EARTHQUAKES SEISMIC HAZARDS

The 6th in the Series of Continuing Education Courses
at the University of California Extension, Riverside

sponsored by
the Inland Geological Society &
the Association of Environmental and Engineering Geologists (Inland Chapter)

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SUMMARIES OF TOPICS (*Draft, advanced copies*)

1. **Evaluation of Earthquake Probabilities in Southern California**

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Beginning in 1988 working groups, made up of geologists, seismologists and geophysicists from the Federal government, State of California, academia, and industry have periodically issued consensus reports that evaluate the probabilities of earthquakes in California. The working group reports have been reviewed and formally accepted by both the State of California and the Federal Government. These reports have served as a foundation for earthquake preparedness and response planning, stimulated widespread building retrofit activities, provided a starting point for evaluation of earthquake hazards (including the California component of the National Seismic Hazards Map), and are now used for setting earthquake insurance rates by the California Earthquake Authority (CEA). In recent years the working group approach for establishing estimates of earthquake probabilities has been adopted for evaluations elsewhere in the US and internationally. The most recent working group reports were released in 1995 for southern California and 2002 for northern California. The 1995 working group estimated an 80-90% probability for the occurrence of a $M \geq 7$ earthquake in southern California for the 30-year period beginning in 1994. The probabilistic evaluations focus on long–term probabilities (generally 5-50 years), and are made by combining geologic, seismic and geodetic information to estimate the occurrence of damaging earthquakes. Because our understanding of, and information about, fault zones is highly variable, a variety of approaches and methods are used to estimate probabilities. Type A faults have information on fault slip rates, slip history, and timing of prior earthquakes. Type B faults are less well known and generally there is little or no information on the times of prior earthquakes. Type C zones are least known and may contain hidden faults. This class will review the methods used to evaluate earthquake probabilities and the principal results of the Working Group studies. Currently a working group convened under the auspices of the USGS, CDMG, Southern California Earthquake Center, and the California Earthquake Authority is preparing a comprehensive statewide re-evaluation of earthquake probabilities. The report is scheduled for release in late 2007.

References

Working Group on California Earthquake Probabilities, 1995, Seismic Hazards in Southern California: Probable Earthquakes, 1994 to 2024, Bull. Seismol. Soc. Am., 88, No. 2, 279–439.

Working Group on California Earthquake Probabilities, 2003, Earthquake Probabilities in the San Francisco Bay Region: 2002 – 2031, U S Geological Survey Open–File Report 03-214, 235p.

2. What Have We Learned Recently about Faults?

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In the simplest sense, a fault is where two pieces of rock slide past each other; however, this is no longer the picture that most geologists and geophysicists have of a natural fault in the Earth's crust. Seismic, geologic and geodetic data have shown that fault slip zones are surrounded by a wide damage zone with a width of several hundred meters up to a few kilometers.

Recent geologic, geodetic, and geophysical studies have made quantitative measurements of near-fault material properties. Recent geologic studies indicate in detail the extent of cracking and damage away from a fault and see several distinct zones in cross-section across a fault (e.g. Chester et al., 2003). Slip during an earthquake happens on a millimeter to centimeter scale zone surrounded by a slightly wider zone of gouge. Gouge is crushed and ground-up rock produced by the high strains close to the fault slip surface. Both the slip zone and gouge zone have been well documented for many years. However, what has come to light more recently is wider zone of cracked rocks with a gradient in damage away from a fault.

Geophysical data confirm the existence of a 100 m – 1 km zone of damaged material far from the main slip surface that extends to depths of at least 5 km. Seismology provides a way to image the region around the fault at various depths. Using both direct travel time measurements and a phenomenon known as fault zone trapped waves we can image the fault at depth. Fault zone trapped waves are waves trapped within the lower velocity zone close to a fault. By studying the properties of these trapped waves such as frequency content and velocity, we can model the damage zone of a fault. These studies typically highlight a damage zone that is 100 m – 500 m in width (e.g. Li et al., 2006). Within this zone, velocities are reduced by 20-40% when compared to the surrounding intact rock. In addition, attenuation (energy lost due to friction heating) is also very high within the fault zone confirming the high incidence of cracks near the fault.

The most recent evidence of a wide damage zone comes from geodetic studies using satellite images that highlight ground motion. InSAR (Interferometric Synthetic Aperture Radar) differences the phase component of two radar images resulting in a map of ground motion in amazing detail. In favorable conditions, InSAR is sensitive to ground motions as small as a few millimeters. InSAR studies have shown that faults close to a large earthquake, but not broken during the mainshock, are strained or show motion on them sympathetic to the static stress field imposed by the mainshock (e.g. Fialko et al., 2002). In other words, faults are more compliant (weaker) than the surrounding crust, so they tend to localize strain. This effect can be understood by imaging a layer of sand between two bricks; if you squeeze the bricks together most of the displacement will take place in the weaker, more compliant sand layer.

These fault damage zones influence the way a fault behaves before, during and after a large earthquake. In the presence of a wide damage zone, faults behave much more weakly than the surrounding intact crust. Thus, faults are more responsive to small forces such as moderately sized regional earthquakes, tidal forces, and human-induced forces from mining excavations and water damming.

3. Paleoseismology and Fault Activity

Case Studies on the San Andreas and San Jacinto Faults

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Earthquake hazard probability models utilize geologic data obtained from fault systems. This data includes paleoseismicity, time since most recent rupture, slip rates, and fault segmentation. From a single paleoseismic site, the data that can be determined includes time of most recent earthquake (MRE), and, if multiple paleo-earthquakes are preserved, the average rate of recurrence can be ascertained. Often the slip amount for the earthquake at that location can be measured. If this slip-per-event data is present, then the probability that rupture will extend for some continued distance can be calculated. For multiple paleoseismic sites along a fault system, we can measure the length of ground motion for the paleo-earthquake, estimate a moment magnitude for the earthquake and begin to evaluate the fault for segmentation and characteristic earthquakes. Rupture source and directivity might be inferred from the data at the various locations. Paleoseismic sites on different strands of a fault system, or within a region can provide insight on fault interactions, temporal evolution and regional accommodation of plate motion. Slip rate data, when available for different time intervals and fault systems can also provide constraints on plate motion distribution across a region. Slip rate determinations have improved over the past decades, as Quaternary dating techniques are developed and refined.

Recent studies suggest a changing view of the interactions between the San Andreas and San Jacinto fault zones and the Eastern California Shear Zone. Paleoseismic sites along the San Andreas, including Pallett Creek, Wrightwood, Tousand Palms, Coachella and Salt Creek suggest a short but variable recurrence interval. Recently developed paleoseismic sites along the northern San Jacinto fault, in San Bernardino and Colton, match an average recurrence interval documented in the central San Jacinto fault, near Anza. Slip rate studies along the San Bernardino and Coachella segments of the San Andreas fault suggest a lower slip rate than determined at Cajon Creek. These sites include Plunge Creek, Burro Flats, and Biskra Palms. Slip rate studies along the San Jacinto fault suggest that the fault is accommodating a significant proportion of the plate motion, and differs from the slip rate that is commonly attributed to this fault.

4. Coseismic Ground Failure

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Earthquakes produce a large variety of abundant and widespread types of ground failure including landslides, liquefaction, and intense ground fracturing. Although primary fault ground-displacement (fault rupture) can continue for hours, ground failures are essentially instantaneous coseismic phenomena. Ground failure is a significant earthquake hazard and can result in considerable loss of life and property. Most of the more than 400,000 lives lost in the 1920 Jiangsu and 1927 Kansu, China, earthquakes resulted from ground failure. In southern California, coseismic landsliding is the most common type of ground failure. Even a moderate earthquake can generate coseismic landslides by the thousands over considerable distance from the epicenter (e.g., the San Fernando M=6.5 and North Palm Springs M=5.9 produced thousands of landslides over hundreds of km^2). Earthquake-generated landslide types documented in southern California include topples, falls, slides, lateral spreads, and flows. Many of the geologic units susceptible to landsliding during periods of heavy rainfall are likewise susceptible to landsliding during earthquakes. Some basement rock units, such as the Pelona Schist (e.g., Lone Pine Canyon, eastern San Gabriel Mountains) include pervasive landslides adjacent to the San Andreas Fault that are undoubtedly coseismic in origin. Other earth materials generally not susceptible to landsliding can generate landslides during earthquakes. In the Peninsular Ranges batholith, granitic rocks generally not susceptible to landsliding fail in close proximity of the San Jacinto and Elsinore Faults suggesting that most, if not all, are coseismic in origin.

Scarps and terrace risers in Quaternary alluvial deposits are susceptible to small-scale landsliding that is marked by extensional graben-like features at the crest of the scarp or riser, and thrust-like toes at the base of the slope. Such features associated with fault scarps have erroneously been interpreted as primary fault rupture. During periods of very high vertical ground acceleration, the rheologic properties of unconsolidated materials can radically change. Some earth materials lacking tensile strength can fail as coherent materials during high ground acceleration. Seemingly defying physical laws, steep lee faces of sand dune deposits can fail as non-deforming slab-like landslides (e.g., Superstition Mountains Earthquake).

Liquefaction is another widespread type of coseismic ground failure. Paleoliquifaction features abound in many areas of southern California. Some areas that have experienced historic liquefaction now have reduced potential for future liquefaction due to lowering of groundwater. However many areas including the Imperial Valley (e.g., Imperial Valley Earthquake) and coastal areas have sufficiently high water tables to be susceptible to future liquefaction (e.g. Point Mugu Earthquake). In some inland areas with very fine-grained alluvium, such as those associated with vertisols, small-scale liquefaction structures are numerous and pervasive (e.g., Lakeview area).

Topographic ‘focusing’ of energy (topographic amplification of seismic waves) likewise produces widespread ground failure generally in the form of shattered ridge tops (e.g., 1971 San Fernando Earthquake). Down-slope movements of the lower parts of shattered ridges can take the form of small ‘thrust faults’ (e.g., North Palm Springs Earthquake). In basement, rocks repeated ‘focusing’ produces extensive ridge-top trenches (e.g., San Gabriel Mountains).

Intense localized fracturing can occur along subsidence ground fissures that are common in many of the closed basins in southern California (Landers Earthquake). Some extremely large liquefaction-like structures may originate as a combination of ground fissuring and liquefaction with liquefied material utilizing a pre-existing ground fissure (e.g., Bernasconi Hot Springs area).

Extensive fractures, commonly with conflicting sense of slip, occur adjacent to primary fault offset and are a result of earth material responding to the primary fault displacement. These strain ‘adjustments’ are more extensive in the close proximity to the primary fault offset but can occur over a considerable distance (e.g., Landers Earthquake).

Intense ground fracturing can occur along the surface trace of a fault in response to static shear strain by faulting at depth. This fracturing can be erroneously interpreted as primary fault ground rupture (e.g., North Palm Springs Earthquake). In these instances detailed measurements of slip on the numerous fractures sum to zero.

Restricted occurrences of ‘thrown stones’ (e.g., Galway Lake and Hector Mine

Earthquakes) and lack of Jim Brunes' 'precariously balanced stones' are examples of coseismic individual rock displacement.

5. Practical Considerations in Performing Fault Rupture Studies

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The California Alquist-Priolo Earthquake Fault Zoning Act has been in existence since 1973 and is the driving force for most fault surface rupture studies. Numerous technical and regulatory changes during this 35-year period have increased the quality of information obtained from trenching studies, but also have complicated the logistics in performing the studies. As a practical look into these issues, this presentation will discuss **some, but not all**, regulatory, data collection, and reporting issues that should be considered prior to, during, and after trenching operations.

Regulatory issues affect all trenching studies. Trenching is a relatively intrusive type of field activity that has been historically shielded under "exploration clauses", but new developments pose additional regulatory hurdles. Trenching activities have long been regulated by CAL-OSHA safety regulations, but in recent years we have observed an increase in the enforcement of these regulations. This last year Riverside County implemented Ordinance 457. "457" regulates the amount of excavation that can be performed before a grading permit must be obtained; the threshold is low and thus, affects most trenching studies. One difficulty is the time frame; many studies are driven by a potential buyer's due diligence during a 30-day escrow period. For practical purposes, it is impossible to satisfy the 457 requirements during a 30-day period. This is having a major effect on the ways these studies are presently being performed. Other examples of regulatory effects are: areas in San Diego County where special use-permits must be obtained before any equipment is brought into the area; regulations involving the Storm Water Pollution Prevention Plan (SWPPP); Department of Fish & Game regulations regarding "blue-line streams''; biology concerns like gnatcatcher and raptor nesting seasons, Delhi Sands flower-loving fly, San Bernardino and Stephen's kangaroo rats, Bell's Least Vireo, as well as numerous types of plants; paleontological and archeological restrictions; and air quality regulations.

As an in-house reviewer of other consultants' trenching studies, I look for an adequate level of data collection and documentation of features observed within trenches. The burden of proof is on the consultant to interpret the geology; an interpretation without substantiating data will not survive the review process. One basic procedure is to review the trench log to ensure that all major and critical aspects of the stratigraphy and fault features were documented. Far too often, pedogenic soils, one of the most important age indicators, are poorly documented or omitted from the logs and subsequent discussion in the report.

The proper scale of trench logging should be determined by the site geology; one inch = five feet is a common scale, but more detail, on the order of one inch = two feet, may be required where complexities exist. Complexities include features that are of questionable tectonic origin such as fractures, primary or secondary depositional features, and Krotovina. In the area of questionable or controversial features, logs should be completed for both trench walls and the trench floor.

In addition to locally increasing the logging scale, photo-documentation of critical features should be routine. The ease and low expense of digital photography make the use of photography now a common geologic tool. How much photography is required? Proposed City of San Diego guidelines specify photo-documentation of the entire trench exposure. From a technical basis, I want to see enough photography to support the author's interpretation of the geology. For example, depending on the geology within the trench, it may not be necessary to photograph the entire exposure. In some cases, it may be useful to log trench walls on a photo-mosaic background or even to create stereo-photography anaglyphs of the walls to document detail.

A critical component of any investigation should be to have the reviewer inspect the site before the trenches are backfilled. This usually necessitates two days to a week notice to the reviewer. During the inspection, be open, show all trench exposures, and do not shy away from controversy. Having the reviewer inspect the draft field log while standing in front of the trench exposure will minimize surprises and claims of "I did not see that in the trench" during the later report review process.

The report is your legacy. Write a poor one and you will be remembered for it. Spend time on graphics, they will be remembered, copied, and reviewed long after the text is archived. One frustrating aspect of reviewing another consultant's report is when one realizes that the written text bears little resemblance to the site you visited. The report should adequately place the site into the regional and local geologic and geomorphic setting. Trench observations should be related to fault features and all of this synthesized into an interpretation that relates back to the local geologic setting. Back up all interpretations with data, not just an opinion. Finally get someone to critically review your report, before it is submitted to a governmental body – "yes-men" need not apply.

6. Fault Rupture Hazard Mitigation in California under the Alquist-Priolo Act

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I. How and why the A-P act came into existence

As a result of extensive surface rupture in urbanized areas during the 1971 M6.7 San Fernando Earthquake, the California legislature determined that, to protect life and property, residential structures should not be built across the surface traces of active faults. The Alquist-Priolo Earthquake Fault Zoning Act, originally passed in 1972, addresses this issue through regulations, policies and a division of responsibilities.

II. How the A-P act is implemented

The State Mining and Geology Board is charged with establishing policy to effect the Act, including creating necessary definitions and procedural guidelines. Construction of certain human-occupancy structures is prohibited across the trace of an active fault.

The State Geologist, as chief of the California Geological Survey, is charged with identifying those faults in the state that present a definable surface rupture hazard (meeting the joint criteria of "sufficiently active" and "well defined") and with issuing maps that identify these faults within "Earthquake Fault Zones" which require fault studies prior to development.

The local permitting agency has the responsibility of regulating and approving development within the Earthquake Fault Zones so that designated projects are not developed across active faults. This is primarily accomplished by requiring studies to accurately locate the faults prior to development within the Earthquake Fault Zone and reviewing those reports for adequacy.

The landowner or developer is responsible for providing the fault study by a registered Professional Geologist to support his/her development plan within the constraints of State and local guidelines. When selling a property within an EFZ, the owner must disclose to the buyer that the property is within this regulatory zone.

III. The geologic analysis and decisions that go into zoning

The zoning process begins with considering all potentially active (Quaternary) faults in California and then focusing on those that may have had Holocene surface rupture. The formal evaluation of a specific fault or fault zone starts with a review of the published and unpublished literature, including consulting reports that may address the location and activity of the fault. Pre-development aerial photos are studied to look for geomorphic and other surface evidence of faulting. Field reconnaissance and local detailed mapping usually follow to corroborate the evidence. All of this data is compiled and analyzed in a Fault Evaluation Report to judge how well the fault meets the established criteria for inclusion in an Alquist-Priolo Earthquake Fault Zone. These criteria require that a fault have evidence of Holocene surface rupture (be "sufficiently active") and that it be locatable at or near the ground surface by a trained geologist (be "well-defined").

After this analytic process, a Preliminary Review Map of Earthquake Fault Zones is prepared to delineate a zone of mandatory fault investigation (the Earthquake Fault Zone) around the identified fault traces. The preliminary review maps go through a public review period following which official maps are distributed to all concerned public agencies. Since the Act was passed, there have been 547 Official Earthquake Fault Zone maps issued. The California Geological Survey continues to add and revise zones as new information becomes available.

IV. Responsibilities of the geologist

The geologist for the developer has the responsibility to locate the active fault traces, assess the hazard to the proposed development from ground rupture and make recommendations for setbacks.

The reviewing geologist has the responsibility to ensure that fault studies are adequate and that setback recommendations are appropriate.

V. Resources

http://www.conservation.ca.gov/cgs/rghm/ap/index.htm

This web page, for the California Geological Survey, Alquist-Priolo Earthquake Fault Zoning program includes many useful references and resources. Of particular value are:

- Special Publication 42 (SP42) - presents the history and implementation of the Alquist-Priolo Act and includes the regulations, policy and guidelines for fault studies and their review.
- Alquist-Priolo Earthquake Fault Zone Maps - available in printed form or on CD. CD publications include raster images and GIS files. Ordering instructions are on the web page.
- Fault Evaluation Reports - these reports document the data that was available and used in making the zoning decisions for the active and potentially active faults since the program was initiated.
- Fault Investigation Reports, prepared by consultants in support of development proposals, are put on file with the State and have been compiled for reference on a set of CDs.