# Earthquake Strong Ground-Motion Measurement For Public Safety

*(Preliminary Procedures for Estimates of the Number and Location of Strong-motion Stations Needed to Significantly Improve Public Earthquake Safety)*

by

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ABSTRACT

Tragic life and property losses from recent earthquakes dramatically illustrate the need to reduce the impact of future earthquakes to manageable levels. Quantitative measurements of damaging shaking using modern instrument technology provide an important new opportunity for significant progress. Thorough sets of shaking measurements on the ground and in man-made structures are essential for improving earthquake resistant design and for improved emergency response capabilities. A new methodology is based on estimates of the annual exceedance rate and annual population exposure for 0.1g, as inferred from probabilistic seismic hazard calculations. Preliminary estimates derived for the United States and Puerto Rico indicate that as many 7100 ground-motion stations are needed to ensure that the next major earthquake is adequately recorded. The estimates, when considered with corresponding estimates for man-made structures, suggest that major new efforts are needed in some urbanized areas to ensure complete sets of measurements for Public Earthquake Safety.

KEYWORDS

Strong-motion instrumentation, Earthquake hazard reduction, Emergency response, Strong motion, National Seismic Hazard Maps.

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## 1. INTRODUCTION

Staggering losses from recent earthquakes impacting Northridge, California ($15 to $25 billion, 64 lives) and Kobe, Japan (> $100 billion and 5500 lives) clearly demonstrate the potential impact of moderate to large earthquakes on modern urbanized societies. These tremendous potential losses argue strongly for dramatically accelerated programs to improve public earthquake safety as quickly as resources permit. Without such efforts in an ever growing urbanized society the cost and potential impact of a single earthquake disaster can have global consequences.

Reduction of life and property losses to low and manageable levels requires significant improvements in both *Hazard Mitigation* and *Emergency Response*. Quantitative measurements of strong shaking and its effects are the basis for significant progress in both areas. Modern technology offers important new opportunities to acquire and interpret these essential measurements in near real-time for each urbanized area likely to experience earthquake disasters.

This report presents a methodology presented at a workshop concerned with "an action plan for strong-motion programs to mitigate earthquake losses in urbanized areas" organized by the Committee for Advancement of Strong-Motion Programs in Monterey, CA, April 2-4, 1997. The methodology is preliminary and can be improved with more detailed information that might become available in the future such as detailed (1:250,000 scale) geologic maps. The methodology is presented here for evaluation and comment from an international perspective.

## 2. HAZARD MITIGATION

The collapse of buildings, bridges, and other man-made structures is the major cause of loss of human life and property during earthquakes. The major cause of structural failure and collapse during earthquakes is strong ground shaking. Consequently, 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 earthquake shaking and its effects on structures can be gained only from instrumental measurements of shaking both on the ground and in the affected structures during the earthquake. Presently, strong motion recordings in the areas of most significant damage from past earthquakes are very limited, with many critical issues concerning the nature of near source motions, soil behavior, and structural response not yet measured for damaging earthquakes. Consequently, billions of dollars are presently being expended to retrofit various public transportation facilities and steel, moment-frame structures for which few actual recordings of strong shaking have yet been measured. Such efforts without complete knowledge of the in-situ shaking performance of the various types of structures are likely to require further improvement and significant additional expenditures in the future.

Comprehensive sets of strong-motion measurements near, on and in structures from the next major earthquake are needed to quantitatively evaluate causes of damage and loss and to develop improved design, construction, and retrofit codes to ensure public safety in subsequent earthquakes. Without instrumentation in place to make such measurements, important opportunities to develop procedures to ensure earthquake resistant structures are missed and costs to rectify the situation in an ever growing urbanized society increase dramatically. Society can not afford to not have the instrumentation in place to accurately measure the next earthquake.

### 2.1 Instrumentation Estimate on a National Scale for the US

Towards developing an estimate of ground-motion instrumentation required to ensure that adequate sets of measurements are acquired in densely urbanized areas of the United States for purposes of *Hazard Mitigation*, preliminary estimates have been developed for the coterminous US. These estimates, based on recently developed preliminary procedures, have been most thoroughly developed for ground-motion instrumentation. Estimates for structural instrumentation are not yet complete and not provided.

Recent earthquakes emphasize that in order to adequately document ground shaking for purposes of Hazard Mitigation, instrumentation must be located throughout the areas near the earthquake source and the urbanized areas most affected by the earthquake. Rapid variations in the intensity of shaking due to distance and local geologic conditions and in the density of structures and population imply that the density of instrumentation must vary accordingly. In determining the appropriate density for instrumentation, factors considered important were the probability for significant levels of ground shaking and the amount of population exposed to possibly damaging levels of shaking.

Working in conjunction with A. Frankel, probability levels for ground shaking were determined from the calculations for the recent probabilistic seismic ground shaking maps developed for the 1997 NEHRP recommended building code provisions (Frankel, et al., 1996). The probability levels were specified as the annual frequency of exceedance for various levels of peak ground acceleration for the reference ground condition NEHRP site class B/C with shear velocity 750 m/s. The annual frequencies were specified for grid cells of dimension 0.1 degree latitude by 0.1 degree longitude for the entire national map. The population distribution for the United States was provided by Frankel for the same set of cells.

The first type of area considered important for instrumentation is that for which significant amounts of the population are exposed to possibly damaging shaking levels. These areas are important because they help identify areas for which life and property losses may be concentrated in future earthquakes. More detailed evaluations must await detailed inventories of the built environment.

Estimates of the population exposed to various levels of ground shaking were estimated as the product of the population specified for each cell and the annual frequency of exceedance for a specified level of ground acceleration. One factor considered important in estimating the amount of necessary instrumentation is the amount of population exposed to a specified level of shaking. With the level of shaking chosen at 0.1g, the corresponding amount of instrumentation for each cell was specified as proportional to the amount of exposed population for the cell, with the maximum amount of instrumentation per cell being chosen at 20 for a cell with near maximum exposure. A cell in the San Francisco Bay region for which the maximum amount of exposed population is 5920 was used. Twenty instruments per cell of approximate dimension 100 square km implies an instrument spacing on a grid with elements spaced at about 2.2 km. This spacing corresponds to about 3 wavelengths for horizontally propagating 1 second shear waves in the reference ground condition, "firm to hard rock" and to more than 12 wavelengths for soft soils (NEHRP site class E; Borcherdt, 1994). This spacing does not preclude spatial aliasing, but should permit significant improvements in ground-motion estimation for purposes of earthquake engineering.

The second type of area considered important for instrumentation is that near the source for which ground motions levels might be especially high, but not necessarily densely populated. To ensure that these areas would be adequately instrumented, instrumentation was specified for each cell in proportion to the annual exceedance of peak acceleration at 0.1g, with the amount of instrumentation chosen as 2 per cell for one of the cells with the highest annual frequency of exceedance in the San Francisco Bay region. This specification suggests a instrument spacing on a grid of about 7.1 km or more than 9 wavelengths for 1 second waves in "firm to hard rock" and more than 39 wavelengths in soft soils.

The final estimates of ground shaking were specified for each cell as the maximum of the amount of instrumentation implied by the proportion of exposed population to 0.1 g and the amount per cell proportional to the annual exceedance probability for 0.1 g. The amount of instrumentation implied by this procedure is illustrated for the coterminous US (Figure 1a), and California (Figure 1b). The amounts are summarized by state in Table 1. Instrumentation for cells for which the proportion is less than 0.1 or the grid spacing is about 32 km were not included in the totals. In addition, in order to develop the estimates using Excel 7.0 it was necessary to reduce the number of cells that Frankel used for the entire map ( $1.5 \times 10^5$). This reduction was achieved by using only those cells for which the population exposed annually to 0.1g was greater than 3. This reduction eliminated cells in extremely remote areas such the Sierra Nevada Mountains and some areas in Nevada.

The estimate for the total number of stations in the coterminous United States is 5280 or about 5300 instruments (Figure 1a, Table 1). This number is at best a rough estimate considering the grid element size of about 100 square km. The estimate does not include Alaska, Hawaii, or Puerto Rico. Guesses for these areas are 125, 75, and 75, respectively yielding a total estimate of about 5550 station locations.

The estimate does not account for increased levels of ground shaking caused by amplification effects of local geologic deposits. As a rough guess based on detailed considerations for the San Francisco region, the estimate in areas of soft soils such as San Francisco, Seattle, Boston, New York, Memphis and Saint Louis needs to be increased by at least 50 percent. A conservative increase of 50 percent to account for soft-soil amplification effects suggests a total number of ground-motion instrumentation stations for the United States of about **7100** (see Table 1). This number though large needs to be considered in the context of population exposed annually, potential losses from future earthquakes, and present retrofit expenditures expected to exceed several billion dollars over the next decade.

For effective evaluations of structural response and failure during earthquakes, thorough and complete sets of measurements are required on a wide variety of man-made structures, including a variety of types of buildings, bridges, and lifelines. Accurate estimates of structures to be instrumented throughout the US can best be derived based on detailed inventories.

One crude estimate for the amount of structural instrumentation might be derived from the number proportional to the population exposed annually to 0.1g. This number for the United States would suggest that about 3500 structures should be instrumented with about 3000 of these being in California. Adjustments to this estimate are easily computed by changing the proportionality constant, derived by assuming that 20 structures per 100 square-km cell with a population of 5920 exposed annually to 0.1g. This number should also be adjusted to account for ground shaking amplification effects.

## 2.2 Station Estimate on a Regional Scale for the San Francisco Bay Area

Towards a more in-depth evaluation of instrumentation needs, estimates of instrumentation needs based on a specific earthquake scenario. The San Francisco Bay Region provides a good location for such considerations, because of dense urbanization near an earthquake source zone with a large potential for a large earthquake. These estimates are used to evaluate the estimates developed on the basis of the criteria available for national estimates.

### *2.2.a Station estimate to document ground-shaking variations*

To thoroughly document damaging levels of ground shaking, instrumentation must be sufficiently dense to document variations in crustal rupture and source radiation characteristics, variations in shaking due to distance from the source, and amplification effects of near-surface geologic deposits.

Ground motion estimates for a repeat of the California earthquake of April 18, 1906 (Borcherdt, et al., 1995) accounting for variations in local geology are shown for the city and county of San Francisco in Figure 2. These estimates are derived from spectral attenuation relations of Boore et al., (1994, 1995) for an event of $M_w$ =7.7 and the NEHRP site factors specified for the 0.1 g level (Borcherdt, 1994). Superimposed on the map is a grid comprised of square elements of 1.7 $km^2$ corresponding to 35 stations per 100 square kilometers. This grid spacing corresponds to about a 75 percent increase in the maximum number of 20 stations per 100 square kilometers assigned for site class B/C for the national consierations.

The map illustrates that the station spacing of about 35 stations per 100 $km^2$ is minimal for providing a thorough record of expected variations in ground shaking in the San Francisco Bay area with its rapid variations in geology. In areas near the margins of the bay with large variations in expected ground motion, the map suggests a more dense spacing is needed. This result suggests that the number of instruments estimated on a national scale also is a minimum estimate. The assumption on which the national estimate is based, implies 42 instruments for the city and county of San Francisco. Figure 2 indicates that a more complete distribution of instruments is needed to thoroughly document expected shaking levels. The distribution shown includes the original 42 stations plus an additional 181 stations.

*2.2.b Station estimate to account for geographic distribution of built environment and expected earthquake losses*

Instrumentation deployed for hazard mitigation and emergency response purposes must account for the location, nature and magnitude of losses expected to man-made structures. The geographic distribution of residential and commercial losses estimated for a repeat of the 1906 earthquake are shown for the city of San Francisco (Figure 3). The losses as depicted were kindly provided by Risk Management Solutions, Inc. The estimates are based on detailed inventories of the built environment and associated assessed vulnerabilities. The estimated losses are shown in units of $1,000 per approximately ½ city block. Superimposed on the map are two grids with cell size of approximately 1.7x1.7 $km^2$ and 100 $km^2$, respectively.

The map shows that the highest expected losses are concentrated in downtown San Francisco. The concentration of especially severe losses in parts of downtown San Francisco suggests that instrumentation in these areas should be relatively dense and not spaced more than several blocks apart. Examination of the spacing implied by the 1.7x1.7 $km^2$ suggests that this spacing is adequate except for those areas of highest damage expected in downtown San Francisco. The map of expected losses shows that most dense instrumentation assumed for areas of the highest population exposure with soft soils is a minimal estimate. For comparison, this assumption implies about 42 stations for the city and county of San Francisco, while a number considered more appropriate to document ground shaking in areas of high loss for purposes of hazard mitigation is about 110.

## 3) EMERGENCY RESPONSE

Reduction of loss of life and property immediately following earthquake disasters can be dramatically improved if the location and severity of damages can be rapidly assessed. Modern instrumentation technology now permits such assessments to be made in densely urbanized areas within a few minutes of the occurrence of the event. Such quick assessments can significantly improve emergency response capabilities. Rapid assessments can speed-up treatment of injuries, reduce number of casualties, facilitate evacuations, if flooding or fire are imminent, and permit more rapid and efficient deployment of emergency operations.

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 permit rapid assessment of probable damage state with resultant appropriate dispatch and routing of emergency response resources. Measurements on lifelines such as electric power transmission facilities, gas and oil lines, and rapid transit facilities allow efficient shut down and prevention of additional disaster.

Reducing the time for disaster assessment and resultant emergency response from hours to a few minutes can save untold amounts of life and property. Important examples illustrating the application of modern technology to Disaster Reduction are now being implemented for Yokohama, Japan.

Ground-motion instrumentation deployed for *Hazard Mitigation* purposes, if equipped with rapid communication capabilities, can also serve critical emergency response purposes. The density of station spacing in the Figures 1a and 1b suggests this station density would also be satisfactory in many cases for measuring shaking levels for purposes of emergency response. Equipping selected stations with appropriate telecommunication capabilities could be a cost-effective means of dramatically improving emergency response and thereby reducing the disastrous effects of future earthquakes.

## 4) ACKNOWLEDGMENTS

Jawhar Bouabid of Risk Management Solutions, Incorporated kindly provided estimates of loss for the City and county of San Francisco California and assisted in the initial display of the ground shaking maps. Arthur Frankel kindly provided calculations of the annual exceedance rates for various levels of ground motion, a corresponding grid of population values, and considerable discussion and insight with respect to their interpretation. William Joyner graciously provided his valuable insight and thoughts regarding estimation procedures. Gary Glassmoyer helped reduce the size of some very large files to manageable levels for a modern spreadsheet. Each of these efforts are sincerely appreciated. M. Celebi, D. Oppenheimer, and C. Stephens provided helpful review comments.

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Table 1. Ground-motion instrumentation estimated for US.

| State | | Population Ann. Exp. to 0.1g | Instru.~ Ann. Exp. Pop. | Instru.~ Ann. Exc. Rate | Max Instr wrt Pop.Exp. & Ann Exc Rate | Max Instr Incl. Amplif. Effects |
|---|---|---|---|---|---|---|
| Arizona | AZ | 190 | 0.6 | 6.6 | 7 | 7 |
| Arkansas | AR | 1,498 | 5.1 | 18.0 | 19 | 19 |
| California | CA | 882,400 | 2981.1 | 2528.4 | 4394 | 5493 |
| Colorado | CO | 56 | 0.2 | 0.0 | 0 | 0 |
| Connecticut | CT | 866 | 2.9 | 0.7 | 3 | 3 |
| Dist. Columbia | DC | 48 | 0.2 | 0.0 | 0 | 0 |
| Georgia | GA | 405 | 1.4 | 0.3 | 1 | 1 |
| Idaho | ID | 786 | 2.7 | 24.1 | 24 | 24 |
| Illinois | IL | 4,447 | 15.0 | 31.5 | 39 | 58 |
| Indiana | IN | 450 | 1.5 | 2.1 | 2 | 4 |
| Kentucky | KY | 977 | 3.3 | 16.0 | 16 | 24 |
| Maryland | MD | 310 | 1.0 | 0.1 | 1 | 2 |
| Massachusetts | MA | 2,133 | 7.2 | 1.3 | 7 | 11 |
| Missouri | MO | 3,579 | 12.1 | 24.4 | 31 | 47 |
| Montana | MT | 937 | 3.2 | 62.7 | 63 | 63 |
| Nevada | NV | 3,534 | 11.9 | 100.4 | 100 | 100 |
| New Hampshire | NH | 250 | 0.8 | 0.2 | 1 | 1 |
| New Jersey | NJ | 8,979 | 30.3 | 2.7 | 30 | 46 |
| New Mexico | NM | 999 | 3.4 | 4.3 | 5 | 8 |
| New York | NY | 9,324 | 31.5 | 4.3 | 33 | 50 |
| North Carolina | NC | 32 | 0.1 | 0.0 | 0 | 0 |
| Ohio | OH | 366 | 1.2 | 0.2 | 1 | 2 |
| Oklahoma | OK | 62 | 0.2 | 0.1 | 0 | 0 |
| Oregon | OR | 10,056 | 34.0 | 116.8 | 123 | 184 |
| Pennsylvania | PA | 2,388 | 8.1 | 0.9 | 8 | 12 |
| South Carolina | SC | 1,871 | 6.3 | 14.7 | 15 | 22 |
| Tennessee | TN | 4,229 | 14.3 | 25.3 | 31 | 47 |
| Utah | UT | 8,385 | 28.3 | 38.1 | 47 | 71 |
| Virginia | VA | 375 | 1.3 | 0.1 | 1 | 2 |
| Washington | WA | 39,348 | 132.9 | 245.6 | 275 | 412 |
| Subtotal | | 989,282 | 3,342 | 3,270 | 5,280 | 6,713 |
| Alaska ~ | | | 75.0 | 75.0 | *125* | *188* |
| Hawaii ~ | | | 50.0 | 50.0 | *75* | *113* |
| Puerto Rico ~ | | | 50.0 | 50.0 | *75* | *113* |
| Total | | 989,282 | 3517.2 | 3445.0 | 5555 | 7125 |

~ Guesses

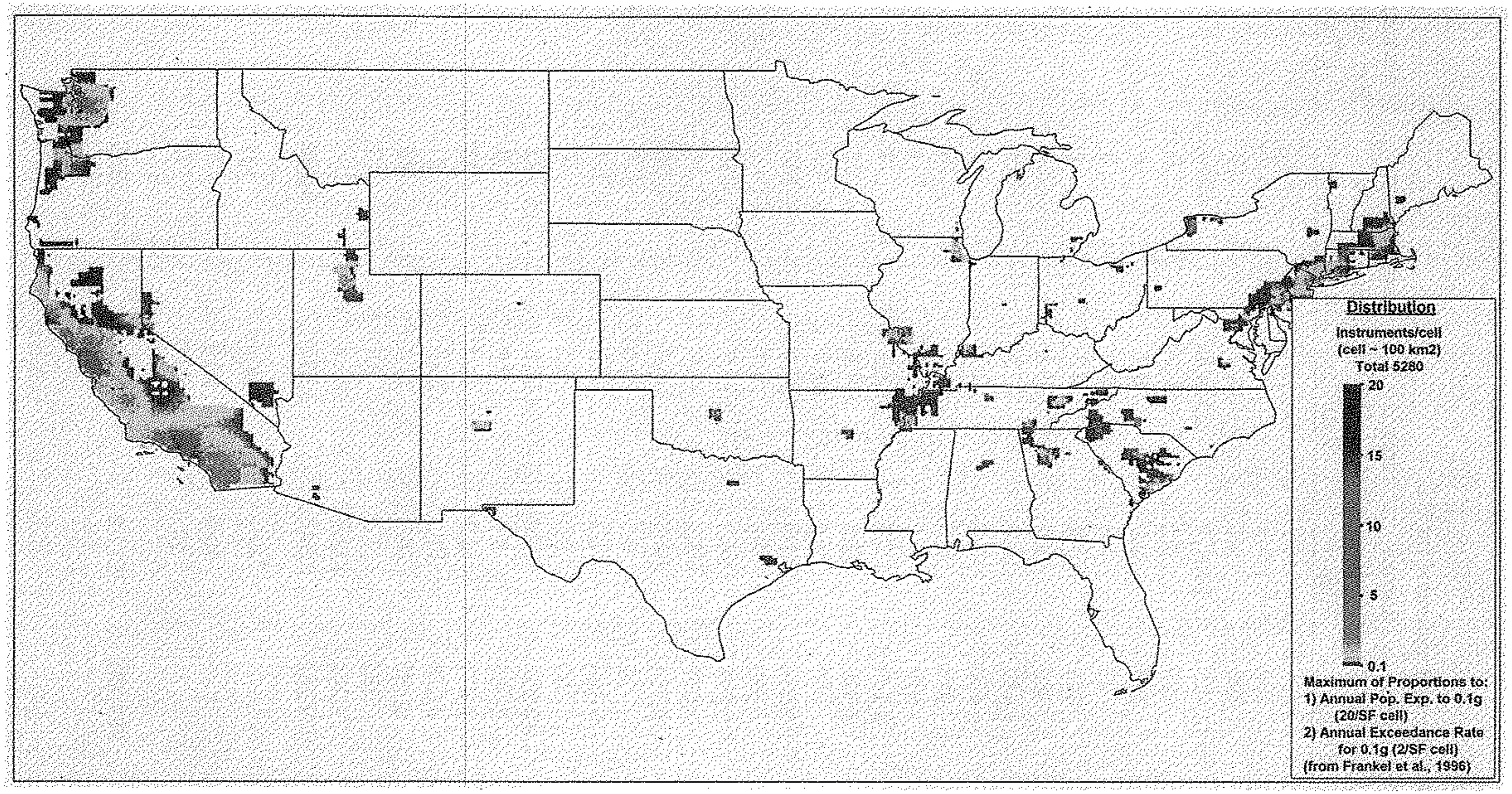


Figure 1. Station distribution for (a) the coterminous US and (b) California and Nevada inferred from the maximum station distribution per 100 square km implied by an estimate of the annual population exposure to 0.1g and annual exceedance rate for 0.1g.

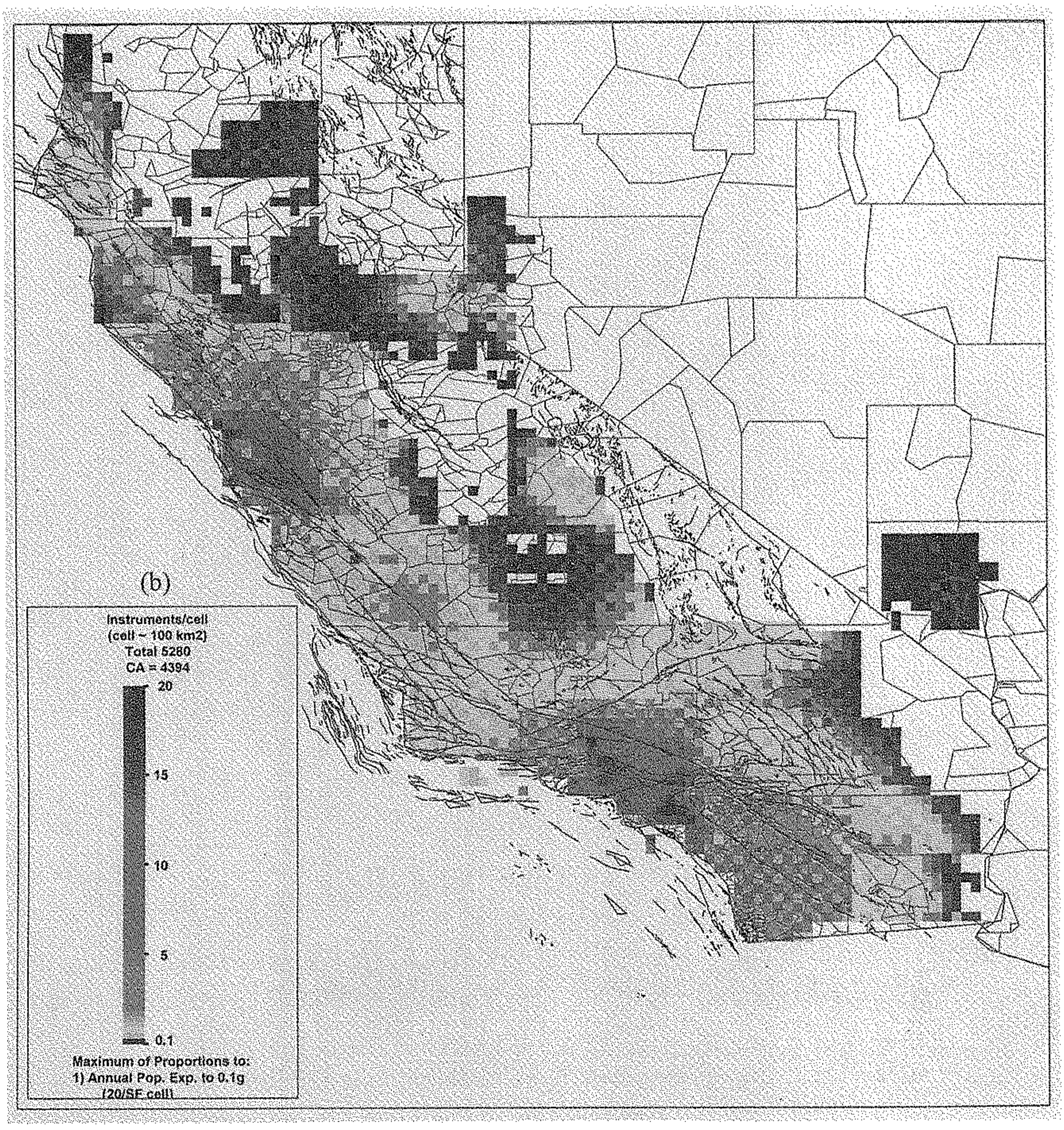


Figure 1b. Station distribution for California and Nevada inferred from the maximum station distribution per 100 square km implied by an estimate of the annual population exposure to 0.1g and annual exceedance rate for 0.1g.

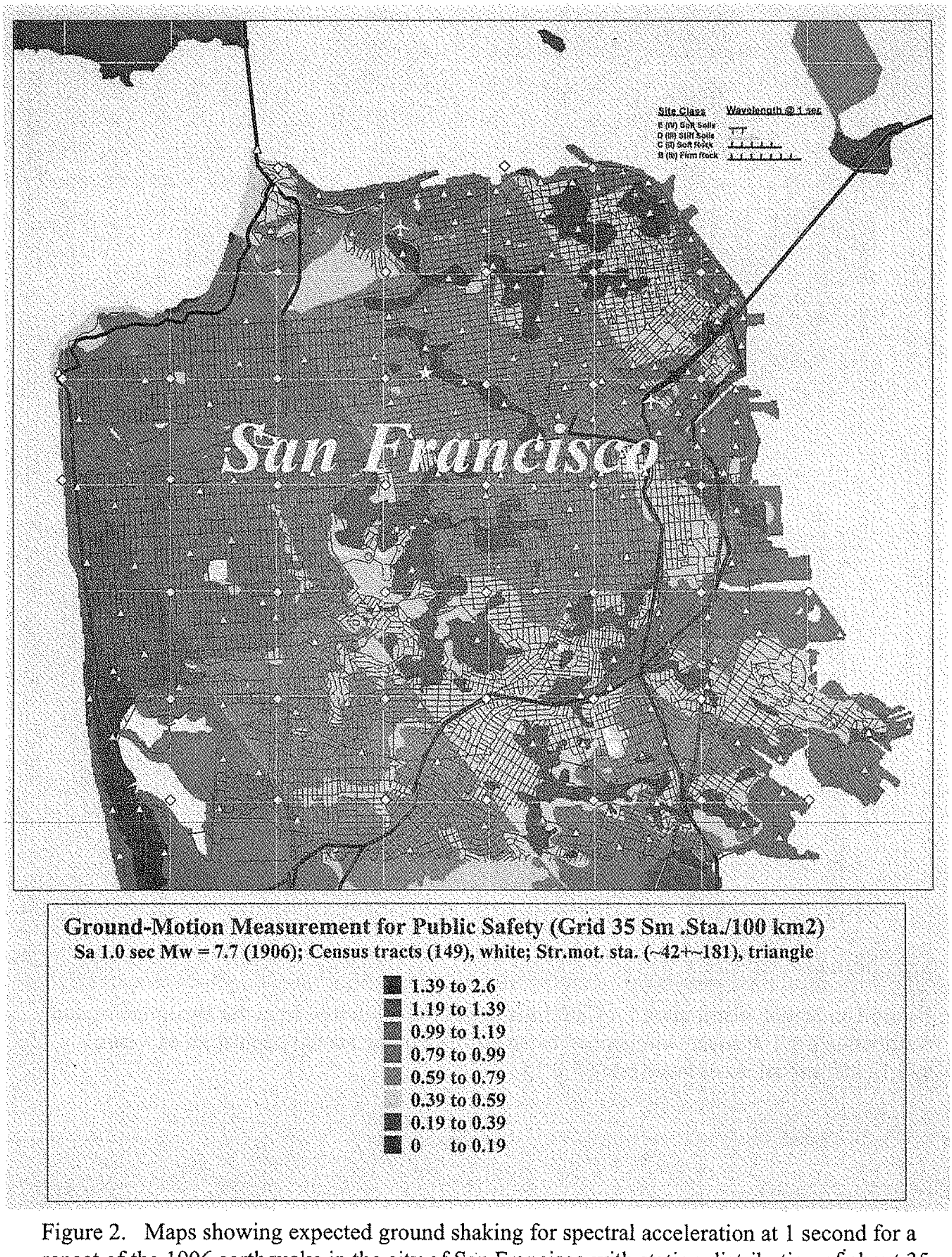


Figure 2. Maps showing expected ground shaking for spectral acceleration at 1 second for a repeat of the 1906 earthquake in the city of San Francisco with station distribution of about 35 stations per square 100 km(42 stations) and station distribution