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THE TŌHOKU EARTHQUAKE OF MARCH 11, 2011: A PRELIMINARY REPORT ON IMPLICATIONS FOR COASTAL CALIFORNIA

To: Commissioners and interested parties
From: Mark Johnsson, Staff Geologist

This report is intended to help the Commission place the recent events in Japan in context and to provide perspective for their possible implications to coastal California, based on preliminary information known at this early date. The discussion below includes the following:

- A description of the Tōhoku Earthquake and tsunami effects
- An evaluation of whether the seismic characteristics of the Tōhoku Earthquake are applicable to the California coast
- A brief description of the earthquake and tsunami risks at California's three coastal nuclear facilities

References and links to web resources can be found at the end of this report. Some words or phrases are further explained in an appendix. These words or phrases are marked in ***bold italics*** where they first occur.

EXECUTIVE SUMMARY

- **The vast majority of faults in California, including the San Andreas fault, could not produce a magnitude 9 earthquake.**
  Most of California is not susceptible to an event of the scale of the Tōhoku Earthquake. Nevertheless, it is important not to become complacent; large earthquakes are inevitable throughout coastal California, and could be devastating in their own right. There is a large population and much infrastructure at risk in central and southern coastal California.

- **The Cascadia Subduction Zone could produce a magnitude 9 earthquake similar to the Tōhoku Earthquake.**
  The northern part of the coastal California, as well as all of coastal Oregon, Washington, and part of coastal British Columbia—the Cascadia Subduction Zone—is susceptible to an

earthquake and tsunami event similar to that of the Tōhoku Earthquake. Emergency response scenarios and land use planning must take this into account.

- **A nuclear emergency such as is occurring in Japan is extremely unlikely at the state's two operating nuclear power plants**.
  The combination of strong ground motion and massive tsunami that occurred in Japan cannot be generated by faults near the San Onofre Nuclear Generating Station and the Diablo Canyon Power Plant. Nevertheless, the geologic conditions near those plants are very likely different than previously believed and ongoing study is warranted. This has been understood for at least the past three years, and some of these studies, and the environmental planning process for other such studies, are underway.

The Tōhoku Earthquake and Tsunami

The magnitude 9.0 Tōhoku Earthquake of March 11, 2011, the fourth most powerful earthquake measured by modern instruments (since about the year 1900), occurred at the interface between the ***Pacific*** and ***North America plates***. Two days prior to the earthquake, a magnitude 7.2 earthquake occurred near what would be the ***epicenter*** of the Tōhoku Earthquake. It was followed by three aftershocks in the magnitude 6 range later that day. In retrospect, these earthquakes can be viewed as foreshocks to the magnitude 9.0 event that followed. The ***hypocenter*** of the Tōhoku Earthquake was located 81 miles off the east coast of the Oshika Peninsula, part of the Tōhoku region of the island of Honshu, near the city of Sendai, at a depth of 20 miles below the seafloor.

Over the next several days, hundreds of aftershocks, the largest of magnitude 6.8, outlined the area of the plate boundary that ruptured. Aftershocks extend to depths of about 340 miles, although most are above a depth of 125 miles. As of March 23, some 726 aftershocks have been recorded, 26 of them magnitude 6.0 or greater, and they are expected to continue, at a decreasing frequency, for the next several years.

The Tōhoku Earthquake is what is termed a "***megathrust earthquake***:" a major ***subduction zone*** earthquake whereby the Pacific plate suddenly lurched beneath the North America plate. The affected portion of the North America plate is a westward and southward extension of the plate from the Alaska region that underlies eastern Siberia and the northern Sea of Japan Some geologists divide this geologically complex region into a number of microplates (for a representation of the geometry of these plates, see http://pubs.usgs.gov/gip/dynamic/slabs.html).

The area of the plate boundary that ***ruptured*** during this earthquake was about 190 miles long and 90 miles wide, which is larger than the areas of San Luis Obispo, Santa Barbara, Ventura, Los Angeles, Orange, and San Diego counties combined. At the location of the earthquake, ***oceanic crust*** of the Pacific plate is being thrust under oceanic crust of the North America plate at an angle of about 15 degrees, creating the Japan Trench, a bathymetric trough on the seafloor. The average rate of this movement is approximately 83 mm/yr, one of the higher rates of ***plate***

convergence in the world. Much of this movement occurs episodically in earthquakes such as the Tōhoku Earthquake.

The Tōhoku Earthquake was accompanied by violent and long-lasting ground shaking. The highest measured ***ground acceleration*** was a devastating 2.75 g[1], measured over 80 miles from the epicenter, although most stations relatively near the epicenter reported ground accelerations more on the order of 1.0 g. Ground shaking intensity reached a ***Modified Mercalli Intensity*** of IX (Violent), and resulted in widespread damage. Damaging secondary effects included liquefaction, lateral spread, and landslides.

The most damaging secondary effect of the earthquake was the resulting tsunami. Megathrust earthquakes of this magnitude occurring beneath the sea at relatively shallow depths always produce large tsunamis and the Tōhoku Earthquake was no exception. About 15 minutes after the earthquake, a tsunami with an amplitude of about 30 feet hit the shoreline. The first wave swept up to six miles inland in flat regions, leveling buildings, and sweeping debris, buildings, ships, vehicles, and airplanes far inland.

The tsunami caused the loss of power, and disabled backup generators, at the Fukushima 1 nuclear power plant. The subsequent loss of coolant in several reactors and spent fuel storage pools resulted in explosions, fires, and partial core meltdowns in at least three nuclear reactors, and the release of radiation to the environment.

The full extent of the damage resulting from the Tōhoku earthquake and tsunami is still unknown and will likely be unknown for some time. Given the thousands of lives that have been lost, the billions of dollars worth of property and infrastructure destroyed, and the ongoing nuclear emergency, it is natural to ask how vulnerable California is to a similar event.

Does the Tōhoku quake increase the likelihood of a similar event in California?

Despite some alarmist articles that have appeared in the press, there is no reason to believe that this earthquake has in-and-of-itself raised the likelihood of an earthquake in California. Although there have been three very damaging earthquakes around the Pacific Rim in just the last year, they are not related in a geologic sense.

The magnitude 8.8 southern Chilean earthquake of 27 February 2010 was a major subduction zone earthquake similar in many ways to the Tōhoku Earthquake, but it occurred on a separate plate boundary (the Nazca/South America plate boundary) with no connection to the Pacific or North America plates.

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[1] Ground shaking during earthquakes is measured by how fast the earth moves, both horizontally and vertically. It is expressed as a comparison to the force of gravity – that is, the acceleration (which is the rate of change in speed) of the ground relative to the acceleration caused by gravity (or g-force). For instance, ground shaking of 1.0g is equal to the acceleration caused by gravity, shaking of 0.5g is equal to half the acceleration of gravity, etc. For any location and earthquake, this value varies based on a number of factors, including the area of the fault plane that slipped, depth of the earthquake, distance from the epicenter, and the underlying site geology.

The magnitude 7.1 Canterbury Earthquake of September 4, 2010 near Christchurch, New Zealand, together with its destructive February 22, 2011 magnitude 6.3 aftershock, was not a major plate boundary earthquake, but rather a significant earthquake on shallow crustal faults. The fact that its major aftershock (dubbed the Christchurch Earthquake) was so damaging is more a product of its location and shallow depth than of its significance as a geologic phenomenon.

The relatively recent magnitude 9.1 and 8.6 earthquakes of 2004 and 2005 off the island of Sumatra were far removed from the Pacific plate, and most seismologists do not feel that stress transfer to the Pacific plate occurred as a result of these events.

Although geologists are increasingly realizing that large earthquakes may load stress on adjacent faults, there is no connection between the faults associated with any of these earthquakes and any faults in California. The United States Geological Survey (USGS) writes on their website for the event:

> The USGS does not believe that the earthquakes in Japan have significantly raised the probability of future major earthquakes. While the probability of future large earthquakes far from northern Honshu has not increased, neither has it decreased and large earthquakes will continue to occur just as we have observed in the past.

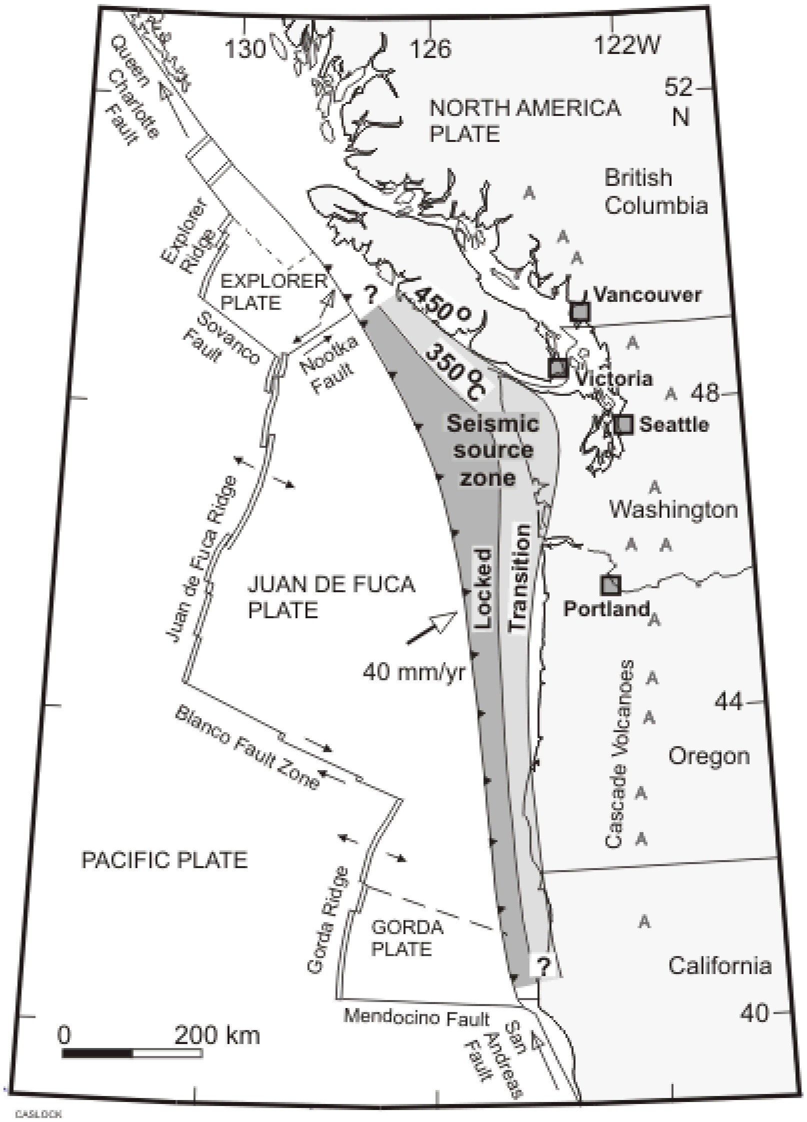
Could an earthquake of this magnitude occur in California?

Most faults in California are incapable of an earthquake of the magnitude of the Tōhoku Earthquake. A magnitude 9 earthquake requires rupturing a fault surface thousands of square miles in area. The shallow faults making up most of the state's California's fault systems, including the San Andreas fault, simply do not have sufficient area to generate such an earthquake.

An important exception is the region north of Cape Mendocino, from about 25 miles south of Eureka to north of Vancouver, British Columbia, an area known as the Cascadia Subduction Zone. This region could generate an earthquake comparable to the Tōhoku Earthquake. There are important similarities, and some differences, between the Cascadia Subduction Zone and the part of the subduction zone off the Tōhoku region of Japan that ruptured during the Tōhoku Earthquake.

The Cascadia Subduction Zone

The Cascadia Subduction Zone lies off the Pacific Northwest, and is the zone where the Gorda, Juan de Fuca, and Explorer plates are being thrust beneath the overriding North America plate. Unlike the situation at the Japan Trench, where oceanic crust is thrust beneath other oceanic crust, here oceanic crust is thrust beneath continental crust. The Gorda, Juan de Fuca, and Explorer plates are separated from the Pacific plate by the Juan de Fuca and Gorda Ridges to the west and by the Mendocino Transform Fault to the south. Two prominent sets of fracture zones, healed ***transform faults***, are zones of weakness and separate the Explorer plate to the north from the Juan de Fuca plate to the south, and the Juan de Fuca plate from the Gorda plate further south. All three subplates are moving together, converging on the North America plate at a rate of about 40 mm/yr and diving beneath it at an angle of about 8 degrees, an angle that increases with depth. The upper portion of the subduction zone is locked (not moving), while the lower section is moving, thus creating great stress in the upper part of the subduction zone. Release of this stress will occur during the next megathrust earthquake.



Source: Geological Survey of Canada
http://gsc.nrcan.gc.ca/geodyn/cascadia_e.php

The Cascadia Subduction Zone, about 800 miles long, is thus divided into three segments. The longest segment, about 450 miles long, is the Juan de Fuca plate segment that lies off central and northern Oregon and Washington. The Juan de Fuca plate segment is flanked by the Explorer plate segment, off British Columbia, and the Gorda plate segment, off northern California and southern Oregon, each about 175 miles long. It is unknown if the segments typically rupture together, separately, or in pairs during megathrust earthquakes. This introduces some uncertainty into the estimation of the magnitude of megathrust earthquakes in the Cascadia Subduction Zone.

Nevertheless, most seismologists agree that a megathrust earthquake involving any of these plates would be in the magnitude 9 range, similar to the Tōhoku Earthquake.

Thirteen past megathrust earthquakes associated with the Cascadia Subduction Zone have been identified through submarine sediment deposits triggered by the earthquakes, tsunami deposits preserved on land, and deposits indicative of sudden land subsidence associated with the earthquakes. Of these past earthquakes, the last seven are reasonably well-dated:

Estimated Date	**Recurrence Interval (yr)**
26 January 1700, ~9:00 PM	780
780-1190 AD	210
690-730 AD	330
350-420 AD	910
660-440 BC	400
980-890 BC	250
1440-1340 BC	unknown

Reference: Atwater et al., 2005

The time of the most recent event is known with such precision because, even though there are no written records from North America, Japanese writings describe an “orphan tsunami” (one not accompanied by an earthquake) arriving in Japan at a time that would correspond to an earthquake on the Cascadia Subduction Zone at about 9:00 PM (local time) on January 26, 1700. This time and date are consistent with the geologic data, and with Yurok legends indicating that the earthquake and tsunami occurred early on a winter night in about that year.

The probability of another megathrust earthquake on the Cascadia Subduction Zone in any given upcoming time interval can be estimated from these recurrence interval data. The mean recurrence interval is 500-600 years. According to a study by Mazzotti and Adams (2004), this yields a probability of between 0 and 12 percent that the next megathrust earthquake will occur in the next 50 years.

However, close examination of the recurrence interval data show that they may be bimodal in distribution: three earthquakes in relatively quick succession, followed by a long pause; then three earthquakes, followed by a long pause, ending in the 1700 event. A sample size of seven events is too small to confirm that this is a real trend, but there are geologic reasons that such a bimodal recurrence interval distribution might make sense. Assuming a bimodal recurrence interval, with the two “modes” being recurrence intervals of 310 and 820 years, the probability of a megathrust earthquake occurring in the next 50 years rises to between 6 and 45 percent.

Finally, it has been recently discovered that, in addition to megathrust earthquakes, a significant amount of the convergence between the Juan de Fuca and North America plates is taken up by what has been termed “slow-slip” events. These are events, lasting one to three weeks and recurring every 13-15 months, when movement between the plates occurs at great depths without causing significant earthquakes. Mazzotti and Adams (2004) calculate that the chance of a megathrust earthquake occurring during one of these slow-slip events is 30 to 100 times greater than between events.

To summarize, an earthquake and tsunami looking very much like the Tōhoku Earthquake is very likely in northern California. It is, however, very difficult to predict the probability of such an event in any given time interval. The interagency Cascadia Region Earthquake Workgroup (CREW) continues to study and prepare for the next megathrust earthquake. In 2005 they published a very useful and informative planning scenario, which can be found at http://www.crew.org/papers/CREWCascadiaFinal.pdf.

Implications for California Nuclear Power Plants and Spent Fuel Storage Facilities

There are two operating nuclear power plants in the California coastal zone and one nuclear plant undergoing decommissioning. The Diablo Canyon Power Plant (DCPP) in San Luis Obispo County and the San Onofre Nuclear Generating Station (SONGS) in northern San Diego County are operating power plants that hold current licenses from the Nuclear Regulatory Commission (NRC). The nuclear unit of the Humboldt Bay Power Plant (HBPP) near Eureka is being decommissioned, although highly radioactive spent fuel and other materials remain on site. A magnitude 9 earthquake near DCPP or SONGS is extremely unlikely. However, the Humboldt Bay plant is in close proximity to the Cascadia Subduction Zone and could be subject to a magnitude 9 earthquake.

All three facilities, including their spent fuel storage facilities, have been subject to numerous seismic investigations. During the permitting process for the Independent Spent Fuel Storage Installation (ISFSI) at each facility, Southern California Edison (SCE) and Pacific Gas and Electric (PG&E) undertook new geologic investigations; particularly extensive for Diablo Canyon and Humboldt Bay. These studies, along with studies undertaken for the original licensing of these plants, ongoing USGS and academic studies, and experience gained from geologically similar regions, were reviewed by the U.S. Nuclear Regulatory Commission (NRC), which ultimately released Final Safety Analysis Reports (FSARs) recommending approval of each facility.

During Coastal Commission review and permitting of each ISFSI, Commission staff reviewed all of this material, conducted independent research of published literature, interviewed knowledgeable parties, and conducted site visits at and around each facility, prior to recommending that the Commission approve each facility. The Commission's adopted findings for each approval can be found at:

DCPP: http://www.coastal.ca.gov/energy/W5a-1-2005.pdf
SONGS: http://www.coastal.ca.gov/energy/e-00-14rf.pdf
HBPP: http://www.coastal.ca.gov/energy/Th6a-9-2005.pdf

The expected earthquake and tsunami risk at each facility is described briefly below.

Diablo Canyon Nuclear Power Plant

Earthquake Concerns: Although a magnitude 9 earthquake is extremely unlikely near the DCPP, a magnitude 7.2 earthquake on the Hosgri Fault, lying only 3 miles offshore, is currently considered possible.

The Hosgri Fault was discovered during the construction of the plant. In 1975 the NRC, in conjunction with the USGS, concluded that that the Hosgri Fault is capable of a magnitude 7.5 earthquake, and that ground shaking at DCPP could be as high as 0.75 g. PG&E retrofitted the plant in 1978 to withstand that level of ground shaking. In 1978 the NRC required the implementation of a Long Term Seismic Program, through which the seismic safety at the plant would be continuously reevaluated. In 1991, NRC approved a report from PG&E that, using improved earthquake models, showed that the maximum credible earthquake on the Hosgri fault was of magnitude 7.2, but that ground shaking at DCPP would be as high as 0.83 g. PG&E demonstrated to the satisfactions of the NRC that the plant had been retrofitted in 1978 with adequate safety margins to withstand that level of ground shaking.

The most recent study submitted to the NRC by PG&E examined ground shaking that would result from an earthquake on the newly discovered "Shoreline Fault" located less than 0.5 miles from the reactor building. Preliminary results of those studies indicate that the potential ground shaking from this fault will be less that those used in the initial plant design. The report of these studies, available at http://diablocanyonpge.com/home/resources/shoreline-fault-zone-report-with-plates.html is currently under review by the NRC, as well as by state geologists from a number of agencies, including the Coastal Commission.

As discussed below, AB 1632 required that the State prepare a report making recommendations to facilitate assessing, among other things, the seismic safety of DCPP and SONGS. One of the recommendations in that report is for further detailed investigation not only of the Shoreline Fault, but of the total seismic environment of the plant. These studies are currently underway. The proposed high-energy studies meant to identify seismic characteristics deep below the plant and surrounding area will be subject to CEQA review and will require review and permitting by the Coastal Commission.

Tsunami Concerns: DCPP is located at an elevation of 85 feet above mean sea level (MSL), atop a high coastal bluff. It is effectively above the range of any conceivable earthquake-induced tsunami, and is mapped as lying outside of the tsunami inundation zone on the Tsunami Inundation Maps recently released by the California Emergency Management Agency, California Geological Survey, and the University of Southern California.

San Onofre Nuclear Generating Station

Unit 1 of the San Onofre Nuclear Generating Station was commissioned in 1968, and was designed to resist ground shaking of 0.67g corresponding to a magnitude 7.0 earthquake on the nearby Newport-Inglewood-Rose Canyon Fault system. Units 2 and 3 were commissioned in

1983 and 1984 to the same design standard. Unit 1 was decommissioned in 1992, but radioactive portions of the reactor still remain at the plant.

Earthquake Concerns: Although a magnitude 9 earthquake is extremely unlikely near SONGS, a few studies indicate that an earthquake larger than the design-basis earthquake may be possible near the reactor site. The Commission considered these studies in its findings for the ISFSI approval in June 2001 and concluded that:

> …there appears to be credible evidence that, in addition to the strike-slip faulting recognized at the time of the SONGS licensing review, thrust faults exist in the area offshore of the SONGS site which might interact with the Newport-Inglewood-Rose Canyon fault system in a complex way during an earthquake. If these faults are active or potentially active, the increase in potential fault rupture area has, at a minimum, the potential to increase the magnitude of an earthquake on the integrated fault system. Geologists' understanding of this area is rapidly evolving, and there are few constraints on the parameters needed to assess the increase in earthquake risk (such as slip rate on each of the potentially active faults, segmentation of the faults, and potential for cascading failure between fault segments). One of the few published estimates is that of Shaw and his students (Rivero et al., 2000), who hypothesize that the combined system may be capable of an earthquake ranging from M_W 7.1 to 7.6, depending on which sets of faults are involved in the earthquake…
>
> Shaw's tectonic model for the area is, however, quite controversial (Jones, USGS, pers. comm., 2001). Commission staff consulted with seismologists and geologists at the U.S. Geological Survey, California Division of Mines and Geology, California Seismic Safety Commission, within academia, and at private consulting firms. Although there was near unanimous recognition that there is an increased earthquake risk given our emerging understanding of the complexities of the region relative to a simple strike-slip model used in the SONGS seismic hazard assessments, no one could assess the potential ground shaking that might be expected at the SONGS site.
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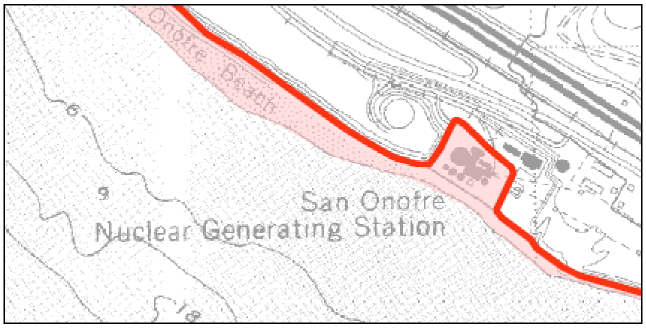
> The Commission thus finds that there is credible reason to believe that the design basis earthquake approved by the NRC at the time of the licensing of SONGS 2 and 3—a magnitude 7.0 earthquake on the Newport-Inglewood-Rose Canyon fault system 8 km from the site, resulting in ground shaking with a high frequency component peaking at 0.67 g—may underestimate the seismic risk at the site. This does not mean that the facility is unsafe—although the design basis earthquake may have been undersized, the plant was engineered with very large margins of safety, and would very likely be able to attain a safe shutdown even given the larger ground accelerations that might occur during a much larger earthquake.

Tsunami Concerns: Tsunami run up and inundation were considered by the SCE and NRC for permitting of the SONGS facility. However, more recent examinations indicate that a larger earthquake or a large submarine landslide could generate a tsunami larger than that considered by SCE or the NRC. The potential tsunami risk was included in the Commission's findings for the ISFSI permit which concluded:

> These studies suggest that large local-source tsunamis could be generated by mechanisms other than those considered during licensing for SONGS 2 and 3, the basis for the 1995 SCE report. However, there have been no local runup studies based on this mechanism that are widely agreed upon, and certainly none for the SONGS site itself. As Dr. [Mark] Legg indicates, tsunami runup maps are currently being prepared for San Diego County by individuals at the University of Southern California in conjunction with the Office of Emergency Services, but they are not currently available.

> Commission staff accordingly concludes that although the proposed project may be threatened by tsunami, the major effect from an earthquake-generated tsunami would be site inundation. Possible inundation has been factored into the [ISFSI] project design, and it would not adversely [a]ffect the stability of the site. There is also a potential for a submarine landslide to generate a tsunami that could threaten this site; however, current mapping and modeling do not provide any information of how the site would be [a]ffected by such an event.

The maps mentioned have since been produced, and they do, in fact, place the SONGS facility in the tsunami inundation zone:



The SONGS site was excavated into the coastal bluff and the nuclear reactors are located at an elevation of less than 20 feet MSL. The tsunami inundation line calculated for this area is at an elevation of approximately 20 feet MSL, and the plant is protected by a 30-foot seawall. Thus, it appears to be protected from the modeled set of tsunamis underlying the state map. How the inundation line on the state map might change if it included the magnitude 7.6 thrust earthquake postulated by Shaw and others is not, however, known. Further study of the tsunami risk at the SONGS facility appears warranted.

Humboldt Bay Power Plant

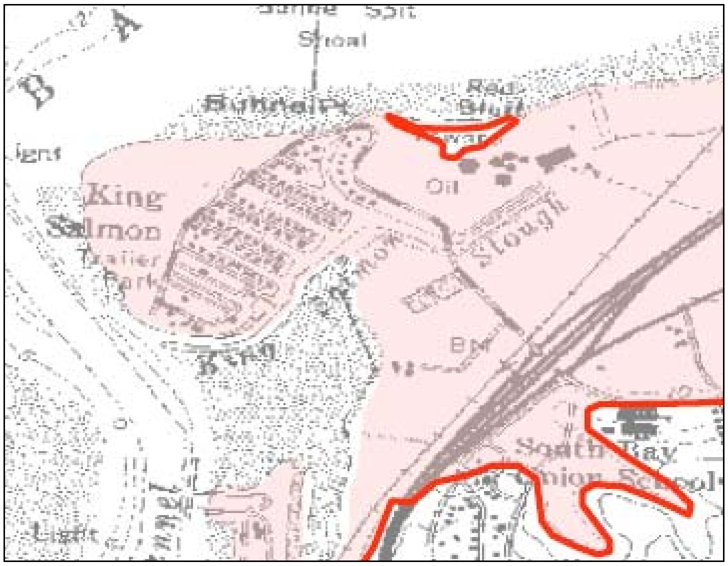
The Humboldt Bay Power Plant is susceptible to a megathrust earthquake on the Cascadia Subduztion Zone. The nuclear unit at HBPP has been shut down since 1976, largely for seismic hazard reasons, and currently is undergoing decommissioning. PG&E expects to complete decommissioning by about 2015. Highly radioactive spent fuel remains on site. Until recently, this fuel was stored in the same type of pool that apparently has been compromised in Japan. In 2005 the Coastal Commission approved a small Independent Spent Fuel Storage Installation (ISFSI) to contain this material. Unlike the ISFSI's at SONGS and DCPP, the casks containing the spent fuel and highly radioactive components of the decommissioned reactor are located below ground, in part to make them less vulnerable to tsunamis.

Earthquake Concerns: Regarding ground shaking, the Commission's findings for the Independent Spent Fuel Storage Installation concluded that the facility was designed to withstand the expected level of ground motion:

> PG&E designed the ISFSI in part using a probabilistic assessment of the "maximum credible earthquake" likely to occur at the site during a 2000-year return period. This design earthquake is

> of magnitude 9.1, roughly equivalent to the recent Sumatra earthquake of December 2004, and has a peak acceleration of almost 2.9 g, which is equivalent to the force near the upper limit of any earthquake anywhere in the world. The Commission's staff geologist has objected to the use of a 2000-year return period and instead recommends the use of a 10,000-year return period; however, the Commission concurs with his determination that the overall assessment provided by PG&E results in a conservative design basis for the ISFSI. The Commission therefore recommends that designing the ISFSI to withstand this rate of ground shaking is consistent with Coastal Act section 30253(1) with respect to the ground motion hazard.

Tsunami Concerns: The site clearly is at high risk for a tsunami generated during a Cascadia Subduction Zone event. This general region is by far the most studied area on the west coast of Noarth America with respect to tsunami hazards, with many of those studies being funded by PG&E and summarized in the NRC's FSAR for the site. The State's Tsunami Inundation Map shows that the entire site, except for a small area at the top of Buhne Hill, lies in the predicted inundation zone. That small hilltop is the approximate location of the ISFSI.



The Coastal Commission found in September 2005 that the ISFSI is susceptible to tsunami hazards, including higher runup levels than predicted during the NRC licensing process, and the danger of bluff erosion due to energy from both incoming and retreating waves. As summarized in the Commission staff report:

> PG&E assessed how the ISFSI site likely would be affected by tsunamis and tsunami runups. It determined that the maximum tsunami runup resulting from a Cascadian Subduction Zone earthquake during Mean Higher High Water would be from about 23 to 38 feet. Because the ISFSI site is at about 44 feet, and because it is below grade, PG&E concludes that the ISFSI would not be inundated and would not be damaged by debris carried by the tsunami.
>
> However, for several reasons, the Commission cannot conclude that the site will be safe from tsunami hazards either during the relatively short-term or in perpetuity. First, similarities between the expected Cascadian Subduction Zone earthquakes and the December 2004 Sumatran earthquake raise doubts as to the validity of the expected tsunami runup height at the ISFSI site.

> The Sumatran quake resulted in tsunami runups of as much as 130 feet, which is about three times higher than the runup predicted at the ISFSI site, but the mechanisms for the earthquakes and the generation of tsunamis in each area are similar. Additionally, the predicted 38-foot runup at the ISFSI site is based only on the height above Mean Higher High Water and does not include the customary additional height provided if the tsunami occurred during a 100-year storm surge. This would put the runup at an even higher level, possibly at or above the 44-foot elevation of the ISFSI structure. Further, the ISFSI site is on a peninsula made up of poorly consolidated soils, and it would be subject during a tsunami to wave energy from both incoming and retreating waves, which could result in substantial erosion and damage to the ISFSI site.
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> Finally, because the ISFSI is expected to remain in perpetuity, Commission staff requested PG&E evaluate the longer-term potential for tsunami effects. PG&E applied the rate of tectonic uplift at Buhne Point (estimated at about 1.3 feet per 100 years) to several scenarios for anticipated rates of sea level rise. The analyses found that during the next several thousand years, overtopping of the site would be likely, though over the next 10,000 years, the anticipated sea level will likely fall due to increased glaciation and that ISFSI site would become less exposed to risks associated with sea level rise or tsunamis.
>
> Therefore, based on the above, the Commission finds that the siting of the ISFSI is inconsistent with the requirement of Section 30253(1) to minimize risks associated with tsunamis and tsunami runup.

Although the Commission found the project was inconsistent with Coastal Act section 30253 for this and other reasons, as well as other Chapter 3 policies of the Coastal Act, it approved the ISFSI, in large part due to the lack of safer alternative storage sites for the material and the hazards of transporting the material offsite. The Commission's findings state:

> Denying the ISFSI on the basis of these inconsistencies would result in the continued presence of the existing storage facility, which would likely result in significant adverse impacts to marine biology, water quality, and environmentally sensitive habitat areas caused by the same geologic hazards that make the blufftop a safer location than the existing storage pool. In such a situation, when a proposed project is inconsistent with a Chapter 3 policy, and denial or modification of the project would be inconsistent with another policy, Section 30007.5 of the Coastal Act provides for resolution of such a policy conflict.

Simply put, although the site is unsafe, keeping the spent fuel in subterranean casks in a hazardous location is less unsafe than keeping the material in the spent fuel pool within the nearby and lower elevation reactor building, where it had been kept for the previous several decades. After Commission approval of the facility, all spent fuel at the site has been moved into the ISFSI. The Commission will soon review an application for an expansion of this facility to accommodate low and mid-level radioactive waste being generated during the HBPP decommissioning process.

Ongoing and Planned Seismic Studies

Both state and federal legislators have in recent days called for renewed study of the seismic safety of nuclear power plants in California and the United States, respectively; however, such studies are in fact already underway in California. AB 1632 (Blakeslee, Statutes of 2006, Chapter 722), directed the California Energy Commission to assess the vulnerability of the state's operating nuclear power plants to a major disruption due to a major seismic event or plant aging, the potential impacts of such a disruption, potential impacts from the accumulation of nuclear waste at the state's existing nuclear plants, and other key policy and planning issues regarding the future role of California's existing nuclear plants. In 2008, the Energy Commission released the required report "An Assessment of California's Nuclear Power Plants" which can be found at: http://www.energy.ca.gov/2008publications/CEC-100-2008-009/CEC-100-2008-009-CMF.PDF

The California Public Utilities Commission has since required PG&E and SCE to undertake the studies recommended in the report, which include, among other things, 3D seismic imaging of the faults around both sites, in order to answer some of the questions about fault geometry and expected ground motions during different earthquake scenarios. The Coastal Commission's staff geologist sits on an Independent Peer Review Panel which reviewed the production of the AB 1632 report and will review the study plan, results, and interpretation of these studies as they proceed. PG&E has begun some of these studies, and has begun the environmental review process for others. SCE, who is not proceeding with relicensing on as aggressive a time schedule as PG&E, has not yet produced plans for the required studies.

Effects of the Tōhoku Earthquake Tsunami in California

The Tōhoku Earthquake produced a tsunami felt throughout the Pacific Ocean. California was moderately impacted, and several harbors around the state suffered damage, collectively totaling tens of millions of dollars. Fortunately, given the state's tsunami preparedness, and the many hours warning time afforded by this distant-source tsunami, early evacuation and preparation were effective and losses were kept to a minimum, although there was one death associated with the tsunami. The Coastal Commission's coastal engineer will prepare an evaluation of preparations, events, responses, and results of this major test of the state's tsunami preparedness and response program in the near future.

Implications for Predictions of Future Sea Level Rise

The way the land responds to a megathrust earthquake such as is expected in the Cascadia Subduction Zone has important implications for planning for future sea level rise. When a subduction zone is locked (not moving through small earthquakes) at the surface, but is moving at depth, as is the case in the Cascadia Subduction Zone, there is a region close to the coast where the land is rising. Further inland is a region of gradual land subsidence. When the locked upper portion of the subduction zone builds up sufficient stress, it suddenly slips (causing a megathrust earthquake), and the region of uplift near the coast suddenly subsides, while the region further inland rises. The Incorporated Research Institutions for Seismology (IRIS) has produced an excellent animation illustrating this process, which can be found at http://www.youtube.com/watch?v=RVaDXsqLUtI

In northern coastal California, the land has been rising faster than global average sea level since the 1700 megathrust event, and the long-term average sea level rise *relative to the land* is actually negative (-0.65 mm/yr at Crescent City, for example); *relative* sea level in this region is falling. As global average sea level rise continues to accelerate, the rate of *relative* sea level *fall* in northern California will decrease, but the uplift of the land will reduce the effects of global sea level rise relative to elsewhere on the coast.

One consequence of the next Cascadia Subduction Zone earthquake is that this effect will be suddenly undone. Past Cascadia Subduction Zone earthquakes have typically resulted in a sudden land subsidence of about six feet. This figure is consistent with what has been observed following other megathrust earthquakes around the world. This sudden subsidence needs to be taken into account when planning for future sea level rise. The National Academy of Science has, at the request of the western states' governors, convened a panel to provide recommendations for predicting sea level trends in California, Oregon, and Washington over the next century. The panel is well aware of this phenomenon, and it will be interesting to see how they incorporate it into their recommendations.

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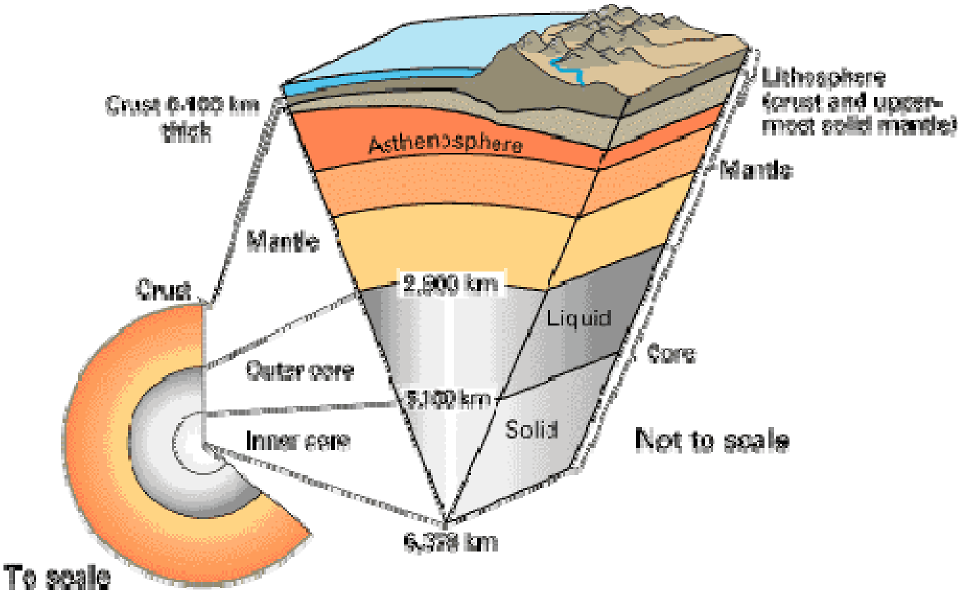
APPENDIX: EXPLANATION OF TERMS AND PROCESESS

Plate tectonics

This section is adapted from a USGS publication entitled *This Dynamic Earth*; see http://pubs.usgs.gov/gip/dynamic/inside.html

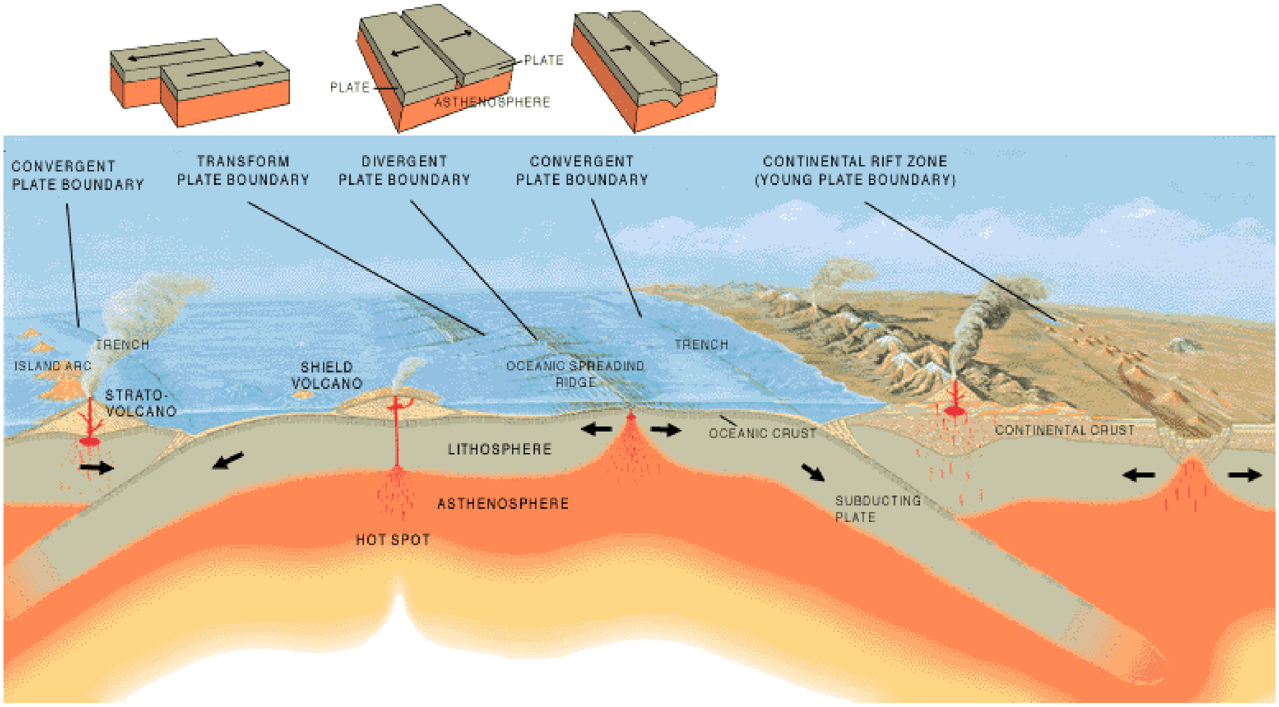
The interior of the Earth can be divided into three sections— the crust, mantle, and core. This layered structure can be compared to that of a boiled egg. The crust, the outermost layer, is rigid and very thin compared with the other two. Beneath the oceans, the crust is made up mostly of dense rocks such as gabbro and basalt and is only about 5 km thick. The thickness of the crust beneath continents is mostly made up of less dense granite and averages 30 km in thickness. The Earth's crust is brittle and can break.



Below the crust is the mantle, a dense, hot layer of semi-solid rock approximately 2,900 km thick. The mantle is hotter and denser because temperature and pressure inside the Earth increase with depth. At the center of the Earth lies the core, which is nearly twice as dense as the mantle because its composition is metallic (iron-nickel alloy) rather than stony. The Earth's core is made up of two parts: a 2,200 km-thick liquid outer core and a 1,250 km-thick solid inner core.

The upper part of the mantle is cooler and more rigid than the deep mantle; in many ways, it behaves like the overlying crust. Together they form a rigid layer of rock called the lithosphere. Averaging 80 km in thickness, the lithosphere has been broken up into the moving plates that contain the world's continents and oceans. Below the lithosphere is a relatively narrow, mobile zone in the mantle called the asthenosphere. The rigid lithosphere is thought to "float" or move about on the slowly flowing asthenosphere. The movement of the lithospheric plates atop the plastic asthenosphere is the root of plate tectonics. The plates interact at the Earth's surface in a number of ways, with three main types of boundaries between them:

- Divergent boundaries -- where new crust is generated as the plates pull away from each other.
- Convergent boundaries -- where crust is destroyed as one plate dives under another.
- Transform boundaries -- where crust is neither produced nor destroyed as the plates slide horizontally past each other



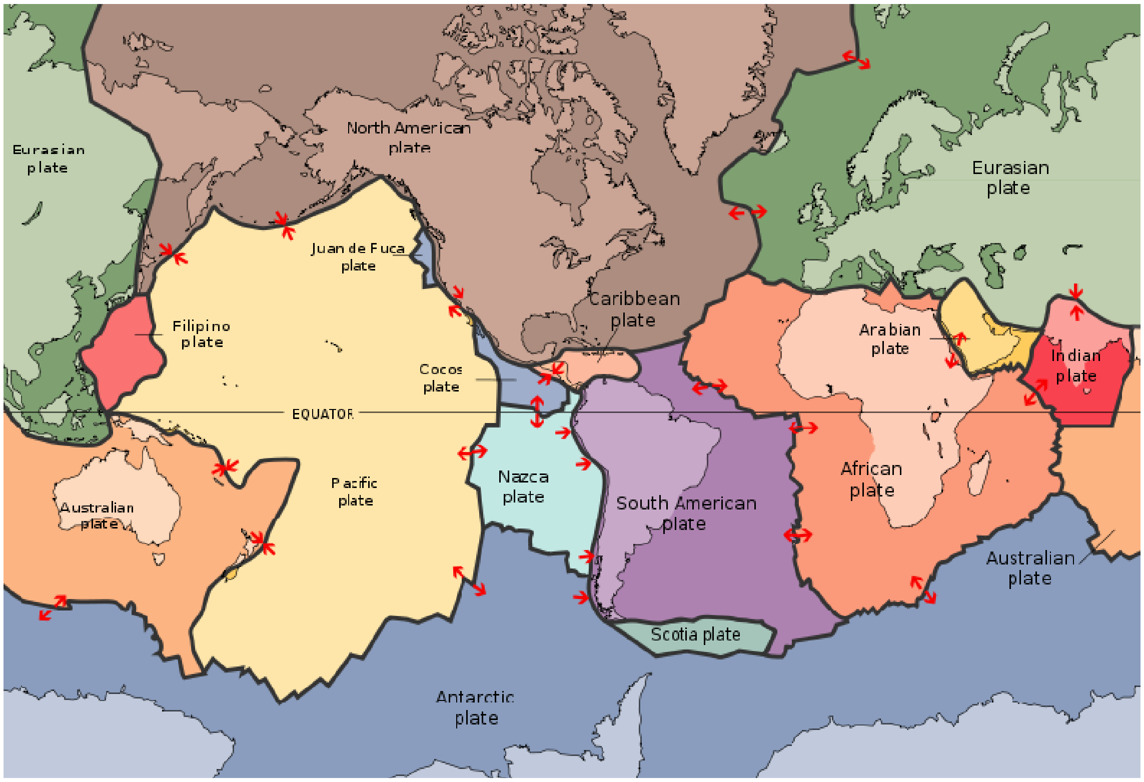
The earth's two largest plates interacted during the Tōhoku Earthquake of 11 March 2011:

North America plate

The North American plate comprises most of North America, Greenland, Cuba, Bahamas, and parts of Siberia, Japan and Iceland. It extends eastward to the Mid-Atlantic Ridge and westward to the Chersky Range in eastern Siberia. The plate includes both continental and oceanic crust. The interior of the main continental landmass includes an extensive granitic core called a craton. Along most of the edges of this craton are fragments of crustal material called terranes, accreted to the craton by tectonic actions over the long span of geologic time. It is believed that much of North America west of the Rockies is composed of such terranes.

Pacific plate

The Pacific lies beneath the Pacific Ocean and is made up almost entirely of oceanic crust. The north-eastern side is a divergent boundary with the Explorer, Juan de Fuca and Gorda plates.. In the middle of the eastern side is a transform boundary with the North American Plate along the San Andreas Fault, and a boundary with the Cocos Plate. The south-eastern side is a divergent boundary with the Nazca Plate forming the East Pacific Rise. The southern side is a divergent boundary with the Antarctic Plate forming the Pacific-Antarctic Ridge. On its western side, the plate is bounded by the Okhotsk Plate at the Kuril-Kamchatka Trench and the Japan Trench, forming a convergent boundary in which it is subducted under the Philippine Sea Plate creating the Mariana Trench. In the south-west, the Pacific Plate has a complex but generally convergent boundary with the Indo-Australian Plate, subducting under it north of New Zealand forming the Tonga Trench and the Kermadec Trench. The Alpine Fault marks a transform boundary between the two plates, and further south the Indo-Australian Plate subducts under the Pacific Plate forming the Puysegur Trench. The northern side is a convergent boundary subducting under the North American Plate forming the Aleutian Trench and the corresponding Aleutian Islands

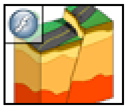


Types of faults

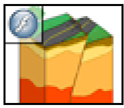
This section is adapted from the USGS *Glossary of Earthquake* terms; see http://earthquake.usgs.gov/learn/glossary/

Faults can be divided into two broad categories, depending on the sense of movement on the dipping fault plant

- **Dip-slip faults** are inclined fractures where the blocks have mostly shifted mostly vertically. If the rock mass above an inclined fault moves down, the fault is termed **normal**, whereas if the rock above the fault moves up, the fault is termed **reverse**. A **thrust** fault is a reverse fault with a dip of 45 degrees or less. Oblique-slip faults have significant components of different slip styles. A **megathrust** earthquake refers to a large earthquake on a subduction zone with a thrust type of mechanism.

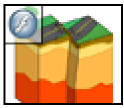


Normal Fault Flash Animation



Thrust Fault Flash Animation

- **Strike-slip faults** are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.



Strike-slip Fault Flash Animation

- A transform fault is a special variety of strike-slip fault that accommodates relative horizontal slip between oceanic crustal plates. They often extend from divergent plate boundaries at ocean ridges. Where no longer active, they are referred to as **healed transform faults**.

Measuring and locating earthquakes

Some of this section is adapted from the USGS *Glossary of Earthquake* terms; see http://earthquake.usgs.gov/learn/glossary/

Earthquake locations

Earthquakes cause slip of an area of the fault plane at depth. The size of this **rupture area** is proportional to the **magnitude** of the earthquake; the larger the rupture area the larger the earthquake magnitude. The earthquake's **hypocenter** is its position in three dimensions beneath the earth. The earthquake's **epicenter** is the two dimensional projection of the hypocenter on the surface of the Earth.

Earthquake magnitude

The magnitude of an earthquake is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used scale for large earthquakes is the moment magnitude (Mw) scale. Like the other scales, the moment magnitude scale is logarithmic. That is, each numeric increase in the scale (from say to a Mw 8.0 to Mw 9.0) represents a ten-fold increase in ground shaking. The energy released increases by a factor of about 33 times.

Ground shaking intensity

Buildings are not designed to withstand an earthquake of a particular magnitude, but a particular level of ground shaking. Whereas earthquake magnitude is an intrinsic property of the earthquake, the level of ground shaking, or intensity, that is felt at any particular location is a function of a number of factors. These include the distance of the location from the earthquakes epicenter, the depth of the earthquake, and characteristics of the location (such as whether it is underlain by dense bedrock, soft sediments, or artificial fill). The intensity felt usually is measured on the **Modified Mercalli Intensity** scale, and is given as a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several other scales exist. There are many intensities for an earthquake, depending on where you are, unlike the magnitude, which is one number for each earthquake.

Ground accelaration

A more quantitative way to describe ground shaking intensity is to measure it by a strong motion accelerometer, a special type of seismograph. Ground motion is expressed as a comparison to the force of gravity – that is, the acceleration (the rate of change in speed) of the ground relative to the acceleration caused by gravity. For instance, ground shaking of 1.0 g is equal to the acceleration caused by gravity, shaking of 0.5 g is equal to half the acceleration of gravity, etc. This is also known as **peak ground acceleration**; the maximum amount of ground acceleration regardless of the characteristics of the seismic waves involved.

Spectral accelaration

In reality, ground shaking is caused by seismic waves emanating from the earthquake's hypocenter, and modified during the travel to any particular site. These waves have a variety of wavelengths, periods, and velocities. Buildings and other structures interact with these various waves in different ways. For example, waves with a frequency of 3 to 8.5 hertz (cycles per second) are of particular interest to nuclear power plants since the critical components of the plants resonate at those frequencies. The level of ground acceleration at any particular seismic frequency is known as its spectral acceleration. A curve describing the acceleration at all frequencies is used to describe the total ground shaking environment at a site.