 U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:4:0::NO, accessed 29 April 2015.
26 Castro Valley General Plan, July 2010, Revised Draft, www.acgov.org/cda/planning/landuseprojects/documents/CVGP.pdf, accessed 22 April 2015.
27 U.S. Army Corps of Engineers, "National Inventory of Dams," http://corpsmapu.usace.army.mil/cm_apex/f?p=838:12, accessed 29 April 2015.
28 Alameda County Water District, "Rubber Dam No.1 Fabric Replacement Project (Project 11G14)," www.acwd.org/index.aspx?NID=456, accessed 22 April 2015.

completed fragility analysis to identify the types of data that were available to characterize the damage. The analysis identified the fragility of roadway elements, such as bridges and roadway tunnels, and segments of roadway. A roadway segment is a section of continuously traveled roadway that provides two-way traffic and is not interrupted by an intersection. A roadway element is a bridge or tunnel or other similar component. The fragility calculation (measured by severity) represents damage and disruption to bridges, tunnels, and roadways from ground deformation. Table 4 provides the Hazus damage categories for roadway segments including roadways, bridges, and tunnels.[29]

TABLE 4— HAZUS DAMAGE CATEGORIES AND DESCRIPTIONS, ROADWAY ELEMENTS[30]

Damage State	Component Type	Damage Description
Complete	Bridges	Collapse of any column and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure
	Roadways	Major ground settlement, e.g., a few feet
	Tunnels	Major cracking of the tunnel liner, including the possibility of collapse
Extensive	Bridges	Any column degrading without collapse, e.g., shear failure, but structurally unsafe; significant residual movement at connections; major settlement approach; vertical offset or shear key failure at abutments; or differential settlement at connections
	Roadways	Major ground settlement, e.g., a few feet
	Tunnels	Major ground settlement at a tunnel portal and extensive cracking of the tunnel liner
Moderate	Bridges	Any column experiencing moderate shear cracking and spalling (columns still structurally sound), moderate movement of abutment (< 2 inches), extensive cracking and spalling of shear keys, connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of approach
	Roadways	Moderate ground settlement (e.g., several inches) or ground offset
	Tunnels	Moderate cracking of the tunnel liner and rock falling
Slight or Minor	Bridges	Minor cracking and spalling of the abutment, cracks in shear keys at abutment, minor spalling and cracking at hinges, minor spalling of columns requiring no more than cosmetic repair, or minor deck cracking
	Roadways	Slight ground settlement (e.g., a few inches or ground offset)
	Tunnels	Minor cracking of the tunnel liner (damage requires no more than cosmetic repair) and some rock falling or slight settlement of the ground at a tunnel portal
None	Bridges	No damage to components
	Roadways	
	Tunnels	

Approximately 460 roadway elements will be unusable because of earthquake damage, interruption of traffic flow, commerce, emergency services, and repair efforts. Damaged bridges and tunnels will interrupt roadways and disrupt traffic at numerous locations throughout San Francisco and the surrounding areas. Damaged roadway

[29] Federal Emergency Management Agency, "Hazus 2.1 Technical and User's Manuals, Earthquake Model Technical Manual, Section 3.2.3," www.fema.gov/media-library/assets/documents/24609, accessed 23 April 2015.
[30] Federal Emergency Management Agency, "Hazus 2.1 Technical and User's Manuals, Earthquake Model Technical Manual, Section 3.2.3," www.fema.gov/media-library/assets/documents/24609, accessed 23 April 2015.

segments will decrease the road's ability to sustain normal traffic volumes and will change traffic patterns as traffic is rerouted to compensate. Table 5 provides the estimated number of unusable roadway elements.

TABLE 5—NUMBER OF UNUSABLE ROADWAY ELEMENTS

Element	Number
Roadway Bridges	372
Roadway Tunnels	4
Roadways	86

Table 6 lists the roadways with the highest normal traffic volumes that sustain damage. The flow on most of these roadways is disrupted at multiple locations along their path. The table lists the points on these routes only where the flow rates are highest and present the greatest challenge in rerouting the flow to maintain commerce; enable emergency and repair vehicle travel; and to move people to their destinations.

TABLE 6—NORMAL FLOW RATES ON HIGHLY AFFECTED ROADWAYS

Interrupted Roadway	Normal Flow (vehicles per lane per hour)
I–680 (Sinclair Freeway) near Vargas Road	10,820
I–880 (Nimitz Freeway) south of Alvarado-Niles Road interchange	9,580
I–580 (MacArthur Freeway) near Dutton Avenue	8,450
I–580 (Arthur H. Breed Freeway) near Castro Valley Boulevard	8,140
Huntwood Avenue just south of Industrial Parkway	5,700
Alvarado Boulevard north of Deep Creek Road	5,490
I–238 West of Ashland Avenue	4,740
I–680 (CA 84) north of the Paloma Way interchange	4,290
Crow Canyon Road near Cold Water Drive	4,170
Niles Canyon Road (CA 84) north of CA 238	4,000

If roads are impassible, drivers will seek alternative routes, leading to altered traffic patterns and, sometimes, considerable delays that affect repair vehicles and personnel, emergency vehicles, access to airports, and commuter and commercial traffic. Table 7 lists some of the alternative routes likely to experience the most significant traffic changes. The calculations in the table are defined as followed:

- Traffic Flow over Normal is the ratio of vehicle flow rate with the earthquake damage to the flow rate without this disruption.
- Traffic volume to roadway capacity (VOC) ratio is vehicle volume divided by road capacity.
- Travel Time over Normal is the analogous ratio for travel time on each road segment; that is, travel time while disrupted divided by normal traffic time. For Mission Boulevard west of the CA 84 interchange, the traffic volume is likely to be more than four times the normal volume during the disruption. Travel time along this stretch is likely to take more than 12 times longer than under normal conditions.

These routes will experience vehicle flow rates from almost 2 to more than 10 times higher than normal traffic loads, exceeding capacity by 2 to more than 13 times normal and causing significant delays for all roadway traffic in and around these routes. Based on experience with earthquake damage to similar roadway structures, these conditions could extend for months and even years as the roadway bridges and tunnels undergo inspections and repairs.

TABLE 7—CHANGES IN SAN FRANCISCO AREA TRAFFIC ON SOME AFFECTED ALTERNATIVE ROUTES

Alternative Route	Traffic Flow Higher Than Normal	VOC Ratio	Travel Time Longer Than Normal
Railroad Avenue south of Whipple Road	4.4	5.9	77
Eleventh Street north of F Street	6.7	8.7	69
Vallejo Way south of CA 238	4.5	5.5	53
Nursery Avenue south of CA 238	4.6	5.8	43
Paseo Padre Parkway east of Ardenwood Boulevard	6.0	5.9	43
Dyer Street east of Union City Boulevard	10.7	13.3	39
Niles Boulevard east of Rancho Arroyo Parkway	3.5	4.8	32
Blaisdell Way near Montalban Drive	3.8	4.8	29
Ardenwood Boulevard east of Lowry Road	4.2	4.2	21
Sequoia Terrace north of Panton Terrace	3.3	4.1	18
Whipple Road east of Ithaca Street	2.9	4.1	18
Alvarado Niles Road east of Western Avenue	4.0	4.0	16
Mission Boulevard (CA 238) west of CA 84 interchange	4.5	5.7	12
West Tennyson Road west of Patrick Avenue	3.6	3.6	11
Union City Boulevard north of Bettencourt Way	3.4	3.4	9
I–880 (Nimitz Freeway) south of Industrial Parkway interchange	2.9	2.9	5
Ithaca Street near Edna Court	2.0	2.7	4
Hesperian Boulevard north of Union City Boulevard	2.4	2.4	2
I–680 (Sinclair Freeway) north of CA 238 interchange	1.8	1.8	1
I–580 (Arthur H. Breed Freeway) west of Foothill Road interchange	2.0	2.0	1

ROADWAY BRIDGES

Roadways are particularly vulnerable where bridges span areas of water of lower elevation, because ground movements and soil liquefaction unseat bridge superstructure from its support structure. Bridges damaged by earthquakes can put key road linkages out of commission for several weeks or months or require demolition and replacement that could take several years.[31] The loss of a roadway bridge can also directly affect other infrastructure, because it is common practice to run electrical and communication lines and other infrastructure connections across the same spans.[32] Figure 5 shows the locations of roadway bridges with Extensive or Complete expected damage.

[31] Yashinsky, M., "The Loma Prieta, California, Earthquake of October 17, 1989—Highway Systems," U.S. Geological Survey Professional Paper 1552-B, January1998.
[32] Rinaldi, S.M.; Peerenboom, J.P.; and Kelly, T.K. "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies," *IEEE Control Systems Magazine,* 0272-1706, December 2001.

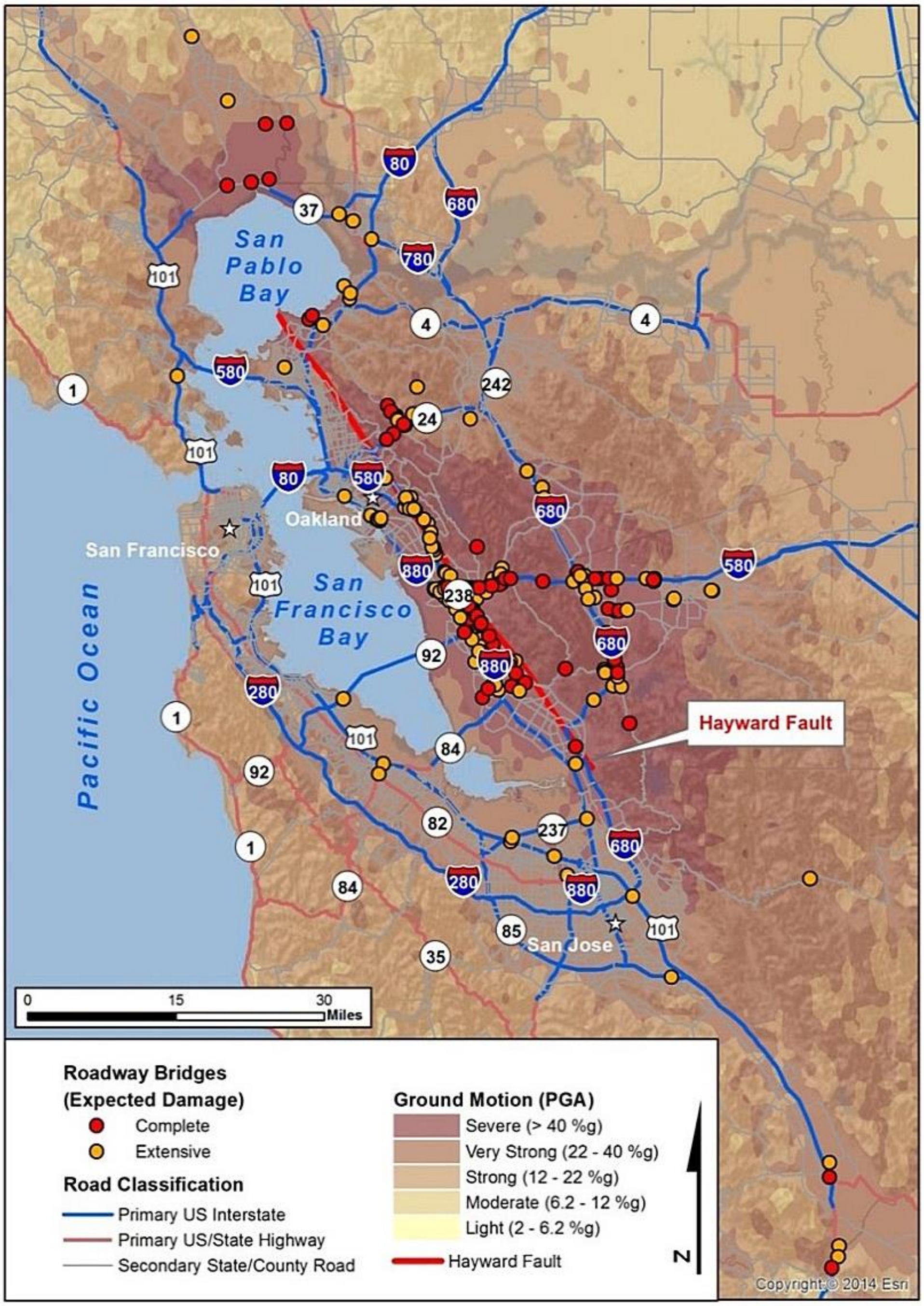

FIGURE 5—AFFECTED ROADWAY BRIDGES, COMPLETE OR EXTENSIVE EXPECTED DAMAGE STATES

Several bridges on I-580 and I-680 sustained Extensive damage under the scenario; all of the bridges required inspections and repairs.[33] Figure 6 shows the number of damaged roadway bridges by expected damage state.

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33 U.S. General Accounting Office, "Transportation Infrastructure: The Nation's Highway Bridges Remain at Risk from Earthquakes," GAO/RCED-92-59, January 1992.

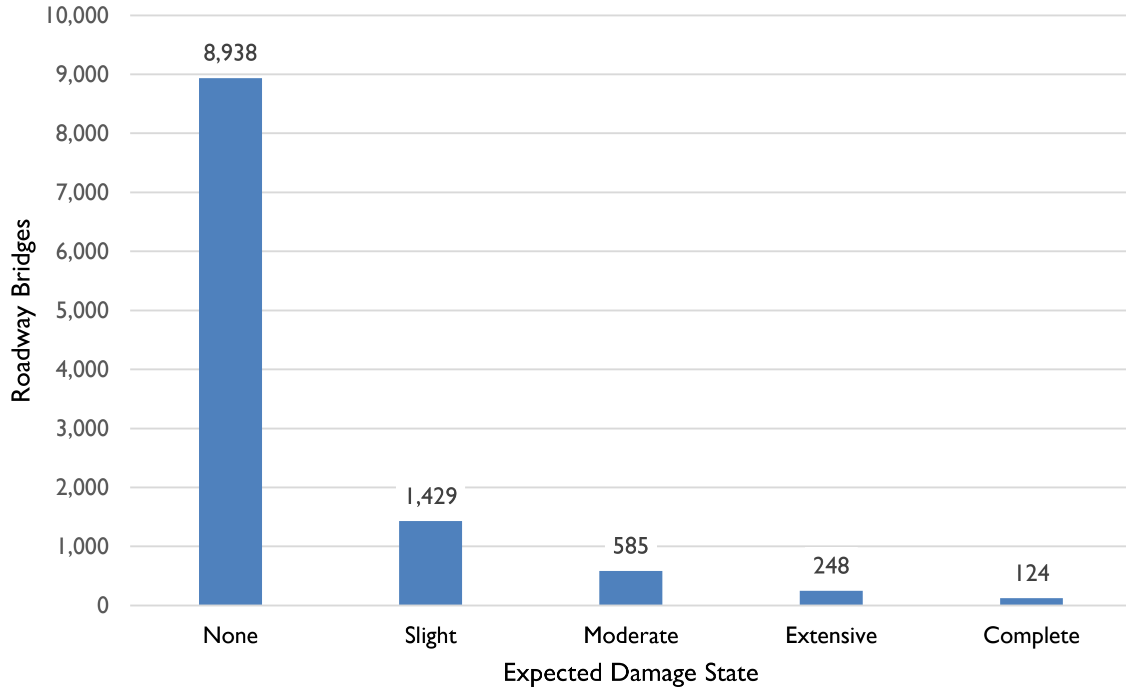

FIGURE 6—NUMBER OF AFFECTED ROADWAY BRIDGES FOR EACH EXPECTED DAMAGE STATE

ROAD TUNNELS

Similar to road bridges, tunnels present dependency challenges, because they often support cables, pipes, and other infrastructure. During earthquakes, tunnels have historically performed better than aboveground structures, such as road bridges, because tunnels are constrained by the surrounding ground and are less subject to amplification of ground vibrations.[34] However, although less numerous than road bridges in a given metropolitan area, tunnels are still at risk during an earthquake and generally require greater effort and time to repair or replace.

Recent examples of underground structures that have failed during an earthquake are the Daikai and Nagata subway stations on the Kobe Rapid Transit Railway during the 1995 Kobe Earthquake in Japan. The Daikai station alone required about a year to restore service.[35]

[34] U.S. Department of Transportation Federal Highway Administration, FWHA-NHI-10-034, "Technical Manual for Design and Construction of Road Tunnels—Civic Elements," December 2009.
[35] Umehara, T., et al., "Restoration of the Collapsed Subway Station due to Hyogoken-Nanbu Earthquake, January 17, 1995," Proceedings of the World Tunnel Congress, Volume 1, 1998.

Under the earthquake scenario, damage to road tunnels ranges from none to Moderate. Three of the four tunnels in the Moderate expected-damage state are bores in the Caldecott Tunnel (part of the same tunnel system) on State Route 24. Figure 7 summarizes the number of damaged tunnels in the San Francisco Bay Area.

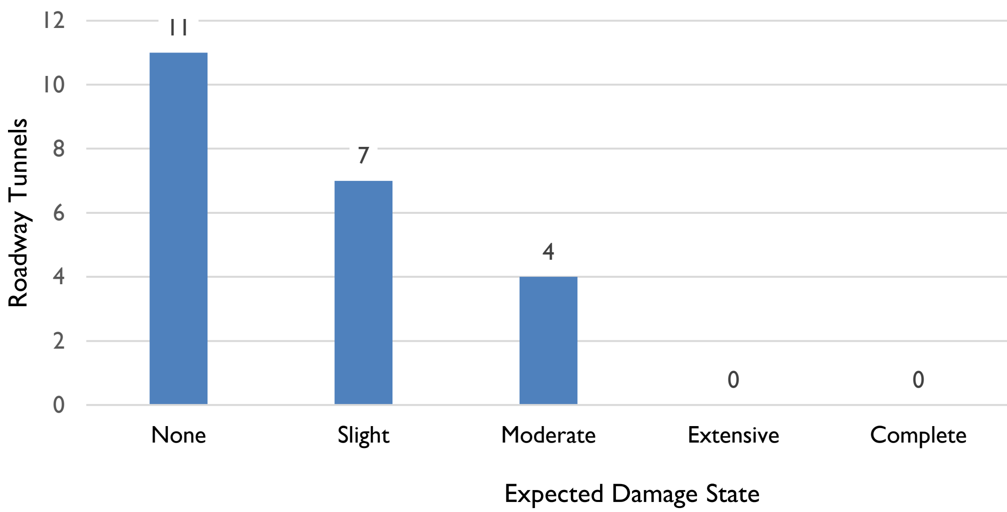

FIGURE 7—NUMBER OF AFFECTED ROADWAY TUNNELS FOR EACH EXPECTED DAMAGE STATE; SAN FRANCISCO BAY AREA

ANALYSIS RESULTS—WATER AND WASTEWATER SYSTEMS

The San Francisco Public Utilities Commission delivers water to 2.6 million residential, commercial, and industrial customers. It relies heavily on the Hetch Hetchy system, which conveys surface water from the Sierra Nevada Mountains 160 miles westward to the city. The system delivered an average of 217 million gallons per day of drinking water to residents and businesses in Alameda, Santa Clara, San Mateo, and San Francisco Counties in 2014.[36] The system splits into four separate Bay Division Pipelines at the city of Fremont. All four Bay Division Pipelines cross the Hayward Fault. Figure 8 shows a map of the Hetch Hetchy regional water system.

[36] San Francisco Public Utilities Commission, "Comprehensive Annual Financial Report for the Fiscal Years Ended June 30, 2014 and 2013," www.sfwater.org/modules/showdocument.aspx?documentid=6428, accessed 16 April 2015.

FIGURE 8—MAP OF HETCH HETCHY REGIONAL WATER SYSTEM[37]

About 85 percent of the water in the Hetch Hetchy regional water system is collected in the Upper Tuolumne River watershed from the Hetch Hetchy Reservoir, which has a capacity of 360,360 acre-feet.[38] The Lake Lloyd and Lake Eleanor Reservoirs collect the runoff from the upper Tuolumne River watershed. Their total capacity is 300,400 acre-feet.[39]

San Francisco has a treated water storage capacity capable of meeting normal demands for 5 days. Lake Merced, within the city, stores an additional 1.5 billion gallons of untreated water. Beyond these reserves, San Francisco does not have any other additional sources to meet average demands.

The water is conveyed to the San Francisco Bay Area reservoirs through an aqueduct. Local surface water in the Alameda and Peninsula watersheds provides the remaining water supply. The Alameda watershed collects local surface water from rainfall runoff into the San Antonio and Calaveras Reservoirs. The maximum storage capacity of the San Antonio Reservoir is 50,500 acre-feet, whereas the capacity of Calaveras is 96,850 acre-feet.[40] The Peninsula watershed provides surface water from rainfall runoff that drains into the upper Crystal Springs (67,800 acre-feet capacity), San Andreas (19,000 acre-feet capacity), and Pilarcitos (3,100 acre-feet capacity) Reservoirs.[41] Some of these reservoirs also store water from the Hetch Hetchy for use in San Francisco. These local reservoirs have a capacity of 237,200 acre-feet. These facilities all connect to the Hetch Hetchy system. Local groundwater resources supply the remaining water. Table 8 provides the Hazus damage categories and description for water and wastewater plants.

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37 San Francisco Water, Power, Sewer, "System Map," www.sfwater.org/modules/showdocument.aspx?documentid=7790, accessed 5 January 2016.
38 San Francisco Public Utilities Commission, "Serving 2.6 million residential, commercial, and industrial customers," www.sfwater.org/index.aspx?page=355, accessed 16 April 2015.
39 San Francisco Public Utilities Commission, "Urban Water Management Plan for the City and County of San Francisco, June 2011," http://sfwater.org/modules/showdocument.aspx?documentid=1055, accessed 8 May 2015.
40 San Francisco Public Utilities Commission Water Quality Bureau, "Technical Memorandum N. 2-04-006, 31 October 2005," www.alamedacreek.org/learn-more/pdf/SFPUC reservoir fish population estimates 2005.pdf, accessed 8 May 2015.
41 San Francisco Public Utilities Commission, "Urban Water Management Plan for the City and County of San Francisco, June 2011," http://sfwater.org/modules/showdocument.aspx?documentid=1055, accessed 8 May 2015.

TABLE 8—HAZUS DAMAGE CATEGORIES AND DESCRIPTIONS, WATER AND WASTEWATER TREATMENT PLANTS[42]

Damage State	Damage Description
Complete	Defined by the complete failure of all pipelines or extensive damage to the filter gallery
Extensive	Defined by extensively damaged pipelines (connecting with different basins) and chemical units; plant shutdown likely to occur
Moderate	Defined by a plant malfunction for approximately 1 week from loss of electric power and backup power (if any); extensive damage to various equipment; considerable damage to sedimentation basins, chlorination tanks, or chemical tanks; imminent loss of water quality
Slight or Minor	Defined by a short-term plant malfunction (fewer than 3 days) from the loss of electric and backup power (if any); considerable damage to various equipment; light damage to sedimentation basins, chlorination tanks, or chemical tanks; loss of water quality may occur
None	No damage to components

DRINKING WATER

Eighty-seven water treatment plants are likely at risk from the scenario earthquake, but 52 facilities are unlikely to experience damage states greater than Moderate directly from the earthquake. Table 9 shows the facility names, water districts, capacity, affected population, and damage state for each plant in the Extensive to Complete damage extent categories. Twenty-three of the 87 water treatment plants do not sustain damage states greater than Slight or Minor.

TABLE 9—AFFECTED WATER TREATMENT PLANTS, EXTENSIVE TO COMPLETE EXPECTED DAMAGE STATES

Facility	Water District	County	Capacity (mgd)	Affected Population	Damage Extent
Mission San Jose	Alameda County Water District	Alameda	3.2	12,800	Complete
Del Valle	Zone 7 Water Agency	Alameda	36	76,300	Extensive
San Pablo*	East Bay Municipal District	Alameda, Contra Costa	not available	0	Extensive
Sobrante	East Bay Municipal District	Alameda, Contra Costa	45	149,600	Extensive
Upper San Leandro	East Bay Municipal District	Alameda, Contra Costa	55	182,900	Extensive
*The East Bay Municipal Utility District's San Pablo water treatment plant is undergoing renovations and is completely shut down.					

[42] Federal Emergency Management Agency, "Hazus 2.1 Technical and User's Manuals, Earthquake Model Technical Manual, Section 3.2.3," www.fema.gov/media-library/assets/documents/24609, accessed 23 April 2015.

Figure 9 shows water treatment plants that are likely to experience Extensive or Complete damage.

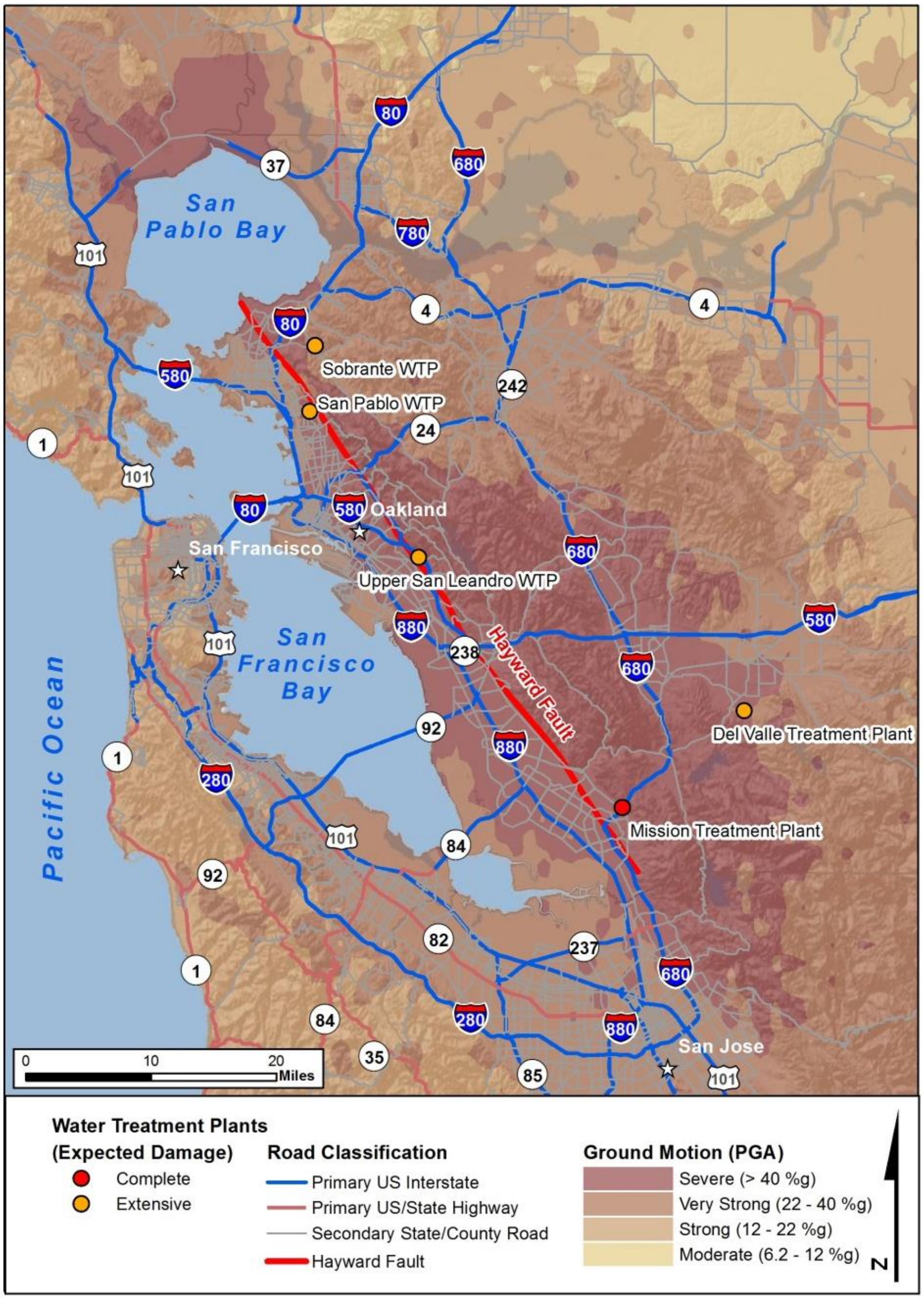

FIGURE 9—AFFECTED WATER TREATMENT PLANTS, COMPLETE OR EXTENSIVE EXPECTED DAMAGE STATES

The scenario earthquake is likely to significantly affect water delivery to consumers. The Hetch Hetchy aqueduct separates into four distinct Bay Division Pipelines at Fremont, California. All of these pipelines cross the Hayward Fault, so they are to likely experience significant damage. The majority of San Francisco consumers will not have water if these pipelines are out-of-service.

The San Francisco Bay Area has several water storage facilities that store additional water during aqueduct repairs or that can be used during an emergency. The likely loss of power in the area can prevent water delivery to customers at higher elevations in the city of San Francisco. The Alameda County Water District, which serves more than 300,000 customers, is likely to experience the most substantial impacts from the scenario earthquake.

As noted in Table 9 and displayed in Figure 9 the Mission San Jose water treatment plant is in the Alameda County Water District. This treatment plant is likely to be out-of-service until the major repairs are completed. This district relies on surface water from the South Bay Aqueduct and has the potential capacity of 8–10 million gallons per day (mgd), but its actual production rate is 3.2 mgd. The Mission San Jose water treatment plant treats 5 percent of the water supplied by the Alameda County Water District. If this facility is out-of-service, it is likely that 12,800 people will be without drinking water.

The Del Valle water treatment plant, part of the Zone 7 Water Agency District, is likely to sustain Extensive damage, which would result in a shutdown of the facility affecting about 76,300 people.[43]

Because of Extensive damage following the scenario earthquake, the Sobrante and Upper San Leandro water treatment plants in the East Bay Municipal Utility District are likely to be out-of-service. If these facilities fail, 332,500 people in Alameda and Contra Costa Counties are likely to lose water service.[44]

The East Bay Municipal Utility District's San Pablo water treatment plant is also likely to suffer Extensive damage, but this facility is undergoing renovations and was not in service as of April 2015.[45]

The scenario earthquake is unlikely to affect facilities in the North Bay Area because of their location relative to the ground motion, liquefaction, and landslide effects under this earthquake scenario.

Seven water treatment plants are likely to experience Moderate levels of damage. Four of these plants are in the East Bay Municipal Utility District. These plants supply water to Alameda and Contra Costa. An outage of these facilities will likely affect about 1,682,600 people.[46] Table 10 shows the facility names, water districts, capacity, affected population, and damage state for each plant in the Moderate damage extent category.

TABLE 10—AFFECTED WATER TREATMENT PLANTS, MODERATE EXPECTED DAMAGE STATE

Facility	Water District	County	Capacity (mgd)	Affected Population	Damage Extent
Martinez	Contra Costa Water District	Contra Costa	14.7	30,200	Moderate
Bear Gulch	Bear Gulch District	San Mateo	6	57,800	Moderate
Walnut Creek	East Bay Municipal District	Alameda, Contra Costa	91	302,600	Moderate
Orinda	East Bay Municipal District	Alameda, Contra Costa	175	581,800	Moderate
Lafayette	East Bay Municipal District	Alameda, Contra Costa	25	83,100	Moderate
Penitencia	Santa Clara Valley Water District	Santa Clara	40	846,200	Moderate
Patterson Pass	Zone 7 Water Agency	Alameda	20	78,600	Moderate

43 Los Alamos National Laboratory Water and Wastewater database.
44 Los Alamos National Laboratory Water and Wastewater database.
45 East Bay Municipal Utility District, "San Pablo Water Treatment Plant Upgrade," www.ebmud.com/water-and-wastewater/project-updates/san-pablo-water-treatment-plant-upgrade, accessed 17 April 2015.
46 Los Alamos National Laboratory Water and Wastewater database.

WASTEWATER

Eighty-five wastewater treatment plants are at risk of damage from the scenario earthquake; 14 are likely to experience Complete damage, resulting in about 207 mgd of lost wastewater treatment capacity. Table 11 provides a list of wastewater facilities that are likely to experience Moderate, Extensive, or Complete damage states.

TABLE 11—AFFECTED WASTEWATER TREATMENT FACILITIES, MODERATE TO COMPLETE EXPECTED DAMAGE STATES

Facility	District	Capacity (mgd)	Population	Damage State
City of Richmond	Richmond Municipal Sewer District, West County Wastewater District, Stege Sanitary District	Not available	103,701	Complete
East Bay Municipal Utility District–Main	East Bay Municipal Utility District	Not available	650,000	Complete
Silicon Valley Clean Water	Silicon Valley Clean Water	Not available	217,000	Complete
San Francisco International Airport	City of San Francisco	1.7 (wet)	Airport only	Complete
Cities of South San Francisco and San Bruno Water	South San Francisco	60 (wet)	110,400	Complete
Palo Alto	City of Palo Alto	22 (wet)	220,000	Complete
Rodeo	Town of Rodeo	0.55 (dry)	8,700	Complete
Sonoma Valley County	Sonoma Valley County Sanitation District	22 (wet)	35,500	Complete
Pinole	City of Pinole	4 (wet)	40,000	Complete
Burlingame	City of Burlingame	16 (wet)	37,000	Complete
Southern Marin	Sewerage Agency of Southern Marin	25 (wet)	29,000	Complete
Vallejo	Vallejo Sanitation and Flood Control District	60 (wet)	115,942	Complete
Dublin San Ramon Services District	Dublin San Ramon Services District	17 (wet)	161,300	Complete
Union Sanitary District Alvarado	Union Sanitary District	33 (dry)	334,600	Extensive
Livermore	City of Livermore	8.5 (dry)	85,200	Extensive
San Jose Santa Clara	Santa Clara Valley Water District	167 (dry)	1,400,000	Extensive
U.S. Navy Treasure Island Naval Station	San Francisco Public Utilities Commission	4.4 (wet)	2,400	Moderate
Easterly	City of Vacaville	15 (dry)	94,300	Moderate
Novato	Novato Sanitary District	47 (wet)	60,000	Moderate
Las Gallinas	Las Gallinas Valley Sanitary District	2.92 (dry)	32,000	Moderate
Mountain View	Mountain View Sanitary District	3.2 (dry)	18,300	Moderate
Sunnyvale	City of Sunnyvale	29.5 (dry)	117,600	Moderate
Napa	Napa Sanitation District	15.4 (dry)	75,000	Moderate
San Mateo	City of San Mateo	60 (wet)	130,000	Moderate
City of Millbrae	City of Millbrae	Not available	22,400	Moderate

Figure 10 shows the wastewater treatment plants with Extensive or Complete expected damage states.

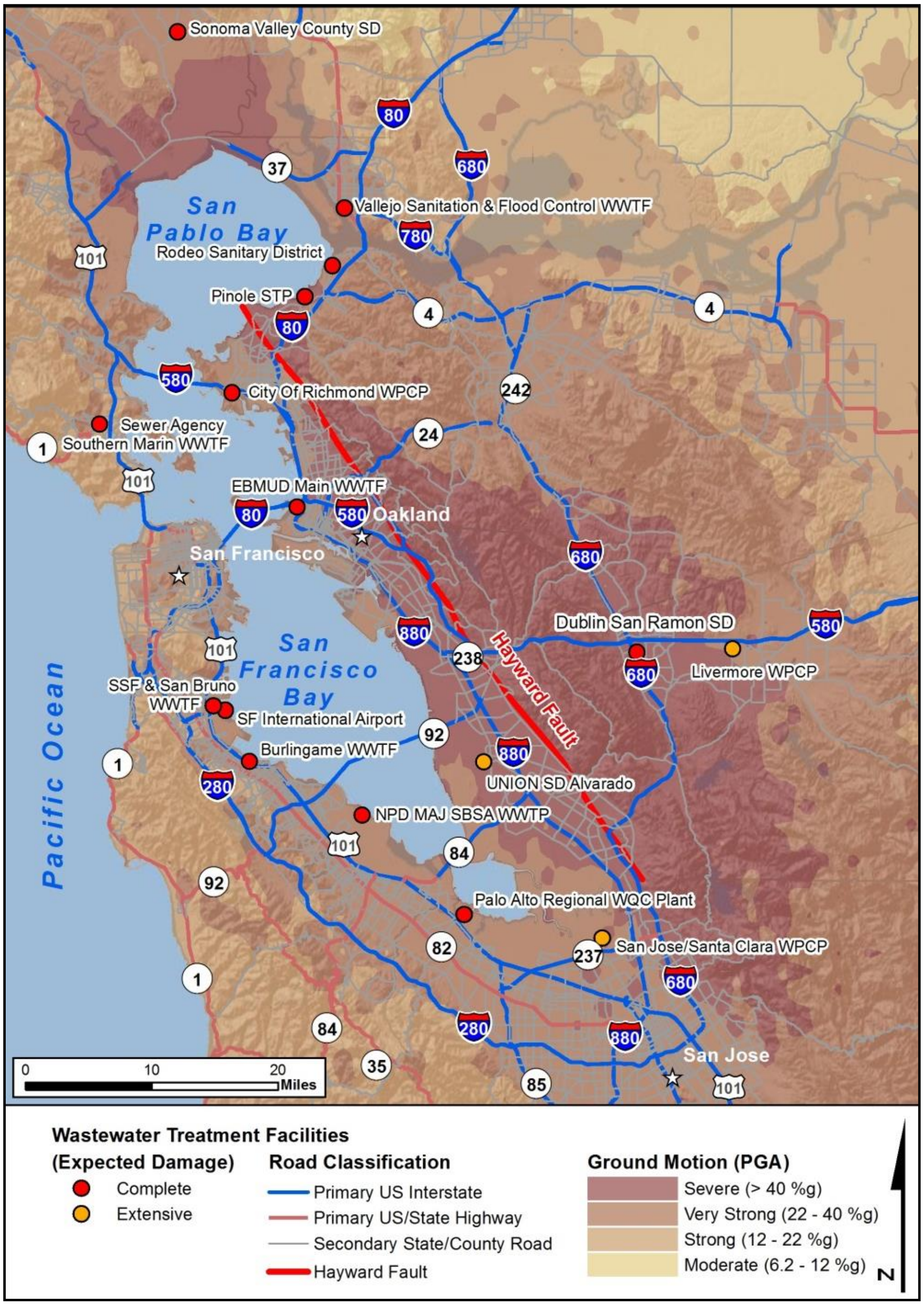

FIGURE 10—AFFECTED WASTEWATER TREATMENT PLANTS; COMPLETE OR EXTENSIVE EXPECTED DAMAGE STATES

Five wastewater treatment plants in Alameda and Contra Costa Counties are likely to experience Complete damage and the loss of these facilities will affect 96,400 people. Another five wastewater treatment facilities in Marin, San Mateo, Santa Clara, Solano, and Sonoma Counties are also likely to experience Complete damage, rendering them out-of-service. The loss of these facilities is likely to affect 764,800 people. Although the wastewater treatment plant at the San Francisco International Airport is likely to be in the Complete damage category, it treats wastewater and storm water for the airport only.

The Union Sanitary District Alvarado and Livermore Water Pollution Control Plant, both located in Alameda County, are likely to suffer Extensive damage, which will cause sewage backup and surface and groundwater pollution. These plants serve approximately 419,800 people.

The San Jose-Santa Clara Regional wastewater facility is also likely to suffer Extensive damage. This facility treats an average of 110 mgd of wastewater and serves eight cities with a combined population of about 1,400,000 people and a business community with more than 17,000 main sewer connections.

The scenario earthquake is likely to cause Moderate damage to the Sunnyvale, San Mateo, City of Vacaville, Napa, Novato, Las Gallinas Valley, City of Millbrae, Mountain View, and the Treasure Island wastewater treatment plants. Moderate damage of these facilities will result in the interruption of wastewater collection, treatment, and disposal services for about 581,900 people for approximately 7 days.

CONCLUSION

OCIA–NISAC analyzed the impacts to the Dams Sector, the Highway Infrastructure and Motor Carrier Subsector, and the Water and Wastewater Systems Sector after a scenario 7.0 magnitude earthquake strikes the Hayward-Rodgers Creek Fault system in the San Francisco Bay Area.

The results of this analysis show a strong earthquake will likely cause significant damage to critical infrastructure in the area affecting 547 dams or water control structures, render approximately 300 roadway segments unusable, and cause damage to 172 water and wastewater treatment systems.

The scenario earthquake will likely cause Slight damage, Minor damage, or Complete damage to 154 dams in the area. Seven of the dams will likely experience Extensive or Complete damage. The Ward Creek Dam, which is used for flood control, is likely to incur Complete damage. Extensive damage to the James H. Turner Dam poses the greatest risk to downstream population.

The earthquake will cause damage to many road segments, bridges, and tunnels in the area. As a result, travel times on these roadways and others will increase significantly. Multiple areas on freeways such as I–680, I–880, and I–580 will have the highest traffic volumes above normal. Several bridges on these freeways will also likely incur Extensive damage. Tunnels in the area will likely have less damage with bores in the Caldecott Tunnel on State Route 24 experiencing only Moderate damage.

The earthquake is likely to significantly affect water and wastewater services. The Alameda County Water District is likely to experience the most substantial impacts to water treatment systems. This district serves more than 300,000 customers. The Mission San Jose Treatment Plant is likely to be out-of-service until major repairs are completed. Extensive damage to the Sobrante and Upper San Leandro water treatment plants in the East Bay Municipal Utility District will likely put these plants out-of-service. If these facilities fail, approximately 332,500 people in Alameda and Contra Costa Counties are likely to lose water service.

Alameda and Contra Costa County wastewater treatment plants are likely to experience the worst impact. Five wastewater treatment plants in these counties are likely to sustain Complete damage. Five wastewater treatment facilities serving Marin, San Mateo, Santa Clara, Solano, and Sonoma Counties are likely to experience Complete damage, rendering them out-of-service.

APPENDIX A: METHODOLOGY

ASSUMPTIONS

OCIA–NISAC uses infrastructure datasets for its analyses. In this report, OCIA–NISAC assumes that the available data are accurate with respect to the scenario under analysis. All models have numerous embedded assumptions.

UNCERTAINTY

OCIA–NISAC intends the results presented in this report to accurately describe the modeling and analysis that supported the given earthquake scenario. The main sources of uncertainty in this analysis stem from the models, the data, and other information unknown or unavailable to NISAC.

Models are a point of uncertainty. Because OCIA–NISAC cannot shut down infrastructure systems to analyze the impacts of an event on a system, it uses models of systems to simulate how a scenario affects system performance. A model is a representation of a physical system that OCIA–NISAC uses to examine the effects of external influences on that system. Because models are representations, they are unlikely to capture all the interactions and parameters of the real-world systems they represent. Modeling and analysis associated with this product use established and documented models of infrastructure in conjunction with the judgment of subject matter experts.

Uncertainty because of data and models in the roadway analysis is reduced by calibrating the model during normal traffic conditions before an earthquake or other disruption. Traffic count data collected at hundreds of locations in the affected area are used to compare modeled results to average daily traffic counts collected at fixed locations on highways and other major roadways.

Although data are required for all models, the variability in standards that occurs when using individual data sources, the lack of data availability, and general errors can introduce uncertainty. OCIA–NISAC must assume that data are accurate and accurately geocoded. Data used in this analytic effort are a compilation of data from multiple sources, including reference data sources used in conjunction with commercial and other sources, to represent the sector parameters most accurately. OCIA–NISAC compiled data from several sources to compensate for missing information. When OCIA–NISAC uses multiple datasets, it makes every effort to ensure accuracy and completeness, but data on some aspects of a system may not be included in a data set. Other data errors, including typos, exist and may be unnoticed during or after the analysis. Errors in the geographic location of sector assets can change analysis results completely. For example, geolocated assets in a sector are superimposed over the geographic electric power outage areas; if the geolocation of an asset is incorrect, the analysis may not accurately reflect the impact of the scenario event.

General unknowns also exist in modeling the real world. These unknowns can include the general status of an area or asset before an earthquake or other exogenous factors. The status of an asset can be very important. For example, a roadway that is under construction cannot be used for evacuation or restoration activities. Other exogenous factors, such as human behavior, will always affect the outcome of a catastrophic event. Although many models try to predict what people will do, human behavior is unpredictable.

OCIA–NISAC typically uses a robust approach to modeling impacts to infrastructure systems. Although these methods involve uncertainty from many sources, retrospective analyses of past events have validated the accuracy of the model results described in this analysis.

METHODOLOGY

OCIA–NISAC used the Multi-Hazard Infrastructure Impact Assessment tool to estimate direct damages caused by the scenario earthquake. Fragility calculations factor in ground shaking, liquefaction, and potential landslides to estimate damages to dams, roadways, roadway bridges, tunnels, water treatment plants, and wastewater treatment plants. A fragility analysis applies damage curves from hazards, such as earthquakes, to infrastructure components to determine the likelihood that a particular component will sustain damage from that type of hazard. Fragility damage estimations provide a range of output for each structure type examined. Many earthquake scenarios are modeled using the Hazus-Multi-Hazard seismic damage estimation methodology developed by FEMA.[47]

Damage to dam structures is represented as a probability distribution over five damage states: None, Slight, Moderate, Extensive, and Complete, following damage curves defined by Hazus. Using a probability-weighted average, OCIA–NISAC computed an expected damage state to indicate the range of damage states possible for this earthquake scenario. OCIA–NISAC used the expected damage level for this analysis.

The locations for roadway elements, such as road bridges and tunnels are characterized by a street name plus latitude and longitude. The analysis requires that these data, characterized as points in space, are compatible with the geographic information system (GIS) in the TransCAD roadway analysis tool. TransCAD geographical information is characterized by census tract areas and roadway segments, represented by lines on a map. OCIA-NISAC developed a method that joins the fragility data represented by points in space with the roadway segments represented in the TransCAD GIS. The method links the location of each damaged road element identified by the fragility analysis with the nearest roadway segment in the TransCAD GIS.

Data requirements for traffic assignment include the following:

- HERE road network[48]
- HERE landscape features, waterways, parks, railroads, and buildings
- Road types, road capacity, and turn penalties
- Income per household, population by census tract from the U.S. Census Bureau
- Housing units, automobiles per household by census tract
- Business employees by census tract from Dun & Bradstreet (D&B) 2007
- Traffic count data at multiple locations throughout the network

Merging the data creates a single database for analysis. In a typical roadway analysis, hundreds of thousands of roadway segments are represented in a database. Each entry in the database contains all of the characteristics of each roadway segment, including street name, length of the segment, speed limit, and other relevant characteristics. Merging the data also adds damage characterizations from the fragility analysis to a small number of these segment descriptions.

OCIA–NISAC estimated the number of retail and non-retail employees for every census tract by converting business data into an ESRI shapefile format for use in the TransCAD Transportation Planning Software. OCIA-NISAC uses these data in the roadway analysis to help characterize the volume of traffic moving between census tracts to travel back and forth to work and conduct commerce. Successfully completing the roadway analysis requires that the study area be large enough to encompass the affected region while restricting its size to the extent practical to reduce execution time for the many steps required in the analysis.

OCIA–NISAC used water and wastewater analysis to examine the direct damage from ground motion, liquefaction, and landslide effects on existing water and wastewater treatment facilities. OCIA–NISAC identified the water and wastewater infrastructure assets at risk from the scenario earthquake using ground motion characteristics and the Los Alamos National Laboratory proprietary water and wastewater datasets. OCIA-NISAC calculated the facilities' damage state using the Multi-Hazard Infrastructure Impact Assessment tool. Using the Hazus approach, the fragility code characterized the facilities based on their expected damage. In addition, OCIA-NISAC assessed potential impacts to the population, using data from publicly available sources.

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[47] Federal Emergency Management Agency, "Hazus 2.1 Technical and User's Manuals, Earthquake Model Technical Manual, Section 3.2.3," www.fema.gov/media-library/assets/documents/24609, accessed 7 April 2015.
[48] HERE, https://company.here.com/here/, accessed 23 April 2015.

OCIA-NISAC used groundwater data from the California Department of Water Resources and ground shaking, liquefaction susceptibility, and landslide susceptibility data provided by the USGS for the analysis.[49,50,51,52]

[49] California Department of Water Resources Groundwater Information Center, "Map Interface," https://gis.water.ca.gov/app/gicima/, accessed 23 April 2015.
[50] U.S. Geological Society, Earthquake Hazards Program, "Shakemap ushaywiredm7.05_se," http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/haywiredm7.05_se/, accessed 23 April 2015.
[51] U.S. Geological Survey, "Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California," http://pubs.usgs.gov/of/2006/1037/, accessed 23 April 2015.
[52] U.S. Geological Survey, "Map and Map Database of Susceptibility to Slope Failure by Sliding and Earthflow in the Oakland Area, California," http://pubs.usgs.gov/mf/2002/2385/, accessed 23 April 2015.

APPENDIX B: UNDERSTANDING EXPECTED DAMAGES

The expected value of a random variable is the probability-weighted average of all possible outcomes of a random variable. In infrastructure resilience terminology, the expected damage level of an asset represents the average damage level that an asset will experience during a hazard event (in this analysis, the scenario earthquake).

To obtain an intuitive understanding of "expected damage," consider the following set of numbers:

{60, 60, 60, 65, 66, 66, 67, 76}

The average value of these numbers is computed by finding the ratio between the sum of these numbers and total amount of numbers in the set. That is,

$$\text{Average value} = \frac{(60+60+60+65+66+66+67+76)}{8} = 65.$$

Rearranging the above equation by grouping like numbers together shows that the average value can be rewritten as follows:

$$\text{Average value} = 60\left(\frac{3}{8}\right) + 65\left(\frac{1}{8}\right) + 66\left(\frac{2}{8}\right) + 67\left(\frac{1}{8}\right) + 76\left(\frac{1}{8}\right) = 65.$$

Denoting the probability of choosing a number x by $P(x)$, then the above average value can be written as follows:

$$\text{Average value} = 60 * P(60) + 65 * P(65) + 66 * P(66) + 67 * P(67) + 76 * P(76).$$

Here, $P(60)$ represents the probability of choosing 60 from our original set of numbers: that is, $P(60) = 3/8$. The other four probabilities are $P(66) = 2/8\,, P(65) = P(67) = P(76) = 1/8$.

The above average value can also be interpreted as the expected value of a random variable. To see this, let an experiment consist of choosing one of the numbers at random, and let x denote the value of that number. Then the expected value of x equals 65.

As the above discussion implies, computing the average value using a frequency interpretation of probability shows an intuitive relationship between the average value and expected value of a set of numbers. The expected value can be viewed as the probability-weighted average value of all the possible outcomes.

Justifying this interpretation of the expected value being the average outcome of an experiment is beyond the scope of this report; however, it can be shown that the average value is close to the expected value if the experiment is repeated a large number of times.[53]

Using this justification, Table 12 represents the outcome of an asset being in one of the five damage states, $P(x_i)$, along with a numerical value, x_i, assigned to each damage state.

[53] Grinstead, C.M., and J.L. Snell, "Introduction to Probability, Second Revised Edition, American Mathematical Society," 1997, www.dartmouth.edu/~chance/teaching_aids/books_articles/probability_book/amsbook.mac.pdf, accessed 29 April 2015.

TABLE 12—SAMPLE VALUES FOR EXPECTED DAMAGE STATES

Damage State	Numerical Assignment	Probability
None	x_1	$P(x_1)$
Slight	x_2	$P(x_2)$
Moderate	x_3	$P(x_3)$
Extensive	x_4	$P(x_4)$
Complete	x_5	$P(x_5)$

Based on the information above, the expected value of the damaged asset, $E(x)$, is determined by

$$E(x) = x_1 * P(x_1) + x_2 * P(x_2) + x_3 * P(x_3) + x_4 * P(x_4) + x_5 * P(x_5).$$

Mapping the expected value $E(x)$ back to the corresponding damage state numerical values x_i results in the expected damage state of the asset.

ABBREVIATIONS

BART	Bay Area Rapid Transit
D&B	Dun & Bradstreet
DHS	U.S. Department of Homeland Security
GIS	geographic information system
FEMA	Federal Emergency Management Agency
mgd	million gallons per day
NID	National Inventory of Dams
NIDD	National Inventory of Dams Dictionary
NISAC	National Infrastructure Simulation and Analysis Center
OCIA	Office of Cyber and Infrastructure Analysis
PGA	peak ground acceleration
USGS	U.S. Geological Survey
VOC	volume to roadway capacity

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For more information about the OCIA, visit www.dhs.gov/office-cyber-infrastructure-analysis.