EARTHQUAKE CHAPTER

Oregon has experienced few damaging earthquakes during its recorded history, leading to decades of complacency and lack of attention to earthquake-resistant design and construction. Since the mid-1980's, an increasing body of geologic and seismologic research has changed the scientific understanding of earthquake hazards in Oregon, and in the last 5 years several large and destructive earthquakes around the world have heightened public awareness. Recognized hazards range from moderate sized crustal earthquakes in eastern Oregon to massive subduction zone megathrust events off the Oregon coast. All have the potential for significant damage as long as most of Oregon's buildings and infrastructure have inadequate seismic resistance. The scale of structural retrofit and replacement needed to make Oregon earthquake safe is huge, and beyond our capacity to implement in anything less than decades. To manage the human and economic impact of the next damaging earthquake will require thoughtful and comprehensive emergency response planning, based on realistic loss estimates driven by accurate and detailed geologic and seismologic, structural and cultural information. To minimize the human and economic impact of the next damaging earthquake will require a sustained program of structural replacement and retrofit, based on cost-effective earthquake resistant design and a combination of public funding and private sector incentives. A full list of acronyms used in this chapter is provided in Appendix 8-B.

Hazard Analysis/Characterization

EARTHQUAKE SOURCES.

Earthquakes are a highly variable natural phenomenon. The vast majority occur when two masses of rock in the earth's crust abruptly move past each other along a large crack or fracture called a fault. The energy released as the two parts slide along the fault produces waves of shaking that we perceive as an earthquake. Faults typically build up stress over decades to millennia in response to large scale movement of the earth's tectonic plates. Even the most active faults only produce damaging earthquakes at intervals of a century or more, and for many the intervals are much longer. As a result, it is very difficult to forecast the likelihood of an earthquake on a particular fault because we rarely have a long enough record to determine a statistically meaningful return period (average time between earthquakes).

The history of earthquakes in a region comes from three types of information. Instrumental data comes from networks of seismic recording instruments (seismographs) that are widely deployed in the Pacific Northwest.

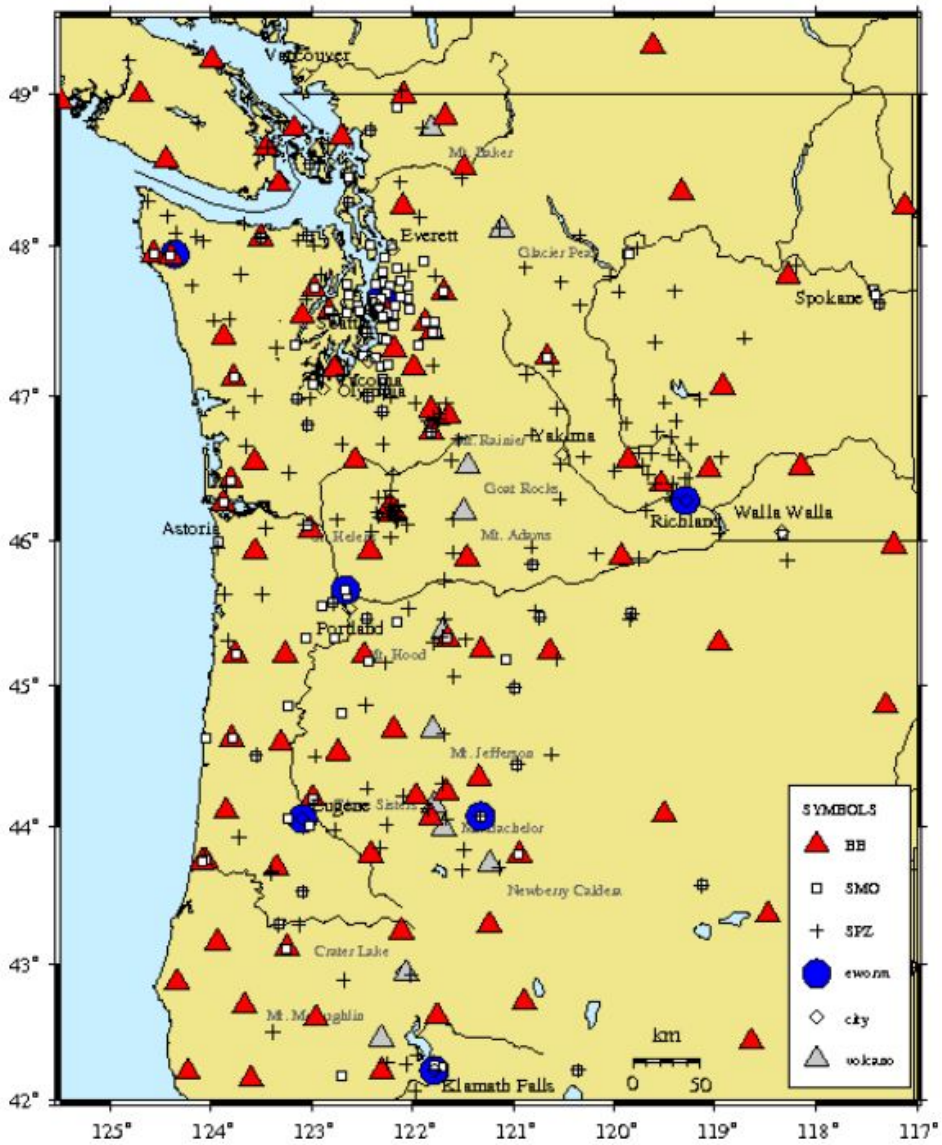


Figure EQ-1: Current configuration of the network of earthquake monitoring stations in the Pacific Northwest, The system is operated out of the University of Washington by the Pacific Northwest Seismic Network.

Seismic networks can detect very small earthquakes, locate them to within a few miles, and determine their magnitude accurately. Seismographs have only existed for about a century, and in Oregon, the instrumental record is really only complete and modern from about 1990 on. Felt location data comes from verbal and written reports of earthquake effects. The felt record extends back to the mid 1800's for Oregon, but only locates moderate to large earthquakes, and those only with an accuracy of tens or even hundreds of miles.

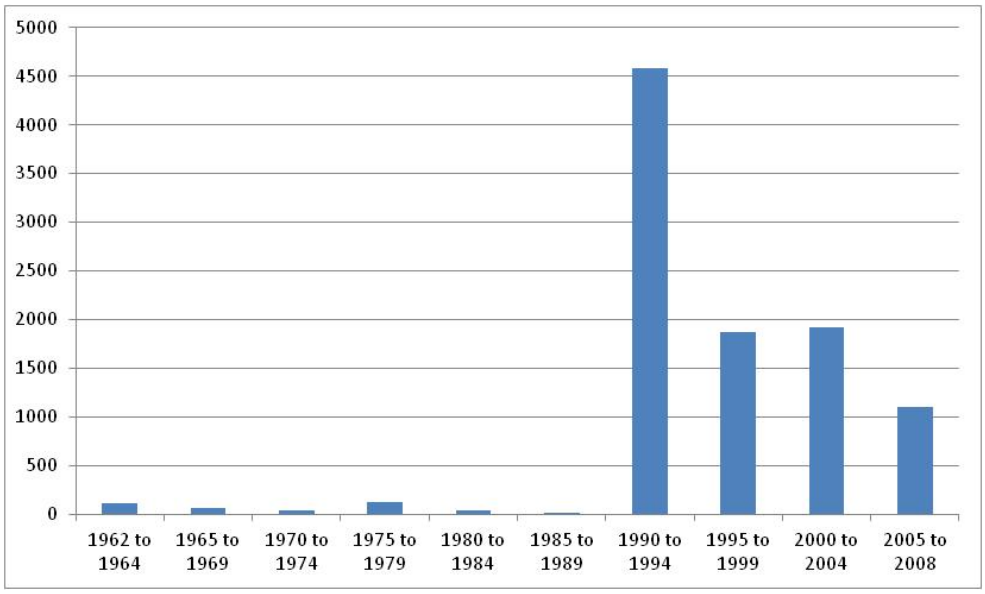


Figure EQ-2: Annual rate of earthquake occurrence in Oregon, in 5-year increments. Seismic instruments began operation in 1970, but the network only became fully effective in 1990. Huge spikes in earthquake numbers in the early 1990s are aftershocks from the 1993 Scotts Mills and Klamath Falls earthquakes.

Paleoseismic data uses geologic records of earthquake effects to determine the approximate size and timing of earthquakes that happened in prehistoric times. The paleoseismic record can extend back for thousands or tens of thousands of years, but provides only approximate information about the size, time and place of past large earthquakes.

Figure EQ-3: Deep sea sediment cores showing submarine landslide layers (turbidites) that record past megathrust earthquakes off the Oregon coast. Red T's mark the top of each layer. Data from Goldfinger and others, 2011.

In Oregon, the combined earthquake history derived from these three sources clearly outlines two major hazards. The first, and by far the greatest, is the hazard posed by frequent **megathrust earthquakes** on the Cascadia Subduction Zone. The second comes from smaller and less frequent **crustal earthquakes** on faults in or near populated areas of Oregon.

The Cascadia Subduction Zone is the boundary between two of the earth's crustal plates. These continent-sized plates are in constant slow motion, and the boundaries between plates are the site of most earthquake activity around the

globe. At the Cascadia Subduction Zone, the Juan De Fuca plate, located offshore of Oregon and Washington, slides to the northeast and under the North American plate, which extends from the Oregon coast clear to the middle of the Atlantic Ocean. The Juan de Fuca plate slides beneath the continent (subducts) at about 1.5 inches per year, a speed which has been directly measured using high accuracy GPS. The fault that separates the plates extends from Cape Mendocino in Northern California to Vancouver Island in British Columbia, and slopes down to the east from the sea floor. The fault is usually locked, so that rather than sliding slowly and continuously, the 1.5 inches per year of subduction motion builds tremendous stress along the fault. This stress is periodically released in a megathrust earthquake, which can have a magnitude anywhere from 8.3 to 9.3.

- ~16,000 dead
- ~4,000 missing (as of 10/12/2011)
- ~6,000 injuries
- ~300,000 homes destroyed
- ~600,000 homes damaged
- 92% of deaths due to tsunami (drowning)
- Fatality rate within the tsunami inundation zone ~16%
- Population within 40 km of coastline ~3,000,000

Figure EQ-4: 2011 Tohoku earthquake numbers

The Cascadia Subduction Zone closely mirrors the subduction zone in northern Japan that produced the 2011 Tohoku earthquake. This magnitude 9 megathrust event and its associated tsunami captured the world's attention with unforgettable images of destruction on a massive scale. Oregon should regard this as a window into our future, as this is the very type of earthquake that our best science tells us is likely on the Cascadia Subduction. Particular attention must be paid to the incredibly destructive tsunami that accompanied the Tohoku earthquake, and we must plan for a similar tsunami in Oregon (see Tsunami chapter).

Crustal earthquakes occur on much smaller faults located in the North American plate, for the most part on shore. These are the more familiar "California-style" earthquakes with magnitudes in the 5 to 7 range. Although much smaller than the megathrust earthquakes, crustal earthquakes may occur much closer to population centers, and are capable of producing severe shaking and damage in localized areas. For many parts of eastern Oregon, crustal faults dominate the hazard, and they may also have a significant impact in the Portland region and Willamette valley.

Intraplate earthquakes are a third type that are common in the Puget Sound, where they represent most of the historical record of damaging events. In Oregon, these earthquakes occur at much lower rates, and none have ever been close to a damaging magnitude. They contribute little to the aggregate hazard in most of Oregon.

Figure EQ-5: Comparison of the subduction zone in northern Japan that was the setting for the 2011 Tohoku M 9.0 earthquake and the Cascadia subduction zone. Yellow patches are the measured earthquake rupture zone in Japan, modeled earthquake rupture zone in Oregon.

EARTHQUAKE PROBABILITY

Since the possibility of a megathrust earthquake in Oregon was first suggested in the mid 1980's, extensive research has developed a rich paleoseismic record that is one of longest and most complete anywhere in the world. Scientists have studied coastal marshes and forests buried when the land sinks during megathrust earthquakes, and have also developed an extremely long and detailed record using submarine landslides triggered by the megathrust earthquakes. The landslides, called turbidity currents, produce distinct layers that can be seen, measured and counted in cores recovered from the deep sea floor. Together these data describe a history of megathrust events that extends back 10,000 years. The most recent earthquake occurred on January 29, 1700, and was recorded in Japan as the tsunami crossed the Pacific and damaged coastal communities. The paleoseismic record includes another 18 M 8.8-M 9.1 megathrust earthquakes in the last 10,000 years that affected the entire subduction zone. An additional 10-20 smaller M 8.3-8.5 earthquakes only affected the southern half of Oregon and northern

California. The return period for the largest earthquakes is 530 years, and the probability of the next such event occurring in the next 50 years ranges from 7-12%.

The size and frequency of megathrust earthquakes are so great, that these events dominate the seismic hazard in western Oregon, and must be the basis for response and recovery planning for that part of the state.

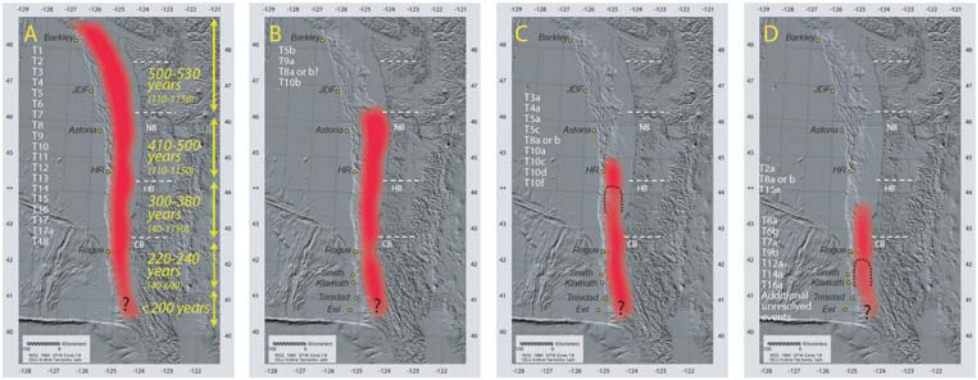


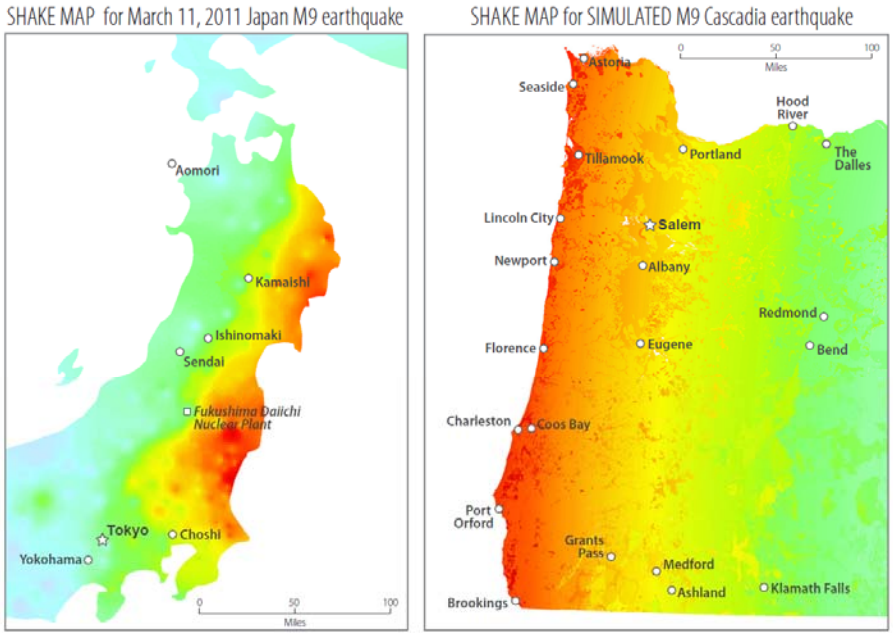
Figure EQ-6: Summary diagram showing Cascadia megathrust earthquake history over the last 10,000 years, "T" numbers identify individual earthquakes. Four distinct modes are seen, ranging from the 19 full-length ruptures in panel A (~M 9) to the 10 smaller ruptures in panel D. Figure from Goldfinger and others, 2011.

EARTHQUAKE EFFECTS

Earthquake damage is largely controlled by the strength of shaking at a given site. The strength of shaking at any point is a complex function of many factors, but magnitude of the earthquake (which defines the amount of energy released) and distance from the epicenter or fault rupture, are the most important. The ripples in a pond that form around a dropped pebble spread out and get smaller as they move away from the source. Earthquake shaking behaves in the same way, and

you can experience the same strength of shaking 10 miles from a magnitude 6 earthquake as you would feel 100 miles from a magnitude 9 earthquake.

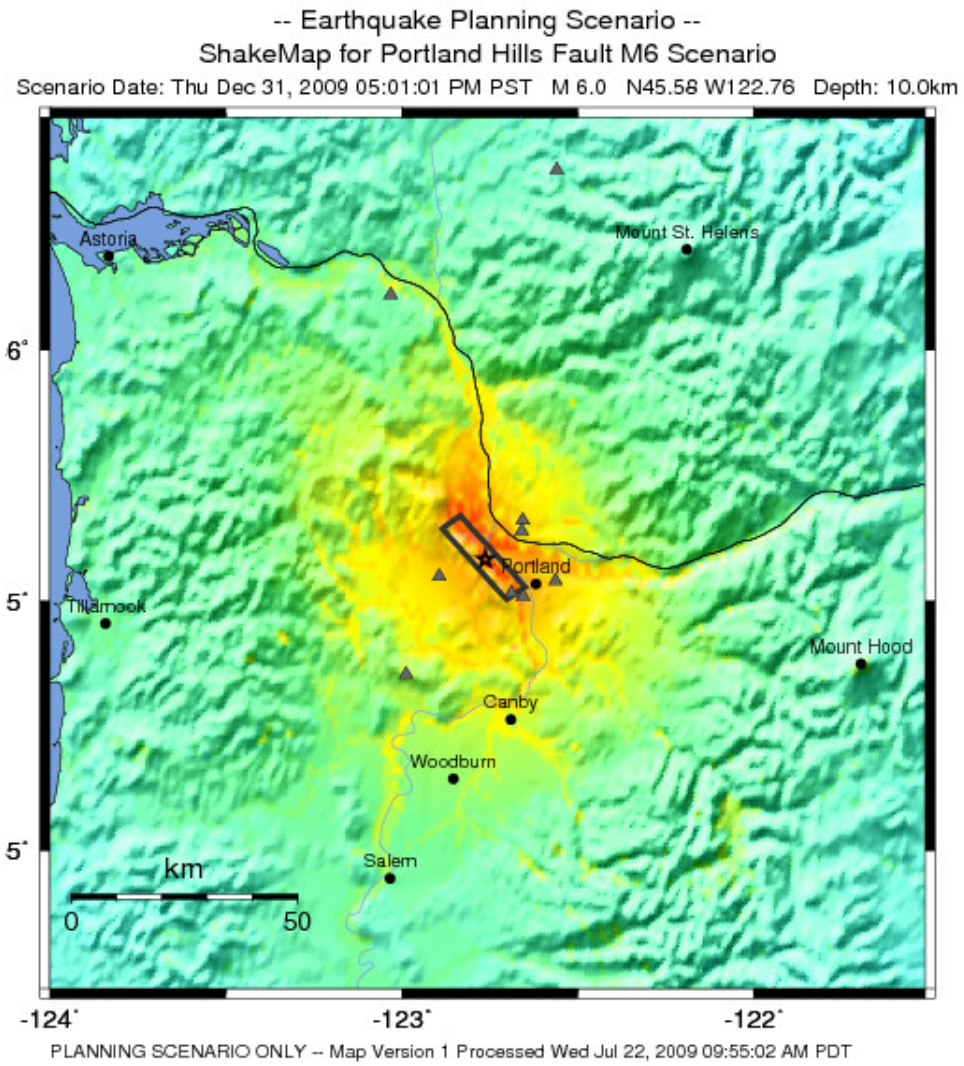
Future megathrust earthquakes on the Cascadia subduction zone will occur off the coast, and the strength of shaking will decrease inland. Oregon coastal communities will experience severe shaking, but the Portland area and Willamette Valley communities are far enough inland that they will feel much less shaking. Because of the size of the megathrust fault, the shaking will impact all of Oregon west of the Cascades, and will still be felt to the east of the Cascades, and will extend to northern California and British Columbia. The other unique characteristic of megathrust earthquakes is that the strong shaking will last for several minutes, in contrast to a large crustal earthquake, which might shake for only 30 seconds. The long duration of shaking contributes greatly to damage, as structures go through repeated cycles of shaking.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure EQ-7: Comparison of measured shaking from Tohoku earthquake and simulated shaking from M 9 Cascadia megathrust earthquake.

Future crustal earthquakes will occur along one of many Oregon fault lines, and the shaking will be strongest near the epicenter, and will decrease fairly quickly as you move away. So a magnitude 6 earthquake in Klamath Falls may cause significant damage near the epicenter, but will be only weakly felt in Medford or Eugene.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure EQ-8: Simulated shaking from M 6.0 crustal earthquake on the Portland Hills Fault.

The other important factor in controlling earthquake damage is the contribution of local geology. Soft soils can strongly amplify shaking, loose saturated sand or silt can liquefy, causing dramatic damage, and new landslides can occur on steep

slopes while existing landslide deposits may start to move again. These effects can occur regardless of the earthquake source, and the geologic factors that cause them can be identified in advance by geologic and geotechnical studies. Liquefaction and earthquake induced landslides are both more likely to occur during the several minutes of shaking produced by a megathrust earthquake, and these effects are expected to be widespread during the next event.

Cascadia Scenario

The Federal Emergency Management Agency (FEMA) is finalizing a regional planning scenario for the Pacific Northwest (Draft Analytical Baseline Study for the Cascadia Earthquake and Tsunami, September 12, 2011) based on a magnitude 9 megathrust earthquake. Using the most current version of HAZUS, FEMA's disaster loss modeling software, they have prepared the most comprehensive and realistic Cascadia scenario to date. In addition to HAZUS analysis, FEMA evaluated likely tsunami effects for several Oregon coastal communities. Data like this provides a critical tool for planning emergency response and for designing a resiliency plan, as it highlights areas of infrastructure damage that affect the entire system. State and local government agencies have been working with FEMA to provide local knowledge to inform the scenario, and the final document and associated databases should be adopted as the basis for planning. In general the scenario results predict severe damage in coastal areas (particularly in tsunami inundation zones, see Tsunami chapter) with widespread but moderate damage along the I-5 corridor. See Figure EQ-9 on next page.

Hazard Mitigation

Conceptually, the real problem with future earthquakes is quite simple. Regardless of which event occurs, the damage that disrupts our communities will be occur in buildings and infrastructure that were not designed and constructed with adequate earthquake resistance. This pattern is clear in earthquake after earthquake around the globe, communities with poorly designed and constructed buildings (Haiti, 2010, Turkey 2011) suffer great damage and loss of life, while communities with well-designed buildings suffer modest damage and loss (Chile, 2010). The solution is also conceptually clear: we need to replace or retrofit all structures and systems that we want to be able to use the day after the next earthquake (immediate occupancy specifications). Of course that simple concept comes with an impossible price tag, so our challenge is to find ways to encourage retrofit and replacement of critical facilities and lifelines in the short run, and of all structures in the long run. In the meantime we must also plan and prepare to respond to the next earthquake based on the likely damage to our built environment as it now exists.

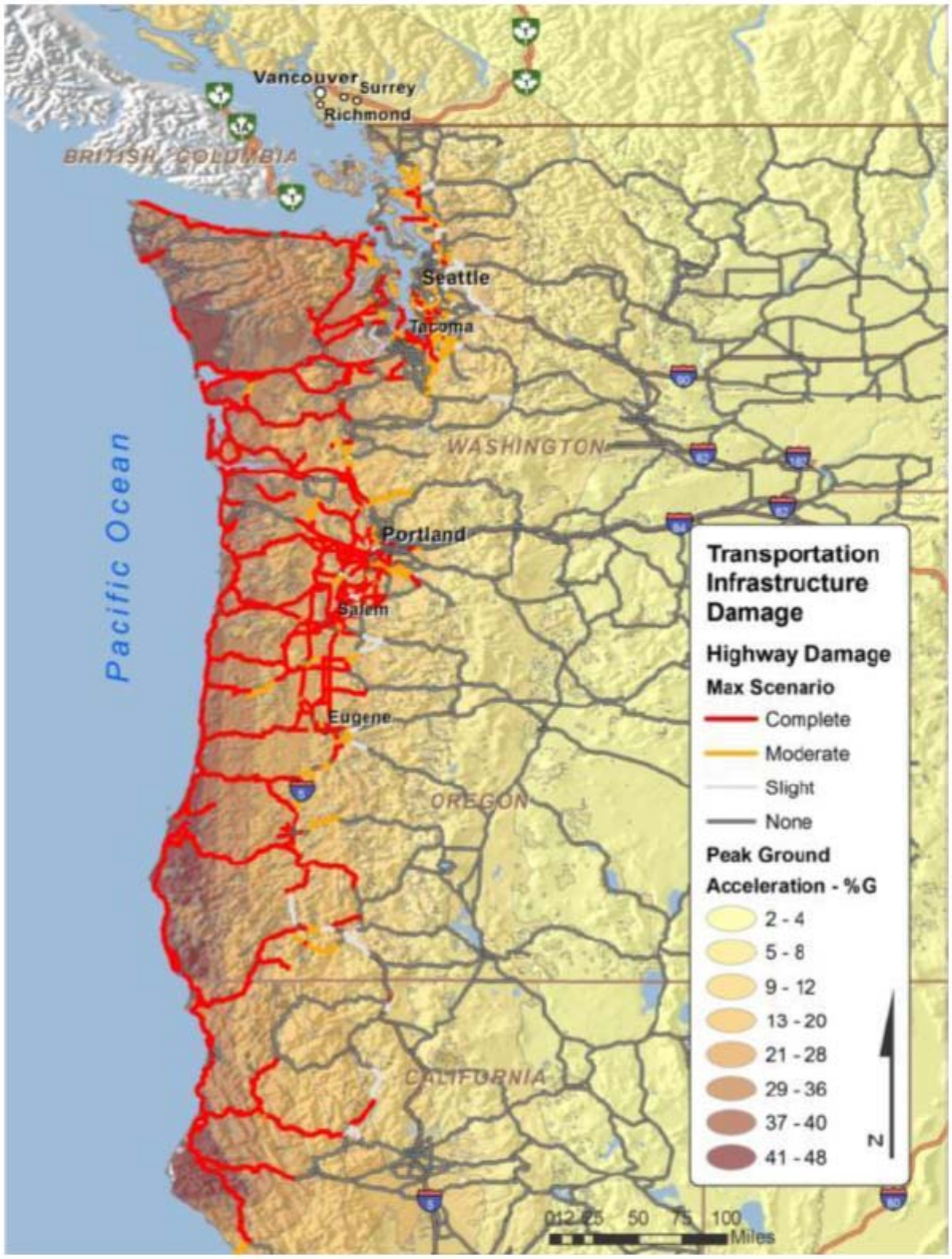


Figure 5-23. Highway road segments in the Cascadia region with expected damage states of slight or more under the 90th-percentile case scenario

Figure EQ-9: Draft HAZUS results from the 2011 FEMA Analytical Baseline Study for the Cascadia Earthquake and Tsunami

Existing Strategies and Programs

LEGISLATIVE

Two recent legislative actions stand out as examples of real progress towards the general mitigation goals described above. Passed in the 2005 legislative session, Senate Bills 2, 3, 4 and 5 estblished a program to provide up to $1.2 billion in general obligation bonds for seismic rehabilitation grants to public schools and

emergency services buildings. The first step of the program was for the Department of Geology and Mineral Industries (DOGAMI) to inventory the potentially eligible facilities throughout the state, and evaluate their earthquake vulnerability using the established Rapid Visual Screening (RVS) technique.

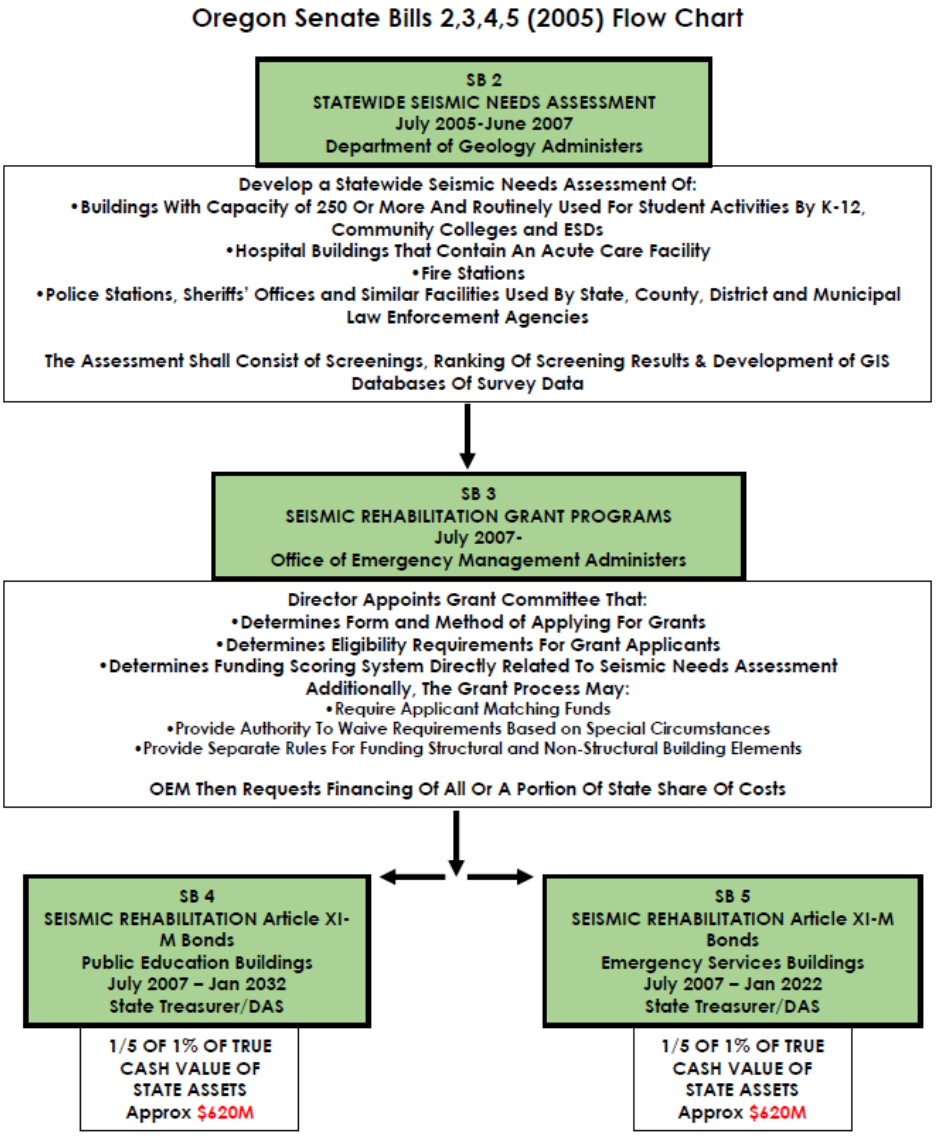


Figure EQ-10: Flowchart showing relationships between Senate Bills 2-5 and elements of Seismic Rehabilitation Grant Program.

The *Statewide Seismic Needs Assessment Using Rapid Visual Screening (RVS)* was completed June 30, 2007, and the results are available at http://www.oregongeology.org/sub/projects/rvs/default.htm . Oregon Emergency Management (OEM) was charged with setting up a grant program (http://www.oregon.gov/OMD/OEM/plans_train/SRGP.shtml) to provide the funds for retrofit (replacement is not allowed) using the results of the DOGAMI study to prioritize need. Subsequent legislatures have approved modest amounts of bond funding, and through 2011 grants totaling $30 million have been made for 25

schools and 18 emergency facilities. The program is considered a national model, and its success is limited only by the budget constraints facing recent legislatures.

Recognizing the need for comprehensive response and recovery planning coupled with smart strategies to reduce structural vulnerabilities the 2011 Oregon Legislature passed *House Resolution 3* (HR3). HR3 recognizes the threat posed to Oregon by future Cascadia megathrust earthquakes, and the need to strengthen public buildings and critical energy and transportation infrastructure. HR3 charges the Oregon State Seismic Policy Advisory Commission (OSSPAC) with the preparation of a resiliency plan for Oregon, enlisting the participation of the appropriate Oregon State agencies. A resiliency plan will help to identify critical weaknesses in facilities, infrastructure and institutions so that Oregon can spend limited resources in the most effective way to minimize future earthquake impacts and facilitate rapid recovery.

Oregon Seismic Safety Policy Advisory Commission (OSSPAC)

OSSPAC is a state advisory commission created in February 1990 through an executive order from Governor Neil Goldschmidt and established in statute by the 1991 Oregon Legislature (ORS 401.337). It is made up of 18 members with interests in earthquake safety: Building Codes Division, Oregon Emergency Management, Department of Geology and Mineral Industries, Department of Land Conservation and Development, Oregon Department of Transportation, two representatives from the Oregon Legislature, one local government representative, one member from education, three from the general public and six members from affected industries, such as homebuilders and banking industries.

The purpose of the work of OSSPAC is to reduce exposure to Oregon's earthquake hazards by: < developing and influencing policy at the federal, state, and local government levels; < facilitating improved public understanding and encouraging identification of earthquake risk; and < supporting research and special studies, appropriate mitigation and response and recovery.

The Commission has proposed concepts to the Oregon Legislature on improving seismic safety in Oregon. They have prepared a document entitled *Oregon at Risk,* which outlines seismic hazards in the state. In 2004 the Commission provided a venue to the General Obligation (GO) Bond Task Force to develop policy recommendations for implementation of SB 14 & 15 (2001). These bills and general obligation bonds for funding of the grant program will improve the earthquake safety of public schools and emergency response facilities across the state.

In the 2011-2013 biennium, OSSPAC has been charged by the Oregon Legislature through HR3 with the development of a state earthquake resiliency plan.

Oregon Board of Geologist Examiners

In 1990 the Oregon Board of Geologist Examiners adopted guidelines to assist professionals in preparing engineering geologic reports in the state. Then in 1996, the Board adopted additional guidelines for site-specific seismic hazard reports for essential and hazardous facilities, major structures and special occupancy

structures as provided in ORS 455.447. A complete listing of all report elements is included in Section 1802.6.1 of the *Oregon Structural Specialty Code.* In 2001, the Board established a Memorandum of Understanding with the Engineering & Land Surveying Examiners Board to clarify the roles of Certified Engineering Geologists and Geotechnical Engineers.

Energy Facility Siting Council

The Energy Facility Siting Council reviews proposed energy facilities for seismic vulnerability through its structural standard, Oregon Administrative Rule (OAR) 345-022-0020. This standard is a safety standard rather than a reliability standard. It ensures that structural failure at an energy facility will not endanger workers or the public. It does not require that energy facilities be proven to remain operable in a seismic event because the Council assumes that key safety facilities such as hospitals will have backup electricity.

The standard requires that:

The applicant, through appropriate site-specific study, has adequately characterized the site as to appropriate seismic design category and expected ground motion and ground failure, taking into account amplification during the maximum credible and maximum probable seismic events;

The applicant can design, engineer, and construct the facility to avoid dangers to human safety presented by seismic hazards affecting the site that are expected to result from all maximum probable seismic events (as used in the rule, "seismic hazard" includes ground shaking, landslide, liquefaction, lateral spreading, tsunami inundation, fault displacement, and subsidence);

The applicant, through appropriate site-specific study, has adequately characterized the potential geological and soils hazards of the site and its vicinity that could, in the absence of a seismic event, adversely affect, or be aggravated by, the construction and operation of the proposed facility; and

The applicant can design, engineer and construct the facility to avoid dangers to human safety presented by the hazards identified.

The Council reviews proposed energy facilities such as power plants, major electric transmission lines, major gas pipelines (greater than 16 inch diameter) for compliance with this standard. They do so in consultation with Oregon Department of Geology and Mineral Industries under an interagency agreement.

In response to an electricity shortage, the 2001 Oregon Legislature created an expedited review process for certain qualifying power plants. These power plants are generally not required to meet the structural standard; however, the Oregon Office of Energy, in consultation with Oregon Department of Geology and Mineral Industries, can still impose conditions on these plants related to the structural standard.

Department of Consumer and Business Services (DCBS), Building Codes Division (BCD)

Until recently, earthquakes were thought to pose little risk to the residents of Oregon. This perception started changing in January 1990 based on the information contained in the national model codes that were adopted in the state at that time. National model codes started up-grading seismic risk for Oregon based on the input provided to them by agencies such as USGS and others whose input were based on the most recent geological and soils science researchers. In response to this growing awareness, the Building Codes Division has incrementally revised construction standards for new buildings to make them more resistant to seismic events.

The most recent state building codes reflect seismic classifications of an area by assigning a Seismic Design Category (SDC) to the site and this SDC could be anywhere from "A" through "F". The SDC of a site is based on the "Seismic Use Group" of the structure and "Severity of Earthquake Ground Motion" at the building site. The Severity of Earthquake Ground Motion is a function of the characteristics of the soil available at the site. SDC "A" represents the lowest seismic risk whereas SDC "F" represents the highest level of seismic risk to the structure. Seismic design requirements in the current building codes are based on potential risk from large earthquakes within 2500 years.

Building codes serve as an overarching program to safeguard property and lives. The Building Codes Division adopts statewide standards for building construction that are administered by the state, cities and counties throughout Oregon. The codes apply to new construction and to the alteration of, or addition to, existing structures.

The *Oregon Residential Specialty Code* (http://ecodes.biz/ecodes_support/free_resources/Oregon/11_Residential/11_ORResidential_main.html)

and the *Oregon Structural Specialty Code* (http://ecodes.biz/ecodes_support/free_resources/Oregon/10_Structural/10_ORStructural_main.html)

govern the construction of buildings in Oregon. The *Oregon Residential Specialty Code* is a prescriptive construction code that provides "how to construct" requirements based on empirical observations of structures for the following types of structures: detached one-and two-family dwellings three stories or less in height, row-houses three-stories or less in height and certain types of apartment buildings three stories or less in height. The currently adopted 2011 *Oregon Residential Specialty Code* is based on the 2009 *International residential Code for One- and Two- family Dwellings*. The *Oregon Structural Specialty Code* is a design code which provides regulations for all structures that are not covered by the *Oregon Residential Specialty Code*. Both of these codes contain maps that provide information related to seismic classification of different areas for Oregon. The currently adopted 2010 *Oregon Structural Specialty Code* is based on the 2009 *International Building Code*, and includes amendments that are Oregon-specific.

The structural code requires (pursuant to ORS 455.447), a site-specific seismic hazard report for projects that are classified as essential facilities (facilities that are required to remain operational after an event such as hospitals, fire and police stations, etc.), hazardous facilities (facilities that contain toxics, explosives, etc.), major structures (buildings over six stories in height with an aggregate area of more than 60,000 square feet) and special occupancy structures (buildings with a large occupant load). The seismic hazard report required by the structural code must take into consideration factors such as the seismic classification of the site, soil characteristics including amplification and liquefaction potential, any known faults, and potential landslides. The findings of the seismic hazard report must be considered in the design of the building. Requirements for seismic site evaluations are covered in chapter 18 of the Oregon Structural Specialty Code. That chapter also addresses restrictions on construction of certain facilities in the tsunami inundation zone.

The Building Codes Division supports training to inspectors, architects, engineers, contractors and post earthquake inspectors by providing funding to agencies that provide training. Various classes in seismic design and construction techniques have been sponsored by the division during the last several years Other classes covering subjects such as soils classification, excavation and grading and landslides, which are often related to earthquakes, have also been sponsored. The division maintains a roster of persons qualified to inspect buildings following an earthquake. As part of this program, the division adopted rules establishing qualifications and training required to be registered as a post-earthquake damage inspector.

Department of Geology and Mineral Industries (DOGAMI)

DOGAMI's organic statute gives the agency broad responsibility and authority for evaluating all geologic hazards statewide, including earthquake hazards. DOGAMI has published numerous maps and reports on the earthquake hazards of the state. The agency, in partnership with other state and federal agencies, has undertaken a wide-ranging program in Oregon to identify seismic hazards, including active fault identification, bedrock shaking, tsunami inundation zones, ground motion amplification, liquefaction, and earthquake induced landslides. Since the last update of this plan in 2007, DOGAMI has completed numerous seismic hazard projects and has several more in progress.

As part of the grant program for seismic rehabilitation of schools and emergency facilities, DOGAMI was charged by the legislature to inventory and assess all public schools and publicly-owned emergency facilities in the state, and assess their seismic vulnerability using the established RVS method. DOGAMI completed the project on time and on budget, cataloging and assessing 2,192 schools, 185 community college buildings and 983 emergency facility buildings. A detailed database was developed along with a summary spreadsheet ranking the buildings into categories of low, moderate, high and very high risk of collapse. The complete report, spreadsheet and a searchable database are available at: http://www.oregongeology.org/sub/projects/rvs/default.htm.

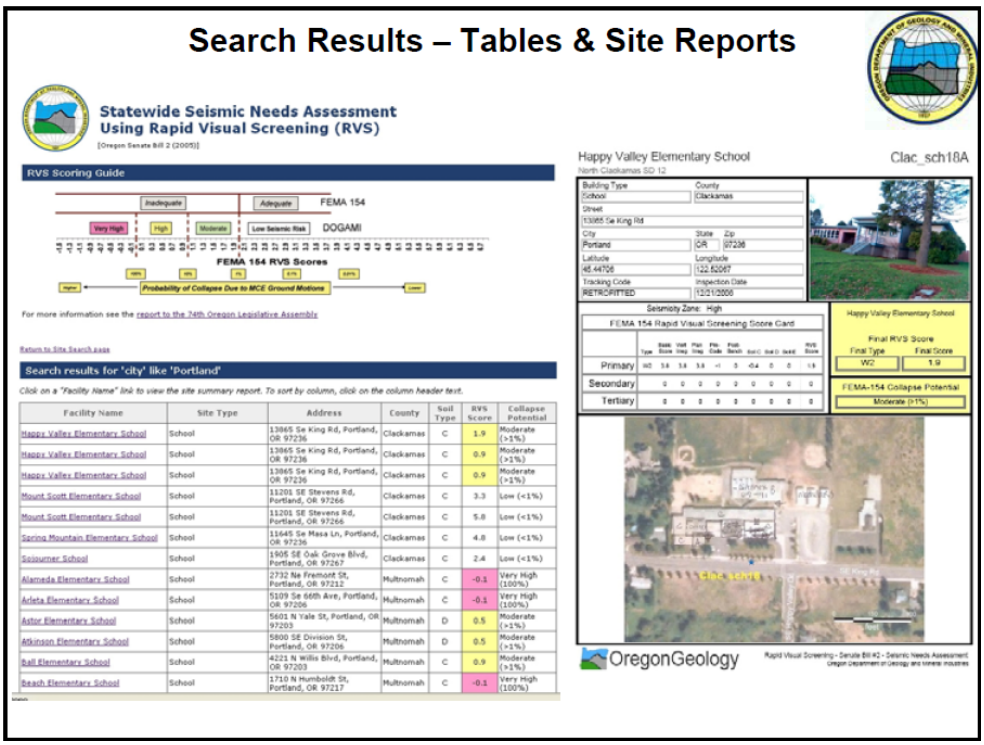


Figure EQ-11: Example database search results from DOGAMI Statewide Seismic Needs Assessment.

Since 2007, DOGAMI has been designated as the lidar (light detection and ranging) acquisition agency for Oregon. Lidar is a relatively recent technology that uses a laser rangefinder mounted in an accurately-navigated aircraft to collect dense sets of location data describing the ground, vegetation and structures. Geologists make extensive use of bare earth images produced with lidar, which show the topography in tremendous detail without obscuring vegetation. To date, about 20% of the state has been covered, including about 90% of the populated areas. The data has wide application in seismic hazard assessment, for location of faults, accurate delineation of geologic features that might enhance damage, and characterization of the built environment.

With funding from FEMA, DOGAMI completed a multi-hazard study of Coos County that used new high resolution lidar topographic data to redelineate riverine flood hazard zones, coastal wave flooding zones, and to map landslide hazards and site dependent liquefaction and amplification earthquake hazards. This was a first effort to use the new lidar data to greatly improve the accuracy, precision and completeness of geologic hazard assessments. In addition to creating the several hazard information layers, DOGAMI used the lidar data as a base for an innovative interactive web map (http://www.oregongeology.org/FEMACoosCountyHazards/index.html) designed to give the public easy access to the hazard information, down to the level of individual buildings. DOGAMI also used building footprints extracted from the lidar to perform building by building risk exposure analysis for some hazards. This kind of comprehensive hazard mapping and interactive web-based delivery system is a model for future state wide efforts.

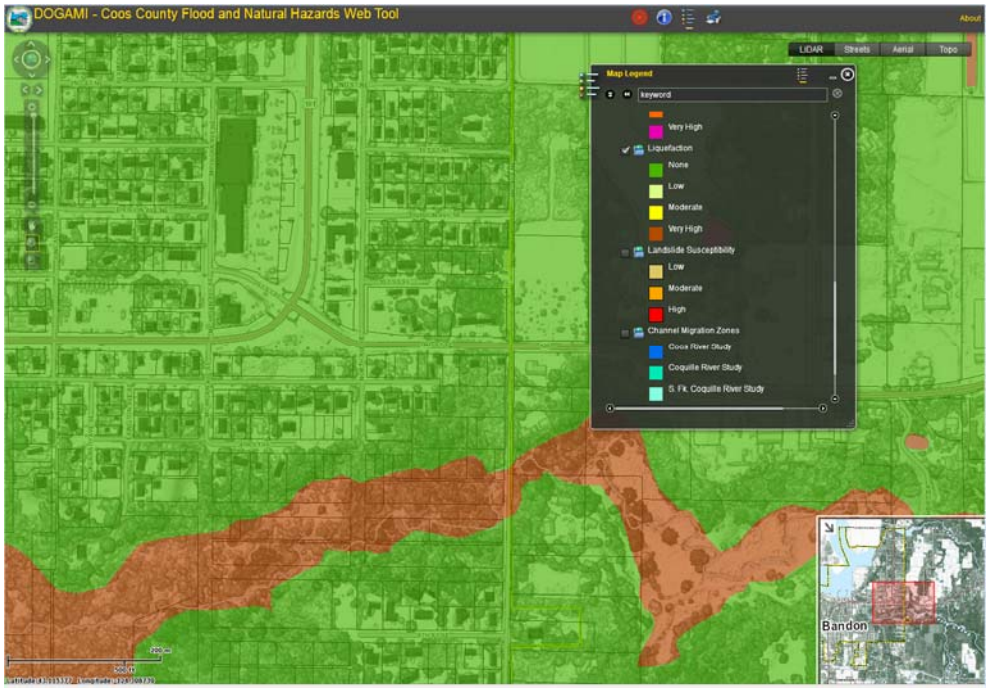


Figure EQ-12: Example of DOGAMI Coos County multi hazard web tool, showing individual houses, trees, autos, overlaid with liquefaction potential zones.

Using ARRA funds from the USGS CVO, DOGAMI prepared a similar multi-hazard study for the Mt Hood area, focusing on volcanic hazards, but including new assessments of seismic, flood and landslide hazards. As with the Coos county study, the results will be displayed on an interactive, lidar-based web tool to make it easy for the public to learn about the hazards facing individual properties. The report and web tool will be available by the end of 2011.

Bare earth lidar images are indispensable for finding active faults in vegetated parts of Oregon. Recent fault movement typically makes a scar across the landscape (called a fault scarp) that can be easily seen in lidar, even though it may be very difficult to see on the ground. DOGAMI has located new recently active faults near Mt. Hood, Bandon, La Pine, Prairie City and Klamath Falls. As funds become available, DOGAMI is excavating trenches across the new faults which provides information about the size and frequency of earthquakes that have occurred there.

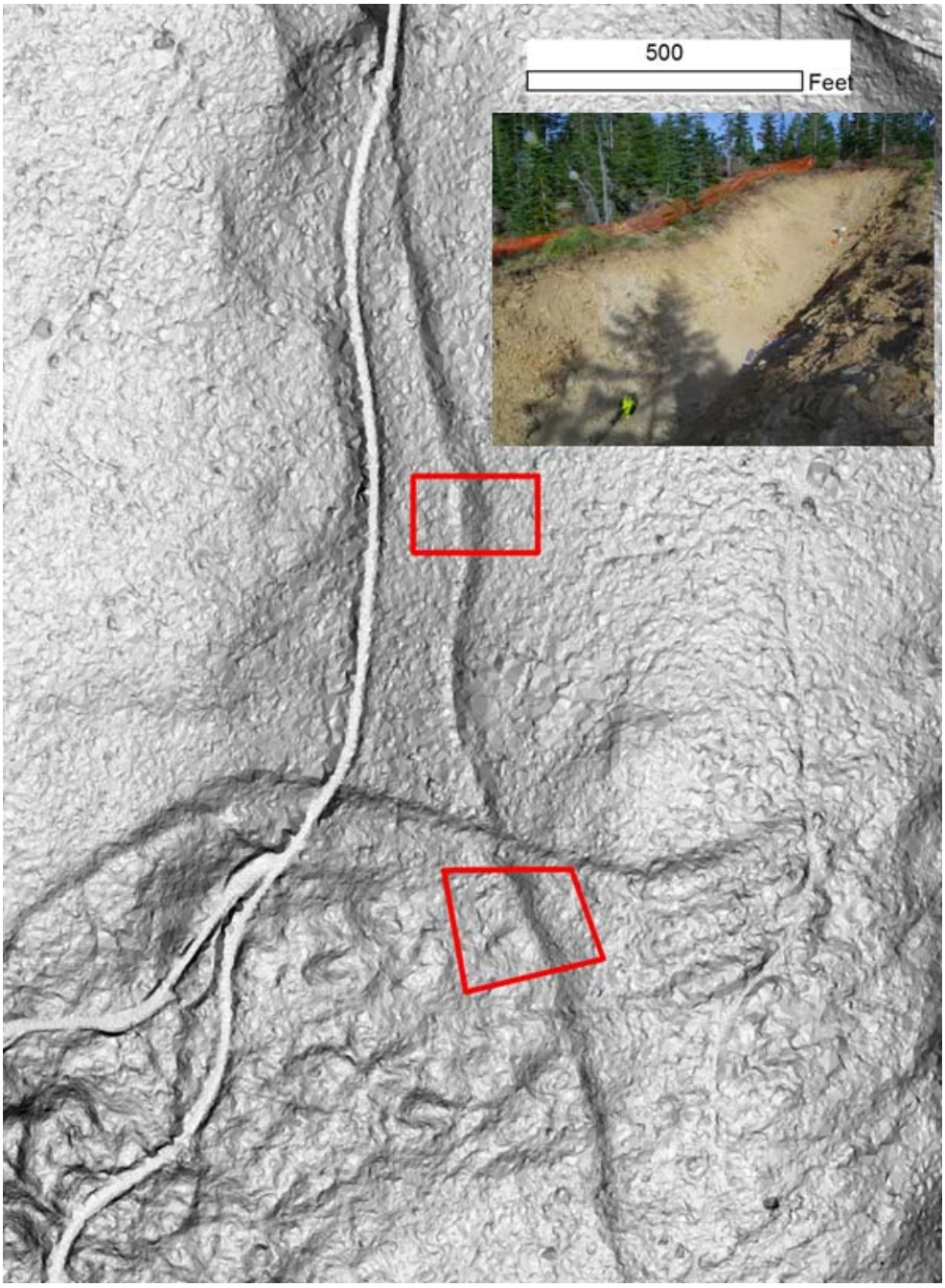


Figure EQ-13: Newly discovered Blue Ridge Fault north of Mt Hood. Dark wavy line from top to bottom is the fault scarp visualized with lidar. Red boxes are trench excavation locations, inset photo shows a fault trench 10 ft deep and 100 ft long.

Surface geologic deposits and soil layers can dramatically enhance earthquake damage through site amplification, liquefaction or earthquake induced landsliding. Evaluating to potential for these effects requires the most accurate geologic map possible, and lidar is essential for this kind of mapping.

DOGAMI is preparing detailed surface geologic maps for the Portland METRO area using funds from the USGS. These highly detailed maps will be coupled with

geotechnical data to produce a 3D model of the surface properties, which in turn can be used to make predictive shaking maps that include the various site effects. Similar lidar-based data has been collected in the Albany-Corvallis-Eugene area, The Medford-Ashland area, and the Hood River Valley.

Future megathrust earthquakes will undoubtedly trigger hundreds of landslides in western Oregon, and many of these will actually be due to the reactivation of existing prehistoric slides. DOGAMI has developed a system for locating, mapping and inventorying these highly hazardous sites, and is preparing and publishing inventory maps in several parts of the state. Landslide mapping is also important because landslide deposits are likely to amplify ground shaking and may also be susceptible to liquefaction.

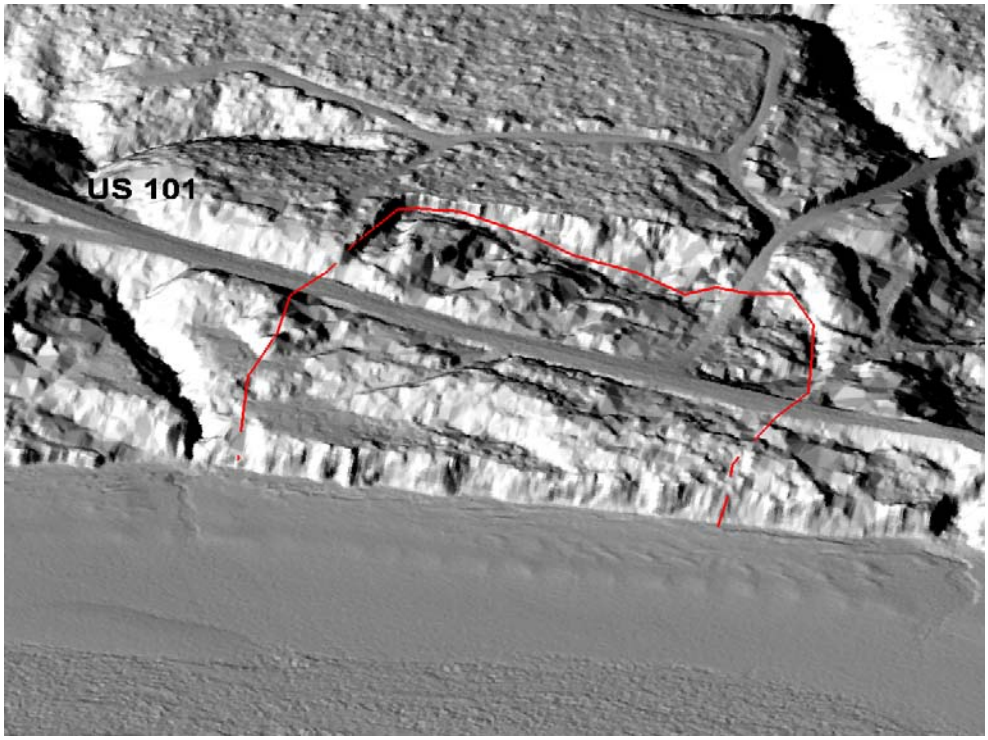


Figure EQ-14: Perspective view of the Johnson Creek landslide on US 101 north of Newport. Extensively studied by DOGAMI and USGS, this landslide moves in every heavy rain, distorting the 800 foot long stretch of the highway that crosses it. Recent USGS research indicates that the slide was triggered by the January 29, 1700 M9 megathrust earthquake.

As part of a multi-year program to produce new, state-of-the-art tsunami inundation models for Oregon (see Tsunami chapter for details) DOGAMI staff worked closely with an international team of experts to develop a record of the timing and size of 19 great megathrust earthquakes in Oregon over the last 10,000 years, and to develop a geologically accurate model of how fault motion in those earthquakes triggers devastating tsunamis.

In 2011, as part of IHMT Task 6, DOGAMI completed a statewide assessment of the exposure of state-owned buildings to a variety of natural hazards. This study developed a comprehensive database of 5,977state-owned or operated

structures and evaluated their exposure to several hazards. DOGAMI used existing and newly developed statewide hazard layers to look at flood, coastal erosion, tsunami, volcano, wildland fire, landslide and earthquake hazards. An example of the earthquake results is shown below, showing for example that there are 770 buildings in areas with high liquefaction potential

Table EQ-1: State Facility Exposure to Various Volcanic Hazards

Liquefaction Potential		**500 year ShakeMap**		**Active Fault Buffer**	
Total Facilities	Critical or Essential	Total Facilities	Critical or Essential	Total Facilities	Critical or Essential
770	29	3,296	118	423	22

Source: DOGAMI

DOGAMI is working with ODOE and the Oregon PUC on an ARRA-funded project to evaluate the vulnerability of the energy hub in the Portland harbor area, and to develop an energy assurance plan for future earthquakes. ODOE secured the grant from the USDOE, and is working with the Oregon PUC to update the Oregon Energy Assurance Plan based on the results of DOGAMI's vulnerability study. The project is currently in progress and will be completed in September of 2012. Information like this will be key to developing the statewide resiliency plan mandated by HR3.

Recent DOGAMI earthquake hazard publications include a multi-hazard study with earthquake loss estimates for several Willamette Valley counties (IMS-24), reports describing FEMA-funded seismic retrofit of buildings on the PSU campus (O-2007-04, SP-38), improvements to the RVS procedure (SP-39) and proceedings from a Critical Energy Infrastructure workshop (O-2008-10).

The Department has a program in cooperation with the Department of Consumer and Business Services Building Codes Division that added a special section to the *Oregon Structural Specialty Code* to require buildings over 60,000 sq. feet or 10 stories to install strong motion instruments in the buildings. The idea is to increase the information on effects of seismicity to large structures. In 2009, DOGAMI used pooled funds from this program to buy several seismographs that had been temporarily installed in Oregon from the ANSS transportable array program. The stations were selected in collaboration with the Pacific Northwest Seismic Network which maintains and monitors the new stations as part of their regional network.

Earthquake hazard maps, mitigation information, and emergency preparedness education can be accessed from the department website:

http://www.oregongeology.com/sub/earthquakes/earthquakehome.html

Department of Land Conservation and Development (DLCD)

Statewide Land Use Goal 7, natural hazards, has been revised and adopted by the Land Conservation and Development Commission effective June 1, 2002. For more information see:

http://www.oregon.gov/LCD/docs/goals/goal7.pdf

The *Technical Resource Guide (Planning for Natural Hazards, Oregon Technical Resource Guide, 2000),* developed for DLCD by the Community Service Center's Oregon Natural Hazards Workgroup at the University of Oregon, provides contacts, documents, and internet resources to assist planners, emergency managers, and citizens in mitigating earthquake hazards along with several other hazards. The TRG may be accessed over the Internet via:

http://www.oregonshowcase.org/downloads/pdf/projects/UO-ONHW_Hazard_TRG_full_1999.pdf

Oregon Emergency Management (OEM)

OEM sponsors statewide earthquake and tsunami drills during the month of April, promoting "drop, cover, and hold" and tsunami evacuation. Non-structural earthquake hazard mitigation is supported by development of a web site with a survey checklist for non-structural hazards that include diagrams depicting how to secure non-structural components of buildings.

OEM promotes the use of HAZUS software by coordinating local HAZUS training and a user's group. It is important to bring the users of HAZUS together periodically to insure development of a coherent use and training strategy for HAZUS in the state.

OEM has co-sponsored several earthquake business contingency forums with the Cascadia Region Earthquake Workgroup, DOGAMI, ODOT, cities and counties. OEM manages distribution of mitigation funds, including the Seismic Rehabilitation Grant Program and FEMA pre-disaster grants. OEM also provides a range of educational and training material for the public and first responders.

Oregon Department of Transportation (ODOT)

All of Oregon's state, county, and city owned bridges (more than 6,000 bridges) have been inventoried and prioritized for seismic retrofit. A summary report identifies structural vulnerabilities of each bridge. The department has cost estimates for retrofitting each bridge in 1997 dollars. Seismic lifeline routes (roads that are considered essential for emergency response during the first 72 hours or needed for economic reasons after an earthquake) have been identified for each county. This project was a joint effort of ODOT, AOC, LOC, and CH2M HILL, an engineering firm. That report was largely superseded in 2009 by a new ODOT report: Seismic Vulnerability of Oregon State Highway Bridges: Mitigation Strategies to Reduce Major Mobility Risks. This report takes a detailed look at over 1900 ODOT bridges along major routes in western Oregon, and evaluates likely damage states for several Cascadia megathrust and local crustal fault scenarios.

ODOT is currently working with CH2M HILL on a facility plan to prioritize a seismic lifelines "backbone" system. The intent is to identify vulnerabilities on key transportation routes to prioritize future funding to ensure that needed routes can be quickly restored to function. The project is scheduled for completion in spring of 2012.

The results of these studies will be key to developing the statewide resiliency plan mandated by HR3.

An earthquake scenario of magnitude 9.0 at the Cascadia Subduction Zone resulted in 6 complete collapses, 64 extensive, 106 moderate and 164 slight damage states. The losses calculated were $1,080 million for bridge repair and replacement and $177 million travel time related losses. *Figure 5.11* shows a map of component damage states for the western part of Oregon.

Figure 5.11 : Component Damage States for a Magnitude 9.0 Cascadia Subduction Zone Scenario EQ

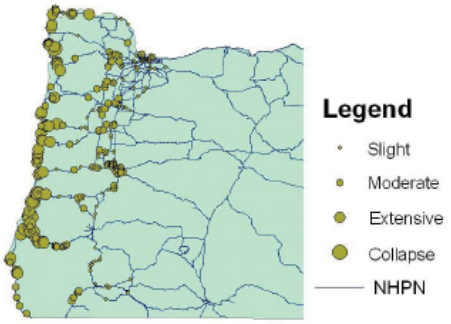


Table5.7 : Summary of Seismic Hazard Analysis

Event	Route	Damage States				Economic loss (in Million $)	
		Slight	Moderate	Extensive	Complete	Bridge Repair/Replacement	Travel Time Loss
CZ9.0	I-5 (Mult-Clack)	5	1	0	0	$8	
	I-5 (Clack-Lane)	18	3	1	0	$14	
	I-5 (Lane-Jacks)	22	0	0	0	$5	
	I-84	10	0	0	0	$3	
	US-101	7	14	35	5	$684	
	US-26	7	4	0	0	$8	
	I-205	8	2	0	0	$10	
	I-405	7	0	0	0	$2	
	US-30	5	3	2	0	$26	
	US-20	4	3	5	0	$19	
	OR-38	3	2	1	0	$9	
	OR-42	4	13	13	1	$147	
	Others	64	61	7	0	$145	
	Total	**164**	**106**	**64**	**6**	**$1,080**	**$177**

Figure EQ-15: Sample results for M 9 Cascadia megathrust earthquake from 2009 bridge vulnerability study.

Water Resources Department (WRD)

The Water Resources Department Dam Safety Program reviews design plans, reports and specifications and approves for construction, modification or enlargement all hydraulic structures greater than or equal to 10 feet height and 3,000,000 gallons reservoir capacity (ORS 540.350). Design approval for High Hazard hydraulic structures typically includes a satisfactory review of Emergency Action Plans and inundation maps.

The Dam Safety Program maintains for the National Inventory of Dams, a database of all Oregon dams and reservoirs that exceed statutory size criteria regardless of ownership. The program also performs regular inspections of all existing non-federal dams statewide. The WRD dam safety program participates cooperatively with existing established federal dam safety programs such as U.S. Army Corps Engineers, U.S. Bureau Reclamation, Federal Energy Regulatory Commission and others in their design review and inspection of federal project dams, reservoirs and appurtenant works.

WRD is the designated state agency and the Hydroelectric Licensing Program is the lead for review and license permitting for new and existing hydroelectric projects. WRD's licensing program collects data and requests from other state agencies, negotiates settlements and assembles the state's criteria for power development and operation. When the process is completed, the conditions and requirements are incorporated into and apply concurrently with issuance of the federal license for all regulated hydroelectric projects statewide (ORS 543, ORS 543A).

Appendix EQ-1: Glossary

Amplification is the modification of frequency or strength of seismic earth movement at a location due to thickness, topography, and physical properties of soft surface sediments.

Bedrock shaking is expected earth movement at a location due to seismic activity without considering soft sediment effects such as amplification and liquefaction.

Cascadia Subduction Zone is the interface between the Juan de Fuca Plate moving from the west and the resulting collision with the North America Plate which overrides it.

HAZUS (**HAZ**ards **U**nited **S**tates) is a loss estimation methodology that is a software program using mathematical formulas and information about building stock, local geology, and the location and size of potential earthquakes, economic data, and other information to estimate losses from potential earthquakes.

Landslide is any detached mass of soil, rock, or debris that moves down a slope or a stream channel.

Liquefaction is the reaction of saturated soil to seismic earth movement causing the soil to behave like a liquid.

LIDAR ((Light Detection And Ranging) is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser.

Locked zone is a location at the boundary of two crustal plates where no relative motion is occurring.

Magnitude (M) is a measure of earthquake size; the amount of energy released by an earthquake. Energy release increases 30 times for each integer on the scale.

Megathrust is both the giant fault that separates the two plates in a subduction zone and the giant earthquake that occurs when that fault moves.

Resiliency means the ability of a community to respond to and recover from a major earthquake.

Surface faulting refers to a fault that ruptures to the surface. Such faults, if active, can pose greater threat to nearby structures.

Tectonic refers to large scale vertical or horizontal movement of the earth's crust.