National and Regional Priorities For Allocation of Strong-Motion Instrumentation in Structures

Panel 2

Kent Ferre, Chair; Roger Borcherdt, Recorder;

John Aho, Walter Arabasz C.B. Crouse, Jon Heintz, Samaan G. Ladkany, Stuart Nishenko, Shahram Pezeshk, M. Saiid Saiidi, J. Carl Stepp, Alfredo Urzua, Mitch Withers

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SUMMARY

The collapse of buildings, bridges, and other man-made structures is the major cause of loss of human life and property during earthquakes. Reduction of life and property loss requires man-made structures that can resist earthquake-induced shaking levels likely to be experienced during the life of the structure. Quantitative knowledge of the effects of earthquake shaking on structures can be gained only from instrumental measurements of the dynamic response of the structures during the earthquake. The "Invited Workshop on Strong-Motion Instrumentation of Buildings" was convened by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) to help assess the needs and priorities for strong-motion instrumentation to acquire essential data on structural response. Needs and priorities for ground-motion instrumentation are considered elsewhere and beyond the scope of this report.

This report provides guidelines for assignment of national and regional priorities for structural instrumentation as developed by Panel 2 of the referenced workshop. National priorities are developed based on both annual population exposure to pga levels > 0.1g and on recent estimates of national annualized earthquake loss (AEL) as developed by FEMA using HAZUS (www.fema.gov/hazus/). The combined distribution of AEL and AEL normalized by the value of the building inventory (AELR), as an estimate of annualized seismic risk, provides an index, which is used to develop quantitative and objective guidelines for a national distribution for structure instrumentation as tabulated in Table 1 of this report. (Nishenko, this proceeding, provides a summary of the FEMA AEL study.)

A recent project entitled Advanced National Seismic System (ANSS) as proposed to Congress and partially but not completely funded indicates that approximately one-half of the resources are to be used for the instrumentation of structures. This number corresponds to 3000 3-channel accelerographs or 30 channels of instrumentation for 300 structures. This number of structures, assuming 30 channels of instrumentation in each, is used to develop a national allocation for structure instrumentation resources in the proposed and partially funded ANSS project. Guidelines for development of regional priorities are suggested based on regional estimates of earthquake loss as implied by HAZUS taking into account expected shaking levels, structure type, foundation conditions, vulnerability, and value of the structure inventory. Recommendations for specific regional guidelines as to structure type, location, etc. are provided in the report of Panel 1, these proceedings.

Panel 2 deliberations reconfirmed that the number of ANSS instruments for 300 structures with 30 channels each was more than 40 times less than previous estimates of US structural instrumentation needs as developed at a national engineering workshop (Vision 2005: An Action Plan for Strong Motion Programs to Mitigate Earthquake Losses in Urbanized Areas, 1997). This significant deficiency suggests that additional structure instrumentation resources need to be pursued for purposes of reducing the loss of life and property during future earthquakes through improved in-situ strong-motion monitoring programs. The panel concluded that state-of-the-art, in-situ measurement experiments for structures need to be coordinated between ANSS and the National Earthquake Engineering Simulation (NEES) instrumentation experiments.

INTRODUCTION

Quantitative knowledge of earthquake shaking and its effects on structures can be gained only from instrumental measurements of shaking both on the ground and in the structures affected during the earthquake. Presently, the number of strong-motion recordings in structures significantly damaged by earthquakes is very limited, with many critical questions concerning the dynamic response and failure characteristics in an in-situ environment unanswered. As a result, billions of dollars are presently being expended to build and retrofit various types of structures for which no in-situ recordings of damaging levels of shaking have ever been acquired. Although other information such as structural laboratory testing and general post earthquake response observation is available to guide design and retrofit, additional strong-motion recordings could be of significant value. To help rectify this situation, comprehensive sets of strong-motion measurements of structural response are needed from the next set of structures damaged by a major earthquake in the United States.

Strong-motion measurements of the earthquake response of buildings and other structures are needed to quantitatively evaluate causes of damage to provide data for calibrating mathematical models and verifying acceptance criteria in codes and design standards. Such evaluations are needed to improve design, construction, and retrofit procedures and to improve codes, so as to ensure public safety in subsequent earthquakes and operability of critical facilities. Without instrumentation in place in various types of structures to make such measurements, important opportunities to improve procedures are missed and costs to retrofit inadequate structures in an ever growing urbanized society increase dramatically. Future costs to society if adequate structure instrumentation is not in place during the next major earthquake will be significantly greater.

Consensus recommendations developed by an international workshop concerning strong-motion instrumentation indicated that as a minimal set, 7000 buildings, 3000 lifelines, and 3000 critical facilities such as hospitals and schools should be instrumented in the United States (Stepp, Ed., 1997). The number of structures currently well instrumented in the United States by the various programs is less than 200. A recent national program proposed to the US Congress as the Advanced National Seismic System is requesting resources corresponding to instrumentation for 3000 three-channel accelerographs to be placed on structures and 3000 three-channel accelerographs/seismographs be placed to measure ground motions in an urban environment. Considering that about 30 channels of information are needed on the average for each structure, the ANSS request corresponds to instrumentation for about 300-30 channel structures. This number is 43 times less than that derived by consensus of an international workshop reviewing 2005 instrumentation needs for the United States. Nevertheless, if the ANSS request is completely funded to instrument 300 structures with 30 channels each, it would be an important step forward. This report provides guidelines for national and regional priorities to allocate the structure instrumentation requested in the ANSS proposal. The methodologies presented provide guidelines that identify those areas with the highest seismic risk. They can be used to direct national resources appropriated from a variety of sources.

GUIDELINES FOR NATIONAL PRIORITIES

Strong-motion measurements of the in-situ, dynamic response of structures that experience failure during earthquakes are limited to a few tens of structures, yet millions of structures could experience earthquake damage during their lifetimes. Considering the important need for these measurements and the rapid rate at which earthquake risk to society is increasing due to increases in urbanization, national priorities must be based on selection of structures and building types with the highest priority of experiencing damaging levels of motion. Such priorities must necessarily be based on a national assessment of the seismic hazard or the likelihood for strong shaking, a national structure inventory, and an assessment of the vulnerability of the inventory.

METHOD I – POPULATION EXPOSURE

Towards developing an estimate of the amount of instrumentation required to ensure that adequate sets of measurements are acquired in densely urbanized areas of the United States for purposes of *Hazard Mitigation*, Borcherdt et al., 1997, developed national estimates based on the exposure of the population to ground acceleration levels exceeding 0.1g as defined by the national seismic hazard maps (Frankel, et al., 1996). Assuming that the geographic distribution of population is an approximation for the geographic distribution of the built environment, this methodology was used to develop estimates of the number of instruments needed to ensure that the next major damaging earthquake is appropriately recorded. This methodology was applied with adjustments applied based on regional network weighting factors for purposes of justifying the ANSS.

The national geographic distribution of population exposure as an approximation for the distribution of the built environment also provides a basis for specifying the geographic distribution of the approximate 300-30 channel structures that are specified in the ANSS document. Specifying the number of structures per cells of size 100 square kilometers as directly proportional to the percent of the total population exposed annually to peak acceleration > 0.1g yields a geographic distribution for 300-30 channel structures as shown in Figure 1. This distribution is tabulated by state and ANSS region in Table 1. Distribution of structures for instrumentation as implied by the percent of population exposure is tabulated. (This distribution is based on population exposure as derived from the 1990 census. Results are not expected to change significantly using recent census data.)

Without further adjustments the distribution implies that the highest priority regions for well-instrumented structures are located in California, with urban areas in Washington and Oregon, Utah, central US and New York and neighboring states requiring less but nevertheless important minimal numbers of instrumented structures.

METHOD II – ANNUALIZED EARTHQUAKE LOSS

FEMA (2001) developed an estimate of annualized earthquake loss based on HAZUS (1999, SR-1), which is a methodology for the computation of earthquake loss using up-to-date assessments of seismic hazard, structural inventories, and structure vulnerabilities. Considering the importance of acquiring strong-motion measurements in various types of structures most likely to experience failure during strong shaking, the geographic distribution of earthquake loss provides a quantitative basis for establishing the geographic distribution needed for well-instrumented structures. This estimate being based on an estimate of the inventory of the built environment is considered more refined than that provided by population exposure.

The geographic distribution of annualized earthquake loss is shown aggregated by county in Figure 2 (FEMA (2001). The AEL is tabulated by state and ANSS region in Table 1. High values of AEL are indicative of areas with high seismic hazard and or high values of the building inventory. The geographic distribution of AEL shows that the highest AEL is expected in California due to its high seismic hazard and large exposure of building inventory. Other areas such as New York also show significant AEL, not because of high seismic hazard, but because of a large valuable building inventory.

To identify areas for which the building inventory, whatever its value, is exposed to a high seismic hazard, the FEMA study computed an annualized earthquake loss ratio (AELR) defined as the AEL normalized by the total replacement value of the exposed inventory. The AELR values as aggregated by state are tabulated in Table 1. They show that states with high seismic hazard levels such as Alaska and Hawaii rank much higher in the list, because of the high proportion of their building inventory that is exposed to the high seismic hazard levels in these states.

A desirable attribute of an index to be used to determine the distribution of the instrumentation is one that accounts for both the national distribution of AEL and the national distribution of AELR. A suggested index to estimate the number of structures per state is

$$No.\,Structures_{30\,channels} / state = Maximum\,[AEL\% / state, 0.50\ AELR\%](0.848)(300)\ , \quad (1)$$

where 0.848 represents the percentage to normalize the index so that the total number of structures is 300 based on 3000 3-channel accelerographs in structures, which is equivalent to 30 channels of acceleration recorded in 300 structures. The percentage of instrumentation to be allocated to each state is defined as the maximum of the percentages implied by AEL and 50 percent of that implied by AELR. The 50 percent applied to the AELR could be increased to place greater emphasis on those locations with high seismic hazard but not necessarily a large inventory. The number of structures implied by this index is tabulated in Table 1 and summarized for each ANSS region in Table 2. Application of this index provides an objective methodology for allocation of instrument resources. These results seem intuitively correct, based on a general knowledge of the national distribution of seismic hazard, value of building inventory, and seismic risk. (Estimates of structure instrumentation for Puerto Rico could not be included, because assessments of seismic hazard had not been completed at the time of the studies by FEMA (Nishenko, 2001) and that for population exposure (Borcherdt et al., 1997). Recent completion of this assessment for Puerto Rico will permit estimates of AEL and guidelines for allocation of structure instrumentation for the region in the future.)

The distribution of instrumented structures implied by the above index is similar to that implied by population exposure with the principal difference being that the number of instrumented structures implied for California is about 16 percent less than that implied by population exposure alone. Consistency between estimates derived using population exposure and a combination of AEL and AELR as two different methods provides additional evidence that the geographic distribution derived using either method provides a basis for assigning national priorities for the instrumentation of structures. The distribution based on HAZUS and inventories of the built environment using the above index is recommended as the most up-to-date basis for assignment of national priorities.

Panel discussion suggested that 30 percent of the inventory should be installed in each of the ANSS regions with the remaining 70 percent allocated using the AEL-AELR index. This suggestion implies that of the 300 30-channel building installations about 14 should be installed as a minimum in each region with the remaining allocated using the AEL-AELR index. Reviewing the allocations shown in Tables 1 and 2 shows that the numbers allocated to each ANSS region meets this minimum number for each region except Hawaii. Further discussion with the workshop chair and others indicates that the fixed percentage allocation is not appropriate in the case of a small area with a relatively small inventory and that the allocation implied by the index is preferred. Allocations as indicated in Tables 1 and 2 are recommended as a consensus of Panel 2 of the workshop.

GUIDELINES FOR REGIONAL PRIORITIES

Priorities for choosing structures for instrumentation for hazard mitigation and emergency response purposes must account for the nature and magnitude of losses expected in a an urban region at risk. The geographic distribution of expected losses as calculated using HAZUS provides a quantitative basis for assigning regional priorities. It provides an objective methodology to estimate losses and depict them geographically. The geographic distribution of expected losses together with the inventory of the built environment provides an objective basis to determine the type and location of structures that need to be instrumented on a regional and local scale.

Panel suggestions indicate that HAZUS can be used to establish regional priorities based on the distribution of regional loss for maximum considered earthquakes in the region. It is suggested that the geographic distribution of loss for these events be used to define areas and types of structures most likely to be damaged. The percent of the total loss for each structure type multiplied by the number of structures allocated to the region based on the national priority allocation provides a quantitative basis for allocation of regional instrument resources for each structure type. Borcherdt, et al., 1997, suggested a similar procedure based on ground motion estimates for a repeat of the California earthquake of April 18, 1906 as a means of developing estimates for instrumentation of the built environment in the San Francisco Bay region. Guidelines provided by this procedure should then be reviewed and interpreted by regional committees as to specific structure types and locations for a ranking of priority installations. Specific building types for consideration in conjunction with guidelines suggested by Panel 1 (this proceeding), especially in high seismicity areas such as Anchorage are:

1) Steel Moment Resisting Frame (10-20 stories),
2) Steel Braced Frame (10-20 stories),
3) Reinforced CMU (5-14 stories),
4) Ductile Concrete Moment Resisting Frame (10-20 stories),
5) Concrete Shear Wall (10-15 stories),
6) Timber Structure (Shear Wall) (5-stories), and
7) Special General Structure (Large, complicated framing system).

Types of bridges, pipelines, storage tanks, electrical distribution facilities, and other structures are recommended for consideration to determine final regional priorities for allocation of structural instrumentation resources.

In regard to the resources requested in the ANSS proposal, 50% of the instruments deployed under its national strong motion program are to be installed in structures, while the remaining 50% are to be installed in the free field for ground-motion monitoring. Panel 2 considers this commitment to be a long-term objective for each region and not a yearly requirement. In our judgment, each ANSS region should have the flexibility to spend its yearly allocation of funding on the most urgent instrumentation needs identified by its seismological and engineering communities as long as the 50% commitment regarding structural and free field instrumentation is met at the completion of the ANSS installation phase. Panel 2 notes that these needs will likely vary from region to region. Furthermore, each region should have the option to use some ANSS funds for mobile instrumentation, to study structural response as necessary. This instrumentation, for example, could be used to measure basic dynamic characteristics of given classes of structures during ambient conditions or during small earthquakes that might occur frequently. Such databases are lacking outside California and are potentially important for determining whether certain code provisions, based largely on California data, are applicable to structures in the less seismic regions. To ensure that structure instrumentation and data needs are met, each ANSS regional organization is encouraged to appropriately constitute its Advisory Committee with a 50% balance of structural engineers.

EMERGENCY RESPONSE

Knowledge of the geographic distribution of strong-ground shaking can be useful during the time period of several hours following a damaging earthquake. This information helps identify those areas that might be most severely damaged and hence those areas for which emergency response efforts should be concentrated. Modern instrumentation deployed on the ground permits areas of strongest shaking to be quickly identified. Instruments on structures such as buildings, bridges, freeway overpasses, and dams can also provide useful information regarding the state of health of the structure. Workshop consensus indicates that in general structures need to be instrumented with arrays of sensors for reliable near real time assessments of the state of health of a particular structure and that a single near real time three-channel accelerograph on a structure is of limited use for this purpose. For specific recommendations regarding the nature and type of instrumentation needed on structures to provide an immediate assessment of structural safety and appropriate emergency response measures, the reader is referred to the recommendations of Panel 1 of this proceeding.

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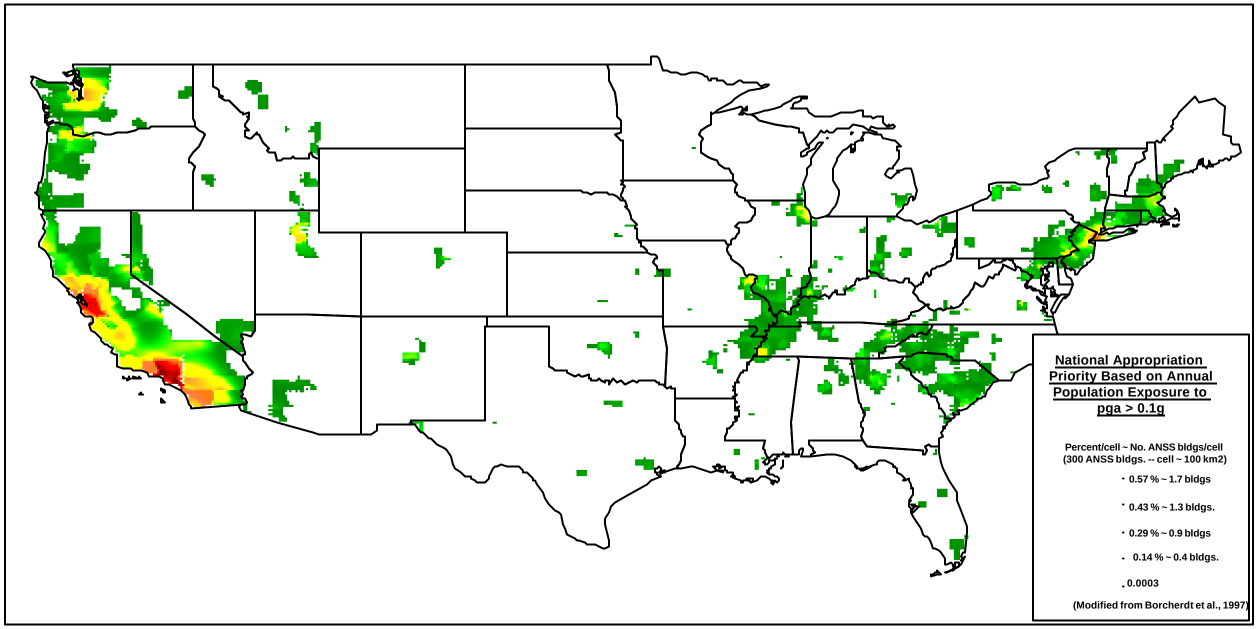

Figure 1. National priority for allocation of structure instrumentation resources based on the geographic distribution of population exposure (modified from Borcherdt et al., 1997). The number of structures per 100 square kilometers is based on an approximate number of 300-30 channel structures to be instrumented by ANSS with 30 channels each.

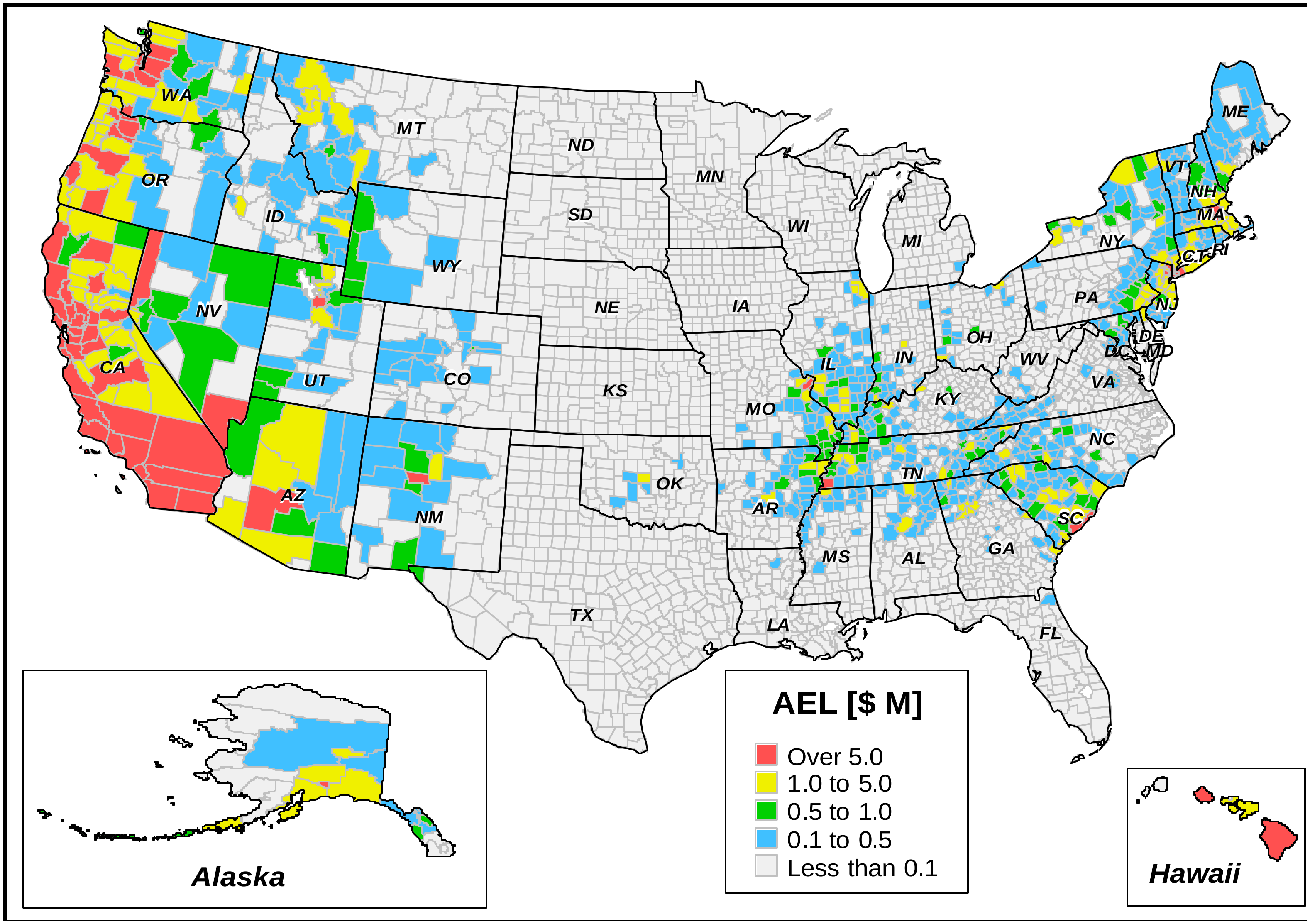

Figure 2. Geographic distribution of annualized earthquake loss as compiled by county (from FEMA, 2001).