GUIDELINES FOR UTILIZING STRONG-MOTION AND SHAKEMAP DATA IN POST-EARTHQUAKE RESPONSE (ATC-54)

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Abstract

The ATC-54 Report, *Guidelines for Utilizing Strong-Motion Data and ShakeMaps in Post-earthquake Response*, prepared by the Applied Technology Council for the California Geological Survey, provides guidance on (1) the use of near-real-time computer-generated ground-motion maps in emergency response, and (2) the use and interpretation of strong-motion data to evaluate the earthquake response of buildings, bridges, and dams in the immediate postearthquake aftermath. Guidance is also provided on the collection of data describing the characteristics and performance of structures in which, or near which, strong-motion data have been recorded.

Introduction

Background

Since the installation of the initial network of nine strong-motion instruments at ground sites and in buildings in California in 1932 (Matthiesen, 1980), the number of strong-motion recording stations and records has grown dramatically. Today there are more than 1000 instrumented sites and structures in California, including buildings, dams, bridges, and other lifeline structures. The instruments are operated by a wide variety of agencies and owners, including the California Geological Survey (CGS), California Division of Water Resources, California Department of Transportation, U.S. Geological Survey (USGS), U.S. Bureau of Reclamation, U.S. Army Corp of Engineers, several universities and university-affiliated centers, utility companies in northern and southern California, and owners of buildings where instruments have been mandated by building code requirements. Hundreds of strong-motion time histories have been recorded at these stations, resulting primarily from large damaging earthquakes, such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes. Such data are available in digital form from the principal network operators (CGS and the USGS) and other sources, including the world wide web virtual data center operated by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS).

Over the last 40 to 50 years, the technology for recording, analyzing, and representing strong-motion data has also advanced significantly. Major advances have included: the development of rapid scanning and processing techniques for converting photographic analog records to digital format; the development and deployment of digital accelerographs; the development of new computer analytical methods that use strong-motion records to verify and refine computer models of structural response and to compute estimated component forces and displacements; and, most recently, the introduction of computer-generated ground-motion maps that provide estimates of the regional distribution of ground shaking within minutes, and without human intervention, after damaging earthquakes.

Collectively the existing network of strong-motion instruments, the existing sets of strong-motion data, and the available techniques and technology for processing, analyzing, and displaying strong-motion data provide an ideal set of tools and information for postearthquake response planning and execution, as well as postearthquake evaluation of structures. In recognition of the enormous potential of these tools and information, and with the realization that practicing professionals do not have guidance readily available on how to take advantage of these current technical capabilities, CGS awarded a Year 2000 California Strong-Motion Instrumentation Program (CSMIP) Data Interpretation Project to the Applied Technology Council (ATC) to prepare the needed guidance. Specifically, the contract required that ATC develop *Guidelines* to: (1) facilitate improved emergency response with the use of near-real-time computer-generated ground-motion maps and; (2) facilitate postearthquake evaluation of structures using strong-motion data from ground sites and instrumented buildings, bridges, and dams. Under this project ATC also provided guidance on the collection of data describing the characteristics and performance of structures in which, or near which, strong-motion data have been recorded.

Guidelines Development Process

The ATC-54 *Guidelines* were developed through a multi-step approach by a multi-disciplinary team of experienced specialists in earthquake and geotechnical engineering, risk analysis, geographic information systems (GIS), and emergency response planning. Initially, the project team identified and described the state-of-the-art in available data resources, building and lifeline inventory data, GIS hazard maps, and loss estimation tools. The next step was to define the state-of-the-practice in emergency response planning at the state, regional, and local level, as well as in postearthquake structural surveys and evaluations. Based on this information, primarily developed through literature reviews and interviews with key individuals in various agencies and organizations throughout the state, an assessment was made of the existing capabilities in emergency response planning and postearthquake evaluation of structures. This assessment served as the basis for determining the level of information and extent of guidance to be provided in the *Guidelines*. The *Guidelines* development process also included a Users' Workshop organized to solicit input on the content and scope of the *Guidelines*. The finalized version of the *Guidelines* is based on input received at the Users' Workshop, as well as review comments from the CSMIP staff and the California Seismic Safety Commission's Strong-Motion Instrumentation Advisory Committee (SMIAC).

Paper Focus and Contents

This paper is seventh in a series of papers initially presented in the SMIP01 Seminar (Brady and Rojahn, 2001; King, Comartin, Reis, Nathe, and Power, 2001; Rojahn, Comartin, and King, 2001) and subsequently in the SMIP02 Seminar (King, Comartin, Reis, Nathe, and Power, 2002;

Rojahn, Brady, and Comartin, 2002; Rojahn, Comartin, and King, 2002). The intent of this paper is to provide an overview of the finalized version of the ATC-54 *Guidelines*, with a special focus on information developed for inclusion in the Guidelines since the SMIP02 Seminar. We begin with a brief discussion of the purpose and scope of the *Guidelines,* followed by a description of the contents of the *Guidelines*. To exemplify the level of detail provided in the recommended procedures, we provide a description of procedures for the evaluation of strong ground motion data to evaluate the potential for damage in nearby buildings. Data, expertise and analysis time requirements are provided for each procedure, and an example procedure is presented in detail.

Purpose and Scope of the *Guidelines*

The *Guidelines* are intended to increase the utilization of strong ground motion data for improving postearthquake response and postearthquake evaluation of buildings, bridges, and dams. They are also intended, as is the goal of all CSMIP data utilization projects, to improve the understanding of strong ground shaking and the response of structures so as to improve seismic design codes and practices.

The audience for this document is diverse and includes local, regional, and state agencies with postearthquake responsibilities; design professionals; facility owners; policy makers; and researchers concerned with the various uses of strong ground-motion data. It is anticipated that most readers will not be interested in all sections of the *Guidelines*.

The *Guidelines* focus on two distinct topics: (1) guidance for using computer-generated ground-motion maps in postearthquake response; and (2) guidance for rapid utilization of near-real-time strong-motion data from ground sites and instrumented structures to evaluate the potential for structural damage.

Organization of the *Guidelines*

The *Guidelines* are organized into four chapters so that users will be able to target quickly their sections of interest (Figure 1). Chapter 1 contains introductory material and pertinent background information. Chapters 2 and 3 (the main body of the report) provide procedures for using computer-generated strong ground-motion maps in emergency response, and for using strong-motion recordings to evaluate the performance of individual buildings, bridges and dams, respectively. Chapter 4 provides guidance for collecting and documenting postearthquake investigation data.

ATC-54: *Guidelines for Using Strong-Motion Data and ShakeMaps in Postearthquake Response*

Contents

Figure 1. Guidelines Table of Contents

Chapter 1 provides a broad range of information designed to familiarize the reader with computer-generated ground motion maps, sources of strong-motion data and computer-generated ground-motion maps (including current web site addresses of principal providers). Chapter 1 also introduces current strategic planning for seismic monitoring statewide, including the goals for the next five years of the California Integrated Seismic Network[1] (CISN). The discussion notes that as efforts are undertaken in coming years to meet these goals, as well as the goals of the proposed Advanced National Seismic System[2] (ANSS), the overview of strong-motion data resources in California provided in Chapter 1 is certain to be superceded by more current information. In general, it is noted that the efforts under the CISN and ANSS will provide additional resources and programs that will undoubtedly result in the more effective implementation of the *Guidelines*.

Chapter 2 covers procedures for using computer-generated maps for postearthquake response (see example in Figure 2). Such maps, known as ShakeMaps, are generated automatically following moderate and large earthquakes and are normally posted within several minutes of the earthquake origin time, without the aid of human-kind. These maps show the distribution of peak ground acceleration and velocity, spectral acceleration at three periods, and an instrumentally-derived, estimated distribution of Instrumental Intensity, which is akin to Modified Mercalli Intensity. Instrumental Intensity maps are based on a combined regression of recorded peak acceleration and velocity amplitudes. Chapter 2 begins with a section on the general framework for the use of real-time ShakeMap data for emergency response, including the data resources and procedures that are

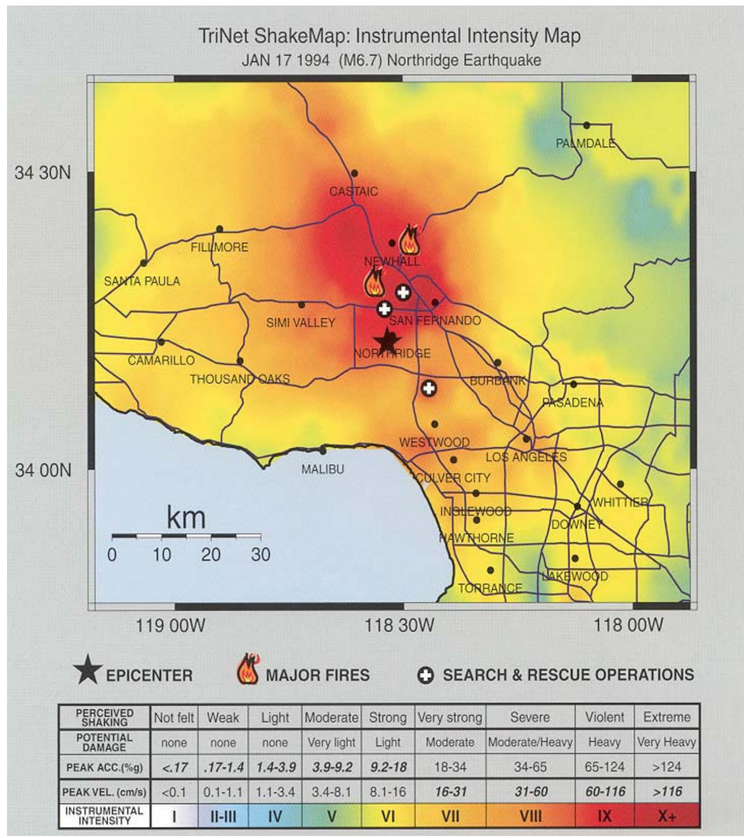


Figure 2. TriNet ShakeMap for the 1994 Northridge, California earthquake (USGS, 2000).

[1] The California Integrated Seismic Network is being proposed to provide the organizational framework to integrate the existing, separate monitoring networks in California into a single seismic monitoring system. The CISN Draft Strategic Plan for 2002-2006 includes the following goals: (1) operate a reliable and robust statewide system to record earthquake ground motions over the relevant range of frequencies and shaking levels; (2) distribute information about earthquakes rapidly after their occurrence for emergency response and public information; (3) create an easily accessible archive of California earthquake data for engineering and seismological research, including waveform data and derived products; (4) maintain CISN infrastructure as a reliable state-of-the-art data collection, processing, and information distribution system; (5) apply the latest research and technology to develop new algorithms for analyzing earthquake data and extracting more detailed information for new user products; and (6) maximize the use and benefit of real-time seismic information and other rapidly evolving tools and technologies through technology transfer to the user community.

[2] The Advanced National Seismic System Network, as currently planned, will be a nationwide network of at least 7,000 shaking measurement systems, both on the ground and in buildings (USGS, 2000).

commonly related to the utilization of strong ground motion data for the various areas of emergency response. The subsequent sections provide guidance (with illustrative examples) on the development and implementation of applications using ShakeMaps for emergency response. The following applications are addressed:

- extent of damaged buildings and planning related safety evaluation inspections;
- condition of hospitals and other emergency response structures;
- impact on utility systems and transportation networks;
- extent of liquefaction, landslide, and inundation;
- casualties and associated need for victim extraction from damaged structures;
- extent of debris from collapsed structures;
- sheltering needs;
- extent of possible hazardous materials release;
- estimates of economic losses; and
- insurance claims.

Chapter 3 provides guidance for interpretation of strong-motion data in the immediate earthquake aftermath (within minutes to days after the earthquake) to evaluate structural performance. Specific procedures are provided for evaluation of strong-motion data in or near buildings and more general guidance on instrumentation and performance assessment is provided for bridges and dams. In general the procedures apply to records of acceleration recorded as a function of time, otherwise known as acceleration time histories, or accelerograms. Extensive background information is also provided, including discussions of (1) prior efforts to evaluate strong-mootion to assess structural performance; (2) the limitations of data from instrumented structures; (3) existing strong-motion networks; and (4) data sources and processing. The main focus of the chapter is a set of procedures for the evaluation of strong-motion data recorded in or near buildings. One set of procedures pertain to the evaluation of ground motion data to determine the likelihood of potential damage in nearby structures. These procedures enable:

- comparisons of ground motions estimated from ShakeMaps with design ground motions (PROCEDURE 1);
- comparisons of recorded ground motions with design ground motions (PROCEDURE 2); and
- estimation of building drift ratios and their significance in terms of damage potential (PROCEDURE 3).

A second set of procedures pertain to the evaluation of strong-motion from instrumented buildings. These procedures include:

- visual examination techniques to (1) identify changes in modal periods of response and estimate mode shapes, story forces, story shears, and overturning moments (PROCEDURE 4); and (2) evaluate high-frequency bursts of acceleration (PROCEDURE 5);

- Fast Fourier Transform moving-window analysis to evaluate changes in building period (PROCEDURE 6);
- displacement time history analysis to estimate building periods, inter-story drift, in-plane bending response, and torsional response (PROCEDURE 7);
- an approach to develop push-over curves using data from more than one earthquake (PROCEDURE 8); and
- system identification techniques to define and verify mathematical computer models of building behavior (PROCEDURE 9).

The description of each procedure includes (1) expertise and time required to execute the procedure; (2) applicable structural framing systems, (3) instrumentation and data required, (4) steps to be taken, and (5) example applications. In certain instances, the procedures applicable to buildings are also applicable to the evaluation of strong-motion data from instrumented bridge and dam sites. The applicability of these procedures is described in those sections of Chapter 3 pertaining to bridges and dams.

Chapter 4 focuses on procedures for documenting structural attributes and performance in the vicinity of ground motion recordings. Similar to Chapter 3, this chapter covers procedures for buildings, bridges, and dams and provides guidance for both instrumented and non-instrumented structures. For non-instrumented buildings, the procedures draw heavily on the approach used after the 1994 Northridge earthquake to collect data on the characteristics and performance of more than 500 buildings within 1000 feet of strong-motion recording sites. For each structure type, the steps for data collection, data formatting and archiving, and data analysis and dissemination are included.

Seven appendices are included that contain supplemental information. Appendix A describes the process that was used to develop this document. Appendix B includes a summary of the most commonly used regional earthquake loss-estimation methods, which are referenced in Chapter 2. Appendix C provides guidance on strong-motion instrumentation of buildings, and Appendix D contains a summary of the most commonly used linear and nonlinear structural analysis software programs. Appendix E provides guidance on strong-motion instrumentation of bridges (with examples instrumented by the California Department of Transportation), and Appendix F provides resources and guidance for strong-motion instrumentation of dams. Postearthquake survey forms are provided in Appendix G.

Procedures for Evaluation of Building Damage Potential Using Strong Ground Motion Data

This set of procedures pertains to the evaluation of recorded or estimated strong ground motion data to determine the likelihood of potential damage to a building or nearby buildings. Data recorded in the upper stories of the building are not used in this set of procedures. The first procedure (PROCEDURE 1, see the following text) uses information from ShakeMaps (described in Chapter 2) to prepare estimated acceleration response spectra for the site(s) under consideration. The remaining procedures[3],[4] use strong-motion data recorded at the ground or basement level of the building, or at a nearby free-field site. For each procedure, information is provided on (1) expertise and time required to execute the procedure; (2) applicable structural framing systems and data required, (3) steps to be taken, and (4) example applications. The requirements for the various procedures that use estimated or recorded ground motion are summarized in Table 1. This table also provides estimates of the uncertainty in the results.

Table 1. Matrix of Requirements for Procedures Using Ground Motion Information and Associated Uncertainty in the Results

Procedure	*Data Required*	*Level of Expertise Required*	*Execution Time (Estimated)*	*Applicable Building Types*	*Uncertainty in Results*
PROCEDURE 1: Comparison of acceleration response spectra computed from ShakeMap data with design lateral-force coefficient	ShakeMap estimates of peak ground acceleration and spectral acceleration response at 0.3 and 1 second; design lateral-force coefficient	Engineering analyst; ability to compute response spectra from ShakeMap data	Minutes to Hours	Low-rise and mid-rise concrete-wall* and masonry-wall buildings (up to 7 stories in height)	High
PROCEDURE 2: Comparison of acceleration response spectra computed for recorded horizontal ground motions with design lateral-force coefficient	Strong-motion record from basement, ground level, or nearby free-field site; design lateral-force coefficient	Engineering analyst	Hours to Days	Low-rise and mid-rise concrete-wall* and masonry-wall buildings (up to 7 stories in height)	Moderate
PROCEDURE 3: Estimation of roof drift ratio using displacement response spectra computed for recorded horizontal ground motions	Strong-motion record from basement, ground level, or nearby free-field site; building height, in feet	Engineering analyst	Hours to Days	Wood-frame, concrete-frame, and steel-frame buildings up to 12 stories in height)	Moderate

***Includes tilt-up buildings**

PROCEDURE 1: Comparison of Shakemap-Derived Response Spectra with Seismic Design Coefficient

This procedure compares acceleration response spectra estimated from ShakeMap ordinates of spectral response to design lateral-force coefficients to evaluate whether the ground motions

[3] PROCEDURE 2: Comparison of Acceleration Response Spectra Computed for Recorded Horizontal Ground Motions With Design Lateral-Force Coefficient

[4] PROCEDURE 3: Estimation of Roof Drift Ratio Using Displacement Response Spectra Computed for Recorded Horizontal Ground Motions

that occurred at the base of a building exceeded those associated with the lateral-force coefficient used in design.

Expertise and Time Required. This procedure requires the ability to (1) interpret ShakeMaps that provide spectral ordinates for 0.3 second and 1.0 second periods; (2) compute response spectra using this information; and (3) estimate the lateral-force coefficient for the building under consideration. This requires a level of expertise normally attributable to an engineering analyst (Professional Engineer), with an ability to use MapInfo or equivalent geographic information system (GIS) software.

The procedure can be executed in minutes to hours, assuming the person executing the procedure has the necessary expertise.

Applicability and Required Data. This procedure applies to stiff, low-rise and mid-rise buildings (up to seven stories), such as masonry-wall, concrete shear-wall, and tilt-up buildings. The procedure requires the computation of acceleration response spectra using spectral ordinates of horizontal motions taken from ShakeMaps. The procedure also requires an estimate of the lateral-force coefficient used in design.

Steps. The procedure consists of the following steps:

1. For the main shock under consideration, download the following maps from the ShakeMap website (www.trinet.org): (1) map showing contours of peak ground acceleration (PGA); (2) map showing contours of pseudo acceleration response for 0.3 sec period ($S_{a,0.3}$); and (3) map showing contours of pseudo acceleration response for 1.0 second period ($S_{a,1}$). Transfer electronic versions of the maps to MapInfo, or equivalent. Locate the building site on each contour map. Determine the value of PGA, $S_{a,0.3}$, and $S_{a,1}$ for the site. Construct an acceleration response spectrum for 5% effective damping, based on the following: (1) $S_{a,0}$ is the PGA value; (2) $S_{a,0.3}$ defines the level of the plateau that will span from T_o to T_s; (3) T_s for 5% damping is given by $S_{a,1} / S_{a,0}$ (see FEMA 356, Equation 1-11); (4) T_o is given by 0.2 T_s (see FEMA 356, Equation 1-12); and (5) the acceleration decreases as $1/T$ from the right-hand end of the plateau, passing through the map value for $T = 1$ sec.
2. Estimate the fundamental period, T (seconds), of the building under consideration, using the following equation: $T = 0.025h^{0.75}$, where h (ft) is the height of the building. The equation is based on the period equation given in FEMA-356 (ASCE, 2000) for "other" buildings; the multiplier of 0.025, however, has been increased from 0.02 (an increase of 25%) to account for the conservative nature of the FEMA 356 equation, which is recognized in the FEMA 356 commentary section as under estimating periods during strong ground shaking.
3. Calculate the average acceleration response in the period range, $0.8T$ to $1.2T$, where T is the fundamental period of vibration. (Averaging the spectra over a range of periods close to the estimated fundamental period of the building is recommended, to smooth the peaks and valleys inherent in acceleration response spectra.)
4. Determine the lateral-force coefficient, defined as the design lateral force divided by the building weight, by referring to the original design calculations, if available, or by determining the design date and referring to the design lateral-force equation in the code that likely was used in the design process. For a multistory building, only a fraction of the building weight is considered to participate in the first mode response. This factor is called

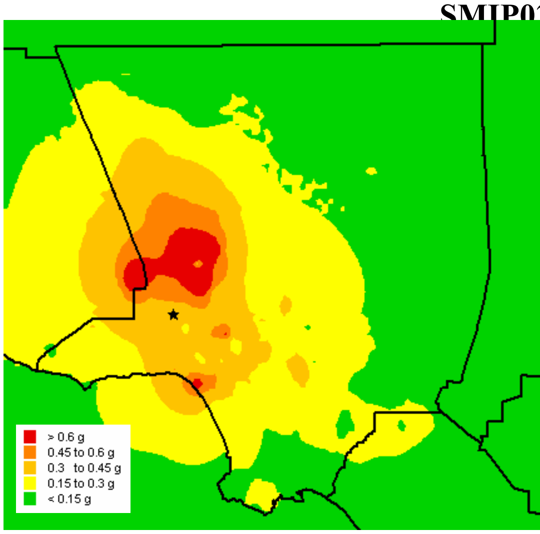
Figure 3. Example Building Used to Illustrate Procedure 1 (ATC, 2000).

the modal mass coefficient, α_1. In this case, the lateral-force coefficient is defined as the design lateral force, V, divided by $W\alpha_1$, where W is the building weight, and α_1 can range from about 0.7 to 1.0, depending on the shape of the first mode. Further details can be found in the ATC-40 Report (ATC, 1996), Section 8.2.2.1, Figure 8-5. If the applicable building code is not available, consult other resources, such as Appendix C of the ATC-9 report (ATC, 1984), or the ATC-34 report (ATC, 1995b), which contain lateral-force equations for various years of construction. If the original design calculations are not available it will be necessary to assume values for the parameters used in the assumed lateral-force equation, such as the soil factor (if any), the seismic zone factor, building period, and other parameters, including K and R_w values used to reflect the earthquake-resisting properties of the building.

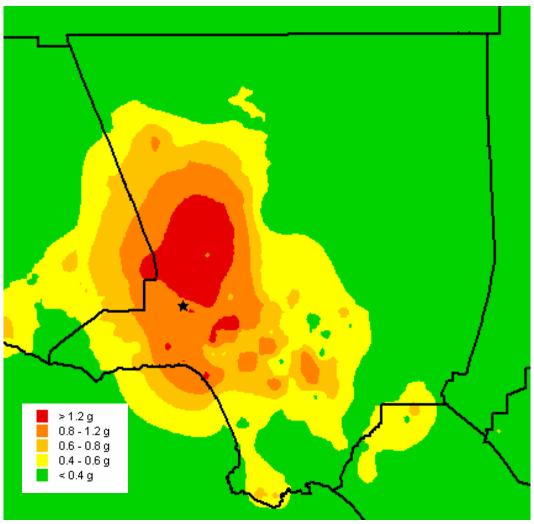
5. Multiply the lateral-force coefficient by 1.4 to account for actual capacities of structural materials being approximately 40% higher than assumed in design (ATC, 1995a).

6. Compare the average acceleration response computed in Step 3 with the lateral-force coefficient, multiplied by 1.4, computed in Steps 4 and 5. Interpretation of these values requires careful consideration of the lateral-force framing type and design requirements. Ratios of the average acceleration response (near the fundamental period) to the design lateral-force coefficient less than one imply that damage is unlikely. Ratios greater than one require careful interpretation of the perceived earthquake-resisting attributes of the building and the assumed or confirmed K or R_w values used in design.

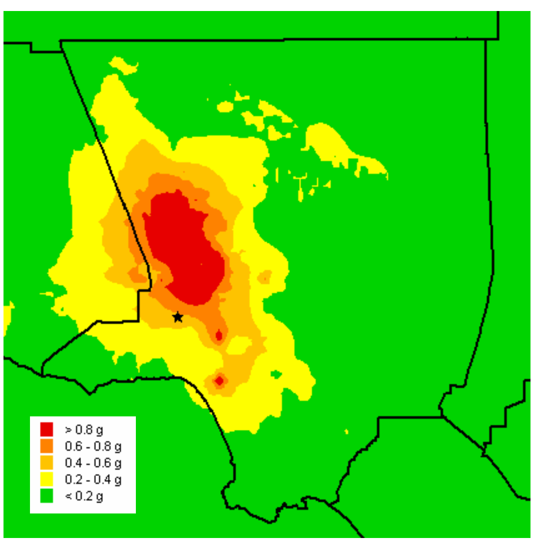
7. Based on the interpretations made in Step 6, and if the building is not obviously damaged, determine if the building should be evaluated for hidden damage by a structural engineer experienced in seismic design.



(a) PGA contours



(b) Pseudo acceleration response at



(c) Pseudo acceleration response at

Figure 4. ShakeMaps for 1994 Northridge earthquake showing location of example building (star).

Example. The building in this example is a tilt-up building located in the San Fernando Valley (see Figure 3), designed in 1978 and constructed in 1979 (location and design and construction dates selected for this example are hypothetical). The building was strongly shaken by the 1994 Northridge earthquake and no damage to the exterior was observed by the postearthquake safety assessment team that inspected the building a day after the main shock. Since the team does not have access to the interior or the roof of the building, they are interested in reviewing quantitative information on strong shaking that would assist them in determining likelihood of hidden damage. The ideal characterization would be a plot of acceleration spectral response.

In *Step 1* ShakeMaps showing contours of PGA, $S_{a,0.3}$, and $S_{a,1}$ were downloaded from the TriNext web site (Figure 4a,b,c) using wireless technology and a lap top computer. Through the use of MapInfo the assessment team was able to determine the following ground motion parameters for the site: PGA, 0.37g; $S_{a,0.3}$, 1.1 g; $S_{a,1}$, 0.56 g. Based on these values and using the instructions of *Step 1*, the response spectrum shown in Figure 5 was constructed in a Microsoft Excel spread sheet.

In *Step 2*, the period of the example building was determined using the default formula for "other buildings", and assuming the story height is 18 ft, as follows:

$$T=0.025\ h^{0.75} = 0.025 \times (18)^{0.75} = 0.22 \text{ sec.}$$

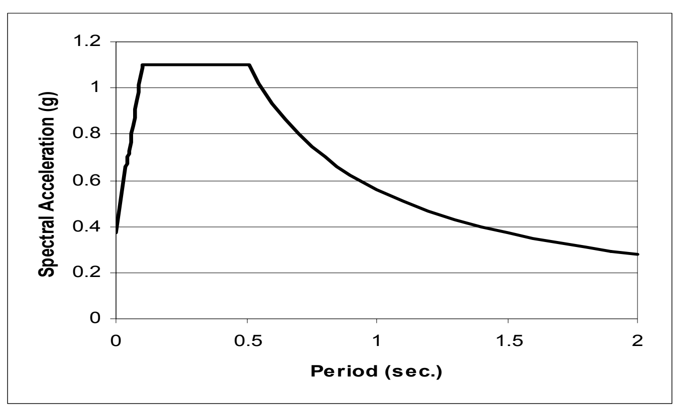


Figure 5. Acceleration response spectrum for example building created from ShakeMap data.

The average amplitudes of acceleration response in the period range from 0.18 to 0.26 sec (0.8*T* to 1.2*T* range) were calculated in *Step 3* using acceleration response values from the Excel spread sheet. The average of these amplitudes is 1.1 g.

In *Step 4*, the lateral-force coefficient was estimated to be 0.186, based on the team's knowledge of construction practices in the area and the formula for calculating base shear in the 1976 *Uniform Building Code*. Divided this amount by the modal mass coefficient, which is assumed to be 1.0, and multiplying the result by 1.4 in *Step 5* yielded an assumed effective lateral-force coefficient of 0.26.

Finally, in *Step 6*, a comparison of the average acceleration response for periods close to the calculated fundamental period of the building (0.22 second) with the assumed lateral-force coefficient (from *Step 5*) indicated that the average acceleration response, based on recorded motions at the site, was 1.1/0.26 = 4.2 times higher than the assumed lateral-force coefficient. Given the high earthquake accelerations, relative to the design coefficient, the postearthquake safety assessment team gained access to the building and determined that there was insignificant structural damage. The building was subsequently posted per the ATC-20 procedures (ATC, 1989, 1995) as INSPECTED (apparently safe based on an interior and exterior inspection).

Concluding Remarks

The ATC-54 *Guidelines* document is envisioned as a living document, with periodic updates and revisions as new knowledge, information, and technologies become available. The Applied Technology Council and the Strong-Motion Instrumentation Program of the California Geological Survey intend that the document remain as a primary resource for guidance on the use of computer-generated ShakeMaps in emergency response and for guidance on state-of-the-art procedures for rapid evaluation of structures using strong-motion data. Suggestions for improvement are encouraged.

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