Earthquake Hazard Studies in Northern California—Probabilities to Prediction.

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Summary

USGS earthquake hazard research in northern California is focused on defining the likelihood of future earthquakes ("probabilities") and anticipating and defining the effects and consequences of those earthquakes ("prediction" of likely shaking, landslide, and liquefaction hazards). New hazard products are being developed and fundamental research is being carried out. Regarding products, a recent comprehensive analysis lead by the USGS concluded that the greater San Francisco Bay region has a 62% likelihood of a major, damaging earthquake (M6.7 or greater) over the next 30 years. A series of prototype urban hazard maps (including deterministic shaking, earthquake-triggered landslide, and liquefaction hazard, as well as non-seismic landslide susceptibility, and liquefaction potential index) have recently been completed for the city of Oakland, a city with complex distribution of young, poorly consolidated sediments and which sits astride one of the most hazardous faults in the region, the Hayward fault. Current efforts are focused on producing two major products for the 100th anniversary of the 1906 San Francisco earthquake: 1) a 3-d structural representation and slip characterization of the Quaternary faults throughout the greater San Francisco Bay region and 2) simulation of 1906 ground motions utilizing a new 3-d velocity model that will be geologic-based and include faults and fault blocks.

1. Introduction

The USGS Earthquake Hazards Program, as a part of the U. S. National Earthquake Hazards Reduction Program (NEHRP), has the broad objectives to improve earthquake hazard identification, maintain comprehensive earthquake monitoring, and improve the understanding of earthquake occurrence and their effects and consequences. These objectives are carried out through a number of regional and topical programs. The USGS currently invests about $7.5M/year on earthquake monitoring and hazards research and products for northern California. Approximately 25% of this total supports university and private researchers funded through a highly competitive external grants program.

Earthquake hazard research in northern California has been focused on defining the likelihood of future earthquakes ("probabilities") and defining the effects and consequences of anticipated earthquakes ("prediction" of likely shaking, landslide, and liquefaction hazards). New hazard products are being developed and fundamental research on first-order hazard research topics is being carried out.

2. Focus of Northern California Hazard Studies

A recent comprehensive analysis lead by the USGS concluded that the greater San Francisco Bay region has a 62% likelihood of a major, damaging earthquake over the next 30 years (Figure 1) (Working Group on Northern California Earthquake Probabilities, 2003). Exposure in the greater Bay Region to this high level of hazard translates to a predicted $1B/year annualized loss due to earthquakes, roughly 25% of the estimated annualized earthquake losses for the entire United States (FEMA, 2000).

Northern California provides an unprecedented opportunity for major advances in the USGS' NEHRP research, monitoring, and assessment efforts for several reasons:

- It is the most densely-sampled (geologically & geophysically) active seismic region in the U.S.
- Our investment is leveraged by major complementary and contributory efforts by other USGS programs—particularly the Geologic Mapping and Coastal and Marine Programs.
- Strong working relationships with the broad user community in northern CA—including transportation, utilities and water, emergency response, and earthquake insurance sectors as well as state agencies, local governments, and other federal agencies.
- Northern and central California will be the focus of the initial deployment of the new NSF-funded EarthScope initiative, a major research equipment
program in earth sciences. EarthScope will provide high-density, state-of-the-art seismic, geodetic, and borehole strainmeter data and downhole observatory on the San Andreas

- The upcoming centennial anniversary of the 1906 earthquake will focus the region’s and the nation’s attention on earthquake science and hazard and risk reduction products

- Role of creeping faults—Northern California has the largest number and distribution of faults with aseismic slip, their influence on the strain release budget is being examined

- Soil non-linearity—the dense sampling of the shallow subsurface structure combined with dense seismic monitoring provides an ideal opportunity to obtain the necessary data to test theoretical models of the non-linearity of soils

- Strain partitioning—though the Bay region is dominated by strike-slip fault systems, it appears that roughly one tenth of the total deformation rate is accommodated on a number of subparallel compressional faults whose slow rates of deformation (relative to strike-slip faults) provide a challenge to assess their hazard

- Precursory phenomena—the combination of dense surface networks of earthquake monitoring systems, borehole instrumentation, and the planned deployment of EarthScope monitoring systems will allow us to continue to search for temporal changes that might indicate imminent future activity

The Working Group earthquake probability study published in 2003 synthesized a wealth of new data and information for the greater Bay Region. The Working Group devoted considerable effort to defining and quantifying uncertainties in all data, models, and parameters used in their analysis. Their sensitivity analysis indicated a number of unresolved issues strongly impacting the probability uncertainties, including:

- effect of stress shadows and the importance of fault interaction
- creep behavior at depth and its relationship to earthquakes
- coefficient of variation for earthquake recurrence
- “strength” and persistence of segment boundaries

These major sources of uncertainties are guiding research priorities in northern California. In addition, significant research continues on developing the capabilities and methodologies to quantitatively predict earthquake effects.

Much of the research summarized below comes from abstracts included in a report on a workshop on Northern California earthquake hazards held in January, 2004 (Zoback, 2004). In order to preserve credit to the individual researchers, the reference to abstracts included in this workshop report are given in italics

Figure 1. Likelihood of a magnitude 6.7 or greater earthquake in the next 30 years for the major fault systems in the greater San Francisco Bay region. These statistics provide a compelling rationale to focus additional research and develop new earthquake hazard products for Northern California.

These factors combined with the tectonic setting of northern California makes the region an ideal natural laboratory to address major NEHRP science questions:

- Fault communication and stress shadows--The close spacing and subparallel nature of the major active faults make this an ideal test bed
- Coefficient of variation/recurrence interval—A concerted multi-year effort to develop thousand plus year records of past earthquakes on the major faults is yielding valuable data on their long-term behavior
3. Earthquake Source Characterization

The Bay Area Paleoseismology Experiment (BAPEX) was initiated in 1998 with the goal of developing a 2000+year chronology of large earthquakes on the major strike-slip faults of the region, see project web page for details: http://quake.usgs.gov/research/paleoseismology/bapex. (Schwartz et al., 2004). To date BAPEX has yielded significant new data on the spatial-temporal pattern of past seismic activity relevant to the coefficient of variation of the recurrence interval, timing of stress shadows and fault interactions, as well as the long-term behavior of creeping faults. A major observation from the BAPEX results is that during a maximum interval of 176 years (from 1600 to 1776 AD at 2-sigma) significant seismic moment was released in the greater San Francisco Bay region by large surface faulting events (M>=6.7) on nearly all the major faults. This suggests that at the beginning of the historical period (~1776 AD) the region had released most of its strain and there was a roughly 60 year period of quiescence before the 1838 M~7 earthquake thought to have occurred on the Peninsula segment of the San Andreas. This earthquake heralded the beginning of a new, extended period of high-level seismicity throughout the region (a magnitude 6 or greater earthquake approximately every four years) that culminated in the 1906 M=7.8 great San Francisco earthquake.

Long paleoearthquake chronologies have been obtained for the southern Hayward fault where the data indicate a mean recurrence interval of 195 ± 15yr over the past 2000 years (Lienkaemper et al., 2002, Lienkaemper et al., 2004; Williams and Lienkaemper, 2004) and for the San Andreas north of San Francisco where a 2500 year record suggests recurrence intervals ranging from 130 to 300 years (Niemi et al., 2004).

An even longer earthquake chronology (6000-10,000 years) is being developed for the San Andreas Fault in northern California by correlation of turbidite chronology across submarine channels on the adjacent continental shelf (Goldfinger et al, 2004). Detailed core analysis and dating have just begun and preliminary results suggest 35 earthquakes in the last 6200 years, roughly a third of which seem to rupture the entire 1906 segment.

A major goal for northern California earthquake hazard studies moving forward will be to create a community Quaternary fault map database for northern California that will synthesize the most recent geologic mapping, (1:24,000 when available), paleo-seismological information, and geophysical data on 3-D fault geometry (Graymer, 2004). The initial product, to be released in April 2006-coinciding with the 1906 centennial, will focus on the greater San Francisco Bay region, including Santa Cruz and Monterey Counties.

4. Deformation modeling

The stress shadow of the 1906 earthquake and uncertainty about its effects at present and into the future is perhaps the biggest issue impacting the accuracy of time-dependent probability in the Bay region. Recent viscoelastic modeling of the stress interaction of all magnitude 5.8 and larger earthquakes since 1838 suggests that the region has emerged from the 1906 “shadow” about 1980, consistent with the acceleration in regional seismicity at that time (Pollitz, 2004). A similar conclusion about the timing of emergence from the Bay Area stress shadow was obtained using a somewhat different finite element simulation of post 1906 stress recovery (Parsons, 2004).

Borehole strain monitoring in northern California will be greatly intensified as a result of the new Plate Boundary Observatory (PBO), part of the NSF-funded initiative, Earthscope (www.earthscope.org). PBO plans to install 1000 continuous GPS stations and 200 borehole strainmeter sites along the western plate margin with the initial deployment focused in central and northern California. In order to take full advantage of this new array for USGS earthquake hazard program goals, we must enhance and better document their automated data processing, more completely compile all the existing strain data (collected both internally and externally), and develop a state of readiness with respect to interpreting borehole strain, creep, and fluid pressure, as well as a plan for real-time interpretation of such data (Roeloffs, 2004).

4. Subsurface structure, basin effects, and 3-D velocity model

A wealth of data from urban seismic arrays and several decades of active seismic experiments throughout the Northern California region are being integrated with gravity and magnetic data to define basin structure, delineate young faulting, build and test models of basin amplification, and define velocity structure.
These data complement numerous site response studies, cone-penetrometer testing in the near surface and the recent correlation and consistent mapping of Quaternary deposits and liquefaction susceptibility for the greater Bay Area. A major effort in Northern California over the next two years will be to synthesize all these data with existing geologic mapping to produce an updated 3-D geologic “map/model” and a new and expanded geologic-based 3-D velocity model for the region, which will include faults and fault blocks (Jachens, 2004; Mooney et al., 2004).

5. Hazard mapping and earthquake effects

A major thrust in urban seismic hazard mapping was carried out in the city of Oakland, CA, a city with complex distribution of young, poorly consolidated sediments and which sits astride one of the most hazardous faults in the region, the Hayward fault. The USGS collaborated with the Oakland Office of Emergency Services, the California Geological Survey, and EQE International to develop prototype urban hazard assessments from earthquake ground shaking, liquefaction, and landslides.

The hazard mapping effort began with an intense period of data collection. Digital versions of the geologic maps were rapidly compiled at a scale of 1:24,000 for the entire city (a total of nine 7.5 minute quadrangles) (Graymer et al., 1996). The digital map data were incorporated into all aspects of the hazard calculations that required a geologic base.

Eleven prototype, wireless MEMS accelerographs (TREMOR sensors) were deployed throughout the city (mainly in fire stations), making Oakland the most densely instrumented city in the U.S (Evans et al., 2004). The TREMOR sensors send peak accelerations, peak velocities, and response spectral amplitudes at three periods in a data packet that arrives within 90 seconds of trigger time. They have successfully recorded a number of small to moderate size events (M3.4-4.7).

To determine the strength and shear velocity of the near surface sediments more than 210 sites were sampled in Oakland and the neighboring island of Alameda using a Cone Penetrometer Truck (CPT). The CPT measures tip resistance, sleeve resistance and shear wave velocity as the penetrometer is pushed vertically through shallow sediments (<= 30m). The CPT data were used to construct a 3D geologic map of near surface sedimentary units and assign physical properties to these units (Holzer et al., 2002).

Several prototype hazard maps were prepared for Oakland using the available data. Maps of shaking, liquefaction, and seismic landslide hazard were produced for a scenario M7.1 rupture of the entire Hayward fault. In addition, a geologic (non-seismic trigger) landslide susceptibility map as well as a map of liquefaction potential index was developed.

The seismic landslide hazard map was developed by Miles and Keefer (2001) using Newmark analysis that treats a potential landslide as a rigid block resting on an inclined plane. The model requires inputs characterizing the susceptibility to slope failure and intensity of earthquake ground motion. Susceptibility to slope failure was characterized by treating each 10-meter pixel within the map as an infinitely long slope and estimating the earthquake ground motion required to displace the slope. Slope inclination was determined using a DEM. Completely saturated ground water conditions were assumed. Regional geotechnical properties were assigned based on the geologic units of the 1:24000 digital geologic coverage and shear-strength testing. Equivalent sliding-block displacements were calculated for each 10-m pixel, and from these, levels of relative hazard for the M7.1 scenario event were rated as: Low, Moderately Low, Moderate, Moderately High, High, or Very High. Pike et al. (2001) produced a map of landslide susceptibility that was based on mapped landslide deposits, geology, and slopes.

The CPT strength results and the 3D geologic map of near-surface sedimentary units developed from the dense sampling led to the development of the first quantitative mapping of liquefaction hazard that maps the probability of liquefaction (liquefaction potential index) (Holzer et al., 2002). The Oakland liquefaction hazard map estimates the percent of area underlain by specific geologic units that will exhibit surface manifestations of liquefaction, i.e., sand boils, ground cracking, and lateral spreading during a M7.1 Hayward fault scenario event. Because the CPT tests also measured the shear wave velocity generally in the upper 30 m, a shaking amplification map was also developed (Holzer et al., 2002).

The detailed 3D map of near-surface sediments was a critical element utilized in developing the shaking hazard map for a scenario M7.1 Hayward fault event. Hand et al. (2004) used a Monte Carlo stimulation of ground motion in a variable 1D velocity structure to produce the shaking hazard map. The velocity structure had three components: a set of
poorly determined Pleistocene and Tertiary sedimentary layers, and a Franciscan basement. They used an equivalent linear approximation of non-linear soil behavior. Their results suggested that despite the extensive mapping and consequent resolution of the near-surface S-wave velocity and thickness performed by Holzer et al. (2002), the prediction of ground motion was most sensitive to the shear wave velocity of the top 30 m (V_{s30}).

References

Note: There are a number of references in the text that are italicized with the year 2004. As noted in the text, these refer to abstracts included in the Northern California Earthquake Hazard workshop report, and are included in the Zoback, 2004 reference below.


For CPT data access, and related articles see: http://quake.usgs.gov/prepare/cpt/alameda.html


