Learning from Earthquakes: a Survey of Surveys

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This paper presents a literature review of efforts to learn from earthquakes: collecting, archiving, and disseminating information. The emphasis is on primary sources, i.e., data-gathering instruments or investigations that include direct observation of earthquake effects. The study addresses seismology and geotechnical engineering; safety and damage to individual buildings; performance of large numbers of buildings and of particular structure types; damage to nonstructural components, lifelines, and industrial equipment; socioeconomic impacts including casualties and business interruption; insurance loss data; and methods and databases that characterize existing facilities. The present paper also examines a few efforts to aggregate data across studies, to incorporate data into predictive models, or to disseminate information for use by others, with attention to how well primary sources meet these needs. A number of common themes appear in the publications examined here. These include the need to document for both data-gatherers and readers clear procedures and definitions; the value of publishing raw data and data-gathering instruments to support conclusions and to allow for aggregating data with efforts by others; the value of standard facility-description and damage categorization systems; avoidance of data loss by publishing in multiple formats and media; the value of coordinating data-gathering efforts and disseminating common tools and databases; the need to provide for statistical analysis; the danger of over-aggregation; the value of providing incentives to survey respondents; the importance of dense instrumentation; the use of predictive tools for data-gathering; and the need for a permanent, curated earthquake experience data archive.

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INTRODUCTION

OBJECTIVES

The scientific aspects of earthquake engineering follow the pattern of all science: observation, hypothesis, prediction of the consequences of that hypothesis, and observations to test those predictions. In the case of earthquake engineering, laboratory experimentation can be used to test many hypotheses, and much valuable science can be developed using reaction walls, shake tables, centrifuges, and computer simulations. Nonetheless, many systems are too large and costly to test in the lab, so we turn to the real-world laboratory of earthquake experience.

The problems with the real-world laboratory are that earthquakes occur infrequently, much of the damage and loss data are highly perishable, and the data can be expensive to gather. Earthquake engineers must therefore be prepared before the earthquake to gather the *right* data—data needed to improve foreseeable preparedness, response and recovery decisions, and data needed to test scientific hypotheses—and to make these data available to the professional and research community. The questions addressed by this paper are:

- What are the right data, and how should they be gathered and disseminated?
- What resources currently exist to aid in learning from earthquakes?

To answer these questions, this paper reviews past efforts to learn from earthquakes. It surveys historic data-collection protocols and dissemination efforts, and presents lessons learned from these efforts. The range of topics on which earthquake data are gathered is quite diverse, making an exhaustive survey impractical. Only a limited sample of references on each topic is examined here. For each reference, the authors' objectives are briefly summarized, along with their approach, the lessons they draw from their efforts, and in some cases, additional lessons that can be extracted for present purposes.

Topics addressed here include issues of seismology, geotechnical engineering, structural engineering, casualties, and business impacts. In addition to post-earthquake data gathering, some attention is paid to recent studies that use historic data gathered by others, and the conclusions these authors draw about data-collection needs. Some important topics are ignored, such as ground failure, tsunami, fire following earthquake, emergency services, and indirect economic losses.

This paper is accompanied by an electronic appendix that contains copies of various data-collection forms, data categorization systems, and other reference material. These materials would be too voluminous to include in the main body of the report, but should nonetheless be available for reference. The electronic appendix is also offered as an example of how raw data and data-collection instruments can be thoroughly documented without sacrificing brevity in a summary article.

PREVIOUS LITERATURE REVIEW

Past studies have examined the question of how best to gather post-earthquake data. As part of the ***NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*** **(*CUREE, 1997*)**, 18 experts in 11 sub-disciplines offer a series of one- to two-page overview statements, addressing among other questions, how future post-earthquake research should be conducted compared with the general pattern of the Northridge Earthquake. Although the most common answer was "with more money" (five of 18 mentioned funding), four of the experts urged advanced planning for multiple PIs to gather specific, fragile, or statistical data using a common, standard methodology. Other common specific answers were coordination conferences, better coordination with transportation agencies, and more attention to multiple-year research.

GENERAL RECONNAISSANCE

EERI FIELD INVESTIGATION PROCEDURES

Before examining specialized earthquake loss-data collection efforts, consider the general effort undertaken by the Earthquake Engineering Research Institute (EERI) to collect earthquake experience information. The ***Earthquake Engineering Research Institute's (2000) Post-Earthquake Investigation Field Guide*** specifies procedures for rapid earthquake reconnaissance of a nearly exhaustive set of earthquake phenomena: geoscience and geotechnical engineering; tsunamis; nature of and damage to engineered buildings and industrial facilities; lifelines and transportation structures; architectural and nonstructural elements; emergency management and response; societal impacts; and urban planning and public policy.

These two-page forms query the surveyor for summary information about the facility that is subject to loss, along with mostly expository descriptions of the performance of the feature in question, as opposed to selection from predefined lists or recording of well-defined numerical performance metrics. The forms are distributed in paper and electronic format. (Copies are included in the electronic appendix of this paper.) Currently, they are filled out on paper, although EERI is exploring implementing these forms on palmtop computers, wireless communication, and a centralized database.

The EERI forms are useful for providing information about the nature of geotechnical and engineering failure and consequent losses. The surveyor can use the forms to document failure modes, factors that may have contributed to failure, and secondary impacts. They primarily serve to focus attention on novel phenomena and to answer the question of whether anything unusual or unexpected happened. They do not provide statistical information, and cannot be used to inform damage or loss models for purposes of quantifying performance of estimating the benefits of mitigation. Data analysis is left to the reconnaissance team. No procedures are specified for publishing the raw data forms.

GENERAL PROGRAMS FOR DATA COLLECTION

The National Earthquake Hazards Reduction Program (NEHRP) has recently drafted a ***Plan to Coordinate NEHRP Post-Earthquake Investigations*** (***Holzer et al., 2002***). The draft plan specifies "a framework for both coordinating what is going to be done and identifying responsibilities for post-earthquake investigations." While the plan does not specify particular data-gathering efforts that should be performed, it proposes nine scheduled tasks to facilitate these efforts, and assigns them to various NEHRP agencies and other entities: (1) implement the plan for potentially damaging earthquakes; (2) establish an incident website; (3) establish a field coordination clearinghouse; (4) select an individual to coordinate NEHRP investigations; (5) meet to summarize initial reconnaissance results and to recommend further data-gathering efforts; (6) meet to discuss supplemental funding (this task is not yet definite); (7) convene a workshop to prioritize investigations; (8) solicit investigation proposals; and (9) disseminate results. It offers four recommendations to improve the comprehensiveness and efficiency of earthquake investigations and data archiving. These are: improve documentation of performance data; increase the use of information technology; formalize data management and archiving; and establish appropriate funding for post-earthquake investigations.

Reitherman (1998) proposes the development of a program of study for collecting nonstructural-component performance data. He offers general recommendations for such a program, rather than discussing particular data-collection protocols or categories of nonstructural components to be studied. He urges that, whatever survey instruments are used, they should be used to gather statistical data from large numbers of facilities, with subsequent study in greater depth on a smaller sample of facilities. The data to be gathered should indicate the fraction of nonstructural components of various categories in various performance levels, when subjected to various levels of seismic excitation. The author estimates that the cost to perform such studies at $750,000 for an event similar to the 1994 Northridge Earthquake, increasing by a factor of 1.5 for every doubling of the size of the event, measured in terms of direct property loss.

SEISMOLOGY AND GEOTECHNICAL ENGINEERING

SEISMIC SOURCES AND GROUND-MOTION TIME HISTORIES

Consider now efforts to gather, analyze, and disseminate particular earthquake data. ***TriNet (2002)*** is a collaborative project to determine seismic sources and collect seismograms and accelerograms for Southern California. It uses a network of 600 stations distributed throughout Southern California, of which approximately 450 have strong-motion instruments, and 150 that have both broadband seismometers and strong-motion accelerometers. The latter set provides continuous digital telemetry via TCP/IP to a central computing facility and to a redundant, active standby facility. The former send their recordings when triggered.

When the instruments indicate that an earthquake has occurred, the central computing facility automatically determines the earthquake origin time, magnitude, location, and source information in near-real-time. Staff seismologists review computed earthquake information, and webservers display the information via a website. This infrastructure collects and archives the continuous telemetry at 20 samples per second. This means that anyone can recall a record from any of these 150 TriNet sites from any point in time since the instrument was installed, for any duration of interest. Furthermore, higher-sampling-rate records (up to 100 samples per second) are archived and available for any instrument in a region near an earthquake of magnitude $M \geq 1.8$, and from the entire network for events of magnitude $M \geq 4$. TriNet is thorough.

TriNet began in 1997, a successor to earlier programs such as the 1990 Caltech US Geological Survey Broadcast of Earthquakes (CUBE) project to provide real-time earthquake information. The system is a collaborative effort of the California Institute of Technology, the U.S. Geological Survey, and the California Geological Survey (formerly the California Division of Mines and Geology). In 2002, TriNet finished, and merged with a similar, Northern-California effort to become the ***California Integrated Seismic Network (CISN, 2001)***. CISN in turn will represent the California region of the currently-developing ***Advanced National Seismic System (ANSS, U.S. Geological Survey, 2000a)***, which if fully funded will be similar to TriNet and CISN, but with a national scope, a more extensive seismic network, and with the addition of instruments in buildings.

The methodologies for determining source information are fairly mature. TriNet, CISN, and eventually ANSS, represent examples of how these methodologies are implemented with sensors, communication, and computer facilities to provide publicly available, rapid, reliable estimates of source mechanism, origin time, location, and magnitude. The archive makes it easy to retrieve these earthquake data at a later time.

Note that the sensors in TriNet and CISN are primarily free-field instruments, important for determining source information, but of limited value for structural engineering purposes, at least compared with instruments in important facilities. There is however no fundamental difference between free-field strong-motion accelerometers and accelerometers in buildings. Consequently, there is no reason why these networks could not be used as resources for collecting and disseminating building-motion data, other than institutional barriers and priority differences between seismologists and structural engineers.

The California Strong-Motion Instrumentation Program (CSMIP, California Geological Survey, 2002a) since 1972 has maintained a network of accelerographs to measure strong shaking. In 2002, the network includes more than 900 stations: 650 record ground motion, 170 stations are located in buildings, 20 are on dams and 60 on bridges. The more modern of these instruments sends its telemetry automatically to CSMIP headquarters when it experiences strong motion. The strong-motion data are available for download from the California Geological Survey's Strong Motion Data Center (California Geological Survey, 1999).

The Consortium of Organizations for Strong-Motion Observation Systems (COSMOS, 2002a) offers an alternative to the TriNet-CISN paradigm for disseminating waveform data. COSMOS provides a database of strong-motion recordings of earthquakes in the United States, Canada, Mexico, Central America, South America, Japan, Taiwan, New Zealand, Armenia, Turkey, and elsewhere. The novelty of this database is that the recordings are collected and maintained by the member institutions such as CSMIP, not by COSMOS itself. COSMOS instead offers a virtual datacenter, virtual in that it provides pointers to the data that the member networks actually maintain. The distinction is immaterial to the user, who sees a nearly seamless dataset of worldwide recordings. Because of the variety of data sources, the strong-motion recordings vary in formats, but these formats are fully defined at the COSMOS site.

SHAKING SEVERITY

Byerly and Dyk (1936) offer an early methodology used to gather data for regional intensity maps. The authors describe a method to ascertain subjective ground-motion intensity measures using postcard questionnaires. The authors find that, when such questionnaires are sent after an earthquake has occurred, the reply rate is low. They improved upon this system by ensuring that postcards are kept on hand by preestablished correspondents. Postmasters, field engineers of an oil company, and employees of large public-service corporations were secured as regular reporters. The questions asked on the questionnaire can be used to determine intensity according to the Modified Mercalli Intensity (MMI) scale. The new system generated large numbers of replies—thousands per year between 1930 and 1936. The authors also address dissemination of results. Duplicate indexed archives were maintained in Pasadena, the University of California at Berkeley, and Washington, D.C. Archives were publicly available. A sample questionnaire is provided in the electronic appendix to the present report.

While instrumental measures of ground motion have largely eclipsed subjective measures (with the notable exception of "Did you feel it?" as described below), one can draw several conclusions and recommendations that are relevant today:

1. *Manage reporting in advance.* Reporting material should be in the hands of skilled and impartial correspondents before the earthquake occurs.
2. *Refresh the reporting process regularly.* The authors recommend reminding correspondents that ongoing data-collection programs are still active and expressing appreciation for their reports.
3. *Human reactions matter.* The authors find that questionnaires are useful checks or supplements to instrumental measures.
4. *Partiality matters.* The authors argue that volunteers who come forward and show interest in the subject are "not the best observers, since they are concerned with some particular theory … rather than [reporting] the phenomena exhibited by the shock."
5. *Data should be publicly available.* The general availability of publicly collected data is not a given. The authors went to special effort to ensure their availability.

"Did you feel it?" (U.S. Geological Survey, 2001) is a 21st-Century approach to creating regional subjective intensity maps, called Community Internet Intensity Maps (CIIM). It uses an Internet-based system that provides, collects, and analyzes questionnaires from the public. The questionnaire allows people who actually experienced an earthquake to describe their experience, the effects of the earthquake, and the extent of damage. It uses an algorithm developed by Dengler and Dewey (1998) for determining community decimal intensity. (Community decimal intensity is similar to MMI but with intensity measured in decimal terms.) Wald et al. (1999) have adapted Dengler and Dewey's (1998) phone-survey approach for this Internet application. The resulting questionnaire, a sample of which is provided in the electronic appendix of this report, includes questions on the correspondent's identify, location, situation during the earthquake (i.e., indoors, outdoors, etc.), qualitative description of the shaking (weak, mild … violent), duration of motion, personal reaction, and visible effect of the earthquake on structures and objects.

There are interesting similarities and contrasts between the CIIM system and that described by Byerly and Dyk (1936). Both cases use a standard questionnaire that relates directly to the MMI scale. Both manage the reporting in advance. Both allow for direct comparison between subjective and instrumental intensity measurements. Byerly and Dyk (1936) rely on preestablished, disinterested correspondents, whereas the CIIM process relies on volunteers who come forward and show interest in the subject, although CIIM accounts for the resulting bias. Both provide detailed data for public use in archival locations, although "Did you feel it?" provides raw data only after they are stripped of personal information, by request from the U.S. Geological Survey, Pasadena office (Wald, 2002).

ShakeMap (TriNet, 2001) is a product of TriNet and CISN that uses the strong-motion network to create maps of shaking severity. These images, called ShakeMaps, display shaking severity for individual events in units of peak horizontal ground acceleration, peak ground velocity, and instrumental intensity (an estimate of MMI based on instrumental measurements). ShakeMaps are available in a format that can be input to the HAZUS software (Federal Emergency Management Agency, 1999) for use in loss estimation. The ShakeMap working group notes that, with the current station distribution, data gaps are common, particularly for smaller events and earthquakes near or outside the edge of the network. They also note that, "Since ground motions and intensities typically can vary significantly over small distances, these maps are only approximate. At small scales, they should be considered unreliable." Conclusions:

1. *ShakeMaps are valuable at the macros scale.* They provide a rapid, readily comprehensible, and reasonably accurate macro-level shaking severity within minutes of the occurrence of strong shaking. These maps are well archived, easily retrievable, and consciously integrated with public loss-estimation software.
2. *ShakeMaps are limited by the density of stations available.* To employ ShakeMaps for ground-shaking assessment at the building-specific level will require a much greater density of instruments.
3. *ShakeMaps do not depict ground failure.* Perhaps 5-10% of earthquake damage is attributable to landslide, liquefaction, lateral spreading, and faulting. This peril is not depicted by ShakeMap, although research efforts to do so are underway (Wald, 2002).

SITE CONDITIONS

One can divide site data into two categories: (1) regional maps showing engineering geology, faulting, liquefaction, and landslide, and (2) site soil boring logs that show a profile of soil material, water content, and density. There exists in the United State no centralized entity like COSMOS or CISN to compile and disseminate this category of earthquake information. Various government and private entities collect, maintain, and disseminate maps of active fault traces, landslide and liquefaction hazard, regional and local engineering geology, and soil borings.

Regional Maps

The U.S Geological Survey's ***National Geologic Map Database Project (U.S. Geological Survey, 2000b)*** provides a GIS-enabled searchable bibliography of paper maps and sources for obtaining them. Some text publications are available online; maps are typically available only in paper format. Some states publish additional information. A notable example is the ***California Geological Survey (2002b, c, d)***, which distributes paper and downloadable electronic maps of fault-rupture zones, the state geologic map at various scales, and maps showing liquefaction and landslide potential. The maps can be informative of general site conditions for a building, such as approximate wave velocity, proximity of fault traces, and gross liquefaction and landslide potential.

Soil Borings

Soil-boring logs are more valuable than regional maps for discerning site characteristics. They are typically created for large structures as part of geotechnical studies for foundation design, and provide crucial information for characterizing and understanding site amplification and ground-failure potential. The geologic studies are available for a limited number of sites from city building departments. In addition, utilities and transportation departments can maintain large collections of soil-boring logs for their facilities.

At present there is no general index of locations where such borings are available, but one appears to be developing. A collaborative effort called ***ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake, 2000)*** has collected and disseminates via a web page soil-boring logs for (currently) 45 strong-motion sites, for purposes of understanding the response of these instruments in the Northridge Earthquake. The ROSRINE project has served as impetus to a multi-agency project called the ***Virtual Geotechnical Database (COSMOS, 2002b)***. The short-term goal of this entity is to develop a pilot web-based system to link and disseminate geotechnical data possessed by Caltrans, Pacific Gas and Electric (PG&E), the California Geological Survey, and the U.S. Geological Survey. Its long-term goal, not yet funded as of this writing, is "to extend the pilot system and develop a web-based system linking multiple data sets, capable of serving the broad needs of practicing geotechnical and earthquake hazards professionals for efficient access to geotechnical data." COSMOS and the Lifelines Project of the Pacific Earthquake Engineering Research (PEER) Center are currently developing the pilot system, and have not yet determined the standards, technologies, data types and formats, access method, and interface of this virtual database.

BUILDINGS

BUILDING AND OCCUPANCY CATEGORIES

The ***HAZUS Technical Manual (NIBS and FEMA, 1999)*** describes technical details underlying the HAZUS loss-estimation software. The manual does not address post-earthquake data gathering, and FEMA publishes no tool specifically designed to gather HAZUS-relevant earthquake experience. Nonetheless, HAZUS is widely used and represents a national standard, so it would be valuable for validating and improving the software if model building type, occupancy class, and damage and loss data were gathered according to HAZUS terminology. (HAZUS models a variety of facility types and perils; only buildings and earthquakes are discussed here.)

HAZUS characterizes occupancies in 28 classes, and buildings in 36 model building types. The model building types are defined using 16 structural systems and up to three height ranges. In addition, buildings are associated with one of four seismic design levels that reflect regional hazard level and era of construction. Nonstructural components are categorized by 17 types of architectural, mechanical, electrical, and plumbing components, and six types of contents. Building locations are characterized either by latitude and longitude or census tract. The electronic appendix of the present paper contains a listing of these occupancy classes, building types, design levels, and nonstructural-component categories.

HAZUS estimates building damage states for each of three features: structural components, nonstructural drift-sensitive components, and nonstructural acceleration-sensitive components. There are five possible damage states, from "none" to "complete," each provided with qualitative descriptions of the damage for each model building type and a point repair cost per square foot of building area by model building type and occupancy class. The manual provides only discrete values of repair costs are provided for each damage state, rather than ranges. However, one can equate the damage states with the following ranges of damage factor, according to the developer (Bouabid, 2003). (Damage factor is defined here as repair coast as a fraction of replacement cost, new). Slight damage corresponds to damage factors of 0-5%; moderate corresponds to 5-20%; extensive corresponds to 20-50%, and complete corresponds to 50-100%. These ranges are not formalized or definite, however, and Bouabid indicates that ranges of 0-2%, 2-15%, 15-40%, and 40-100% for slight, moderate, extensive, and complete, respectively, are also valid.

SEISMIC ATTRIBUTES OF EXISTING BUILDINGS

ATC-50 (Applied Technology Council, 2001 draft) is not a post-earthquake data-gathering tool, but it is interesting for the present study because of its five-page assessment form. A structural engineer can use this form to characterize 37 attributes of woodframe dwellings that are believed to relate to the building's seismic vulnerability. The attributes address features of the building, its site conditions, and the local seismic hazard. Each choice is associated with a numerical value. A simple equation and a lookup table produce an estimate of the dwelling's damageability—essentially an estimated damage-factor range in a large, rare earthquake—and a letter grade, A to D, with A indicating good expected performance, D indicating poor performance. The document also provides guidelines for the seismic rehabilitation of woodframe dwellings, making it a tool both for diagnosis and treatment of seismic deficiencies.

A related document, ATC-21 (***Applied Technology Council, 1988***, also published as FEMA-154), offers a similar one-page form that an engineer can use to identify buildings of questionable seismic safety. It addresses a wide variety of structure types, and provides for rapid visual screening of buildings for high collapse potential in a large, future earthquake. These two documents are particularly interesting for present purposes in several respects.

1. *ATC-21 and ATC-50 parameterize relevant building features.* Both documents provide rigorous data-collection protocols for rapidly tabulating building features believed relevant to seismic performance. Even if no ATC-21 or ATC-50 form has been completed for a building before an earthquake, they can be used after an earthquake to describe a building with a small, finite number of seismically relevant features.

2. *They have been extensively exercised.* Both forms have been used to create large databases of buildings. ATC-21, for example, has been used to create a database of every

building in downtown Portland, OR (Theodoropoulos, as noted in Porter, 2000). ATC-50 has been used to create a database of hundreds of California woodframe dwellings. Extensive training materials are available for both documents.

3. *They represent important experiments waiting to be performed.* The documents encode hypotheses about the seismic damageability of buildings based on their detailed features. The next large earthquake that strike an area with a large number of buildings screened with ATC-21 or ATC-50 will allow engineers to test the hypothetical relationships between detailed features and the building damageability, as long as seismic excitation can be determined for each site. The ATC-21 form and a 2001 draft of the ATC-50 form are duplicated in the electronic appendix of the present paper.

RAPID POST-EARTHQUAKE SAFETY ASSESSMENTS

ATC-20 (Applied Technology Council, 1989, 1991, and 1996) has emerged as the dominant methodology to assess the post-earthquake safety of buildings based on observable damage. The procedures, developed for use by structural engineers and building department officials, provide for both rapid and detailed safety evaluations. For both levels of detail, the engineer completes a brief checklist, and based on the results, posts a placard on the building in one of three colors: red for unsafe, yellow for restricted use, or green for inspected. Under the rapid-evaluation procedure, any one of five readily-observable conditions makes a building unsafe to occupy, including various stages of collapse, significant residual drift, other structural, damage, falling hazards, and ground failure. The detailed form allows the engineer to record damage to a variety of building components and to sketch the building or its damaged portions. ATC-20 offers simplicity, speed, and broad applicability; as a consequence it is used by most California cities and other jurisdictions. The electronic appendix of the present paper contains copies of the forms, which can also be downloaded from www.atcouncil.org. They are currently designed for printing and using on paper, as opposed to being completed electronically. Since its introduction, ATC-20 has undergone modifications that are instructive for present purposes.

1. *Allow for judgment.* The authors found it desirable to allow for greater exercise of judgment. Early versions provided only for a yes/no/unknown answer to each condition, a yes statement calling for posting the facility as unsafe. The current form allows for three possible descriptions of each condition: Minor/None, Moderate, or Severe.

2. *More gradations of safety.* In earlier versions, the yellow tag was available in case of uncertainty about whether an unsafe condition existed, whereas the current form allows for restricted-use posting in cases of “localized severe and overall moderate conditions.”

3. *Secondary use to record damage state.* The form now includes a field for the surveyor’s estimate of the building damage state, in terms of the ATC-13 (1985) damage factors.

For purposes of this survey, the present author offers two additional comments based on his own professional experience:

4. *Expect ATC-20 data, but beware of its limitations.* ATC-20 is effective for rapidly assessing the seismic safety of individual buildings with apparent physical distress. However, because it focuses on safety and because inspections are typically called for in cases of obvious structural or architectural distress, it is poorly suited to capture economic losses or to provide unbiased statistical data.

5. *Provide for electronic collection and aggregation.* Paper ATC-20 forms must be collected and transcribed to electronic format—a nontrivial issue. Virtually all cities

affected by the 1994 Northridge Earthquake created electronic databases of the ATC-20 evaluations. Despite the common form, the cities used a variety of software applications to compile them, and mapped information from the paper forms to the computer files in dizzyingly diverse ways. The labor involved in compiling these data to a standard format was substantial. A common platform-independent means of completing the form, and another for compiling ATC-20 data into a city's database and then into county or state databases could greatly improve the efficiency and accuracy of the resulting dataset.

BUILDING-SPECIFIC PERFORMANCE

The ***ATC-38 (Applied Technology Council, 2000)*** project set out to record detailed damage and loss characteristics of buildings located near strong-motion recording sites. Its goal was "to correlate the relationship between recorded ground shaking, … the observed performance of buildings (both damage and non-damage), and key characteristics such as design date, structural framing type, and number of stories." The approach employs a six-page survey form (duplicated in the electronic appendix of this study) to be completed by field inspection teams comprised of licensed civil or structural engineers. Survey data address building site, construction data, model building type, features that are expected to modify performance relative to the model building type, nonstructural features, general damage state, nonstructural damage, injuries and functionality, geotechnical failures, recording station information, and strong-motion time-histories and their response spectra. Most of these data would not be available from other sources such as building permits.

The survey form was employed after the 1994 Northridge Earthquake to gather data on 530 buildings located within 300 meters of strong-motion recording sites that were strongly shaken by the earthquake. The field inspection teams comprised two licensed civil or structural engineers, with each survey taking approximately two person-hours per building. Detailed data with photographs are provided in a relational database (several formats). Extensive data reduction and correlation studies are also included. Repair costs are not recorded, but are inferred from the qualitative damage state and an assumed relationship between damage state and damage factor (repair cost as a fraction of replacement cost). The authors reach the following conclusions and recommendations:

1. *Carefully design forms to assist users and data-entry efforts*. Because of problems with data-collection and data entry, the authors revised the forms to make their layout similar to the database. They clarified wording, made changes to avoid opportunities to leave blank spaces, provided fewer but larger spaces for comments, and expanded the glossary.
2. *ATC-38 can be used to create motion-damage relationships*. Because survey buildings are selected independently of their damage state (i.e., selection is conditioned only on proximity to a strong-motion recording), results are not biased toward greater damage.
3. *Collect large datasets.* The 530 entries gathered after Northridge are too few to create robust motion-damage relationships for most structure types. It seems that thousands or tens of thousands of records are required to discriminate seismic vulnerability by structure type and era of construction, or to discern the effects of other building features.
4. *Compile data from multiple earthquakes.* The authors recommend the use of ATC-38 in future earthquakes to add to the Northridge Earthquake dataset. ATC makes the performance-assessment form available over the Internet, at www.atcouncil.org.

The present author offers the following additional recommendations.

5. *Develop electronic data collection.* The Acrobat performance-assessment forms should be transformed to allow for electronic data entry via portable devices. This will further reduce opportunities to leave empty data fields, and will reduce transcription effort.
6. *Centralize results.* A centralized database should be created to which these records could be posted, either wirelessly from the field or by batches. This will reduce delays between data collection and data availability.

PERFORMANCE OF PARTICULAR STRUCTURE TYPES

Unreinforced Masonry Buildings

Martel (1936) describes an effort designed, in part, to determine "if significant differences in damage [in an earthquake] resulted from differences in the building's subtype, occupancy, or adjacency to other buildings." The author examined 1,261 unreinforced-masonry buildings (UMBs) in Long Beach, CA, which were shaken by the March 10, 1933, Long Beach Earthquake, and in a supplementary study, a number of woodframe residences in Compton, CA. The author's survey drew on the Sanborn Fire Insurance Atlas, supplemented by field checks, to create an initial list of subject buildings. His initial data include number of stories, shape and amount of wall openings (seven types), interior gravity system (four categories), occupancy (six categories), and adjacency (three categories). He used building permits and city tax assessor records to determine the initial value and reduction in value associated with earthquake damage. The author finds that the completeness of these records was aided by the fact that property owners who reported damage received a reduced tax assessment, which probably biased the sample toward high-value and highly damaged structures. These reports provided data on earthquake-related reduction in value for 60% of the subject buildings. Building-permit information provided data on 30% of the subject buildings, and field checks were used for the remaining 10%. Important conclusions include the following.

1. *Multiple data sources* were required to achieve a large, unbiased sample.
2. *Provide incentives*. Incentives to building owners contributed to the extensive data set.
3. *Establish standard definitions.* Consistency between data sources was possible because of the single investigator, single jurisdiction, and focused objectives of the survey. In general this will not be the case unless the engineering community makes a concerted effort to define and disseminate standard definitions for data and assertions about data.

   The present author offers the following addition conclusion.

4. *Definitions of loss matter*. The study reports reduction in assessed value but not the cost of repairs. Reduction in assessed value is taken as the repair cost times the ratio of depreciated building value to purchase price. Consider Martel's example (p. 144) of a property costing $10,000. Of this amount, $5,000 represents the replacement cost new of the building (50% of cost), which after 10 years of depreciation is valued at $4,000, or 40% of cost. If earthquake repairs cost the owner $800, only 40% of this amount, or $320, would be assigned to reduction in assessed value. Losses are presented in terms of reduction in assessed value as a fraction of pre-earthquake assessed value, in this case, $320/$4,000, or 8%. Today, the loss would commonly be depicted in terms of repair cost divided by replacement cost new, $800/$5,000, or a 16% damage factor.
5. *Archive raw data.* Martel's source data contained all the information needed to assess the present-day damage factor, but these data are now lost. The original author's need to

summarize and distill for efficient publication is at odds with the needs of later investigators to reexamine the raw data to draw new lessons. This is true for any scientific endeavor. The risk, realized in the present case, is that valuable source data eventually disappear unless carefully archived.

More recently, ***Rutherford & Chekene (1990)*** and ***Lizundia et al. (1993)*** present results of a survey of 2,007 unreinforced masonry buildings in San Francisco in the months after the 1989 Loma Prieta Earthquake, using ATC-20 (1989) and a 1-page supplementary damage-assessment form created by the authors. The form is entirely multiple choice other than building location and a box for comments. It includes 62 check-boxes to indicate the nature and location of structural damage, sections to indicate damage state in the ATC-13 (1985) and Wailes and Horner scales, and a single check-box to note evidence of pre-earthquake seismic strengthening. The authors analyze the survey results in Lizundia et al. (1993) to relate building damage state with ground motion and site soil, for purposes of developing a loss-estimation methodology.

Regarding the use of the supplementary damage-assessment form, the authors of Rutherford & Chekene (1990) find that some inconsistent entries arose because of the large number of inspectors, their varied experience, and the difficult circumstances under which they worked, but that the resulting database is "probably the most complete ever collected for a single building type in a given area." They find that observed damage was substantially less than would be estimated using ATC-13 (1985), and speculate on the causes of the difference. In Lizundia et al. (1993), the authors recommend the use of the supplementary damage-assessment form in future earthquakes, but urge that it be coupled with follow-up work to ascertain actual dollar losses and the final course of action taken by the owner. Because of the lack of strong-motion instruments in or near many affected buildings, the authors recommend that instruments be installed in vulnerable buildings to assist in loss modeling, and that geologic conditions at strong-motion sites be investigated. The supplementary damage-assessment form is reproduced in the electronic appendix of the present paper.

Pre-Northridge Welded Steel Moment-Frame Buildings

The SAC Joint Venture performed detailed investigations of damage to pre-Northridge welded-steel moment-frame (WSMF) buildings, in an effort to understand and mitigate brittle failures of the welded connections.

Durkin (1995) describes a SAC postcard survey to gather data on a large number of buildings in the strongly-shaken region affected by the 1994 Northridge Earthquake. A small sample of these buildings is studied in further detail via telephone survey. The postcards gathered summary data on 1,284 buildings, including location, structure type, inspection status, occurrence of damage, an indication of whether structural damage occurred, a qualitative measure of the extent of structural damage, status of repair activities, and a contact person for followup investigations.

From this set, a sample of 150 steel-frame buildings is selected for more-detailed data gathering via a telephone survey. The telephone survey is modest in scope. Answers to its 10 questions are adequate to provide meaningful statistics about inspection and posting status, nature of inspections, summary information about the building (age, square footage, and height), general extent and nature of physical damage and repairs, and basic yes/no information about injuries and loss of use. The one-page survey form is included in the electronic appendix of the present paper. Future studies could be improved by publishing raw data (important for verifying authors' conclusions and for adding data from future studies), and by asking respondents whether they would be willing to answer additional questions from later researchers.

Another SAC publication, ***FEMA 352 (SAC Joint Venture, 2000)***, is an exemplar of a data-gathering procedure designed to inform a nuts-and-bolts-level structural-engineering decision process. It specifies data-gathering, analysis, and reporting procedures for evaluating the safety of welded-steel moment-frame (WSMF) buildings, and for determining required rehabilitation measures. The data-gathering aspects of this study are extraordinary in that they document performance at a level of detail similar to studies of laboratory specimens. An appendix of the report contains a form (duplicated in the electronic appendix of the present study) that details the geometry and performance of individual beam-column connections.

Using this form, the surveyor notes information about the site, location of the connection within the building, and precise details of the deformation and physical damage to welds, plates, bolts, beam, and column elements. Damage is characterized using a system of 23 types of damage, in which each damage type is defined in pictures and words in terms of the connection element damaged, the location of the damage within the element, and the severity of the damage. Surveyors compiled complete data on 2,238 connections—damaged or undamaged—in 31 frames of six buildings.

In companion studies ***(SAC Joint Venture, 1995),*** structural engineers estimate the structural demands imposed on each connection in a variety of terms (elastic beam-end moments, inelastic rotation, and interstory drift). The structural demands can then be compared with the observed performance of each connection. The most valuable features of this study, which should be emulated in future investigations of the performance of structure components include:

- Clearly defined data-gathering procedures, including objectively-defined performance metrics, depicted both in words and in pictures;
- A large sample set of subjects, gathered without apparent bias with respect to any particular performance metric or conclusion, with published raw data;
- The approximate excitation experienced by each subject; and
- Oversight by a panel of experts specializing in all the relevant fields.

Future studies would benefit from more information about the seismic excitation of the subjects, which requires a denser network of strong-motion instruments in buildings.

Woodframe Buildings

McClure (1973) presents results of a detailed study of 169 single-family dwellings in the epicentral region of the 1971 San Fernando earthquake, all of which were subjected to peak ground acceleration of 0.25g to 1.0g, and almost all of which experienced damage in excess of $5,000 (approximately equivalent to $20,000 in 2002). The author's objective was to use the earthquake experience of these dwellings to review the Federal Housing Administration's (FHA) Minimum Property Standards (MPS; U.S. Department of Housing and Urban Development, 1971), which address single-family dwelling location, site planning, engineering, structural design, and construction.

He desired to observe the effects on seismic performance produced by differences in rise type (one story, one-and-two story, two-story, one-and-two-story split level, and other), seismic excitation (shaking only, and shaking and ground failure), soil condition (four types), and site grading (four types). He selects a non-random sample of dwellings to permit "an intensive study of the performance of structural and nonstructural and nonstructural elements across the various categories of interest." He refers to the process as quota sampling. The sample is limited to single-family detached dwellings built since 1950.

The author designed a survey form, modified and field tested it, carried out with the assistance of "graduate civil engineers under the direction of licensed structural engineers," and analyzed the results. The survey form includes approximately 200 questions. (It is duplicated in the electronic appendix of the present study.) The survey appears to have been mostly multiple-choice. It includes many qualitative or subjective questions such as "interior finish damage," with possible answers "none, slight, moderate, severe, total, or not applicable." Qualitative definitions of each damage state are provided in the text. Several conclusions are relevant to the design and conduct of surveys.

1. *McClure's (1973) survey is informative of the effects of detailed features.* The author discerned effects on seismic performance from detailed structural, architectural, and site features, and made recommendations for revisions of the building-code-like MPS.
2. *Quota-sampling reveals the trees but conceals the forest*. The author found that quota sampling is necessary and valuable for understanding the effects of the study characteristics, but because of the non-random nature of the sample, could not draw statistical inferences about the universe as a whole.
3. *Define damage states.* For consistency and clarity, define damage states in detail.
4. *Test and revise survey forms.* The author tested and revised the survey form three times before performing the complete survey.
5. *Publish the survey form and the raw data.* McClure's survey form is not included in the document, but his raw data are provided in a compendium.

Schierle (2002a) examines woodframe dwelling losses of the 1994 Northridge earthquake. One important objective was to create seismic vulnerability functions—relationships between earthquake repair costs and shaking severity—for six categories of dwelling. Dwellings are categorized by plurality (i.e., single-family or multiple-family) and era of construction (pre-1941, 1941-1976, and 1977-1993). Repair costs are expressed in terms of the damage factor, i.e., as repair cost divided by an estimate of replacement cost, and in terms of cost per square foot of floorspace. Shaking severity is parameterized in terms of peak ground acceleration taken from TriNet maps, discretized in three levels: less than 0.30g, 0.30-0.60g, and greater than 0.60g. The author draws on three primary data sources for repair cost and dwelling category: (1) a file of damage-factor estimates for 45,702 buildings, created by City of Los Angeles Building Department officials during rapid post-earthquake field investigations, (2) Los Angeles County Tax-Assessor files, which provide the assessor's record of square footage, number of dwelling units, and year built; and (3) building-permit applications for 1,230 buildings. These provide the contractor's valuation of repair work and describe the work to be performed. For large projects, building departments perform rough, independent cost estimates to ensure that the contractor's valuation is reasonable, so one can think of these permits as reasonably reflecting actual construction cost. With smaller projects, some contractors may underreport valuation for tax-avoidance purposes (Schierle, 2002b).

Of particular interest in this study are the author's comparisons between building-specific costs based on rapid loss estimates and costs from building permits. (The translation from damage factor to repair cost is made by assuming a common per-square-foot replacement cost.) For individual structures, the average absolute discrepancy between loss estimates ranges from 40% and 300%, as a fraction of the contractor's stated repair-cost estimate, for a given dwelling category and range of shaking severity. In aggregate, the two sources agree better, with the sum of repair costs for a large number of buildings agreeing within 5% to 50%, depending on dwelling category and shaking level. One can draw at least two lessons from this study about the utility of public records for the creation of seismic vulnerability functions:

1. *Adequate data*. Public loss records of the type described here provide adequate data to create mean seismic vulnerability functions that distinguish the effects of era and general type of construction.
2. *Reasonable agreement between two types of data.* Seismic vulnerability functions based on large numbers of rapid loss estimates generally agree in the mean with seismic vulnerability functions created using the repair-cost valuation stated in contractors' permit applications.

REGIONAL LOSSES

US Coast and Geodetic Survey (1969) deals with efforts to collect and analyze earthquake data for use in developing earthquake-insurance alternatives. Chapter 3 of volume 1 is particularly relevant here. Its author, Frank E. McClure, presents "a program of study and research in gathering earthquake damage statistics, concerning the dollar value loss, by class of construction, in terms of earthquake resistance." He reports on a study of approximately 1,139 buildings that were reported as damaged by the M7.6 Kern County earthquake of July 21, 1952, and its aftershocks.

McClure's objective is to estimate the fraction of all structures, by class of construction and "amount of lateral bracing," that were demolished, repaired, or undamaged as a result of the earthquake. His data sources include a private, unpublished report of 362 buildings that had suffered damage; building permits from the City of Bakersfield Building Department; Sanborn Map Company maps from 1952-1953; and a study by Steinbrugge and Moran (1952) of 78 unreinforced masonry buildings. McClure lacks the number and value of woodframe and light-metal buildings exposed to damage, so he is unable to determine the fraction of these buildings that were damaged. He does not attempt to create motion-damage relationships, but merely to estimate the losses should the 1952 events recur in 1969. None of his sources provide information on shaking severity. McClure offers several pieces of advice for future investigations:

1. *Plan for investigations before the earthquake.* A single government agency should be responsible for performing future earthquake investigations. The agency should establish objectives; liaise with engineering professional societies; use reconnaissance teams of structural engineers, seismologists, engineering geologists, building officials, and architects; develop and provide reference materials and data-gathering worksheets; and provide geological maps and maps that indicate building layout and structure type.
2. *Set up a base office.* After an earthquake, teams should meet at the base office to receive housing, transportation, credentials, messages, research assignments, and other logistical necessities. The base office would also establish a system by which buildings are unambiguously identified. (Note that EERI's Post-Earthquake Investigation Field Guide provides for such a base office.)

3. *Create field worksheets and a central data repository*. Gather data with brief worksheets that use standard, well-defined terminology for degree of damage, class of construction, and occupancy. The data should be compiled along with data from tax-assessor, city and county public works, building departments, and other public entities.
4. *Perform second-round, value-loss investigations*. Buildings initially identified as having experienced nonnegligible damage should receive an on-site follow-up investigation by an appraiser, architect, experienced insurance claims-adjuster, and structural engineer, to estimate the economic loss.

Note that in discussing maps that indicate building layout, McClure refers to now-defunct Sanborn Maps. The value of these maps was that they were publicly available, provided standardized building configuration and construction information, and had wide geographic coverage. Despite the demise of the Sanborn Map Company, modern near-equivalents exist. Comerio (2002) points out that several city planning departments maintain geographic information systems (GIS) that contain much of this data, albeit in nonstandard formats and nonstandard ontologies that are idiosyncratic to each city.

EERI could promote the development and use of a standardized system. One possible route would be to partner with the private sector, perhaps promoting a data-standards entity such as is common in high-technology development, to address data standards for building information. Starting points do exist: the city of Glendale, California, for example, maintains such a GIS database.

The National Research Council's ***Committee on Assessing the Costs of Natural Disasters (1999)*** examines the question of compiling comprehensive post-event loss information from natural disasters. The authors argue that although governments, businesses, and private entities have an interest in accurate loss data, no comprehensive disaster loss information is available either from public or private sources, and that no standardized estimation technique or framework exists for compiling these data. The authors recommend that U.S. Department of Commerce's Bureau of Economic Analysis be made responsible for compiling information on losses at a societal level. The authors do not suggest particular data-collection protocols to be used, but they do detail the categories of desirable information, under three general headings: direct losses, indirect losses, and indirect gains.

For compiling direct losses, the authors suggest a grid of 16 general types of loss (rows in the table) and five categories of entity initially bearing the loss (columns). Types of direct loss include damage to various kinds of buildings, contents, landscaping, vehicles, agricultural products, cleanup and response costs, loss-adjustment costs, living expenses, fatalities and injuries. (The complete table for direct losses can be found in the electronic appendix of the present study.) Indirect losses include wages, sales and profits lost because of business interruption at damaged facilities or resulting from infrastructure failure; input/output losses to businesses because of business interruption suffered by suppliers or customers; and ripple effects, i.e., reduction in economic activity triggered by business closures or cutbacks. Indirect gains include economic activity displaced from the affected region to areas outside of it, and the ripple effects thereof; income gains outside the affected region because of cost inflation resulting from disaster-induced shortages; and the economic activity associated with repairs and cleanup.

BENEFIT OF SEISMIC REHABILITATION

Onder Kustu, the author of ***ATC-31 (Applied Technology Council, 1992)***, set out to assess the benefit of seismic retrofit of buildings. To achieve his ends, the investigator needed a statistically significant and representative sample of information about retrofitted buildings, including four basic parameters for each building: shaking severity, structure type, structural retrofit, and damage factor. (He could then assess the benefit of seismic retrofit by comparing the apparent vulnerability of retrofitted buildings with the judgmentally derived ATC-13 vulnerability functions, which he considered to represent the unretrofitted case.)

His data source is a survey of members of the Structural Engineers Association of California (SEAOC), along with data collected by SEAOC members, other practicing engineers and building departments. These data were collected using a 2-page paper survey form containing approximately 51 data fields. Shaking severity is expressed in terms of MMI, using the building's location per an approximately 4-km grid. Structure type is described in terms of 15 categories of "vertical" system (i.e., elements of the lateral-force-resisting system and gravity system other than floor and roof components) following the ATC-14 and ATC-21 taxonomy, eight categories of "horizontal" system (floor and roof elements), and three foundation types. Structural retrofit is described in terms of 18 categories. Damage is described by ATC-13's seven qualitative damage states, which are used to infer damage factor. The database contains information about 113 retrofitted unreinforced masonry buildings and 43 concrete tilt-up structures affected by the 1987 Whittier Earthquake or the 1989 Loma Prieta Earthquake.

The author reaches a number of conclusions relevant to the present study. First, he finds that inadequate data have been gathered to reach firm conclusions either about the benefits of seismic retrofit at MMI VI shaking levels, or about the benefits of competing retrofit methods. He finds that some survey fields were erroneously filled because the respondent did not understand the structure type classification system. The implications of these observations are that:

1. *Large datasets are required.* Strong conclusions about seismic vulnerability require thousands of samples to assure statistically significant subsets of data.
2. *Test survey forms.* Survey forms must include detailed definitions, and must be tested before use.

The author offers three additional recommendations that are relevant here:

3. *Modify standard post-earthquake damage-assessment forms*, used by government agencies such as FEMA and OES, to include "Data on retrofit criteria and methods, … general information on the structural characteristics of the buildings, and expanded descriptions of type and extent of damage."
4. *Enlist the assistance of building departments* to identify and track seismic retrofitting projects as part of their permitting process. (If this recommendation is followed, special effort must be made to ensure that actual construction costs are recorded and distinguished from other costs such as tenant improvements.)
5. *Use ATC-31 in the future.* Projects similar to ATC-31 should be undertaken following future earthquakes, in order to assess the benefits of seismic retrofit.

NONSTRUCTURAL COMPONENTS

MCEER NONSTRUCTURAL DATABASE

Kao et al. (1999) present a database of 2900 instances of damage to nonstructural components. The database includes information about the earthquake, the site location, the nature of the facility, the shaking severity in terms of ground and floor accelerations, the overall facility damage factor, the affected component, a text description of the damage, the impact of the component damage on the facility performance, and a reference to the source from which the information is drawn. It includes a few forms and queries for summarizing, viewing, printing, and appending records. The database is actually a secondary source, a summary of information drawn from 103 books, reports, and periodicals about 52 earthquakes between the 1964 Anchorage, Alaska Earthquake and the 1999 Quindio, Colombia Earthquake. The database is available online in its published, 1999 form, in Microsoft Access format, from the Multidisciplinary Center for Earthquake Engineering Research.

The database provides a valuable survey of failure modes to which a variety of nonstructural components are prone. Neither component names nor performance descriptions are standardized, so the user must be thorough in querying the database for information. For example, 11 synonyms for air-conditioning equipment appear in the database. The database is not intended to be an unbiased sample of equipment performance, and so cannot be used to calculate failure probabilities as a function of shaking severity.

KOBE CONTENTS-DAMAGE SURVEY

Saeki et al. (2000) present data on household property loss resulting from the 1995 Kobe earthquake. The data come from 965 questionnaires returned by insurance-company employees living in the Hyogo and Osaka prefectures. The questionnaires ask about damage to the building itself and damage to household property. Building-damage data include address, building size (1-2 stories, 3-5 stories, and 6+ stories), and degree of damage to the building ("total loss," "half loss," "partial loss," and "undamaged").

Questions about household property address ownership of and damage to 10 categories of contents: six categories of durable possessions such as furniture, appliances, and electronics; and four categories of non-durables such as curtains, tableware, and clothing. In the case of durable possessions, the authors sought household damage ratios: number of durable possessions in each category that were damaged, divided by the total number possessed. In the case of non-durables, where counting damaged items was more problematic, the authors define the damage ratio as the number of households with some loss in the category, divided by the number of households responding.

The authors performed a regression analysis, comparing damage ratios with seismic intensity (JMA scale) to create a fragility function for each category of household content. The authors detail their content-categorization system, and provide the parameters of the fragility functions. The required brevity of the paper prevents the authors from providing the questionnaire or the raw data. The electronic appendix of the present paper contains a copy of the content-categorization system.

EQUIPMENT-SYSTEM RISK EVALUATION

Johnson et al. (1999) offer a tool to estimate and manage the seismic reliability of equipment systems, based on a detailed examination of the system components, and using a simplified logic-tree analysis of the system. The methodology produces a "seismic score" for an overall equipment system, which relates to the annual probability of the equipment system failing to perform its required function. Individual equipment components are assessed using a set of standard, 2-page, multiple-choice forms, one for each of 37 component types. The forms allow the analyst to estimate the seismic reliability of the component, considering the type of component, the seismic hazard at the site, the location of the component within the building, and its installation conditions such as adequacy of seismic restraint and potential for interaction with other components. The scores are then used to assess the reliability of the overall equipment system.

Although this study provides a method to predict risk prior to an earthquake rather than performance after an earthquake, it is nonetheless valuable for the present study in the same way as ATC-21 (Applied Technology Council, 1988) and ATC-50 (Applied Technology Council, 2001 draft). It offers a detailed, formal structure for inventorying building equipment, for indicating their installation conditions, and for depicting their relationship to overall system performance. It offers a pre-established taxonomy of components and of common installation conditions and deficiencies. The materials provided in this report could be adapted to post-earthquake surveys by adding fields to each form to indicate observed performance, e.g., operational or non-operational, with the surveyor circling observed deficiencies and observed causes of failure.

LIFELINES

PIPELINES

Lund and Schiff (1991) present a database for recording and compiling pipeline damage records. The database is composed of records, one record for each pipe failure. Each record consists of 51 data fields, indicating the associated earthquake, the pipeline owner, pipe break location, soil condition, details of construction and installation, and nature of the break. The database, which contains information about 862 pipe breaks in the 1989 Loma Prieta earthquake, is defined to facilitate appending pipe-break data from future earthquakes.

The authors recommend its use in future earthquakes, but advise that such work can only be performed several months after the earthquake has occurred, since pipeline breaks can take some time to be discovered and repaired. The authors also recommend coordinated collection of pipeline damage data, to minimize redundant data-gathering efforts. They acknowledge that the value of the database would be enhanced by detailed descriptions of the systems suffering damage. (Since the subject paper was published, the use of geographic information systems by utility districts has become much more widespread.) Finally, the authors recommend the use of their methodology and database in future earthquakes.

It is noteworthy that the authors archived their database in two common formats—DBF and comma-and-quote text file—both of which are readily accessible today, independent of the software used to create them, and likely to remain accessible for some time. Furthermore, their report and database are available online, distributed by the National Information Service for Earthquake Engineering (NISEE) at University of California, Berkeley. The online version of the report appears without its associated figures and tables, although these should be visible in the paper copies archived at various locations listed in the report.

BRIDGES

The California Department of Transportation maintains a log of bridges on state highways ***(Caltrans, 2002)***, a database of state bridge sufficiency ratings ***(Caltrans, 2001a)***, and a database of local bridge sufficiency ratings ***(Caltrans, 2001b)***. The log of bridges shows bridge location (district, county, city, route and postmile), material and structural system, bridge length, width, number of spans, year built, years of widening or extension, and current operational status. The sufficiency ratings tables show location, material and structural system, year built, number of lanes, average daily traffic, the number of miles a vehicle would have to travel if the bridge were closed, and condition of the deck, superstructure, and substructure. None of the tables indicate latitude and longitude, seismic rehabilitation, or any direct indicator of expected seismic performance. They do, however, offer a basis for consistent identification of bridges that experience strong motion and damage.

Basoz and Kiremidjian (1998) present results of a study of bridge damage data from the 1989 Loma Prieta and 1994 Northridge Earthquakes. Their objectives were to compile, review, and analyze bridge damage data, and to correlate observed damage with structural characteristics, ground motion, and repair cost. They present a set of fragility functions for a number of categories of bridges, relating the probability of reaching or exceeding certain damage states as functions of peak ground acceleration.

The authors' fragility analyses are beyond the scope of the present paper, but it is worthwhile to describe the databases they compiled. The authors created two databases, one for each event. Each database contains five data types: structural characteristics, bridge damage, repair cost, shaking severity, and soil characteristics.

- *Structural characteristics*. These are compiled from Caltrans' Structural Maintenance Systems (SMS) database. Their characteristics include abutment type, number of spans, type of superstructure and substructure, bridge length and width, skew, number of hinges at joints and bents, abutment and column foundation types, and design year. The authors create a taxonomic system based on single- vs. multiple-span construction, abutment type, column bent type, and span continuity. These features produce 21 categories of concrete bridge. The bridge taxonomy is copied in the electronic appendix of the present paper.
- *Damage states and repair cost.* The authors describe bridge damage states in both descriptive terms and in terms of ranges of damage factor (repair cost as a fraction of replacement cost). Damage descriptions were compiled from Caltrans reports, which characterize damaged bridges in one of two damage states for Loma Prieta (minor or major) and four for Northridge (minor, moderate, major, or collapsed). The damage descriptions were subjective, and no guidelines existed to define them, so in collaboration with Caltrans engineers, the authors developed damage-state definitions (Basoz and Kiremidjian, 1996). They compiled repair costs from Caltrans' supplementary bridge reports, and calculated damage factors by assuming a bridge replacement cost of $90 per square foot of deck.
- *Shaking severity and soil characteristics.* Shaking severity for the Northridge Earthquake is determined from maps of peak ground acceleration (PGA). Severity for Loma Prieta is estimated using seismic attenuation relationships. The authors do not discuss the source or their use of soil data.

The authors find that the databases on which they rely contain occasional discrepancies. Redundant databases containing structural characteristics differed frequently (15%) in abutment type, and occasionally (2 to 3%) in design year and skew. These discrepancies were corrected by reference to structural drawings. These changes in some cases materially affect the resulting fragility functions. More serious are discrepancies in shaking severity. Estimated ground motions in Loma Prieta differ substantially from recordings at strong-motion instruments. There are also substantial differences in shaking severity between two maps of Northridge PGAs. These differences necessitated the authors' developing redundant fragility functions, one set for each map. Finally, as noted above, the authors find that Caltrans' damage-state descriptions are subjective and inconsistently applied, hence the need for their new damage-state definitions.

INDUSTRIAL EQUIPMENT

Yanev (1990) summarizes an extensive database of the observed seismic performance of industrial equipment and nonstructural components. The database was developed for the Electric Power Research Institute (EPRI), and compiled from surveys by engineers of EQE International (now ABS Consulting). The focus of the database is on facilities related to electric power, including power plants, electrical-distribution substations, oil refineries, and natural-gas processing and pumping stations. There are also extensive entries related to the earthquake performance of water-treatment and pumping facilities, large commercial facilities, hospitals, and conventional buildings. By 1990, the database reflected equipment performance at more than 100 major facilities, many smaller facilities, and hundreds of buildings that experienced strong motion (typically peak ground acceleration of 0.15g or greater). Surveys at that time included experience in 42 events since the 1971 San Fernando Earthquake.

Database entries regarding equipment include an equipment description (using a formal, internally developed taxonomic system); photographs; in some cases manufacturer's literature for some components; information about the seismic installation (i.e., fixity and connection to other components); seismic excitation experienced; and a description of the source and nature of damage. Damaged and undamaged components are reflected in the database. There are also notes and audiotaped interviews of facility engineers describing the facility experience in the earthquake, along with other records such as log books, damage reports, maps, schematics, and drawings. No formal survey form was used to compile the database. Rather, a format was imposed after the fact. The database is licensed by ABS Consulting of New Hampshire.

CASUALTIES

Seligson et al. (2002) describe their efforts to gather "comprehensive Northridge Earthquake casualty statistics … to refine current engineering-based casualty model results to make them more meaningful to the engineering and medical communities for emergency response and planning purposes." A portion of that work involved performing 1,800 random-digit telephone interviews of people in the region affected by the Northridge earthquake. They find that 8% of interviewees reported that an injury of some kind occurred in their household. Each interview resulted in knowledge of the geographic location, injury severity, and injury mechanism in terms of the physical damage to the building or its contents that caused the injury. In another effort, they thoroughly surveyed coroners and hospitals for earthquake injury and fatality data. These data also show injury mechanism. The authors do not publish the data-gathering procedures involved in the telephone interview, although

Bourque et al. (1997) and ***Shoaf and Peek-Asa (2000)*** discuss disaster-survey methods, random-digit telephone surveys and population-based surveys of hospitals and morgues.

To facilitate their surveys, the authors developed a standardized classification scheme for earthquake-related casualties (***Shoaf et al., 2000***). The scheme includes demographic data, cause and severity of injury, treatment and costs, activity at the time of injury, location, characteristics, and damage of the facility in which the injury occurred. Using this classification scheme in their surveys, the authors find that deaths are primarily associated with collapse or partial collapse. The fraction of occupants killed in a collapsed portion of a building is typically less than 1.0, owing to voids remaining in the collapsed structure. The fraction varies by structure type. Survey methods developed by these authors (and the data they gathered from the several large earthquakes since 1994) can be used to inform future casualty data-gathering methods and to improve engineering models and public-health planning for future earthquakes.

HUMAN BEHAVIOR

Bourque et al. (1994) present a study of human behavior during and immediately after the 1989 Loma Prieta Earthquake. The Loma Prieta study examines what people did during the earthquake, their use of broadcast media, and whether and why they evacuated their homes. The authors performed a telephone survey (called random-digit dialing, to indicate that respondents are selected at random) of 656 people throughout the San Francisco Bay Area. The survey was performed 224 days after the earthquake, took approximately 30 minutes per respondent, achieved a response rate of 70 to 81 percent, and focused on regions shaken at mean Modified Mercalli Intensities of 6.7 to 7.9. The survey questions address several particularly interesting questions: How do location and companions influence one's efforts to avoid harm? Do people seek information from broadcast media, and how does that effort vary depending on location and companions? Who leaves their homes and why? The answers are relevant to safety planning, use of the media to inform the public, and programs to assist displaced persons.

The authors present a variety of interesting results that demonstrate the efficacy of the survey. For example, they found that many fewer people evacuated their homes than reported damage or the loss of utility service, and of those who evacuated, many left their homes because they were upset, rather than because of damage or utility failure. The authors point out some of the limitations of random-digit dialing, most notably that the very people most likely to be underrepresented in such a survey, such as people in single-room occupancy hotels at the time of the earthquake, might have been disproportionately dislocated by the earthquake. The authors hope that comparison of survey data with census information would help to assess the extent of under-representation of groups like this in the survey. The authors also note that the survey instrument has evolved over multiple applications. It had been adapted by questionnaires by Bourque et al. (1973), Turner et al. (1986), and included modifications from that of Goltz et al. (1992) to explore posttraumatic stress; to identify location more precisely; and to address unique details of the earthquake (year, name, etc.). The survey instrument for Loma Prieta is presented for the first time in the electronic appendix of the present study. The resulting database is available for download at NISEE's Loma Prieta Data Archive (1991).

BUSINESS DISRUPTION

Tierney (1997) and ***Tierney and Dahlhamer (1998)*** describe surveys of disaster-related business impacts of the 1993 Midwest floods and the 1994 Northridge Earthquake. In both cases, a 20-page questionnaire covers eight general topics: business characteristics, nature of physical damage, lifeline service interruption, business closure, business relocation, insurance and disaster-assistance programs, disaster preparedness, and losses. The sample size was in the thousands, with response rates of 23% (Northridge) and 50% (Des Moines) producing 1,100 responses in both cases. The authors summarize the survey methodology, which involved an initial mailing of surveys and telephone follow-ups.

The authors find that postcards and second-reminder mailings, common features of mail-survey research, were unnecessary for their purposes. The surveys are informative of the extent of business interruption, particularly with respect to lifeline service interruption, a crucial issue for evaluating societal costs and benefits from lifeline seismic rehabilitation.

The Northridge survey indicates poor earthquake preparedness and limited effectiveness of the measures that businesses had taken. The surveys are also informative of indirect effects: loss of material flow into and out of the business and loss of customers are common reasons cited for business interruption. The authors find low utilization of insurance or government programs, leaving open the question of why, a question that the questionnaires do not address. The authors call for additional research to explain this fact, and to explore the significant relationship between business vulnerability associated the size of the business. Although the authors summarize the survey results, the raw data are unpublished. The questionnaires however are published for the first time in the electronic appendix of the present study.

Surveys such as those described by Tierney (1997) and Tierney and Dahlhamer (1998) shed light on an important issue in earthquake-loss evaluation. The authors cite an estimate that 23% of Northridge Earthquake losses were attributable to business interruption. The fact that businesses' poor level of preparedness harmed their performance suggests an opportunity for significant loss-reduction in future events, and argues for better understanding of business owners' preparedness decision-making.

INSURANCE

Insurance-loss information is valuable to earthquake engineering for at least three reasons. First, insurance losses are indicative of underlying physical damage and can be used to inform engineering damage models. Second, insurers and regulators use past loss data to make important decisions about ratemaking, reinsurance, and reserves, decisions that earthquake engineers are often called upon to assist. Third, government can become the insurer of last resort, meaning that earthquake engineers are often called upon to use insurance-loss information to assist in public-policy planning.

Loss data are available to varying degrees from three sources: primary insurers, who collect claims data at the level of individual policies; insurance regulators such as the California Department of Insurance, who gather summary data from insurers; and from insurance industry groups such as the Insurance Services Organization, who collect and publish aggregate industry-wide loss data. The first and the last are considered here.

PROPERTY INSURERS

Property insurers each maintain their own proprietary databases of insured property and claims experience. These databases are typically developed internally, comprise a combination of paper and electronic files, are idiosyncratic to each insurer, and are usually available only to company staff or to consultants hired by the insurer for loss analysis. Some researchers do manage to acquire insurance information, so it is worthwhile briefly to discuss these data. The following observations are based on the author's experience with approximately ten insurers' earthquake-insurance databases.

Insurers maintain two basic types of earthquake-insurance information: policy data and claims data. The policy database contains information about all of the insurer's policies in a geographic area that are exposed to loss. Policy information is often provided by the insured to the insurer in an office interview, by phone, mail, or the Internet, without an inspection of the insured property. Policy data typically contains, among other fields:

- Policy number.
- Location. For residential properties, this is typically the address of the insured property. Commercial insurance covering multiple sites may not indicate the location of each site.
- Policy limits. This is the maximum amount the insurer will pay. Separate limits are typically expressed for buildings, ancillary structures, contents, and time-element losses, i.e., additional living expenses or business interruption. Limits are not necessarily the same as the value of the insured property. Content values can be much less than content coverage, and building replacement costs can significantly exceed building coverage.
- Deductible, typically as a percentage of policy limits. Deductibles can apply to each coverage separately or to the combined loss.
- Structure type. Nonstandard systems for classifying structure type are common.

The claims database contains information about amounts paid to insureds after particular earthquakes. Information on claims paid is typically provided by a claims adjuster, and includes the policy number, site location (often but not always), and amount paid, sometimes but not always broken out by coverage (primary structure, ancillary structures, contents, and time element). Claim amounts can differ substantially from the actual cost of repairs, aside merely from the deductible. Claim payments can reflect payments made to repair pre-existing damage, because of a lack of knowledge on the part of the insured or adjuster. Payments can fail to reflect hidden earthquake-related damage, invisible at the time the claim is paid. Also, insurers often pay for repair work that would otherwise not be performed in the absence of insurance. For example, they will pay to repaint an entire room when only one wall is damaged; this is the so-called *line-of-sight* issue. Claims adjusters sometimes round-up claim amounts to forestall customer complaints. Finally, demand-driven cost inflation (*demand surge*) can cause significant increases in repair costs after major catastrophes.

PROPERTY CLAIMS SERVICES

Summary estimates of insurance-industry catastrophe losses are more readily accessible than insurers' policy and claims databases. The main source of industry-wide catastrophe loss experience in the United States is the Property Claim Services (PCS) of ***ISO (2002)***. PCS considers a catastrophe to be an event that causes "$25 million or more in direct insured losses to property and that affect a significant number of policyholders and insurers." For each such event, PCS estimates the total insured property loss in five categories: fixed property, building contents, time-element losses (additional living expenses and business interruption costs), vehicles, and inland marine (diverse goods and properties, typically in transit).

PCS creates its loss estimates by polling a subset of insurers and then extrapolating to an industry-wide figure using the polled insurers' market share and using PCS' estimate of the number and type of structures, by ZIP Code, across the United States. PCS typically issues a number of loss estimates for each catastrophe, starting with an initial "flash" estimate within hours of the event, and then one or more times in subsequent days and weeks with follow-up estimates as claims data become available to the polled insurers.

PCS maintains a proprietary database of these losses since 1949, which it calls its Catastrophe History Database. The database contains date of occurrence, state(s) affected, type of catastrophe (10 categories), amount of loss (estimated payment, average payment, number of claims, and total dollars), and type of estimate (preliminary, resurvey, or final).

AGGREGATING AND INTEGRATING SURVEY DATA

INTEGRATING SAFETY ASSESSMENTS WITH PLANNING AND RECOVERY

Cities and other jurisdictions use the ATC-20 methodology to determine the seismic safety of buildings, and to prevent or limit access to unsafe or potentially unsafe structures. Once a building is posted with an ATC-20 evaluation however, there remains the problem of designing, approving, and performing seismic repairs or demolition. To address this problem, Accela, Inc., has developed the ***Emergency Response System (ERS; Accela, Inc., 2002a)*** and ***Kiva Development Management System (DMS; Accela, Inc., 2002b)***. These systems comprise computer hardware and telecommunication and database software that integrate ATC-20 evaluation with land management, construction permitting, and inspection. ERS allows city inspectors to perform safety evaluations using palmtop devices wirelessly connected to a central GIS-enabled database. The GIS feature reduces the potential for ambiguity over the precise location of inspected buildings—a significant problem in cases where a single structure has multiple addresses. City engineers can then use the same database and the DMS to record and track building permit applications and construction inspections, producing an end-to-end record of damage, safety assessment, loss, and restoration.

The City of Glendale has adopted ERS and DMS as part of a broader data plan. According to a city official (Fabbro, 2002), the intent is that all non-private disaster and recovery data will be permanently available via the Web for research purposes. To achieve a durable dataset, the data are stored in as generic a form as possible, so that changes to software applications do not hinder access. The city has a GIS system that shows parcel boundaries, and building outlines, and will eventually show UBC construction category for every structure (this is the potential replacement for Sanborn maps alluded to above). It is currently in the process of adding scanned images of all construction drawings that accompany permit applications, both past and future, which will facilitate the study of seismic performance of more-detailed structure types.

AGGREGATING REGIONAL SAFETY, DAMAGE AND LOSS DATA

A study of the Northridge Earthquake by ***EQE International, Inc., and the Governor's Office of Emergency Services (1995, 1997)*** represents perhaps the most-thorough effort ever to document one of the most-costly natural disasters in U.S. history. It summarizes efforts to collect a centralized, exhaustive database of the effects of the 1994 Northridge Earthquake. The data contained in these reports address the seismological and geotechnical aspects of the earthquake; the characteristics of the building stock exposed to strong motion; building damage data including ATC-20 safety evaluations and repair-cost estimates; coroner data on earthquake-related fatalities; relocation and injury data from cities, the Red Cross, and the Salvation Army; and insurance losses reported by the California Department of Insurance. The two volumes of this study present a wealth of summary data in tabular, graphical, and map format, along with extensive analysis of the information.

Because of privacy considerations, restrictive-use agreements, and the use of proprietary information, the underlying raw data are not provided with the report. The California Governor's Office of Emergency Services (OES) offers to makes the raw data of Northridge available. However, because of privacy concerns, OES does not provide personal information and conceals detailed facility locations using generic, nearby locations (Kehrlein, 2002). These precautions, though necessary, inhibit data-checking and follow-up data gathering. Furthermore, the format of the Northridge data is also absent from the report, which limits the use of the database as a pattern for future data-gathering.

The authors make a number of relevant conclusions regarding the data-collection effort. Among these are:

1. *In some counties, tax-assessor data can provide crucial inventory data.* To understand the damage, one must also establish the quantities and characteristics of the building environment exposed to damage. The authors identify six desirable pieces of information for each building in the affected region: (1) street address; (2) construction and material type; (3) height or number of stories; (4) age or construction date; (5) use or occupancy type; and (6) total square footage. For some counties, tax-assessors files can provide these data for much of the built environment. Construction and material-type information in tax-assessor files can be of limited reliability.

2. *Assessor information is imperfect or undesirably summarized.* The comprehensiveness of tax-assessor data vary substantially between counties. Few publicly owned buildings appear in assessors' databases. Some information on structure type was available for Los Angeles County (five categories including "other"), but none for Ventura County. Number of stories was available for commercial buildings in Los Angeles County, but summarized by height ranges that differed from the authors' preferred grouping.

3. *Census data are unreliable in terms of age distribution of buildings.* The authors' comparison of assessor data and the Census of Housing indicates that the census modestly underestimates the total number of residential buildings, and exhibits a strong bias in terms of age of dwellings. Any use of census data for inventory purposes should therefore be checked using assessor files, field surveys or other sources.

4. *A large, detailed, systematically organized database of building damage can be collected.* Building-specific damage data were of two types: ATC-20 safety-assessment (tag color) of 115,000 buildings, rough estimates of dollar damage for 97,000 buildings, and of damage factor for 72,000 buildings. After filtering for buildings whose structure type, use, year built, and geolocation could be determined, these figures are 85,000, 84,000, and 63,000, respectively. The authors attribute the unprecedented damage database to five factors: the earthquake occurred in a highly urbanized region; the earthquake was large; the affected region was densely instrumented with strong-motion recording

devices; government agencies were prepared to use new technology to gather data for decision-making purposes; and advances in hardware and software made collection and depiction of large datasets practical.

5. *Damage data are far from exhaustive and take a long time to accumulate.* Damage information was collected on 100,000 buildings, yet the insurance industry reported more than 350,000 claims. In addition there were an unknown number of uninspected, uninsured buildings. Dollar damage estimates are based on cursory inspections, many of which did not include access to the interior of the structure, and which did not include furnishings, fixtures, equipment, and other contents. Time-consuming processes in government aid, new regulations, insurance claims adjustment, structural engineering decision-making, and building permitting contribute to long delays in the final accounting of loss data.

6. *Permanently and publicly archive disaster data.* The authors recommend coordinating loss determination via a data storage and retrieval clearinghouse. The California Governor's Office of Emergency Services served the role of storage facility after the Northridge Earthquake, but has not yet created an effective clearinghouse.

Some additional observations can be made on areas for improvement in such a study, and efforts that EERI could undertake to improve these sources of survey data.

7. *Create mechanisms for data-checking and followup data-gathering.* It may be that government attorneys are over-cautious in their restrictions on disseminating location information. EERI could work with government agencies to review these restrictions, and perhaps find the means to protect proprietary or private information, while still making important data readily available to researchers.

8. *The accuracy of rough repair-cost estimates is unknown.* It will likely remain problematic to get repair-cost information that is both accurate and exhaustive for large populations of damaged buildings. However, it seems practical to collect accurate repair costs for a statistically significant sample set of damaged buildings, which could be compared with preliminary rough estimates. This would require access to true site addresses in preliminary assessments.

9. *More-detailed structure categories are needed.* The categories of structure type recognized by tax assessors are of limited usefulness for improving loss-estimation models. EERI could work with governments to establish more-detailed, standard structure categorization by government agencies, and establish methodologies to ensure accurate assessment of structure types.

10. *Prepare and maintain hardware, databases, and data-collection procedures.* A complete data-collection system could be constantly maintained by state or federal agencies, ready for rapid deployment in the event of a disaster.

11. *Plan for data aggregation before the earthquake.* A variety of data sources were compiled into the EQE/OES effort at great effort. These sources could be coordinated in advance to ensure a common ontology. For example, EERI could promote to state and county agencies the use of standard data elements in assessor files for earthquake-information purposes.

COORDINATING PUBLIC AND NGO DATA-COLLECTION

An effort is currently underway in California to coordinate post-earthquake damage assessments by the ***Inter-Agency Damage Inspection and Assessment Working Group (2002a)***. The group comprises governmental and nongovernmental organizations (NGOs) such as the American Red Cross, local governments, the California Governor's Office of Emergency Services, the Federal Emergency Management Agency, the California Earthquake Authority, and the Small Business Administration. The participating organizations have found that after a disaster, multiple agencies contact the same people, gathering much of the same information and annoying the contacts. The group formed with the object of "reducing duplication, minimizing discrepancies, sharing common information, and implementing effective technologies." The group is not attempting to review which data are needed and why, but rather is focusing on improving the efficiency of data-gathering for currently used forms. As of this writing, the group is in the process of establishing its objectives and workplan. Objectives elucidated so far are as follows:

- Establish a forum of entities involved in damage inspection and assessment
- Compile and compare damage inspection and assessment forms and processes
- List data elements for use in identifying common information
- Evaluate technology for data-gathering and recommend hardware devices to be used
- Propose data repositories and information-sharing procedures
- Implement and field-test standardized data-gathering processes

The group has begun this effort by creating a list of 18 standard forms used by member agencies. It then cross-tabulated all the data fields (there are 544 in the current list) against the various forms on which they appear, to determine cases of duplicate questioning. Copies of the group's working documents (Inter-Agency Damage Inspection and Assessment Working Group, 2002a-f) are provided in the electronic appendix. Although the group's agenda covers a variety of disasters, most of the forms are relevant to earthquakes. Earthquake-related forms tend to focus on safety (both ATC-20 forms appear in the group's list), habitability, and requests for government assistance. Little structural engineering or geotechnical data appear in them. Furthermore, it appears likely that privacy considerations will limit the dissemination of any raw data gathered using these techniques.

DATA STORAGE AND DISSEMINATION

A number of entities already discussed provide public access to earthquake-related data. TriNet, COSMOS, ROSRINE, the U.S. Geological Survey and others offer web- and ftp sites of their maps and other data. A few other resources are worth mentioning, along with an idea for a centralized archive of earthquake experience data.

GEOGRAPHIC INFORMATION SYSTEMS

California Geographic Information Systems (2001) maintains the California Spatial Information Library. This library offers a variety of GIS data, 10-meter satellite imagery, raster graphics of USGS topographic quadrangles, and interactive web-based mapping capability. The GIS data include administrative and political entities, water districts, infrastructure, cultural geography, and physical geography. Most relevant for post-earthquake investigations are the infrastructure data (airports, roads, railroads, health facilities, colleges and universities, and prisons) and the 1990 Census data. Census data show census tracts, population, racial demographics, population and housing density, and poverty statistics. The infrastructure data are limited, offering summary characteristics but no engineering features. The library does not currently offer geotechnical data.

California GIS Council (2002) and ***Federal Geographic Data Committee (FGDC, 2002a)*** are working to develop standards for the compilation and depiction of spatial data in the United States. The FGDC has created a clearinghouse ***(Federal Geographic Data Committee, 2002b)*** through which "governmental, non-profit, and commercial participants worldwide can make their collections of spatial information searchable and accessible on the Internet using free reference implementation software developed by the FGDC." Relevant clearinghouse participants include FEMA and the U.S. Geological Survey. The ***Bay Area Automated Mapping Association (2002)*** provides pointers to sources of GIS data for the San Francisco, California Bay Area. Some of the most relevant of these resources are discussed elsewhere in the present study.

MEDIA AND DATA FORMATS

Some brief note should be made of the electronic media and data formats available for compiling earthquake experience information. The reason is that media and format are relevant to broad and long-term data accessibility. Seismograms have historically been recorded on photographic film, heat-sensitive paper, computer punch cards, and magnetic-tape media. Sources examined here have compiled their electronic data in a variety of idiosyncratic formats and file types, for example, versions of Filemaker, SPSS, and Microsoft's Word, Excel, and Access. Both the media and the file formats over decades become obsolete and difficult to use.

Open-Standard Formats. Regarding the physical storage of data, suffice it to say that as long as the media do not degrade and networked hardware exists to read them, they can be ported to new media as needed. Regarding file types, the World Wide Web Consortium (W3C, 2003a and 2003b) has developed Hypertext Markup Language (HTML) and Extensible Markup Language (XML). XML allows one to define a new mark-up format when HTML does not suffice, and is being used increasingly for data. Both are open standards that can be read and written by a wide variety of software. Note for example that the office suites of Microsoft Corporation (2003), Corel Corporation (2001), and Sun Microsystems (2003) are designed to export and import between their native (proprietary) formats and HTML and XML. While it is difficult to predict for how long a WordPerfect, Excel, or Access file will be readable, the W3C believes that HTML and XML will remain the lingua franca of electronic publishing for a long time by a wide variety of software.

EARTHQUAKE DATA CLEARINGHOUSE

Many data sources discussed here publicly provide online information about seismic hazard, ground motion, geotechnical conditions, and infrastructure. The FGDC clearinghouse provides assistance in disseminating any type of digital geospatial data.

Scawthorn (2001) points out that public and private entities spend significant resources in post-earthquake reconnaissance, gathering data on observed performance of the earth, earthen structures, buildings, structures, infrastructure, people, organizations, communities and economies in real earthquakes. Despite these efforts, the data tend to perish within a few years, owing to the lack of a long-term data archive. This prevents other researchers from accessing the data, merging them into larger datasets, or using them for comparative purposes. Scawthorn therefore advocates the creation of a National Earthquake Experience

Database (NEED), a real or virtual data center for archiving and disseminating earthquake experience data.

NEED could conceivably employ the anticipated storage power of the George E. Brown Network for Earthquake Engineering Simulation (NEES). Scawthorn calls for the development of a design specification and implementation plan with representation by a variety of relevant research organizations such as the NEES Consortium, Earthquake Engineering Research Institute (EERI), Consortium of Universities for Research in Earthquake Engineering (CUREE), the Pacific Earthquake Engineering Research (PEER) Center, Mid-America Earthquake (MAE) Center, Multidisciplinary Center for Earthquake Engineering Research (MCEER), Applied Technology Council (ATC), the American Society of Civil Engineering's Technical Council on Lifeline Earthquake Engineering (ASCE TCLEE). The specification and implementation plan would be developed by representatives in an advisory panel and at an invitational workshop.

Some online archives already exist to disseminate earthquake experience information. The National Information Service for Earthquake Engineering (NISEE, 2002) maintains the ***Earthquake Image Information System*** **(*EQIIS*)**. As of this writing, EQIIS contains approximately 12,500 digital images, most of which are publicly accessible, from at least 267 earthquakes between 464 BC (Sparta, Greece) to 1999 (Chi-Chi, Taiwan). Images are searchable by earthquake, structure name, subject keyword, and photographer. Open-archive procedures were successfully used for some contributions, most notably in the case of Chi-Chi. James (2002) believes that it will become increasingly important to referee contributions as the archive grows.

NISEE also maintains the ***National Clearinghouse for Loma Prieta Earthquake Information*** **(*NISEE, 1991*)**, established under the sponsorship of the US Geological Survey and the National Science Foundation. This archive offers 15 downloadable files and 10 additional datasets on eight CD-ROMs containing information gathered by various earth scientists, engineers, and social scientists. The breadth of topics covered is large. A number of contributions present seismicity information—before and after the earthquake—along with ground motion recordings and response spectra, geological topography, wave velocities, and permanent ground displacements. There are studies of local geology and site amplification in the San Francisco Marina District, along with experimental soil-test results of a device that measures pore water pressure, an important parameter for liquefaction. There are structural analysis input files for three instrumented buildings, and survey reports of losses to publicly-owned infrastructure. Lund and Schiff's (1991) pipeline damage database, already mentioned, is archived here. Authors provide data files for statistical analysis of risk perceptions and their impact on the housing market, of public warnings during the disaster, and of other human reactions to and casualties arising from the earthquake.

The Loma Prieta Earthquake database has a basic Web interface, with holdings described on a single page with a brief subject heading and author names. Each item has a link to an abstract. The page lacks a search tool, but it is small enough not to need one. Some items have minimal documentation, which may become a problem as the holdings and their authors age. Because the database is intended to reflect only the Loma Prieta earthquake, no means are provided for visitors to contribute additional materials regarding later earthquakes. Nonetheless, NISEE's Loma Prieta and EQIIS databases represent pioneering examples of earthquake data archives, and could provide important lessons and material contributions to an open archive for future earthquake experience data.

USING SURVEY DATA AFTER EARTHQUAKES

The foregoing text primarily deals with how earthquake-survey data are collected and analyzed by the investigators who collected them. An interesting test of the robustness of survey data is how readily they can be adapted to novel uses not envisioned when the survey was created. Several studies provide insight into robust data; four are discussed here.

ANAGNOS ET AL. (1995)

These authors set out to improve the judgmentally-derived motion-damage relationships of ATC-13 (Applied Technology Council, 1985) using, not raw data, but information from available literature. They collected and analyzed empirical damage data from twelve recent publications covering California earthquakes as early as 1906. Their demands were fairly simple. They needed four pieces of information, namely: (1) by structure type and (2) shaking severity, (3) the value of property available to be damaged (its replacement cost), and (4) the cost of the actual damage. This is the minimum dataset required to evaluate a mean seismic vulnerability function.

To their dismay, the authors find that "many of these data are not particularly useful because they were collected under different formats and with different interpretations by the individuals gathering the data. In addition, ground motions are not available for the majority of the data (p. v)."

The basic problem is that the authors of the data sources were trying to solve different problems than were Anagnos et al. (1995). The former did not need all four of these data elements, and so did not collect them. This was the case with several sources that variously lacked ground-motion severity, structure type, repair cost, or replacement cost. Alternatively, the original authors extracted and published only summary information that was sufficient for immediate purposes but insufficient for other, later uses. For example, sources fail to distinguish between repair costs and structural upgrade. The consequences that the source authors cared about varied slightly, which resulted for example in inconsistent indicators of damage: ATC-13 damage state; insurance loss in excess of deductible; Wailes and Horner damage state; or cost of reconstruction. Finally, in some cases the electronic database or even the original paper-based data had been lost. In cases where the basic paper records survived, Anagnos et al. (1995) find that the effort to extract the needed data would have been too burdensome for their means.

It should be noted that, had Anagnos et al. (1995) successfully compiled and presented all the data relevant to their purposes, their own data would have been insufficient for use in later studies with a slightly different agenda, e.g., a different structure categorization system, different measures of shaking severity, or different damage scale. Several lessons can be drawn from Anagnos et al. (1995):

1. *Use standard, well-defined terms.* This study reinforces McClure in US Coast and Geodetic Survey (1969), in that many terms commonly used to describe structure type, value, and loss can be ambiguously defined. For example, repair cost is different from insurance claim amount and from the cost of work shown on a building permit. An unambiguous, standard set of definitions (an *ontology*, in information-technology argot) is crucial to communicating about earthquake consequences. Such an ontology could be established, maintained, and disseminated by professional societies or governmental institutions, similar to standards established by the American Society for Testing and Materials (ASTM).

2. *Use multiple or universal terminology.* Inconsistent terminology for describing location, ground motion, structure type, and loss can thwart researchers' attempts to synthesize disparate datasets. This problem could be addressed by gathering and storing data at a level of detail in excess of the researcher's immediate needs. Repair cost, for example, could be recorded in terms of dollars or perhaps dollars for each of several repair tasks, as opposed to ranges of damage factors.
3. *Permanently store data in electronic format.* While paper records are available in some cases, they can be too burdensome for use in studies that involve large numbers of facilities. It would be help if inexpensive means were available to transcribe or scan paper data to electronic format and, just as importantly, to store these data in a curated archive. This is true regardless of access rights, considering the many cases in which original data-gatherers lose their underlying paper or electronic files.
4. *Allow for cross-referencing of location.* Seismic excitation can vary substantially within a ZIP Code. Location references could include latitude and longitude, or street address range number, without compromising privacy.

COMERIO ET AL. (1996)

This study for the California Policy Seminar examines disaster-response and recovery programs. The study emphasizes changes to government-assistance programs, earthquake insurance, and their effectiveness in benefiting populations in need. The authors examine the history and interrelated roles of the major government and nongovernmental organizations (NGOs) in disaster response and recovery. They provide chronologies of government and NGO activities following several key California disasters since 1989, and examine in depth the residential losses that resulted from the 1994 Northridge Earthquake, with special attention to the implications and limitations of the database compiled by the California Governor's Office of Emergency Services. They discuss modeling issues and their relevance for future earthquakes. These last two topics—the damage database and loss modeling—are particularly relevant to the present study.

Regarding modeling issues, the authors find poor results from their regression analyses that relate aggregate inspector-estimated losses to dwelling size, safety-inspection tag color, shaking severity (peak ground acceleration), and a few other parameters. The authors observe that linear regression against these independent variables account for no more than 20 to 40% of the variance of ZIP-Code-aggregate losses. They attribute these poor results to the general shortcomings of loss models that work on an aggregate basis. They conclude that building-specific exposure information is crucial to developing accurate predictive models of loss, including detailed building design, condition, and seismic rehabilitation, and site soils.

The authors comment on how the quality and level of detail in inspection data vary by jurisdiction and inspector. Inspectors estimated repair costs in some jurisdictions but not others. Some recorded number of habitable and uninhabitable units in multi-family dwellings, while others did not. As already noted, a generalized structure type was available for buildings in Los Angeles County but not in Ventura County. The authors also comment upon the completeness of the EQE/OES database, comparing it with ZIP-Code aggregate claims data collected from insurers by the California Department of Insurance, and concluding that the public-inspection database "drastically underestimates the dollar value of damage to both single and multifamily structures."

Some of these problems have been mitigated since 1994. Future government efforts to compile wide-scale loss data most likely will continue to rely on ATC-20 safety-evaluation forms, current versions of which require the inspector to note structure type, inhabitable and uninhabitable dwellings, and range of building damage factor. However, the newer ATC-20 forms probably will not materially improve the accuracy or completeness of repair-cost estimates, since they rely on the same rapid visual assessments—often based on limited exterior inspection—that characterized inspections by building officials in the Northridge Earthquake.

Furthermore, these inspections are performed primarily for buildings whose safety is questionable, rather than on a population basis or for statistically unbiased samples. The authors also determine, via comparison of the OES database with insurance data, that many homeowners call their insurance agent or lender to perform post-earthquake inspections rather than the building department. The implication is that loss models that depend solely on building-department inspection data for seismic vulnerability data are prone to underestimate actual damage.

While extrapolation from a statistically biased sample set to the population is conceptually possible, it is a daunting challenge. However, given that the focus of future efforts will likely be similar to that undertaken by OES after the Northridge Earthquake, it would probably be valuable for EERI to encourage research to provide a sound basis for such extrapolation.

CUREE-CALTECH WOODFRAME PROJECT (PORTER ET AL., 2002)

This project by the present author and colleagues set out to model the seismic vulnerability of 19 particular woodframe dwellings on a building-specific basis. Earlier studies have attempted similar ends, but this one is examined here both because of its familiarity to the present author, and because it models building performance in greater detail than do earlier efforts. Our objective was to assess the benefits of seismic retrofit or redesign measures and the effect of construction quality on future seismic performance. The methodology for this project, entitled assembly-based vulnerability (ABV), models building-specific seismic vulnerability using an engineering model of the building and its components. One aggregates the modeled behavior of the components to characterize the performance of the entire building. This is in contrast with whole-building approaches that employ empirical data or judgment about overall losses to entire buildings. Like a whole-building approach in miniature, ABV creates its component performance models using four pieces of information: (1) by highly detailed component type and (2) level of structural response (such as interstory drift or floor acceleration), one must know (3) the quantity of similar components exposed to damage and (4) the quantity of components so damaged.

This effort focuses on woodframe construction, and so requires performance information about woodframed gypsum wallboard partitions, stucco exterior walls, woodframed walls with plywood and oriented strandboard (OSB) structural sheathing, windows of various sizes, and residential water heaters. Because the study sought to distinguish the effects of important details, it discriminates between components at a highly detailed level, essentially equivalent to the level of detail that laboratory tests examine. Our component taxonomy is that of R.S. Means Co., Inc.'s (2000) assembly-numbering system, enhanced to indicate details of seismic resistance. The use of this standard helps in estimating repair costs, and is particularly useful because it is so well established. With its modest enhancements, this system provides the necessary level of detail.

Interestingly, despite the effectively boundless source of performance information about how these components performed in recent earthquakes, we found that actual field data available in the literature are inadequate to describe the performance of these components in the needed terms. In the end, it was necessary to use a limited quantity of laboratory tests to characterize component performance, which could not be directly compared with real-world earthquake experience. Three general shortcomings of real-world performance data caused this. First, the data lack the structural response to which components were subjected. Second, the field data do not record engineering details such as nail spacing, stucco strength, window dimensions, and other features that laboratory tests, by contrast, explicitly examine. Third, damage questionnaires are ambiguous about whether the surveyor is supposed to be recording fragility or vulnerability information. (Fragility involves the fraction of components of a particular type that had suffered damage of a particular nature, whereas vulnerability addresses loss, often as a fraction of replacement cost.) The lessons one can draw from this study therefore echo those of researchers who attempt to model whole-building losses:

1. *Define and measure components using a standard and detailed taxonomic system.* R.S. Means Co., Inc.'s (2000) assembly-numbering system is a good starting point. While the level of detail might seem burdensome, it avoids the over-aggregation that proves so common in other studies. The detail can always be aggregated out after the fact, while the reverse is not true: one cannot add detail to overly-aggregated performance data.
2. *Distinguish between fragility and vulnerability.* To create fragility functions requires information about the fraction of components damaged as a function of seismic excitation, whereas vulnerability functions require information about loss (often as a fraction of exposed value) as a function of seismic excitation. Future efforts should be clear about how damage is to be measured. Fragility information is readily gathered in initial surveys, before repairs are undertaken and their costs are known. Follow-up surveys can undertake to collect loss data.
3. *Prepare in advance to measure seismic excitation of important components.* To learn about the performance of portions of structures requires that one know the excitation to which that component was subjected, the interstory drift index of a wall segment, for example. Excitation can often be inferred from shaking severity and basic structure information, but not with the accuracy commonly demanded of laboratory tests. EERI should support efforts to install strong-motion instruments in significant numbers of facilities that include important component types.

CONCLUSIONS AND RECOMMENDATIONS

A rich literature of data-gathering protocols exists to gather information about earth-science, engineering, and social-science aspects of earthquake experience. From these studies we can draw several generalizations.

Protocols exist to collect data on most aspects of earthquake experience. Research reviewed here provides formal means to quantify: ground motion; site soils; characteristics of existing buildings and bridges; physical damage to buildings, contents, equipment, and lifelines; deaths and injuries; human behavior; business disruption; and other economic impacts. Authors have studied how best to integrate data from multiple sources so as to understand an earthquake's macroscopic socioeconomic effects.

Protocols vary between researchers and over time. Limited consistency exists between protocols developed by different researchers, and it can be difficult to compare or aggregate these studies. No entity standardizes earthquake-data protocols, so they tend primarily to serve the immediate needs and interests of the researchers who design them. Furthermore, protocols carried out by a single research group evolve over time, both as survey problems are corrected, and as additional issues are addressed.

Raw data perish. Raw data are typically unavailable, either because they are too voluminous to publish, or for the privacy of individual facilities and respondents. No single entity exists to serve as a clearinghouse of earthquake experience data. As a consequence, raw data tend to perish, and it becomes difficult to compile data from different researchers and different earthquakes, which hinders long-term research. Important, pioneering efforts have been undertaken to store and disseminate data collected by others, but with limited exceptions, these efforts focus primarily on seismological issues.

The present research has highlighted many procedural and technological opportunities to overcome these limitations.

1. *Provide consistency and clear directions.* Several authors find that to compile a meaningful dataset requires that the data gatherers or survey respondents possess clear definitions and procedural guidelines before they begin. Researchers should test and refine data-gathering instruments. Where possible, use multiple-choice questions and anticipate problems that might lead to no answer.
2. *Consider comprehensibility to outside readers.* Several authors call for clearly defining all terms in final publications. One should not assume that all interested readers possess familiarity with specialized terminology. Where possible, use well-established, standardized definitions and categorization systems. Professional societies can assist by developing and disseminating these though permanent committees and websites.
3. *Demonstrate scientific basis for conclusions.* It is common to provide summary results but not to demonstrate that data-gathering instruments or raw data are available for review and verification purposes. Brief research summaries are valuable for communicating the important conclusions of a study, but rigorous defense of those conclusions requires that others can check them. EERI could encourage publication of raw data and data-gathering instruments by insisting that assertions made in its publications be supportable from published raw data and data-gathering procedures, even if these data and procedures are documented elsewhere.
4. *Provide for aggregating data with earlier or later efforts.* Publishing raw data and survey instruments can also benefit later efforts, by allowing subsequent researchers to compile earthquake lessons from various times and places. Toward this end, it may also help to use terms and definitions consistent with earlier efforts.
5. *Avoid loss of data through obsolete formats.* It is valuable for electronic data to be presented in multiple file formats and media, with an eye to formats and media most likely to be supported for decades. When creating an electronic database, include copies in nonproprietary formats such XML or comma-and-quote-delimited ASCII text. Include durable electronic media with paper text. Avoid compression formats that are likely to become obsolete or are unique to an operating system.
6. *Minimize duplication of data-gathering efforts.* Develop and disseminate standard electronic forms and databases that can be used by others, if it is reasonably anticipated that other entities will find them useful.

7. *Provide for statistical analysis.* Without statistical data, earthquake reconnaissance primarily provides anecdotal insight into possible failure modes, achievable capacities, and common behaviors. As interesting as these are, scientific advancement often requires large, unbiased datasets with the possibility of statistical analysis to test hypotheses.

8. *Avoid over-aggregation.* Where practical, provide a level of detail beyond that needed for present purposes. Others may find it useful in the future.

9. *Provide incentives.* Respondents may cooperate more readily with surveyors if they are offered incentives to participate, are assured of the importance of their replies, and are thanked for their efforts.

10. *Promote dense instrumentation.* Motion-damage relationships cannot be greatly improved by earthquake experience if seismic excitation, in site-specific, instrumental terms, is unknown. This includes both ground-motion excitation and structural response. Few low-rise and mid-rise buildings are instrumented to capture responses of interest such as interstory drift ratios and upper-story floor accelerations.

11. *Use predictive tools for data-gathering.* Tools such as ATC-21, ATC-50, and the Johnson et al. (1999) forms can provide useful taxonomic systems, training tools, and clear, well-tested multiple-choice forms for describing facility features. Their extensive sample datasets can also represent large experiments waiting to be performed.

12. *Domicile reports and data at permanent, curated archives.* Archive paper documents at numerous libraries, in acknowledgement of the fact that a single-source publisher may not exist or may lose original manuscripts or data files within a few years or decades. Anticipate that electronic media may become obsolete and unreadable. Publish redundant data online through durable institutions. A truly long-term solution to publishing raw data may require the creation of an institution that provides electronic, curated open archives where researchers can deposit their data and discover data compiled by others.

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ABBREVIATIONS

ABV, Assembly-Based Vulnerability
ANSS, Advanced National Seismic System
ASCE, American Society of Civil Engineering
ASCII, American Standard Code for Information Interchange
ASTM, American Society for Testing and Materials
ATC, Applied Technology Council
CIIM, Community Internet Intensity Maps
CISN, California Integrated Seismic Network

COSMOS, Consortium of Organizations for Strong-Motion Observation Systems
CSMIP, California Strong-Motion Instrumentation Program
CUBE, Caltech US Geological Survey Broadcast of Earthquakes
CUREE, Consortium of Universities for Research in Earthquake Engineering
DMS, Development Management System
EERI, Earthquake Engineering Research Institute
EPRI, Electric Power Research Institute
EQIIS, Earthquake Image Information System
ERS, Emergency Response System
FEMA, Federal Emergency Management Agency
FGDC, Federal Geographic Data Committee
FHA, Federal Housing Administration
GIS, Geographic Information System
HAZUS, Hazards United States
JMA, Japan Meteorological Agency
MAE, Mid-America Earthquake Center
MCEER, Multidisciplinary Center for Earthquake Engineering Research
MMI, Modified Mercalli Intensity
MPS, Minimum Property Standards
NEED, National Earthquake Experience Database
NEES, Network for Earthquake Engineering Simulation
NEHRP, National Earthquake Hazards Reduction Program
NGO, Nongovernmental organization
NIBS, National Institute of Building Sciences
NISEE, National Information Service for Earthquake Engineering
OES, Office of Emergency Services
OSB, Oriented strandboard
PCS, Property Claim Services
PEER, Pacific Earthquake Engineering Research Center
PGA, Peak ground acceleration
PMF, Performance modification factor
ROSRINE, Resolution of Site Response Issues from the Northridge Earthquake
SAC, Structural Engineers Association of California, Applied Technology Council, and the Consortium of Universities for Research in Earthquake Engineering (a joint venture of these three entities)
SEAOC, Structural Engineers Association of California
SMS, Structural Maintenance Systems
TCLEE, Technical Council on Lifeline Earthquake Engineering
TCP/IP, Transmission Control Protocol and Internet Protocol
UBC, Uniform Building Code
USGS, United States Geological Survey
W3C, World Wide Web Consortium
WSMF, welded-steel moment frame
XML, Extensible Markup Language

ELECTRONIC APPENDIX

Universal resource locators (URLs) are provided for many of the references cited here. Furthermore, this document and an electronic appendix are available on CD-ROM from EERI, in several formats. The present study is provided in Microsoft Word 2002, HTML, and Adobe Acrobat formats. The electronic appendix is provided in Adobe Acrobat and JPEG formats. It contains the following materials:

1. Applied Technology Council (1988) ATC-21 Screening Forms and NEHRP Map
2. Applied Technology Council (1992) ATC-31 Revised Survey Form
3. Applied Technology Council (1996) ATC-20 forms and placards
4. Applied Technology Council (2000) ATC-38 Postearthquake Building Performance Assessment Form
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21. U.S. Geological Survey (2001) Community Internet Intensity Map (CIIM) sample questionnaire