Prepared for COSMOS (Consortium of Organizations for Strong-Motion Observation Systems) Workshop on Structural Instrumentation

Emeryville, Ca. November 14-15, 2001

Current Practice and Guidelines for USGS Instrumentation of Buildings Including Federal Buildings

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ABSTRACT

This paper presents a summary of the seismic instrumentation activities as practiced by the United States Geological Survey (USGS). The paper discusses both historical and current status and methods used for instrumenting structures. Cooperative efforts with private and other federal agencies in enhancing structural instrumentation are summarized. Technical requirements to record specific response issues and related cost issues are discussed. The extent to which a structure should be instrumented by creating a balance between the cost and data utilization needs is emphasized. A recent initiative, the Advanced National Seismic System (ANSS) promises to emerge as a potential means to enhance both the quantity and quality of structural instrumentation to pursue outstanding issues in structural engineering. Another initiative related to Federal Buildings Instrumentation is described.

ACKNOWLEDGEMENTS AND DEDICATION

The author dedicates this paper to the many past and present technicians and staff who worked on the structural instrumentation program at USGS.

1. INTRODUCTION

Seismic monitoring of structural systems constitutes an integral part of the National Earthquake Hazard Reduction Program in the United States. Recordings of the acceleration response of structures have served the scientific and engineering community well and have been useful in assessing design/analysis procedures, improving code provisions and in correlating the system response with damage. Unfortunately, there are only a few records from damaged instrumented structures to facilitate studies of the initation and progression of damage during strong shaking (e.g. Imperial County Services Building during the 1979 Imperial Valley earthquake, [Rojahn and Mork, 1981]). In the future, instrumentation programs should consider this deficiency. Jennings (1997) summarizes this view as follows: "As more records become available and understood, it seems inevitable that the process of earthquake resistant design will be increasingly, and quite appropriately, based more and more upon records and measured properties of materials, and less and less upon empiricism and qualitative assessments of earthquake performance. This process is well along now in the design of special structures".

In summary, therefore, an instrumented structure should provide enough information to (a) reconstruct the response of the structure in enough detail to compare with the response predicted by mathematical models and those observed in laboratories, the goal being to improve the models, and (b) make it possible to explain the reasons for any damage to the structure. The nearby free-field and ground-level time history should be known in order to quantify the interaction of soil and structure. More specifically, a well-instrumented structure for which a complete set of recordings has been obtained should provide useful information to:

(1) check the appropriateness of the dynamic model (both lumped-mass and finite element) in the elastic range;
(2) determine the importance of nonlinear behavior on the overall and local response of the structure;
(3) follow the spreading nonlinear behavior throughout the structure as the response increases and determine the effect of this nonlinear behavior on the frequency and damping;
(4) correlate the damage with inelastic behavior;
(5) determine the ground-motion parameters that correlate well with building response damage;
(6) make recommendations eventually to improve seismic codes;
(7) facilitate decisions to retrofit/strengthen the structural system; and
(8) develop new techniques for measurement and analyses to meet needs of the user community and to validate performance of new applications in design and construction methods.

Therefore, for both California Strong-Motion Instrumentation Program (CSMIP) and USGS, the main objective to date has been to facilitate response studies in order to improve our understanding of the behavior and potential for damage of structures under the dynamic loads of earthquakes. As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized. Up to now, it has not been the objective of either instrumentation program to create a health monitoring environment for structures. Thus, the principal objective has been the quantitative measurement of structural response to strong and possibly damaging ground motions for purposes of improving design and construction practices.

This paper describes in detail the past and current status and guidelines used for the structural instrumentation program conducted by the United States Geological Survey (USGS). In general, the overall objectives of the USGS structural instrumentation program has been and still are in agreement with and complementary to the structural instrumentation program of CSMIP. Detailed procedures used by USGS structural instrumentation program are compiled in USGS Open-File Report 00-157 titled "Seismic Instrumentation of Buildings" (Çelebi, 2000) [now available from http://geopubs.wr.usgs.gov/open-file/of00-157/).

The scope of this report includes the following issues as practiced by USGS: (a) building selection criteria, (b) types of building arrays and responses to be captured, (c) recent developments in instrument technology and implications, (d) federal building instrumentation proposal (details in Appendix A) and (e) issues for the future.

2. HISTORICAL PERSPECTIVE

2.1. General Statistical Summary of USGS Instrumentation

To date, USGS has conducted a cooperative strong ground motion and structural instrumentation program with other federal and state agencies and private owners. Table 1 summarizes the current inventory and cooperative affiliations of the USGS Cooperative National Strong-Motion Network (NSMP). Cooperative structural instrumentation efforts are summarized in Table 2. Nationwide distribution of structural arrays are summarized in Table 3. Details of the nationwide structural arrays are provided in Appendix B (R. Porcella, *written comm..* 2001).

Table 1. Cooperative Participants and General Summary of the Variation of Instrumentation in the National Strong-Motion Network (updated on 10/15/01, R. Porcella, *written comm..* 2001).

Owner Agency	Stations	Recorders	Comments
Army Corps of Engineers	46	180	all dams
Property Owner (Code mandated)	04	04	down from 30+
Calif. Department of Water Resources	03	06	2 dams + Pumping Plant
Department of Veterans Affairs	59	74	Long Beach & Palo Alto VA
General Services Administration	02	04	Bldgs
Geophysical Institute, Univ. of Alaska, Fairbanks	13	13	all remote sites
Hawaii State Civil Defense	05	05	Big Island
Metropolitan Water Dist. of Southern CA (MWD)	16	32	dams + 1 bridge
NASA-JPL (new)	05	06	all digital
Oregon Department of Transportation	10	38	10 digital bridges
University of Puerto Rico	41	53	2 structures
U.S. Geological Survey [includes cooperative Instrumentation + latest ANSS* additions]	446	499	San Jose Bridge- 15 ch+12 ch DH]
Utah Geological Survey	07	07	older digital
Washington, Tacoma Public Utilities	02	06	2 dams
Washington Dept.of Natural Resources	01	01	Bldg
TOTALS	660	928	

Table 2. Cooperative National Strong-Motion Network [Extensively Instrumented Bldgs (> 6 channels)] (updated 10/15/2001, R. Porcella, *written comm..* 2001)

Owner Agency [* Federal funds]	Stations	Recorders
Department of Veterans Affairs [*]	05	09
General Services Administration [*]	02	03
Los Angeles County	01	02
NASA-JPL [*]	05	06
University of Puerto Rico [**NSF funds]	01	05
U.S. Geological Survey [*]	19	30
Washington Dept of Natural Resources	01	01
USGS-ANSS [*]	02	05
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TOTALS	36	61

Table 3. Nationwide Distribution of USGS Cooperative Structural Instrumentation Arrays [R. Porcella, *written comm..* 2001]

Extensively Instrumented Buildings [>6 channels]		Extensively Instrumented Bridges [>6 channels]		Extensively Instrumented Dams, Reservoirs, Pumping Plants and Power Generating Facilities [>6 channels]	
Alaska	3	California	2	Arizona	1
California	25	Oregon	10	California	33
Hawaii	1	Utah	1	Idaho	2
Missouri	2			Montana	1
Puerto Rico	1			New Mexico	1
South Carolina	1			Oregon	13
Tennessee	2			Utah	1
Utah	1			Washington	7
Washington	1				

2.2. General Instrumentation Guidelines

2.2.1. Data Utilization

Ultimately, the types and extent of instrumentation must be tailored to how the data acquired during future earthquakes will be utilized. Although several data utilization objectives may be interwoven, it is important to consider in advance how the data is to be used. Table 4 summarizes some sample data utilization issues with sample references. As an example of data utilization, recently, Jennings (1997) analyzed data from two buildings within close proximity (<20 km) to the Northridge epicenter, calculated the base shear from the records as 8 and 17 % of the weights of the buildings, drift ratios as 0.8 and 1.6 % (exceeding code limitations). Jennings (1997) concluded: “A difference between code design values and measured earthquake responses of this magnitude – approaching a factor of ten – is not a tenable situation.”

Table 4. Sample List of Data Utilization Objectives & Sample References

GENERIC UTILIZATION
Verification of mathematical models (usually routinely performed) (*e.g.*Boroschek et al, 1990)
Comparison of design criteria vs. actual response (usually routinely performed)
Verification of new guidelines and code provisions (*e.g.*Hamburger, 1997)
Identification of structural characteristics (Period, Damping, Mode Shapes)
Verification of maximum drift ratio (*e.g.* Astaneh, 1991, Çelebi, 1993)
Torsional response/Accidental torsional response (*e.g*. Chopra, 1991, DeLalera, 1995)
Identification of repair & retrofit needs & techniques (Crosby, 1994)
SPECIFIC UTILIZATION
Identification of damage and/or inelastic behavior (*e.g*. Rojahn & Mork, 1981)
Soil-Structure Interaction Including Rocking and Radiation Damping (Çelebi, 1996, 1997)
Response of Unsymmetric Structures to Directivity of Ground Motions (*e.g.* Porter, 1996)
Responses of Structures with Emerging Technologies (base-isolation, visco-elastic dampers, and combination (Kelly and Aiken, 1991, Kelly, 1993, Çelebi, 1995)
Structure specific behavior (*e.g*. diaphragm effects, Boroschek and Mahin,1991, Çelebi, 1994)
Development of new methods of instrumentation/hardware {[e.g. GPS] (Çelebi et. al., 1997, 1999, 2001, [e.g. wireless] Straser, 1997)}
Improvement of site-specific design response spectra and attenuation curves (Boore, et. al. 1997, Campbell, 1997, Sadigh *et. al*., 1997, Abrahamson and Silva, 1997
Associated free-field records (if available) to assess site amplification, SSI and attenuation curves(Borcherdt, 1993, 1994, Borcherdt, 2001, Crouse and MacGuire, 1996)
Verification of Repair/Retrofit Methods (Crosby et al, 1994, Çelebi and Liu, 1996)
Identification of Site Frequency from Building Records (more work needed)
RECENT TRENDS TO ADVANCE UTILIZATION
Studies of response of structures to long period motions (e.g. Hall et al, 1996)
Need for new techniques to acquire/disseminate data (Straser, 1997, Çelebi, 1997, 1998)
Verification of Performance Based Design Criteria (future essential instrumentation work)
Near Fault Factor (more free-field stations associated with structures needed)
Comparison of strong vs weak response (Marshall, Phan and Çelebi, 1992)
Functionality (Needs additional specific instrumentation planning)
Health Monitoring and other Special Purpose Verification (Heo et al, 1997)

2.2.2. Code versus Extensive Instrumentation

The most widely used code in the United States, the Uniform Building Code (UBC-1997 and prior editions), recommends, for seismic zones 3 and 4, a minimum of three accelerographs be placed in every building over six stories with an aggregate floor area of 60,000 square feet or more, and in every building over ten stories regardless of the floor area. The purpose of this requirement by the UBC was to monitor rather than to analyze the complete response modes and characteristics. UBC-code type recommended instrumentation is illustrated in Figure 1a. Following 1971 San Fernando earthquake, in Los Angeles, the code-type requirement was reduced to one tri-axial accelerometer at the roof (or top floor) of a building meeting the aforementioned size requirements.

Over the last three decades, USGS-NSMP has been responsible to install and maintain accelerographs in a number of code-type instrumented buildings. As noted in Table 1, the number of stations with code-type of instrumentation maintained by USGS-NSMP has dropped to only 4. Some of these stations are now being maintained by other institutions. And in some of these buildings, as illustrated later in this paper, the instrumentation schemes have been revised such that they are no longer considered as code-type instrumented buildings. The de-emphasizing of code-type instrumentation is the result of strong desire by the structural engineering community to gather more data from instrumented structures to perform structural response studies. Experiences from past earthquakes show that the minimum guidelines established by UBC for 3 tri-axial accelerographs in a building are not sufficient to perform meaningful model verifications. For example, three horizontal accelerometers are required to define the (two orthogonal translational and a torsional) horizontal motion of a floor. Rojahn and Matthiesen (1977) concluded that the predominant response of a high-rise building can be described by the participation of the first four modes of each of the three sets of modes (two translations and torsion); therefore, a minimum of 12 horizontal accelerometers would be necessary to record these modes. Instrumentation needed to provide acceptable documentation of the dominant response of a structure are addressed by Hart and Rojahn (1979) and Çelebi and others (1987). This type of instrumentation scheme is called the ideal extensive instrumentation scheme as illustrated in Figure 1b.

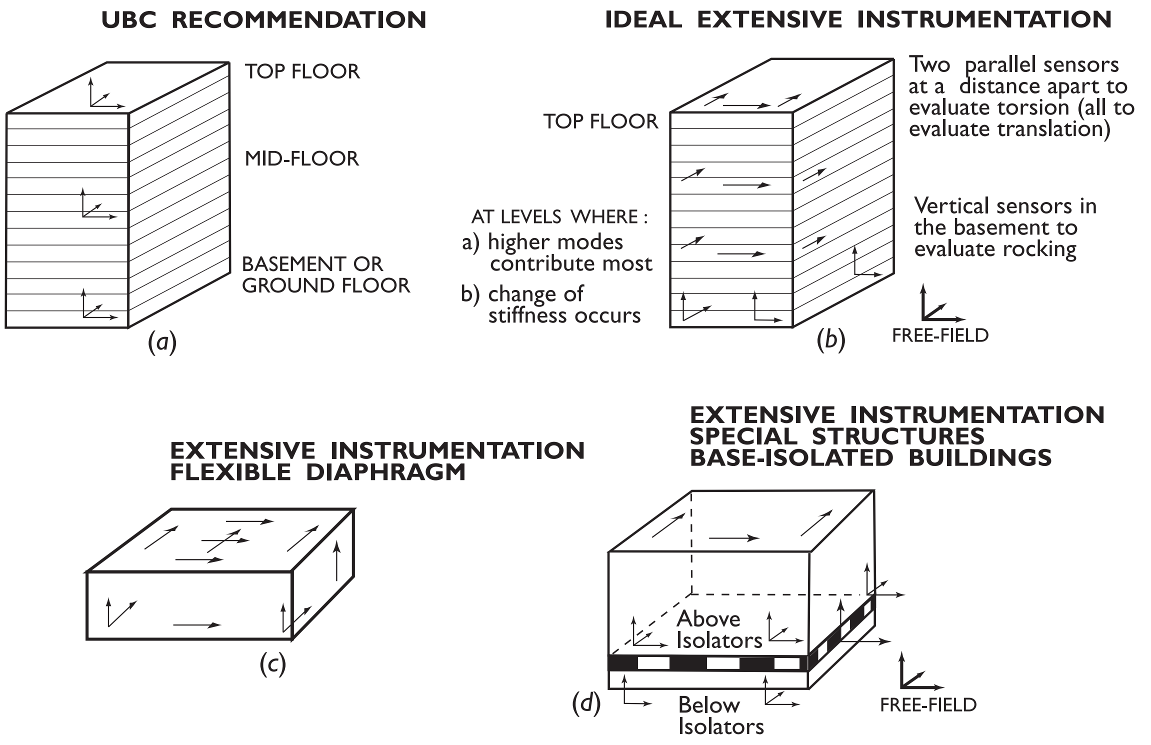

Figure 1. Typical Instrumentation Schemes

Figure 2a illustrates a 12-story building in Alhambra, California which was instrumented according to the code prior to the 1987 Whittier-Narrows earthquake. Later, the instrumentation scheme was upgraded as shown in Figure 2b. The upgrade includes an associated free-field surface station to provide qualitative measurement of input motions.

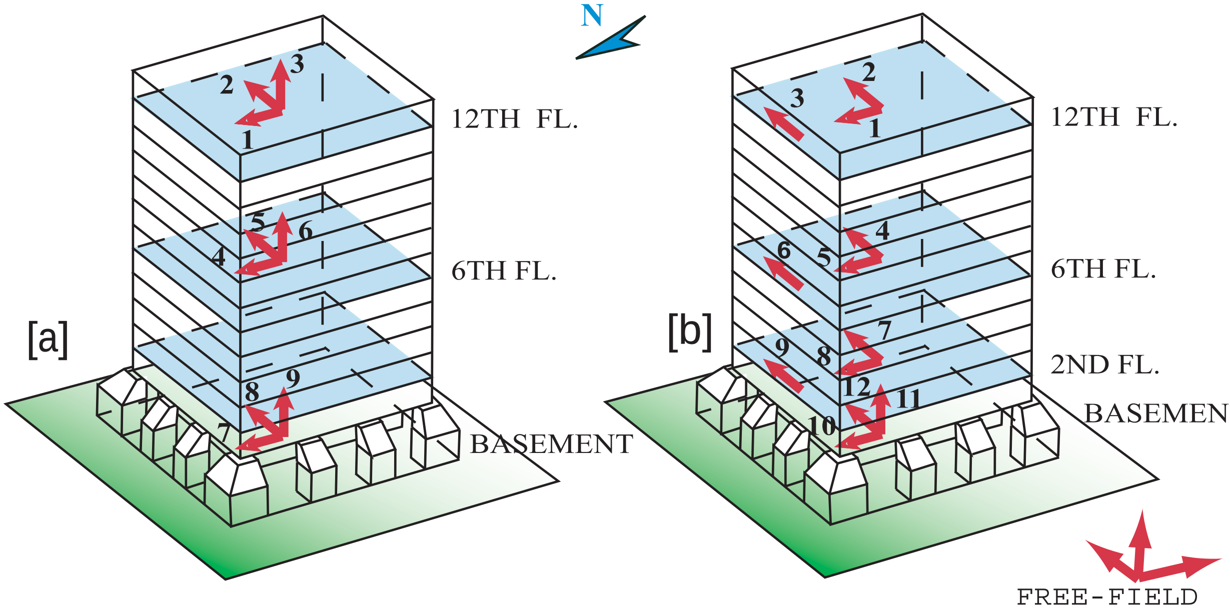

Figure 2. Building in Alhambra, California [(a) original analog code-type instrumentation and (b) upgraded to digital array with free-field station to better document building response].

2.2.2.1. *Soil-Structure Interaction Array(s)*

Measurement of soil-structure interaction effects are required to fully understand the response of a major structure. This is easily accommodated along with the instrumentation schemes of the superstructure. Sensors at critical locations of the foundation are required to capture its relevant motions. Additional sensors may be needed to record the motions of the surrounding geological materials. For example, if vertical motion and rocking are expected to be significant and need to be recorded, at least three vertical accelerometers are required at the basement level (Figure 1b). Horizontal and vertical spatial downhole sensors will provide information on how the motions change while traveling through the media and how much they will be affected by the building response. Detailed proposals for soil-structure interaction experiments resulting from a workshop are presented in USGS OFR-92-295 (Çelebi and others, 1992).

2.2.2.2. *Associated Free-Field Instrumentation*

More information is required to interpret the motion of the foundation substructure relative to the ground on which it rests. This requires free-field instrumentation associated with a structure (Figure 1b). However, this is not always possible in an urban environment[1]. Engineers use free-

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[1] For example, in San Francisco, California, it is not possible to find a free-field location around the Transamerica building, which is extensively instrumented.

field motions as input motion at the foundation level, or they obtain the motion at foundation level by convoluting the motion through assumed or determined layers of strata to base rock and deconvoluting the motion back to foundation level. Confirmation of these processes requires downhole instrumentation near or directly beneath a structure. Downhole data associated with building structures are especially scarce, although a few such arrays have been developed outside of the United States. These downhole arrays will serve to yield data on:

(1) the characteristics of ground motion at bedrock (or acceptably stiff media) at a defined distance from a source and
(2) the amplification of seismic waves in layered strata.

2.2.3. Special Structural Instrumentation Arrays

Specially designed instrumentation arrays are needed to understand and resolve specific response problems. For example, thorough measurements of in-plane diaphragm response requires sensors in the center of the diaphragm (Figure 1c) as well as at boundary locations. Performance of base-isolated systems and effectiveness of the isolators are best captured by measuring tri-axial motions at top and bottom of the isolators as well as the rest of the superstructure (Figure 1d). In case of base-isolated buildings, the main objective usually is to assess and quantify the effectiveness of isolators. If there is no budgetary constraints, additional sensors can be deployed between the levels above the isolator and roof to capture the behavior of intermediate floors.

2.2.4. Record Synchronization Requirement

High-precision record synchronization must be available within a structure (and with the free-field, if applicable) if the response time histories are to be used together to reconstruct the overall behavior of the structure. Such synchronization has been achieved through extensive cabling from the sensors to the recorder. Recent developments enable decreasing or minimizing and in certain cases eliminating use of extensive cabling. For example, the global positioning systems (GPS) are now widely used to synchronize a building instrumentation with that of a separate recorder system for the free-field; thus, eliminating cable connection between the free-field recorder and recorder within a structure. The issue here is that the choice of cable or wireless transmission for synchronization becomes an integral part of the cost consideration for the instrumentation scheme.

2.2.5. Cost Issues

Cost issues have been a major consideration in the design and implementation of structural instrumentation arrays at USGS. Historically, and unlike the CSMIP program, the USGS program has never had a line-item budget or dedicated continuous funding sources for structural instrumentation. The funding sources for the USGS instrumentation program have been from (a) year-to-year internal proposal process, (b) special USGS funding, (c) funding from owners including state, county and city organizations as well as private entities and (d) other federal agencies including Veterans Administration, General Services Administration, NASA-JPL, and Corps of Engineers. Cooperative instrumentation agreements with other federal agencies are being pursued at present. This topic is discussed further later on in this paper.

2.2.6. Recording Systems and Constraints

Commercially available recording systems have been limited to maximum 12-18 channels *(e.g.* analog recorder CRA-1[2] , 13 channels; the digital K-2[2], 12 channels; digital Mt. Whitney[2], 18 channels). Although multiple numbers of recording units may be used to accommodate requisite multiple-channel instrumentation systems for a building, cost restrictions usually limit the number of channels to 12 or 18, unless more channels are needed or special financing is available. In certain cases, we have deliberately separated free-field deployment associated with a building in order to conserve the available channels for use within the building. However, because of cost issues, we have, in the majority of cases limited the number of channels within regular and symmetric buildings to 12. Figure 2b shows such a 12-channel instrumentation scheme. Figure 3 shows an instrumentation scheme for a non-typical building structure with three wings. In this case, all wings and the core had to be instrumented to capture any effect of directionality of earthquake motions on such wing structures. The recording system in the structure consists of two 12-channel K-2's and another 6-channel K-2 to record the downhole and surface free-field motions at the south free-field site (Figure 3).

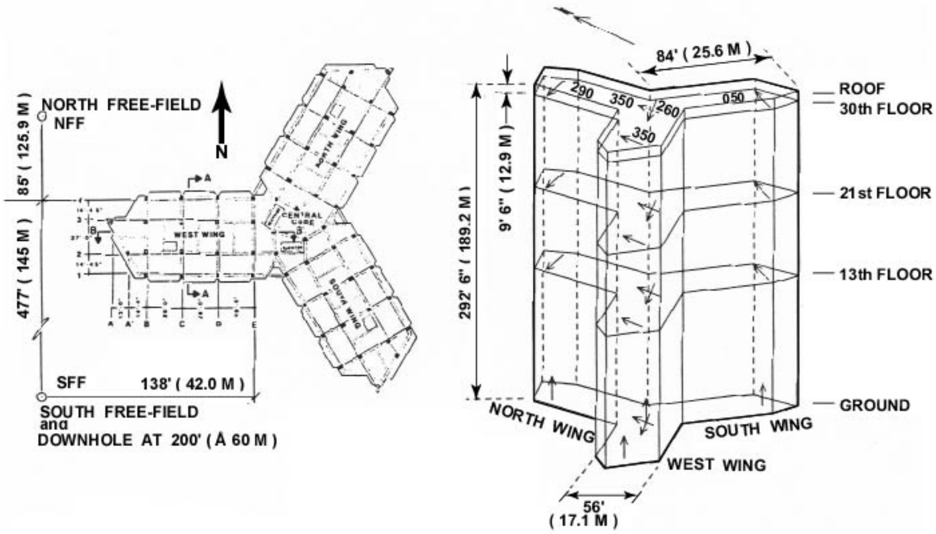

Figure 3. Instrumentation scheme of Pacific Park Plaza, Emeryville, California. The accelerometers shown are now connected to digital recorders. Following the 1989 Loma Prieta, CA earthquake, a tri-axial downhole accelerometer was added at the south free-field.

3. SELECTION PROCESS OF STRUCTURES TO BE INSTRUMENTED

3.1. General Overview

Since USGS has to work with other entities including private owners, state and local government organizations and other federal agencies, the selection process of structures to be instrumented has varied. However, most of the time, decisions have been made according to the funding source of the particular instrumentation project:

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[2] Use of commercial names or trademarks cited herein does not imply endorsement of these products by the U.S. Geological Survey.

(a) USGS funds allocated by annual internally competitive funding,
(b) USGS funds plus owner's funds used [owner can be private, state, county or local government]
(c) Other federal agencies,
(d) Special (one-time only) funding and,
(e) Recent ANSS[3] funding

3.2. USGS Funding and/or USGS plus owner funding

3.2.1. Regions Considered between 1984-1994

Figure 4 shows the regions of the United States where USGS seismic instrumentation activities were carried out between 1984-1994. In each of the regions (except for Reno, NV) a committee was formed. Comprised of local practicing engineers, academicians and local city and county building officials, these committees were charged with developing a recommended list of structures for possible instrumentation.

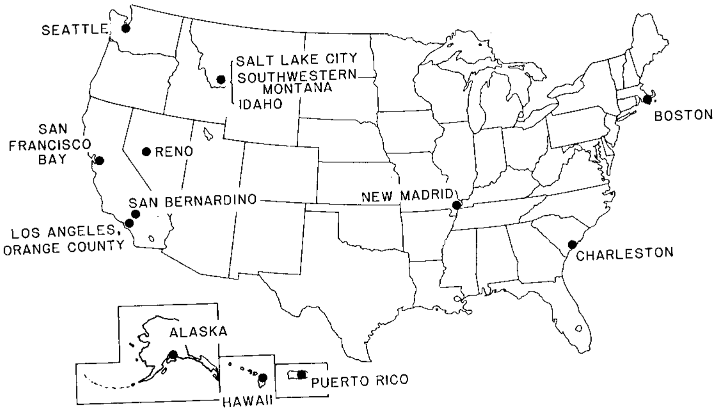

Figure 4. Seismic Regions of the United States where structural instrumentation activities were pursued.

3.2.2. Regional Committees and Sample Ranking Processes

The regional committees, in most cases developed a report that contained a description of the selection process and lists of recommended structures. Table 5 shows a list of reports developed by regional committees. These reports are now available via the internet at http://nsmp.wr.usgs.gov/publications/online_reports.html

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[3] Advanced National Seismic System

Table 5. Reports of Regional Committees and Instrumentation Status [The open-file reports (OFR) are scanned and can now be obtained from: http://nsmp.wr.usgs.gov/publications/online_reports.html]

REGION	DOCUMENT	Instrumentation Accomplished
SF Bay Region	USGS OFR 84-488	X
San Bernardino County	USGS OFR 85-583	X
Southeastern US	USGS OFR 86-398	X
New Madrid Region	USGS OFR 87-59	X
Los Angeles Region	USGS OFR 88-277	X
Alaska	USGS OFR 88-278	X
Boston & Vicinity	USGS OFR 88-351	X
Puget Sound Region	USGS OFR 89-374	X
Hawaii	-	X
Reno & Vicinity	-	
Salt Lake City & Region	-	X
Puerto Rico	-	X

In selecting structures for seismic instrumentation, unless other factors are considered and/or specific organizational choices are made apriori, in general, the following general parameters can be followed to rank structures for instrumentation:

1. Structural parameters: the construction material, structural system, geometry, discontinuity, and age,
2. Site-related parameters:
   a. Severity-of-shaking factor to be assigned to each structure on the basis of its closeness to one or more of the main faults within the boundaries of the area considered (e.g. for the San Francisco Bay area, the San Andreas, Hayward, and Calaveras faults are considered).
   b. Probability of a large earthquake ($\underline{M}$ = 6.5 or 7 occurring on the fault(s) within the next 30 years was obtained. The purpose of this parameter is to consider the regions where there is strong chance of recording useful data within an approximately useful life of a structure.
   c. Expected value of strong shaking at the site, determined as the product of (a) and (b).

The next step in ranking structures is to assign rational weighting factors for structural parameters and site-related parameters. A ranked list of structures emerges from this effort. As an example, the USGS, with input from an Instrumentation Advisory Committee for the San Francisco Bay Area, in 1983 developed a ranked list of structures for seismic instrumentation (Çelebi and others, 1984). The criteria and partial list of ranking results are tabulated in Table 6. However, regional approaches in selection of structures and ranking for seismic instrumentation have been and could, in the future, be different. For example, Table 7 summarizes a different approach for the selection criteria used by the New Madrid Region committee (Cassaro and others, 1987).

3.3. Structures Selected by Owners (Private or otherwise)

There have been and still continue to be cases whereby the owners (private or otherwise) provide full or partial funding and initiate the selection of a building structure for instrumentation. There are a few instrumentation projects of buildings financed by private or local governments as owners. For example, the base-isolated Salt Lake City and County Building in Salt Lake City, Utah is a county building instrumented with financing from the county (Figure 5).

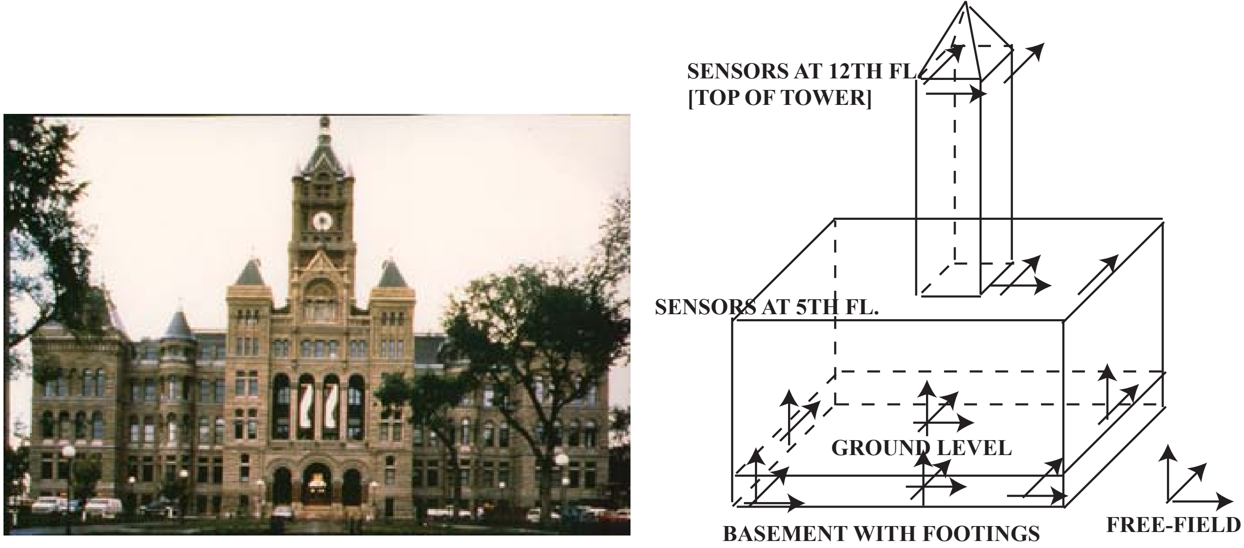

Figure 5. Instrumentation of Salt Lake City and County Building

3.4. Federal Buildings

Federal buildings instrumented to date are Veterans Administration (VA) hospitals, General Services Administration (GSA) buildings, and NASA-JPL buildings and facilities. Instrumentation and installation costs of each federal facility is borne by the owner federal organization. In most cases, each federal agency has selected the buildings to be instrumented either directly or with guidance from USGS staff. A recent program initiated by NASA-JPL aims to fund instrumentation of approximately 30 buildings in their California facilities. Table 2 summarizes the distribution to date of buildings, including federal buildings, instrumented cooperatively by USGS. Figure 6 shows two federally owned buildings instrumented cooperatively by USGS.

In 1998, USGS issued Open-File Report 98-117 “Seismic Instrumentation of Federal buildings – A Proposal Document for Consideration by Federal Agencies”. Details of this initiative is provided in Appendix A.

Table 6. Sample Ranking Used for San Francisco Region (from Çelebi and others, 1984)

RANKING INDEX I = $F_{site} + F_{structure}$

- Structural Parameters [$F_{structure}$] materials of construction, structural system, geometry, discontinuity, age [a total weighting factor from 0-3 for Structural Parameter]
- Site Related Parameters [F_{site}] proximity to fault, shaking level factor, probability (from USGS Map-30 yr)

	Structural Weighting Factor	**Site Related Parameters/Factors**						**Rank**
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Structure [Partial List]	**F (str)**	**Proximity to Fault (*)**	**Shaking Level Index (**)**	**Shaking Level Factor**	**Probability (*)**	**Col 4 X Col 5 (***)**	**Col 6 X 2.14 (****)**	**Col 1 + Col 7**
Wurster Hall (UCB)	3	NH	A	5	0.2	1	2.10	**5.1**
Bay Bridge	3	NH/SA	B/C	4/3	0.2/0.05	0.95	2.04	**5.0**
Bart Tunnel	3	SA/NH	C/C	3/3	0.05/0.2	0.75	1.61	**4.6**

(*) Probability of a large earthquake (M=6.5 or 7) occurring on the faults within 30 years):NH (Northern Hayward Fault) – 0.2, SH (Southern Hayward Fault) – 0.1, SA (San Andreas Fault) – 0.05 [0.03-0.08] (Reference: Lindh, A. G., 1983, Preliminary assessment of long-term probabilities for large earthquakes along selected fault segments of the San Andreas Fault system in California, USGS OFR 83-63.

(**) A code indicating severity of shaking [A(very violent)=5, B(violent)=4, C(very strong)=3, D(strong)=2, E(weak)=1

(***) The expected value of shaking intensity at a site (product of columns 4 and 5)

(****) Largest structural factor is 3. Therefore, in order to give equal weighting to structural and site related parameters, column 6 is multiplied by 2.14 in order to bring the largest site related parameter to 3.

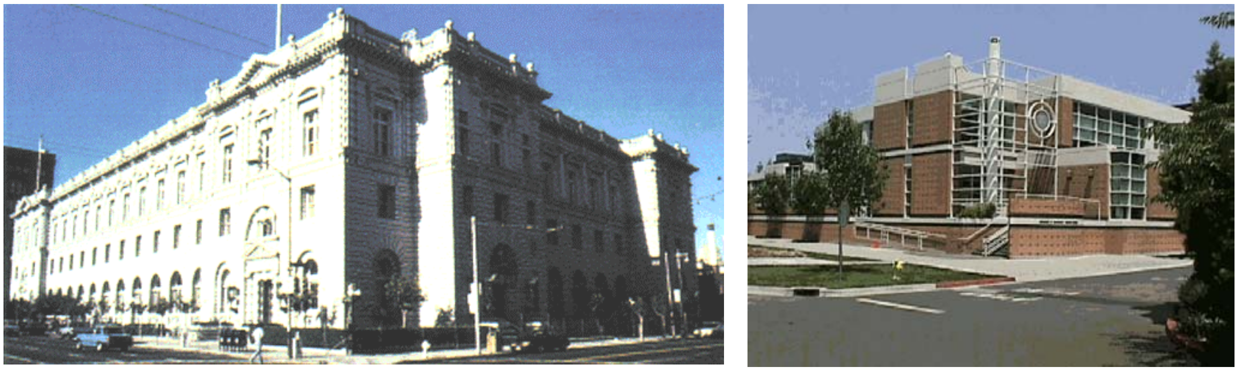

Figure 6. [left]Court of Appeals Building (San Francisco, CA) and [right] McKelvey Building (Menlo Park, Ca) instrumented with GSA funding.

Table 7. Sample Ranking Used for New Madrid Region (from Cassaro, Çelebi and others, 1987)

RANKING INDEX $I = [C_1 \times \sum F_{site} + [C_2 \times \sum F_{structure}]+[C_3 \times \sum F_{other}]$

•C_1, C_2, C_3 – arbitrary coefficients, •F_{site} ,$F_{structure}$, F_{other} weighting factors

•F_{site} {(shallow [0.5] d<100ft, deep[1.0] d >100 ft), (soft [1.0], hard [0.5)}

•$F_{structure}$ {materials of construction – masonry [1.0], RC[.8], Steel[.6], Timber[.5]}, {structural system, Geometry, Long/short period (T>2sec), Availability (calcs, drawings etc)}, •F_{other} (Lifeline/Special Interest, Proximity to New Madrid Fault)

General Area	Structure	Index
St. Louis Area	1. Gateway Arch	8.4
	2. Poplar St. Bridge	8.1
	3. Barnes Hospital Complex	8.0
	4. Southwestern Bell	7.4
Memphis, TN	1. One Memphis Place	7.8
	2. Clark Tower	7.6
	3. First Tennessee Bank	7.6
	4. National Bank of Commerce	7.6
	5. Union Planters National Bank	7.6
	6. White Station Tower	7.6
Louisville, KY	1. Humana Tower Hospital	7.7
	2. Galt House	7.4
	3. First National Bank	7.1
Kansas City, MO	1. AT&T Bldg.	7.4
	2. Mutual Benefit Life	7.3
	3. Mercantile Bank	7.1
Other	1. Baptist Medical Center (Little Rock)	7.3
	2. Lourdes Hospital (Paducah)	7.3
	3. Memorial Hospital (Carbondale)	7.3

3.5. Special Cases - Special Funding

In very rare cases, USGS has obtained special funding which has been used for multi-channel instrumentation purposes (e.g. funding following 1994 Northridge earthquake). Figure 7 shows the nine-story Millikan Library at Caltech Campus in Pasadena and the 15-story UCLA Factor Building in Los Angeles. In both buildings the general objective is to thoroughly document the response of multi-story buildings including the propagation of seismic waves. Another example of an instrumentation scheme with special funding, in this case an upgrade, is the twin towers at Century City, Los Angeles (Figure 8). The objective here, in addition to the general response study aims, is to better facilitate studies of the drift problem by means of recording the responses at several pairs of consecutive floors. Each of these buildings is now also equipped with real-time dynamic GPS units to record displacements at the roof.

Figure 9 shows a special example of instrumentation (accomplished by special funding) at the roof of a 34-story building in San Francisco, CA. The instrumentation includes diagonally deployed accelerometers and GPS units that are connected to a PC. The system is the first permanent dynamic monitoring using GPS to study (a) feasibility of recording real-time displacements and (b) comparing with displacements obtained by double integration of acceleration records. Details of applications of GPS technology for real-time dynamic monitoring of structures is discussed elsewhere (Çelebi and others, 1997, 1999, 2001).

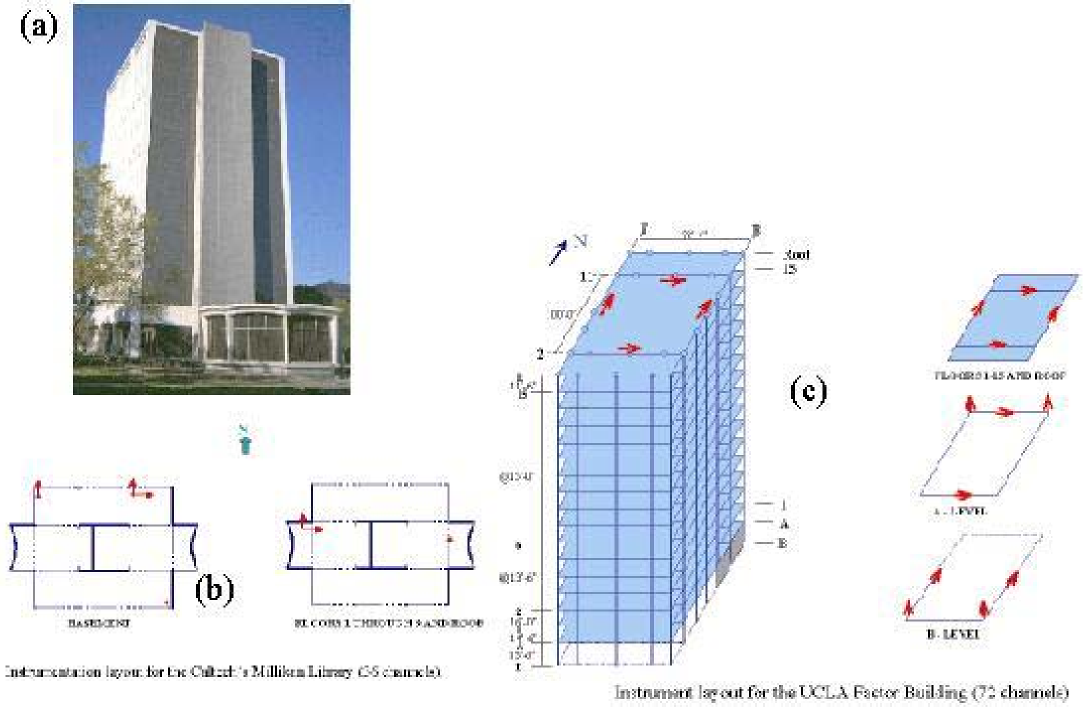

Figure 7. (a) Millikan Library (Pasadena, CA) and (b) its instrumentation scheme, and (c) Factor Building at UCLA (Los Angeles, CA) campus and its instrumentation scheme (Safak, *pers. comm. 2001*).

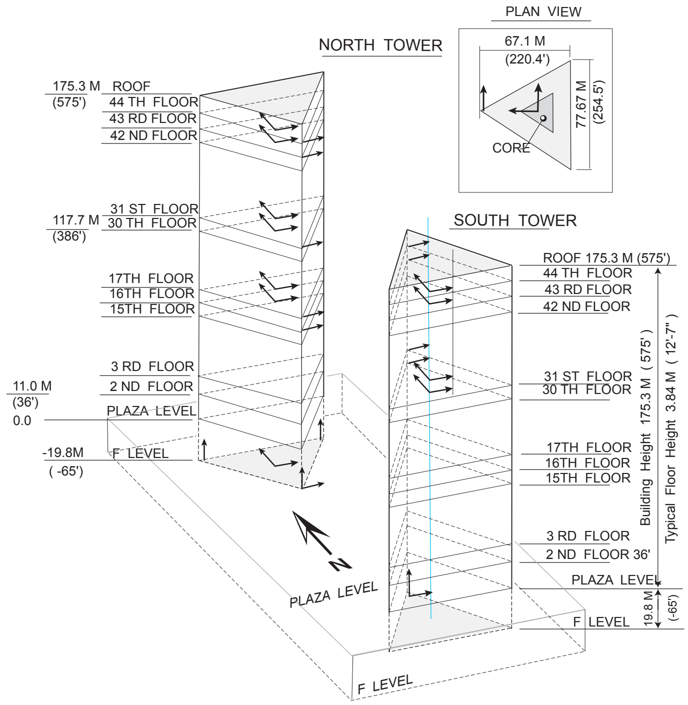

Figure 8. Twin Towers of Century City (extensively instrumented for drift studies)

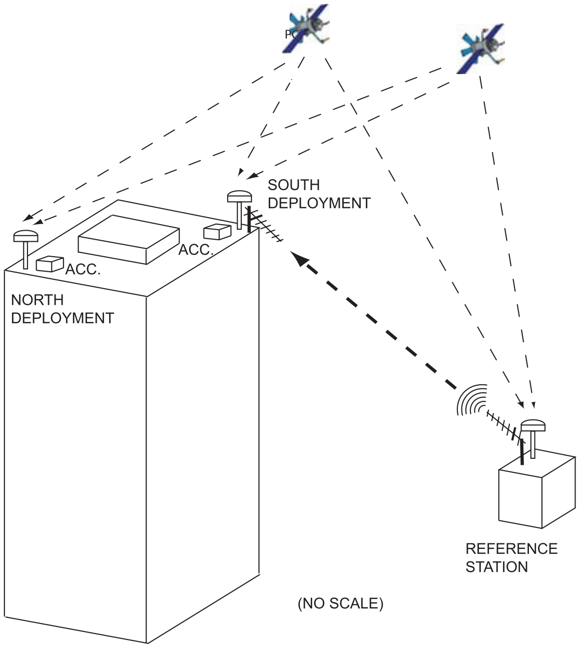

Figure 9. Special Instrumentation Using GPS and Accelerometers (San Francisco, CA.)

3.6. ANSS Funded Instrumentation

Perhaps the first structured and reasonably well funded instrumentation program is expected to emerge from the Advanced National Seismic System (ANSS) initiative (USGS Circular 1188, 1999[4]) now authorized by the U.S. Congress. The circular states "3000 strong-motion instruments should be installed in buildings and structures to resolve outstanding issues in engineering design practice. The strong-motion instruments described here are intended to provide data on critical structures, facilities, and buildings for emergency response applications and for engineering research and applications". This timely initiative is in the process of organizing with respect to structural instrumentation. The instrumentation of the first two buildings (with partial ANSS funding) are now in completion stage (Figure 10). In designing the detailed instrumentation schemes for these buildings, as before, cost limitations have been a major factor.

ANSS has a nationwide regionalized organizational structure; hence, it is essential to determine the balance between the national and regional needs, cost issues, regional selection process and national guidance and oversight to the identified seven regions.

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[4] An Assessment of Seismic Monitoring in the United States – Requirement for an Advanced National Seismic System, U.S. Geological Survey, Circular 1188 , 1999.

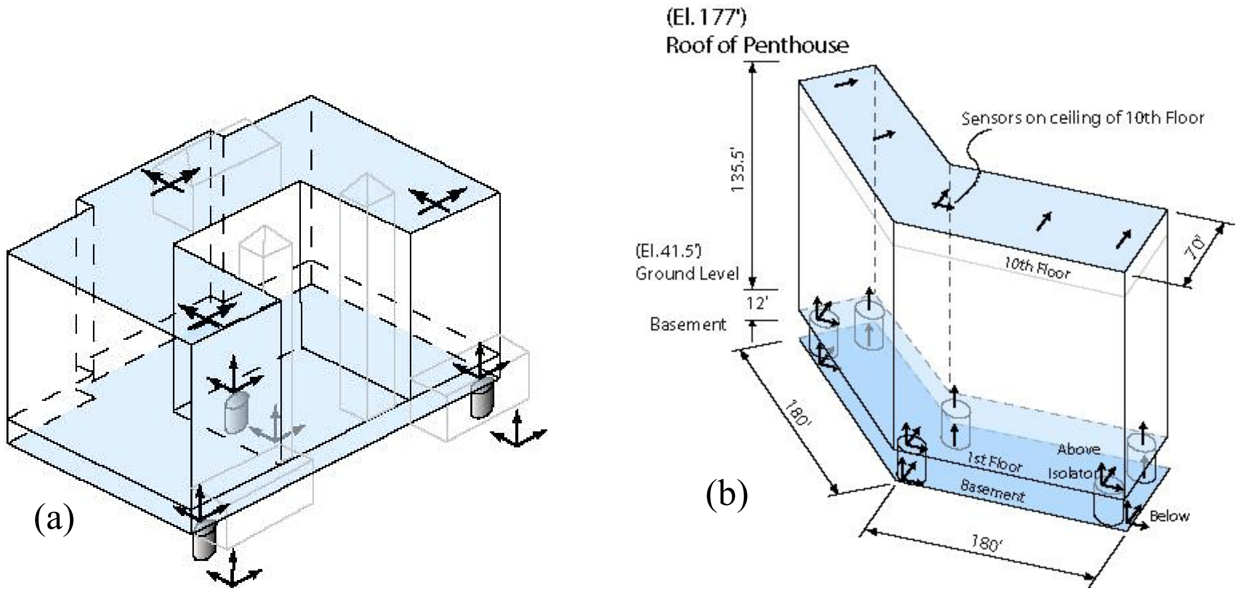

Figure 10. First two buildings instrumented in 2001 with partial ANSS funding (a) in Berkeley, CA and (b) in Palo Alto, CA.

4. ADDITIONAL CONSIDERATIONS AND STEPS

The following additional issues and considerations may influenc the USGS structural instrumentation program decision making:

- Availability of structural drawings and additional site and soils information.
- Ease of permitting.
- Instrumentation of structures needs interconnection of cables between the accelerometers and recorders for triggering and common-time recording. Until such time when wireless remote motion detection and recording is feasible, reliable, and readily available, cables will have to be used to achieve common-time recording. Furthermore, recent digital systems with GPS options require additional cable connection between the GPS antenna unit (which has to be placed at the roof or appropriate location so that the GPS unit can see the sky) and the recording/receiver unit.
- Long-term maintenance arrangements.
- Data retrieval processes.
- Data processing and dissemination responsibilities.

5. OUTSTANDING ISSUES

The following outstanding issues need to be considered in future instrumentation efforts but are not discussed in detail in this paper:

- Soil-structure interaction issues – dedicated specific instrumentation experiment is necessary. USGS held a workshop on this subject in 1992. The recommendations of this workshop are documented in U.S. Geological OFR- 92-295 (Çelebi, Lysmer and Luco, 1992).

- How to instrument to validate performance based design procedures,
- Health monitoring needs and related cost issues for both installation and maintenance.
- Drift assessment related instrumentation needs. USGS already has 4 buildings with multiple sensors on consecutive floors that will yielde data to assess drift ratios. Do we need more?
- Wireless instrumentation – is it here?
- Use of GPS for real-time displacement measurement and limitations. Currently this capability is useful for long-period structures but has great potential for verification of performance based design processes (Çelebi and others, 1998, Çelebi and Sanli, 2001).
- Monitoring capability in large urban areas such as New York – in light of September 11, 2001 event.
- Verification of specific emerging technological application (e.g. unbonded braced system, damper systems used in new and retrofit design and construction).

CONCLUSIONS

This paper presents the current status of and methods used for the structural instrumentation program at the U.S. Geological Survey. The paper also discusses extent to which a structure should be instrumented balanced with the financial resources. Several examples of instrumented buildings are shown. Included in the appendices of the paper are (a) discussions related to a proposal for instrumenting federal buildings and (b) current inventory of USGS extensively instrumented buildings. The paper discusses both historical and current status and methods used for instrumenting structures. Cooperative efforts with private and other federal agencies in enhancing structural instrumentation are summarized. The extent to which a structure should be instrumented by creating a balance between the cost and data utilization needs is emphasized. A recent initiative, the Advanced National Seismic System (ANSS) promises to emerge as a potential means to enhance both the quantity and quality of structural instrumentation to pursue outstanding issues in structural engineering.

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APPENDIX A. FEDERAL BUILDINGS INSTRUMENTATION : A GENERAL DISCUSSION

USGS-NSMP has had a long history of collaboration with other federal agencies in free-field and structural strong-motion network installation and operation. This stems from the fact that USGS is the only NEHRP agency that has the capability as well as responsibility for operation of a nationwide strong-motion and seismic network. To build on this history, USGS started the discussion on a "federal buildings seismic instrumentation" initiative and issued USGS Open-File Report 98-117 authored by USGS, FEMA, NAF and NIST staff (Çelebi and others, 1998). The initiative has been endorsed by CASMP (now COSMOS), ATC, ICSSC Executive Committee and unofficially by GSA. The following are excerpts from USGS-OFR-98-117.

Initially, the program, if funded, would concentrate on instrumenting federally owned and leased buildings.

A.1. Why Instrument Federally Owned Buildings?

- In general, it is very difficult to pursuade private property owners to instrument their buildings. In most cases, it is not possible to get private property owners to allow federal or state (public) agencies to deploy seismic instruments or conduct comprehensive damage surveys. Part of the problem for building owners is the concern for possible future litigation. *This problem can be circumvented by instrumenting federally owned/leased structures.* **Federally owned/leased buildings will not require permits to deploy instruments by a federal agency** nor will they be closed to federal inspection teams following a damaging earthquake. *Making the connection between recording strong ground motions and documenting building performance is essential to a national earthquake engineering program.* [For example, very few (only 2) steel buildings that were damaged during the Northridge earthquake were instrumented (only minimally). Approximately 800 steel buildings that are being investigated for possible damage did not have any instruments in them. Currently, we are having trouble in obtaining permission from one of the owners of a (Northridge earthquake) damaged/retrofitted (SAC) steel buildings to deploy a seismic monitoring system (even at no cost to the owner)].

- Instrumentation of federally owned and leased buildings supports the aims of the 1977 National Earthquake Hazards Reduction Act which refers to priorities such as (a) Assist in developing improved building codes, and (b) Assess earthquake hazards in federal facilities.

- Instrumentation of federally owned and leased buildings is compatible with the spirit of the Public Law 101-614 NEHRP Reauthorization Act. Section 8(a)(1) of this law states: " The president shall adopt, not later than December 1, 1994, standards for assessing and enhancing the seismic safety of existing buildings constructed for or leased by the Federal Government…."

- Instrumentation of new and existing federal buildings is particularly important in light of Executive Orders 12941 [Seismic Safety of Existing Buildings] signed in December 1, 1994 and Executive Order 12699 [Seismic Safety of New Buildings] signed on January 5, 1990. These two executive orders demonstrate both the concern and the need for safety of both the personnel that work within the buildings and the public that use the buildings. Public safety will be enhanced by data acquired by seismic instrumentation will facilitate:

- Assessment of the causes of damage, if any.
- Development of the best methods to repair damaged structures.
- Assessment of the vulnerability of the buildings
- Evaluation of the dynamic characteristics of the buildings for planning for and selection of the best methods to strengthen and retrofit structures, if necessary.

- ***There are approximately*** *84,000 federally owned and 5000 federally leased buildings in Seismic Areas 3 and 4* (as defined in the Seismic Zone Map of the United States in the Uniform Building Code [UBC 1997]) **. *The acquisition value of these buildings is $16 billion (does not include contents).*** Therefore, protection of property is also an issue. The distribution of federally owned/leased properties are illustrated in Table A.1 and Figure A.1 (both from GAO/GGD 92-62 Quake Threatened Buildings, 1992). Instrumentation of federal buildings therefore will lead to improvements in the seismic performance of the buildings, result in safety to employees, public, and protection of public property.

- Federal agencies should set an example by instrumenting federally owned/leased buildings.

- Evolution of new technologies in earthquake resistant design, construction and retrofit practices requires systematic and efficient verification of the performance of structures built with the new technologies or retrofitted with new methods. Such verification can only be accomplished in essence by strategically deploying seismic sensors in such structures to record their performances during future events. Several federal buildings in seismic areas are being retrofitted by such emerging technologies (e.g. VA Hospital in Long Beach, Court of Appeals Building in San Francisco [both buildings using base-isolation], a Navy Building in San Diego [using viscous elastic dampers]).

Table A.1. Statistical Distribution of Federally Owned/Leased Buildings and Employees in Seismic Risk Zones Nationwide (from GAO/GGD -92-62: Quake Threatened Buildings)

Level of Seismic Risk	Level of Expected Damage	Number of Owned Buildings	Number of Leased Space Locations	Number of Employees
VERY HIGH	Most Buildings	32,000	2,000	215,000
HIGH	Many Buildings	52,000	3,000	224,000
MODERATE	Some Buildings	99,000	22,000	668,000
LOW	No Buildings	234,000	41,000	1,759,000

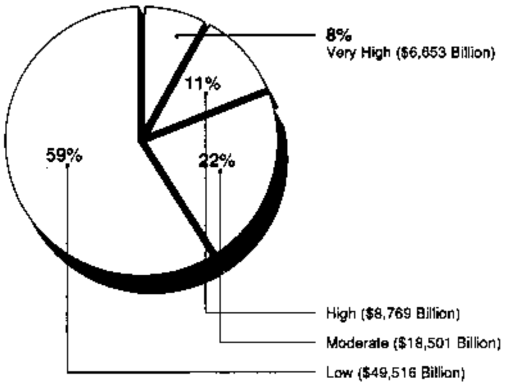

Figure A. 1. Distribution of Federally Owned Buildings and Acquisition Values (from GAO/GGD -92-62: Quake Threatened Buildings)

- The severity of damages to numerous steel structures during the January 17, 1994 Northridge earthquake ($\mathbf{M}_s$=6.7) and Kobe (Japan) earthquake of January 17, 1995 ($\mathbf{M}_s$=6.8) is a perfect example that points to the need for instrumentation of both the new generation design of mid-rise to high-rise steel buildings but also those that were repaired and/or retrofitted by methods developed for the particular damage problem. It is therefore essential to obtain data during future events for response studies to assess the effectiveness and revise and/or improve the new methods of design, construction and retrofitting.

- Federal building inventory should be compatible with at least the recommendations of Uniform Building Code.

A.2. SUGGESTED ACTIONS

(a) Instrumentation of federally owned and leased buildings should be confined only to Seismic Areas 3 and 4 according to the Seismic Zone Map of the United States in the Uniform Building Code [UBC 1997] and on ***a selective basis*** that reflects the objectives of the strong-motion instrumentation of structures program. Alternatively, the areas for instrumentation can be identified by the recent seismic hazard maps of conterminous United States that indicate the highest risk or highest PGA with 10 % probability of excedence (Frankel and others, 1997a and 1997b).

(b) As an initial target, 0.1 % of the buildings can be feasibly instrumented. The number would reach approximately 90 (of the approximately 84,000 federally owned and 5000 federally leased buildings in areas 3 and 4) based on the current information and data base of inventory and geographical distribution of federally owned/leased structures within the seismic areas of the United States). ***This will create a visible program and set an example to other instutions, state agencies, private owners***.

(c) Funding for this effort should be provided by:
  - Individual agencies,
  - Federal Emergency Management Agency (FEMA),
  - General Services Administration (GSA),
  - Department of Defense

- Tie into EO 12941 and 12699
- A new Executive Order
- Other sources [*e.g.* special add-on to budget, NSF, etc.].

(d) USGS should provide expertise, guidance in deployment and in continuous monitoring on a reimbursable basis as well as in management and dissemination of acquired data. **USGS should have umbrella agreements with FEMA, GSA and all other federal agencies.** [USGS currently cooperates with Veterans Administration and to a lesser extent with GSA to instrument, monitor, retrieve and disseminate data].

(e) Seismic instrumentation of federally owned/leased buildings should be included in the revisions of TR 4 & TR 5 prepared by ICSSC.

(f) Final selection of buildings to be instrumented should be made according to a protocol to be developed by an interagency committee drawn from members of the ICSSC. Some of the issues that would be addressed by this protocol include:

A.3. **Selection Criteria**

A.3.1. Building Types

- Which of the 15 model building types [*e.g.* FEMA 178] do we instrument?
- Additional priorities based on occupancy class, usage [re ICSSC TR-17]
- Are there specific lessons or experiments that we need to conduct/learn for a specific building type?
- Do we want to develop "Demonstration" Experiments? [*e.g.* similar structures in close proximity, with and without retrofit/rehabilitation or built to different codes [pre- and post- ICSSC benchmarks]

A.3.2. Building Locations

- Selection with respect to ground conditions (*e.g.* "hard rock" vs. "soft rock")
- Selection with respect to geologic considerations[*e.g.* distance from a specific earthquake source -- strike slip, normal, thrust faults)
- Selection with respect to geographic considerations[*e.g.* California, Seattle, Utah, Central US]
- "Demonstration" Experiments [*e.g.* Two similar structures in close proximity, built on different types of ground]

- Site Surveys for Geologic Conditions (all sites of instrumented buildings should be included in a separate or ongoing site characterization efforts). Some possible considerations for site surveys are:

    - Development of a standardized approach [adopt ATC-26-1 standards for all sites?]
    - Surface geology, Borehole logs [Lithology, Shear wave velocities, other geotechnical parameters]
    - Consideration of 3-D Sedimentary Basin structure, Wave Focusing and Defocusing Effects

- Instrumentation
    - **Hardware**
    - Deployment

  I. **Within the building(s), development of standardized deployment for specific structure classes, and designs**
  Outside the building(s), development of 'rule of thumb' for distance from structure to record true 'free field' measurements [re. soil-structure interaction].

(g) Schedule

- Develop funding base for initiative and/or partnership agreements
- Set up ICSSC Sub-Committee for Instrumentation Issues to deal with :
    (a) development of selection criteria of structures for instrumentation,
    (b) preliminary selection of specific structures,
    (c) strong motion experiments as necessary and feasible,
    (d) instrumentation,
    (e) data archiving & distribution,
    (f) organization of workshops as necessary
- Meeting to finalize building selection and strong motion experiments.
- Deployment

4.0 COST/BUDGET ISSUES:

- The cost of hardware and installation for each building can vary between $30-60 K based on the number of channels involved. It seems feasible to provide a standardized 12-18 channel instrumentation scheme that follows in general the illustration shown in Figure 1b. Therefore on the average $ 50 K per building is the current average expenditure for a building. This normally will include a triaxial free-field station in the immediate vicinity of the building, if physically possible. Therefore, notwithstanding special cases discussed below, hardware and installation costs for 90 federally/owned and leased buildings will be $4.5 M. This amount is for a duration of 5 years based on a calculation that approximately 18 buildings/per year can be instrumented. Instrumentation costs of $50 K for **a building and its contents** is a small investment when compared with the actual worth of a building (and its contents).

- In special cases, the geotechnical , geological and topographical environment of a building could provide opportunities to deploy additional hardware in the vicinity of the building to assess the performance of building structures in relation to those environs. I suggest consideration of $0.5 M for such special cases, again for the 5 year duration. For example,

    - One important aspect of structural response is the soil-structure interaction. In many cases, under specific geotechnical environment, certain structures will respond differently than if that structure was built as a fixed based structure on a very stiff (e.g rock) site condition. This alteration of vibrational characteristics of structures due to soil-structure interaction can be both beneficial and detrimental for their performances. To date, the engineering community is not clear about the pros and cons of SSI. In Mexico City, during the Michoacan earthquake of Sept. 19, 1985, many structures were negatively affected due to SSI because the lengthening of their fundamental periods placed them in a resonating environment close to the approximately 2-second resonant period of Mexico City lakebed. On the other hand, under different circumstances, SSI may be beneficial because it produces an environment whereby the structure escapes the severity of the response spectra due to shifting of its fundamental frequency. Certainly, in a basin such as that of Los Angeles area, SSI may cause both beneficial and detrimental effects in the response of structures. The identification of the circumstances under which SSI is beneficial or detrimental and the parameters is a necessity. **In some cases; therefore, we may wish to deploy additional hardware (e.g. free-field accelerographs on the surface and in boreholes [downhle accelerographs].**

- There are many urban areas in the United States where structures are built on hills. There is now sufficient evidence to consider a phenomenon known as the topographical effect – amplification of ground motions due to the geological and geometrical characteristics of the topography of the site of a building. In some cases; therefore, we could deploy additional free-field accelerograph to assess whether the motions at the site of the building are amplified due to topographical effects.

- ***The total budget envisioned for the 5 year duration of this effort will be $5 M. or $1M /year.***

- **Other costs such as maintenance costs should be arranged by an umbrella agreement between USGS and the agencies involved.**

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Appendix B –USGS National Strong-Motion Program- Cooperative Network Station List: Multi-Channel Buildings [R. Porcella, *pers. comm.* (11/01/01)]

Station number	State	Station name	Station location	Station coord.		Recorder	Serial	Owner
				Latitude	Longitude	type *	number	**

[see footnotes, end of list]

8016	AK	Anchorage; BP Building	East Benson; 12-ch array w/freefield; 14-story	61.1922	-149.8645	K2	1356	USGS
1812	CA(N)	Berkeley; City Hall	Milvia St; 12-ch, array 1; 6-story	37.8693	-122.2711	K2	1790	USGS
1812	CA(N)	Berkeley; City Hall	Milvia St; 12-ch, array 2; 6-story	37.8693	-122.2711	K2	1792	USGS
1103	CA(N)	Berkeley; Great Western Savings	Shattuck Ave; structure array; 12-ch	37.870	-122.269	K2	1031	USGS
1662	CA(N)	Emeryville; Pacific Park Plaza	Christie Ave; 12-ch, array 1; 30-story	37.840	-122.297	K2	734	USGS
1662	CA(N)	Emeryville; Pacific Park Plaza	Christie Ave; 12-ch, array 2 w/freefield; 30-story	37.840	-122.297	K2	615	USGS
1662	CA(N)	Emeryville; Pacific Park Plaza	Christie Ave; 6-ch downhole array	37.840	-122.297	K2	733	USGS
1745	CA(N)	Menlo Park; McKelvey, Bldg 15	Middlefield Rd; 12-ch array w/freefield; 3-story	37.457	-122.169	K2	1074	GSA
1811	CA(N)	Palo Alto; Channing House	Webster St; 12-ch array; 10-story	37.4458	-122.1548	K2	1789	USGS
1447	CA(N)	Palo Alto; VA Hospital	Miranda Ave; Bldg 5; 3-ch, array 1; 4-story	37.387	-122.130	SSA2	125	VA
1447	CA(N)	Palo Alto; VA Hospital	Miranda Ave; Bldg 5; 3-ch, array 2; 4-story	37.387	-122.130	SSA2	126	VA
1447	CA(N)	Palo Alto; VA Hospital	Miranda Ave; Bldg 5; 3-ch, array 3; 4-story	37.387	-122.130	SSA2	127	VA
1447	CA(N)	Palo Alto; VA Hospital	Miranda Ave; Bldg 5; 3-ch, array 4; 4-story	37.387	-122.130	SSA2	128	VA
1446	CA(N)	San Francisco; Chevron Bldg	Market St; 12-ch, array 1; 41-story	37.79	-122.40	K2	556	USGS
1446	CA(N)	San Francisco; Chevron Bldg	Market St; 12-ch, array 2; 41-story	37.79	-122.40	K2	669	USGS
1721	CA(N)	San Francisco; Marina Bldg	Jefferson St; 12-ch array; 2-story	37.805	-122.442	K2	1037	USGS
1800	CA(N)	San Francisco; New Main Library	Larkin St; 12-ch array; 5-story	37.7791	-122.4158	K2	1033	USGS

1239	CA(N)	San Francisco; Transamerica Tower	Montgomery St; bsmt, 12-ch array; 49-story	37.795	-122.401	K2	1038	USGS
1239	CA(N)	San Francisco; Transamerica Tower	Montgomery St; bsmt, 6-ch array; 49-story	37.795	-122.401	K2	608	USGS
1735	CA(N)	San Francisco; US Court of Appeals	Seventh St; 18-ch, array 1; 4-story	37.779	-122.411	MW	168	GSA
1735	CA(N)	San Francisco; US Court of Appeals	Seventh St; 18-ch, array 2; 4-story	37.779	-122.411	MW	169	GSA
482	CA(S)	Alhambra; LA County Public Works Hdqtrs	S. Fremont Ave; 12-ch array; 12-story	34.085	-118.149	K2	699	LDPW
482	CA(S)	Alhambra; LA County Public Works Hdqtrs	S. Fremont Ave; triaxial freefield	34.085	-118.149	K2	533	LDPW
5281	CA(S)	Irvine; Brinderson Tower No. 2	MacArthur Blvd; 12-ch array; 14-story	33.6559	-117.8598	CRA1	318	USGS
5229	CA(S)	Loma Linda; VA Hospital	Benton St; 9-ch array; 4-story	34.050	-117.250	CRA1	230	VA
5106	CA(S)	Long Beach; VA Hospital	Bldg 126; 18-ch array w/freefield; 11-story	33.778	-118.118	MW	158	VA
5106	CA(S)	Long Beach; VA Hospital	Bldg 126; 18-ch array; 11-story	33.778	-118.118	MW	157	VA
5233	CA(S)	Los Angeles; 1100 Wilshire	Wilshire Blvd; 21-ch array; 32-story	34.052	-118.260	CRA1	270	USGS
982	CA(S)	Los Angeles; Century City, 2029 CPE	Century Park East; 18-ch, array 1; 44-story	34.059	-118.413	MW	131	USGS
982	CA(S)	Los Angeles; Century City, 2029 CPE	Century Park East; 18-ch, array 2; 44-story	34.059	-118.413	MW	132	USGS
981	CA(S)	Los Angeles; Century City, 2049 CPE	Century Park East; 12-ch array; 44-story	34.058	-118.412	K2	612	USGS
5405	CA(S)	Los Angeles; UCLA Factor Bldg	Circle Drive S; 18-ch, array 1; 15-story	34.066	-118.441	MW	135	USGS
5405	CA(S)	Los Angeles; UCLA Factor Bldg	Circle Drive S; 18-ch, array 2; 15-story	34.066	-118.441	MW	136	USGS
5405	CA(S)	Los Angeles; UCLA Factor Bldg	Circle Drive S; 18-ch, array 3; 15-story	34.066	-118.441	MW	137	USGS
5405	CA(S)	Los Angeles; UCLA Factor Bldg	Circle Drive S; 18-ch, array 4; 15-story	34.066	-118.441	MW	138	USGS
5082	CA(S)	Los Angeles; Wadsworth VA Hospital	Bldg 1; 9-ch array; 6-story	34.053	-118.452	CRA1	233	VA
5246	CA(S)	Newport Beach; 840 Twin Towers	Newport Center Dr; 12-ch array; 10-story	33.618	-117.878	CRA1	231	USGS
5239	CA(S)	Norwalk; 12440 Imperial	Imperial Hwy; 12-	33.917	-118.067	CRA1	127	USGS

		Highway	ch array 1 w/downhole					
5239	CA(S)	Norwalk; 12440 Imperial Highway	Imperial Hwy; 12-ch array 2	33.917	-118.067	CRA1	128	USGS
5239	CA(S)	Norwalk; 12440 Imperial Highway	Imperial Hwy; triaxial, basement	33.917	-118.067	K2	539	USGS
5239	CA(S)	Norwalk; 12440 Imperial Highway	Imperial Hwy; triaxial, freefield north	33.917	-118.067	Etna	1428	USGS
5239	CA(S)	Norwalk; 12440 Imperial Highway	Imperial Hwy; triaxial, freefield south	33.917	-118.067	K2	591	USGS
5416	CA(S)	Pasadena; JPL Bldg 144	12-ch array; multi-bays	34.202	-118.174	K2	1533	JPL
5410	CA(S)	Pasadena; JPL Bldg 179	High Bay; 12-ch array, east	34.199	-118.173	K2	1098	JPL
5410	CA(S)	Pasadena; JPL Bldg 179	Low Bay; 11-ch array, west	34.199	-118.173	K2	1099	JPL
5415	CA(S)	Pasadena; JPL Bldg 180	18-ch array; 9-story	34.200	-118.175	MW	183	JPL
5412	CA(S)	Pasadena; JPL Bldg 230	16-ch array; 4-story	34.200	-118.174	MW	178	JPL
5414	CA(S)	Pasadena; JPL Bldg 302	12-ch array; 3-story	34.201	-118.169	K2	1532	JPL
5407	CA(S)	Pasadena; Millikan Library	S. Wilson Ave; 18-ch, array 1; 9-story	34.137	-118.126	MW	133	USGS
5407	CA(S)	Pasadena; Millikan Library	S. Wilson Ave; 18-ch, array 2; 9-story	34.137	-118.126	MW	134	USGS
5245	CA(S)	San Bernardino; County Services Center	N. Arrowhead Ave; 12-ch array; 5-story	34.1065	-117.2884	CRA1	302	USGS
5105	CA(S)	San Diego; VA Hospital	Jolla Village Dr; 12-ch array; 6-story	32.876	-117.231	CRA1	305	VA
2490	MO	St. Louis; One Bell Center	Chestnut St; 18-ch array; 43-story	38.626	-90.194	MW	142	USGS
2491	MO	St. Louis; One Bell Center; Visitor Center	Chestnut St; triaxial freefield; 1-story	38.626	-90.191	Etna	1435	USGS
3023	PR	San Juan; Plaza Imaculada	Ponce de Leon; triaxial, array M; 25-story	18.443	-66.062	SSA2	1264	UPR
3023	PR	San Juan; Plaza Imaculada	Ponce de Leon; triaxial, array S1; 25-story	18.443	-66.062	SSA2	1263	UPR
3023	PR	San Juan; Plaza Imaculada	Ponce de Leon; triaxial, array S2; 25-story	18.443	-66.062	SSA2	1262	UPR
3023	PR	San Juan; Plaza Imaculada	Ponce de Leon; triaxial, array S3; 25-story	18.443	-66.062	SSA2	1261	UPR
3023	PR	San Juan; Plaza Imaculada	Ponce de Leon; triaxial, array S4; 25-story	18.443	-66.062	SSA2	1260	UPR

2498	TN	Memphis; Sedgwick Center	Ridgeway Loop; 15-ch array w/freefield; 6-story	35.106	-89.863	MW	126	USGS
2289	UT	Salt Lake City; City/County Bldg	S. State St; 12-ch array; 12-story	40.770	-111.886	K2	1358	USGS
2289	UT	Salt Lake City; City/County Bldg	S. State St; 12-ch array w/downhole; 12-story	40.770	-111.886	K2	1359	USGS
7015	WA	Olympia; DNR Bldg Array	Washington St; 16-ch array; 7-story	47.038	-122.897	MW	141	WDNR
7010	WA	Seattle; Crowne Plaza Hotel	Sixth Ave; 12-ch array; 34-story	47.608	-122.331	K2	1032	USGS

* recorder type: SMA and CRA are analog recorders; Etna, K2, and MW are digital recorders.

**	GSA	U.S. General Services Administration
	JPL	NASA, Jet Propulsion Laboratory
	LDPW	California, Los Angeles Department of Public Works
	UPR	University of Puerto Rico
	USGS	U.S. Geological Survey
	VA	U.S. Department of Veterans Affairs
	WDNR	Washington Department of Natural Resources