# The Loma Prieta, California, Earthquake of October 17, 1989—Loss Estimation and Procedures

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SOCIETAL RESPONSE
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THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989:
SOCIETAL RESPONSE

LOSS ESTIMATION AND PROCEDURES

# INTRODUCTION

By Susan K. Tubbesing,
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This Professional Paper includes a collection of papers on subjects ranging from evaluation of building safety, to human injuries, to correlation of ground deformation with building damage. What these papers share is a common goal to improve the tools available to the research community to measure the nature, extent, and causes of damage and losses due to earthquakes. These measurement tools are critical to reducing future loss.

Unlike the other authors, Bruce makes no effort to predict future losses but, rather, focuses on evaluating the efficacy of a specific procedure, ATC-20, designed to evaluate the safety of damaged buildings. Developed by the Applied Technology Council and introduced in large training sessions just weeks before the Loma Prieta earthquake, this method was put into widespread use immediately after the earthquake. Bruce evaluates the effectiveness of this methodology and proposes various revisions to improve its accuracy and usefulness in future earthquakes.

The papers by Durkin and others and Wagner and others focus on human injuries. Durkin's looks at injuries and illnesses throughout the entire earthquake-affected region, with specific attention to causality. The paper includes a section dealing with the delivery of health services, and on the basis of this work, the authors recommend approaches to improve emergency response and the development of casualty-estimation models.

The paper by Wagner and others reports on an epidemiological study of various risk factors that resulted in physical injuries in Santa Cruz, California, during the first 72 hours after the earthquake. This ongoing investigation is being carried out by an interdisciplinary team, in an effort to provide a better understanding of the relative contributions that the built environment and behavior make to earthquake-related casualties.

Taylor and others focus on losses resulting from ground deformation based on data gathered from more than 700 buildings in San Francisco. Their study demonstrates a weak correlation between loss and ground failure in the general vicinity of the city. The authors suggest a number of ways in which data may be improved and studies developed to compile superior, much improved loss data in the future.

# REVIEW, EVALUATION, AND REVISION OF THE ATC-20 POSTEARTHQUAKE BUILDING SAFETY EVALUATION PROCEDURES TO INCLUDE THE LOMA PRIETA EARTHQUAKE

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### ABSTRACT

The Loma Prieta earthquake caused damage to thousands of buildings and immediately created the need for hundreds of inspectors to assess these buildings for safety of occupancy or limited entry. The Applied Technology Council (ATC) had published ATC-20, "Procedures for Postearthquake Safety Evaluation of Buildings" one month before the earthquake and had held two large training seminars to introduce the book. This fortuitous introduction and distribution of the publication resulted in its wide use for the earthquake recovery.

The extensive use of the ATC-20 revealed the strengths and shortcomings of its methodology. To take advantage of this assessment of the methodology by hundreds of users, the National Science Foundation funded a project to use the Loma Prieta experience to evaluate and revise ATC-20. This project, ATC-20-2: Review, "Evaluation and Revision of the ATC-20 Postearthquake Building Safety Evaluation Procedures," is ongoing. Building evaluation aspects being reconsidered or introduced include evaluation records management, format and use of posting placards and evaluation forms, asbestos in damaged buildings, "windshield" (drive-by) survey evaluation procedures, agreement with related publications, structural degradation assessment, removal of goods from red-tagged buildings, repair cost estimation, and training and qualifications of the volunteers.

## INTRODUCTION

The need for an organization, legal framework, and methodology for voluntary assistance by design professionals to earthquake-stricken communities was recognized in California in 1978 by an agreement between the Structural Engineers Association of California (SEAOC) and the California Office of Emergency Services (OES). This agreement provided a structure for SEAOC engineers to volunteer through OES to building jurisdictions requesting assistance in the evaluation of buildings for safety of entry and occupancy. In 1983, a similar agreement was made between the American Society of Civil Engineers (ASCE) and OES to provide for the evaluation of lifeline facilities such as bridges, pipelines, airports, roads, and water- and wastewater-treatment plants and for the geotechnical evaluation of soil-related damage. Engineers volunteering through these agreements enjoy certain liability immunities and workers compensation benefits.

Under the SEAOC-OES agreement, engineers volunteered in the 1983 Coalinga and 1984 Morgan Hill earthquake recoveries. The response to these earthquakes revealed to the SEAOC Disaster Emergency Services (DES) Committee the need for a written manual on the methodology of safety evaluation of buildings.

The DES Committee recognized that there were three main types of postearthquake hazards in buildings: overall or partial building frame collapse; falling hazards; and other hazards such as fire, gases, asbestos, and so forth. For each of these hazard types, the needs in developing a methodology were to describe agreed-upon evaluation methods, debate and resolve those methods and issues where there was disagreement, and further expand the methodology of safety evaluation to cover all building types and damage scenarios. Work on such a manual was begun in 1984 by the DES committees of the four SEAOC chapter organizations. It soon became apparent that the development of the manual was beyond the means of volunteer committees. The SEAOC-DES committee approached the Applied Technology Council (ATC) to request their assistance in obtaining funding and producing the manual. Funding was obtained from the California Office of Emergency Services, the California Office of Statewide Health Planning and Development, and the Federal Emergency Management Agency. A subcontractor was chosen (R.P. Gallagher Associates) and a Project Engineering Panel (PEP) of engineers and building officials was selected.

The 1987 Whittier earthquake occurred while the project was in progress. The Whittier earthquake differed from the Coalinga and Morgan Hill events in that it occurred in a heavily populated area. It demonstrated the extent of damage and need for numerous safety evaluation inspectors that can result from a relatively small magnitude (Richter 5.9) event. For this earthquake, building inspectors from less-affected neighboring communities provided safety evaluation services for the recovery.

The first printing of the project publication ATC-20, "Procedures for Postearthquake Safety Evaluation of Buildings" (Applied Technology Council, 1989a) and the companion ATC-20-1, "Field Manual, Postearthquake Safety Evaluation of Buildings" (Applied Technology Council, 1989b) was in September 1989. ATC scheduled seminars in Los Angeles and San Francisco to introduce the publication. Each seminar was attended by about 500 building officials and engineers, who received copies of the publication.

The Loma Prieta earthquake occurred about one month later. It was quickly determined that damage was widespread. Later damage assessment studies would show that the modified Mercalli intensity zones VIII and VII for the earthquake included areas of seven counties and that about 1,400 buildings were destroyed and about 27,000 buildings damaged. There was an immediate need for large numbers of safety evaluation volunteers in the stricken areas.

## BUILDING SAFETY EVALUATION AFTER THE EARTHQUAKE

The need for safety evaluation volunteers was recognized within hours of the earthquake. They were requested through OES by the various jurisdictions, usually in accordance with the OES-SEAOC or OES-ASCE agreements. Beginning the morning after the earthquake, SEAOC and ASCE volunteer engineers were deployed to serve in the requesting jurisdictions. Two weeks later, SEAOC volunteers had served 670 person-days performing building evaluations (Structural Engineers Association Of California, 1991). ASCE volunteers performed evaluations of lifelines, soil conditions, and low-rise buildings.

The principal building jurisdictions served by the safety evaluation volunteer engineers were the cities of Aptos, San Francisco, Los Gatos, Scotts Valley, Oakland, Watsonville, and Santa Cruz County.

Most volunteers used the ATC-20 methodology, evaluation forms, and placards for building assessment. Evaluation forms and placards developed earlier by OES were used in some jurisdictions. As the recovery progressed, both the strengths and the shortcomings of the ATC-20 methodology became apparent to the volunteers and jurisdictions.

To improve the methodology, ATC was granted a contract with the National Science Foundation to review, evaluate, and revise ATC-20 to include the experience gained from the Loma Prieta earthquake building safety evaluation effort. This on-going project, ATC-20-2, "Review, Evaluation and Revision of ATC-20 Postearthquake Building Safety Evaluation Procedures," will result in an addendum to ATC-20 and additional and replacement pages for the ATC-20-1 field manual.

The project is guided by a Project Engineering Panel (PEP) selected for both their overall expertise and their specific experience in the Loma Prieta earthquake evaluation effort. The PEP members are:

- David R. Bonneville, H.J. Degenkolb Associates
- David J. Hammond, Structural Engineer
- Fred Herman, City of Palo Alto
- William H. King, City of Los Angeles
- Larry. L. Litchfield, City of San Francisco Bureau of Building Inspection
- David L. Messinger, David L. Messinger & Associates
- Sherry D. Oaks, Colorado State University
- Richard A. Ranous, Southern California Earthquake Preparedness Project

Debriefings have also been held to learn the experience of other Loma Prieta safety evaluation volunteers. About 40 volunteers from the City of Los Angeles and Sacramento County have been debriefed (as of May 1992), and a further debriefing session is planned for San Francisco.

### EVALUATION OF THE USE OF THE ATC-20 IN EARTHQUAKE RECOVERY

The significant needs for improvement or further work in postearthquake safety evaluation that were revealed as a result of the Loma Prieta earthquake evaluation effort are discussed below. Each will be considered in the ATC-20-2 project.

## RECORDS MANAGEMENT

A building jurisdiction during earthquake recovery must immediately begin to effectively process building evaluation documents. This paperwork includes numerous requests for evaluations, completed written evaluations, and records of volunteer activity. This need occurs at a time when the staff is usually shorthanded and overworked, and when it is imperative that good records be kept to facilitate the recovery of aid funds. Representatives of many jurisdictions affected by the Loma Prieta earthquake have emphasized the importance of adequate preplanned, prerehearsed procedures for processing and managing evaluation documents.

## FORM AND USE OF POSTING PLACARDS

The ATC-20 posting system of "inspected," "limited entry," and "unsafe" placards and an "area unsafe" designation had been adopted from earlier similar OES posting systems. Most building jurisdictions used this system or a similar OES posting system without significant incident for the Loma Prieta recovery. Others felt that it had certain shortcomings, as follows:

1. A posting distinction differentiating a building which is hazardous to adjacent rights-of-way or properties from one which is only hazardous within was seen as necessary by some jurisdictions. This distinction allows jurisdictions to more vigorously demand owners to mitigate hazards to rights-of-way. Then, once the building is only hazardous within, the jurisdiction can proceed more slowly with the owner to affect repairs to the building.
2. Some jurisdictions had a problem with the "area unsafe" designation, which allows part of a building to be posted "unsafe" and the remainder to be posted "inspected" or "limited entry." The jurisdictions would prefer that only one posting classification be given to each building.
3. The "limited entry" posting is the most difficult posting to define and enforce. There is often confusion as to what the entry and use limitations are and whether they are to be enforced by the jurisdiction or by the building owner.

The desire for re-entry into even the most precarious buildings is often strong, especially for individuals whose livelihood is dependent on the belongings within. An account of the events influencing the removal of goods from damaged buildings is given in by Wilson (1991):

> The city was***under enormous pressure to provide access to damaged buildings. Residents wanted to remove***valued personal belongings*** cash and essential documents. Business owners wanted to remove inventory***computers ***files. At each afternoon's city council meeting they pleaded for access. ***We had to decide whether to err on the side of access or safety. The needs for access were urgent and compelling, but the dangers were real and manifest. ***many of the occupants of even the three most seriously damaged buildings were more than prepared to risk their lives to retrieve contents. ***Final decisions about access of course fell to me.

The original intent of the ATC-20 methodology was that brief entry to remove goods was allowed in "limited entry"-posted buildings. Entry was to be in accordance with the specific conditions written on the placard by the safety evaluation inspector. Goods could not be removed from "unsafe"-posted buildings until sufficient shoring, removal of falling hazards, and so forth was done to allow it to be reposted "limited entry." However, during the Loma Prieta earthquake recovery, the removal of goods from "unsafe"-posted buildings often occurred under the guidance of the jurisdiction or engineers, and the "limited entry" posting was often interpreted by the jurisdiction to allow more continuous occupancy.

The meaning of the "unsafe" and "limited entry" placards must be well defined to differentiate (1) absolutely no entry, (2) limited entry for removal of goods when supervised by an engineer or the jurisdiction and (3) limited entry supervised by the owner. The PEP discussed modifying the "limited entry" posting to read "restricted use." The use restrictions would be clearly noted on the placard and would be enforced by the building owner/manager. Buildings where no entry is recommended or where entry must be strictly controlled by the jurisdiction would be posted "unsafe." The jurisdictions could choose to enforce this control by requiring that an engineer and contractor retained by the building owner obtain a permit for the task of evaluating and preparing the building for limited entry to remove goods.

## EVALUATION FORM REVISION

The OES Evaluation Form and the ATC-20 Rapid Evaluation Form were most often used to record the evaluation information for use by the jurisdiction. Safety evaluation volunteers had both positive and negative comments on these forms. These and other existing or proposed forms have been reviewed by the PEP and by Loma Prieta earthquake safety evaluation volunteers with the aim of incorporating the best features of each.

## ASBESTOS IN DAMAGED BUILDINGS

The ATC-20 document did not provide specific training in the recognition of asbestos hazards. During the Loma Prieta earthquake evaluation effort, several buildings appeared to have asbestos hazards and were appropriately closed. The greatest risk appears to be from damaged friable asbestos building materials and from free asbestos fibers previously in enclosed spaces being released due to damage to finishes and frame deformation. The risk is to both the safety evaluation volunteers and to future occupants (Pacific Asbestos Information Center, 1990; Chambers, 1988).

Friable asbestos-containing materials are those that can be easily broken by hand pressure. When these products are disturbed, they can easily release asbestos into the air. These products include certain sprayed acoustic ceilings, fireproofing, and pipe insulation. If damaged, friable asbestos-containing products are present in a building, it should be assumed that some level of asbestos will be present in the air. Even if asbestos fibers were not airborne prior to inspection they can easily and unknowingly be stirred up by the safety evaluation team.

Asbestos sources other than friable materials are also possible. Nonfriable asbestos-containing materials include tightly bound asbestos fibers. They are less likely to release asbestos when disturbed or damaged. Crawl spaces, attics, and ceiling spaces may have had asbestos debris accumulation from the above sources before the earthquake. This debris can be easily become airborne and be inhaled by safety evaluation team.

The health effects of asbestos can take 5 to 40 years to develop after the original exposure or exposures of breathing in the fibers. Three major illnesses, asbestoses, lung cancer, and mesothelioma, are caused by asbestos exposure. The effects of exposure are cumulative, and these diseases have no cure. No exposure level is considered safe.

Safety evaluation volunteers should be knowledgeable about how to identify damaged asbestos products in buildings. Damage to a friable asbestos product should be considered cause for posting the building (or certainly the area) "unsafe," pending verification by trained asbestos professionals. Damage of this type would include cracked ceilings with acoustic coatings and damaged pipe insulation. Other damage which may warrant an "unsafe" posting would be cracking or separation at taped gypsum board joints, significant damage to vinyl flooring, and collapsed ceilings below structural soffits with pre-1978 sprayed-on fireproofing.

## "WINDSHIELD" SURVEY EVALUATION PROCEDURES

This preliminary evaluation is carried out within hours of the earthquake, often by building inspectors, or firemen, to determine the scope of damage in the jurisdiction. The survey has been called a "windshield" survey because it is usually done by driving the streets and quickly assessing and recording obvious damage, usually without stopping to post structures. Safety evaluation volunteers could likely be requested and respond quickly enough to assist in this survey. A methodology for this survey procedure will be developed.

## AGREEMENT WITH RELATED PUBLICATIONS

There are several other draft or published documents for California or nationwide use which are concerned with postearthquake safety evaluation. They are as follows:

State of California Office of Emergency Services Post Disaster Safety Assessment Plan

Structural Engineers Association Of Northern California Plan for Utilization of Damage Assessment Engineers (in draft)

International Conference of Building Officials Building Department Guide to Disaster Mitigation Planning (Internal Conference of Building Officials, 1991)

Local Building Officials' Guide to the Utilization of Volunteer Engineers (Bay Area Regional Earthquake Preparedness Project, 1989)

Persons working on these documents have been participating as PEP members or as guest project meeting attendees to coordinate their efforts so as to produce consistent, mutually beneficial documents.

## STRUCTURAL DEGRADATION ASSESSMENT

Postearthquake safety evaluation and posting of buildings involves assigning an appropriate level of occupancy or entry to buildings with some degree of earthquake damage. It is essential that the evaluation and posting be appropriate to the actual risks of occupancy. Unconservative posting can place occupants at risk from falling hazards or collapse, whereas overly conservative posting will unnecessarily restrict residential and commercial users from occupancy of buildings and recovery of goods critical to their livelihoods. Building jurisdictions have typically been under great pressure after earthquakes to allow at least limited entry.

Evaluating an earthquake-damaged building for safety of occupancy requires that its probable structural integrity, and eventually its posted level of occupancy or entry, be determined from its observed degradation. The inspector must decide to what degree the structural strength, stiffness, and stability of the overall structure and its parts have been lessened, based on observed degradation conditions, and then evaluate the resultant risk to occupancy or entry. As earthquakes are infrequent, engineers and building inspectors do not often practice building safety evaluation and have even less chance of verifying their decisions.

Certain specific conditions have repeatedly been found to be difficult to assess. These conditions include the following:

1. In reinforced concrete construction, how much structural degradation is indicated by given crack patterns, crack widths, and frame deformations? What is the relationship of crack width to reinforcement clamping and dowel action and reinforcement plastic elongation and fracture? How is element degradation related to overall frame strength and stability? Existing studies (Applied Technology Council, 1989a; Otani, 1988; Umemura, 1989) have discussed these relationships but have not

fully developed the relationship of the degradation to risk. A further study of the known relationships between observed degradation and risk in reinforced concrete structures is especially needed.

2. How are considerations similar to the above (without the reinforcement effects) applied to unreinforced masonry?
3. How does an inspector best use the observed degradation of the nonstructural sheathing finishes (gypsum board, curtain walls, glazing) to estimate structural collapse risk and falling hazard risk? Finish degradation can indicate the structural degradation of a concealed frame, but this is dependent on the frame's stiffness. Cracked gypsum board in an unreinforced masonry building may be a symptom of concealed structural wall weakening, whereas cracked gypsum board in a steel moment frame building may only show that the gypsum board was stiffer but weaker than the frame. Cracked interior gypsum board often appears hazardous to occupants, who see it as a potential falling hazard and a sign of impending building collapse. Safety evaluation volunteers must be knowledgeable of all these considerations and confident in their assessment. This could be an important issue in a large event where there will be a large modified Mercalli intensity VI area containing numerous buildings with minor gypsum board damage.
4. How can engineers correctly evaluate the safety hazards of mobile homes displaced from their support jacks? Mobile home construction, more often than site-built construction, uses the framing and the sheathing together compositely to achieve strength and stiffness. This composite construction is not well known to most safety evaluation volunteers.
5. How can soils engineers assess the probability of further movement of slumped soil masses under buildings? This assessment can be important where the buildings on the displaced soils do not appear to be a collapse hazard. This was a common condition as a result of the 1964 Alaska earthquake.

It will be beyond the scope of the ATC-20-2 project to fully research and develop all aspects of the technology of degradation assessment. Further research to improve this assessment could draw upon past laboratory test programs of structural and nonstructural elements, studies of overall frame stability, and the collected observations of actual earthquake-damaged buildings. It is unlikely that the degradation assessment methodology could ever become an exact procedure, but research leading to an improved methodology would be highly beneficial to the earthquake recovery process.

## REPAIR COST ESTIMATION

Jurisdictions have often asked safety evaluation volunteers to estimate the cost to repair the observed damage. Volunteers often feel that they cannot provide these estimates with any usable accuracy because they are not experienced estimators and they do not know the full extent of damage and the local construction costs, reconstruction code requirements, or property values. Estimates are especially difficult for damaged unreinforced masonry buildings. Should jurisdictions ask for these estimates?

Proponents of cost estimation by safety evaluation volunteers argue that early valuation is often needed to obtain outside assistance and for media inquiries and that the safety evaluation volunteers estimates are acceptably accurate. Opponents have argued that early repair cost estimates by safety evaluation volunteers tend to become fixed and cast doubt on later estimates and that the volunteers, working with insufficient information and under time pressure, will not make acceptably accurate estimates.

It is often difficult to accurately estimate building repair costs. For example, cracked slabs-on-grade within buildings may permit occupancy, but the slabs are often irreparable. The building must then ultimately be demolished and rebuilt. Cripple wall collapses look drastic and make the building uninhabitable, but the house can often be readily lifted and repaired if the upper structure is reasonably undamaged. Veneer failures may expose decay and shear strength inadequacies, which compound the repair. In unreinforced masonry buildings, the decision on whether a given cracked or displaced masonry element can be structurally epoxied or must be replaced will have major cost implications. Slight differential settlements may require extensive foundation remedies. Archaic construction often cannot be rebuilt in kind.

Recent experience has shown the difficulty even for experienced safety evaluation volunteers of making accurate estimates. In a 1987 damage assessment exercise by the Structural Engineers Association of Northern California, experienced teams of engineers assessed mock damaged buildings and were asked to fill in the cost of repair on the evaluation forms. Estimates by teams varied widely. In the Loma Prieta earthquake evaluation effort, the City of San Francisco asked that safety evaluation volunteers make repair estimates as they performed their evaluation work. City officials later observed that the estimates were often highly inaccurate.

The PEP agreed that the safety evaluation volunteer should be asked to only estimate the percentage of loss (cost of repair/total replacement cost). The jurisdiction, using their property valuation records, would then convert the percentage loss to a loss valuation. The ATC-20-2 will include training and guidelines for conducting a percentage loss estimate. It is not yet clear how the cost of required upgrades would be considered in this estimate.

## DEMOLITION CONSIDERATIONS

The question of whether safety evaluation volunteers should be asked to recommend demolition is frequently raised. The purpose of demolition during the immediate recovery is usually to eliminate hazards to a public right-of-way due to the collapse or falling hazards of an adjacent building. Closure of the threatened public right-of-way is the immediate remedy to the risk, but this can be a significant hardship for the community. Once a building no longer poses a threat to the public rights-of-way, its repair then becomes the problem of its owner and tenants, and the jurisdiction should no longer have a compelling need to order demolition. Thus the real issue to be addressed may be: Should safety evaluation volunteers be asked to make recommendations on how to mitigate a collapse or falling hazard to a public right-of-way?

The safety evaluation volunteers can advise the jurisdiction as to what portions of the building are likely to fall or collapse and over what area of the public right-of-way they are likely to impact. They could further advise the jurisdiction as to whether they think that removal or shoring of the falling or collapse hazard is feasible. Service or recommendations beyond this point are inappropriate. Removal of a collapse or falling hazard, such as a precarious parapet or window glass panel, is best done by contractors. The design of shoring is not an appropriate task for a safety evaluation volunteer: it should be done by an engineer hired by the building owner or the jurisdiction.

Once a building no longer threatens the adjacent public rights-of-way, the considerations regarding demolition can be more thoroughly weighed. The owner, aided by consultants, will consider the damage to the building, the cost of rehabilitation, its potential value if repaired, and what code will govern reconstruction.

## VOLUNTEERS TRAINING AND QUALIFICATIONS

California Office of Emergency Services officials, safety evaluation volunteers, and building officials agree that better training is needed to prepare for safety evaluation work. This training has in the past taken the form of classroom sessions combined with field exercises where volunteers form teams and proceed to evaluate actual buildings with simulated damage and post appropriate placards. Further training could include other volunteers from related professions, such as architects and soils engineers.

## CONCLUSIONS

The Loma Prieta earthquake provided an opportunity to use the existing postearthquake safety evaluation procedures. Any postearthquake evaluations are difficult by nature and are made more so by the circumstances and pressures. The consequences of erring conservatively or unconservatively are both significant. To be prepared for the inevitable "big one," it is imperative that we further develop evaluation knowledge and methodologies and train large numbers of engineers and other professionals in their use.

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THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989:
SOCIETAL RESPONSE

LOSS ESTIMATION AND PROCEDURES

# CASUALTIES AND EMERGENCY MEDICAL RESPONSE

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## ABSTRACT

Findings are presented from studies of casualties, health-care utilization (demand), and health-service response (supply) as a result of the Loma Prieta earthquake. Specific demand and supply factors are explored that are useful in developing both earthquake casualty-estimation models and more effective emergency-response procedures. Work-related injuries and illnesses were assessed from the entire affected region, including where the injured sought care, and a case study of emergency medical response in heavily damaged Santa Cruz County is presented. The casualty analysis found that (1) almost all fatalities and most serious injuries were associated with structural failure, (2) the majority of fatalities and serious casualties came from a small number of damaged structures, most notably the Cypress Street Viaduct collapse, (3) falling sections of unreinforced masonry buildings, striking passersby and falling on top of other buildings, caused deaths and serious injuries, (4) occupant contact with nonstructural elements and building contents was the major source of minor injuries, (5) although interior nonstructural elements and building contents posed a relatively low risk of serious injury to building occupants, certain elements and settings were particularly hazardous, and (6) occupant actions contributed to injuries—many victims were injured while attempting to take protective actions.

The health-care utilization analysis found that 60 percent of the victims were treated in nonhospital settings. The emergency medical-response case study in Santa Cruz County found that (1) the 9-1-1 emergency response system was severely taxed, but remained functional and responsive, (2) advanced life-support ambulance transports

were fewer than normal, (3) the medical system was able to accommodate the injury load because the county health-care system was extensive. Although normal operations were initially disrupted, the three community hospitals did not suffer severe structural damage, and the demand for major medical care was light. A revised 9-1-1 emergency medical service procedure is recommended for disaster periods and is expected to improve substantially disaster management of limited ambulance resources, while maintaining rapid call processing.

Existing earthquake casualty-estimation procedures are reviewed to evaluate them in terms of our research results. The findings presented have three major implications for earthquake casualty modeling: (1) Structural damage potential remains the major predictor of serious earthquake casualties, but occupant contact with nonstructural elements remains a key source for minor injuries and a potentiality for major ones; (2) casualty estimates based exclusively on hospital utilization data may greatly underestimate the true medical need; and (3) future casualty models should estimate the resiliency of an entire regional health-care system.

## INTRODUCTION

Casualties have only recently been included in loss estimation studies for earthquakes, mostly because of the difficulty of acquiring accurate casualty data. Recent advances, however, in injury studies have made possible a new framework for loss estimation that includes data on injuries, as well as the capacity of the health-care system to respond (Durkin and Thiel,1990; Johns Hopkins University,1989; U.S. Geological Survey,1990). Casualty estimation consists of two facets:

1. Estimating the demand--the number, type, and location of casualties requesting health services
2. Estimating the supply--the capacity of the health-care system to respond to estimates of casualties

These estimations are typically oversimplified in most casualty-estimate models because presenting data in absolute numbers does not identify subtle patterns important in determining the medical care needed (demand) and the medical care available (supply). For example, estimates are often distorted because only hospitalized injuries are reported, not doctor-treated injuries; nor are the circumstances, location, and distribution of injuries typically reported. Such inadequacies in supply and demand numbers are crucial because they affect decisions about the facilities, training, and loss-mitigating measures prior to a disaster.

Injury data from the Loma Prieta earthquake offer the opportunity to improve the understanding of the relationship among supply, demand, and mitigation. From these data, patterns emerge from which conclusions can be made. For instance, the spatial distribution of injuries, which applies to both supply and demand issues, shows that the extensive health-care system of the San Francisco Bay area was adequate to meet the care for relatively few injuries in this moderate earthquake. It is noteworthy that the injury severity and distribution patterns for the Loma Prieta earthquake are similar to those for other earthquakes.

Three major topics are covered in this paper. First, examination of the types, severity, and distribution of casualties (demand for medical services). Second, examination of the medical care provided by the emergency medical services (EMS) and hospitals (supply of medical services). Lastly, implications of data from the Loma Prieta and other earthquakes on casualty-estimation modeling. For each major topic, findings and recommendations that warrant consideration by the appropriate research and applications community are presented. The most immediate of these is our recommendation for revision of the current 9-1-1 dispatch system, which offers substantial improvement without additional capital expenditures.

## CASUALTY DATA

The data sources we used for this study need to be put in the context of the different research approaches that we and other investigators have used to study Loma Prieta earthquake casualties. No single approach provides a complete picture, each having disadvantages as well as advantages. Given the weaknesses of any single method, we determined that the best method for developing a reliable picture was by comparing the findings of different approaches and looking for confirmation. We used the following types of analyses, as well as others that are still being developed:

1. An analysis of earthquake-related fatalities for the entire affected region
2. An analysis of Santa Cruz County earthquake-related injuries requiring hospitalization
3. An analysis of work-related injuries and illnesses for the entire region

We chose these analyses because fatalities and hospitalizations clearly depict earthquake severity and effects and because work-related injuries clarify the relationship between settings and effects as well as the personal characteristics of victims.

### REGIONAL FATALITIES

Determining the number of and reasons for fatalities underlies any comprehensive earthquake-injury investigation because mitigation strategies, at the very least, should be directed at minimizing mortality. In fact, although present seismic codes are designed to minimize deaths, they do not necessarily prevent injuries. We based this analysis primarily on a review of data compiled by county coroner's offices in the affected counties and interviews with coroner's office personnel. Because relatively few fatalities were associated with the Loma Prieta earthquake, reasonably complete information was available.

One limitation is that the factors related to any death were described by witnesses and determined through other circumstantial evidence, so we assume these sources to be accurate. A second problem is that coroner's reports do not contain information about others who escaped death in the same setting. Therefore, while it is possible to calculate gross epidemiological rates using census and other population data, it is difficult to derive place-specific fatality rates. With this shortcoming in mind, we investigated one location where place-specific rates could be obtained: the Cypress Street viaduct in Oakland. Given that so many casualties were concentrated at the Cypress viaduct we reviewed and analyzed data collected by the California Highway Patrol on casualties in that setting. The California Highway Patrol study was a good example of a place-specific, historical cohort, epidemiological analysis in that it systematically documented fatalities as well as examined the behavior of the injured and uninjured on and near the Cypress viaduct.

Finally, our regional fatality data was supplemented by work-related casualty data (see section "Work-Related Casualty Data" below).

## SANTA CRUZ HOSPITALIZATION DATA

The rationale for investigating those hospitalized from Loma Prieta earthquake injuries is similar to that for fatalities: Given limited resources, injury-prevention strategies should first be designed to reduce the sources of major injury; thus these strategies should be based on an empirical understanding of the types of serious injuries.

Unlike subjective reports of injury type, hospital documentation provides an objective medical diagnosis. Emergency room data are, however, not used because people use emergency rooms as their initial point of medical contact for a variety of reasons and may not have severe injuries. Studies that rely exclusively on hospital emergency-room gross numbers tend to overestimate severe injuries; also, they may underestimate the number of minor injuries because many with minor injuries do not go to an emergency room.

We restricted our study to Santa Cruz County in order to calculate the gross, earthquake-related hospitalization rates using the current county census data. The degree to which our data can be generalized to other counties is not clear; however, we have supplemented this data with regional, work-related hospitalization data.

## WORK-RELATED CASUALTY DATA

The Loma Prieta work-related injury and illness data are especially important because the timing and location of previous California earthquakes resulted in relatively few documented injuries in work settings. The California Department of Industrial Relations (DIR) collects specific data on occupational injury and illness as part of its ongoing responsibilities (California Department of Industrial Relations, 1989). California employers are required to report all Workman's Compensation claims to DIR. Each report includes details of the victim's personal characteristics, the type of injury, the physical setting where the injury happened, the victim's activities before and at the time of injury, the injury mechanism(s), and the setting(s) where the victim received medical care. DIR maintains data on 100 percent of work-related fatalities, and systematically samples 50 percent of disabling—that is, nonfatal—injuries and illnesses. A disabling injury or illness is one that causes the worker to be absent from work for a full day (or shift period after the time of occurrence). This definition is used in Workman's Compensation cases, and, as such, they do not usually tax the health care system.

Immediately following the earthquake, DIR agreed to identify those fatal and "disabling" (according to the above criteria) cases that were earthquake-related. A total of 17 work-related fatalities and 325 "disabling" injuries and illnesses was identified. The work-related casualty analysis in the following sections is based on these data. The DIR set aside approximately 100 additional nonfatal cases. We excluded these cases from this analysis because they did not fit the "disabling" criteria and therefore were not part of a systematic sample.

Compared to other data sources, the Loma Prieta work-related injury and illness data have the following advantages and disadvantages. Unlike medical documentation such as hospital emergency-room logs and medical records, which contain scant information about how or where injuries occurred, the DIR data contain detailed descriptions of the circumstances surrounding each injury and its place of occurrence. This locational data can subsequently be correlated with damage data from visual inspections or public records and can serve as a basis for estimating physical setting performance. A second advantage is that the work-related injury accounts were prepared within hours or days of the event. They therefore do not have the problem of personal recall accuracy that can lessen the reliability of survey data collected months and even years after an event. The third advantage is that, unlike studies restricted to a small geographic area, the DIR data base is regional and therefore can be used to explore regional differences in injury patterns.

The disadvantages of the DIR data typify other data sources, all of which call for additional investigation. One disadvantage is that, like studies that depend exclusively

Table 1.—Spatial distribution by county of work-related fatalities and disabling injuries and illnesses

[(From Durkin and others (1991); seventeen fatal injuries were attributed to the period of shaking; one heart attack was attributed to the earthquake. One additional work-related fatality in Santa Cruz was not reported to DIR, but independently confirmed, and is not included here. Numbers and percentages do not include San Benito County. N, number of cases; Pct., percentage of total]

| County | Fatalities | | Non-fatal disabling injuries | | | | Total | |
|---|---|---|---|---|---|---|---|---|
| | | | During shaking | | After shaking | | | |
| | *N* | Pct. | *N* | Pct. | *N* | Pct. | *N* | Pct. |
| Santa Clara | 2 | 11.1 | 105 | 37.5 | 11 | 25.0 | 118 | 34.5 |
| Alameda | 10 | 55.5 | 57 | 20.4 | 6 | 13.6 | 73 | 21.3 |
| San Mateo | -- | | 40 | 14.3 | 4 | 9.1 | 44 | 12.9 |
| San Francisco | 5 | 27.7 | 27 | 9.6 | 10 | 22.7 | 42 | 12.3 |
| Santa Cruz | 1 | 5.5 | 26 | 9.3 | 6 | 13.6 | 33 | 9.6 |
| Monterey | -- | -- | 4 | 1.4 | 2 | 4.5 | 6 | 1.8 |
| Contra Costa | -- | -- | 6 | 2.1 | 0 | .0 | 6 | 1.8 |
| Marin | -- | -- | 3 | 1.1 | 0 | .0 | 3 | .9 |
| Sonoma | -- | -- | 2 | .7 | 0 | .0 | 2 | .6 |
| Sacramento | -- | -- | 0 | .0 | 1 | 2.3 | 1 | .3 |
| Not specified | -- | -- | 10 | 3.6 | 4 | 9.1 | 14 | 4.1 |
| Totals | 18 | 99.8 | 280 | 100.0 | 44 | 99.9 | 342 | 100.0 |

on hospital emergency-room data, the DIR reports tend to underestimate the total number of injuries. In the case of work-related injuries this underreporting appears due primarily to underreporting by victims. However, underreporting is probably confined primarily to less severe injuries because victim compensation, especially to those fatally or severely injured, is dependent on reporting. A second disadvantage of current work-related injury data is that place-specific injury rates cannot be calculated without further follow-up investigations to determine the population at risk in particular situations. A third difficulty is determining whether work-related injuries are representative of nonwork-related injuries in type and scope; data here are too preliminary for answers.

## AN EARTHQUAKE CASUALTY INDEX

As aptly pointed out by Steinbrugge (1982) in his seminal work on building damage, casualties vary greatly with situation and setting. Durkin and Thiel (1990) have developed an injury index to aid in classifying injuries for casualty estimation purposes. Injuries vary greatly—from scratches, cuts, and abrasions that can be self or nonprofessionally treated (a so-called Red Cross training level) to those requiring specialized medical care. The first type do not degrade severely with delay (becoming life threatening) from professional treatment, whereas the latter can quickly become life threatening. There are three distinct components to categorizing injury severity: the type of assistance needed to move the patient to the medical provider, the skill level required to treat the injury, and the degree to which the injury becomes more serious with lack of treatment. Recognizing that these distinctions have serious implications for preparedness planning and for public policy decisions, we have developed an injury index (see table 9). The scale reflects the degree of medical skill required and the ability of the injured to transport himself to the care provider; an important factor not considered in the table is the degree to which the injury could become life threatening if not treated quickly. This index is not meant to replace currently used medical severity scales, but for possible use as a planning tool in earthquake preparedness.

## REGIONAL ANALYSIS OF WORK-RELATED AND NONWORK-RELATED CASUALTIES (HEALTH-CARE DEMAND)

### NUMBER, TYPE, AND LOCATION OF CASUALTIES

Our health-care demand study includes the spatial distribution of casualties at the regional level, the relationship of building damage to casualties, the physical setting performance and occupant actions that contributed to injury, and the distribution of injuries by type. The California Office of Emergency Services (OES) reported that there were approximately 3,800 casualties (deaths and injuries) attributable to the earthquake (Housner and Thiel,1990). The accuracy of this estimate is suspect because the consistency of data-collection methods among reporting agencies is unclear, but the data are associated with hospital and emergency-room reports from the medical community.

Table 1 presents the distribution of work-related disabling casualties by county. All but one of the fatalities and 86 percent of the nonfatal work-related casualties happened during the period of shaking; 14 percent of the nonfatal work-related casualties occurred in the earthquake's aftermath. Two-thirds of the deaths took place in Alameda County and about one-third in San Francisco County. Santa Cruz County had only one work-related death. Work-related fatalities accounted for 27 percent of the total 63 deaths attributed directly to the earthquake.

The vast majority, 90 percent, of the nonfatal work-related casualties were reported in the 5 counties closest to the epicenter. Injury frequency declined with distance from the epicenter as a function of decreasing earthquake intensity (on the modified Mercalli intensity scale, see fig. 1), with the exception of Alameda County, where the Cypress viaduct collapse generated numerous injuries. Santa Clara County accounted for over 37 percent of work-related injuries during the earthquake. Santa Cruz County, where the heaviest damage occurred, accounted for less then 10 percent of the total work-related injuries.

Table 1 also gives the injury data reported by the OES, which shows that the percentage of work-related casualties (DIR) to total casualties (OES) remains nearly constant between counties. The DIR percentage for Alameda County is high, owing to the one catastrophic collapse of the Cypress viaduct; that for Santa Cruz County is lower, owing to agriculture and tourism as its principal industries. (As will be noted later, there were apparently few tourists in the county at the time of the earthquake.) The information available on DIR injuries, because of careful auditing and recordkeeping, offers a new resource for understanding some aspects of casualties to comparable populations for which casualty data are not readily obtainable.

## DISTRIBUTION OF FATALITIES BY PLACE

The Loma Prieta earthquake was directly or indirectly responsible for at least 65 deaths. A total of 43 deaths resulted from injuries sustained in Alameda County; 13 in San Francisco County; 6 in Santa Cruz County; 2 in Santa Clara County; and 1 in Monterey County. At least 18 of these 64 deaths (28 percent) were considered work related.

Table 2 summarizes the cause and geographic location of these fatalities, as well as their frequency and proportional

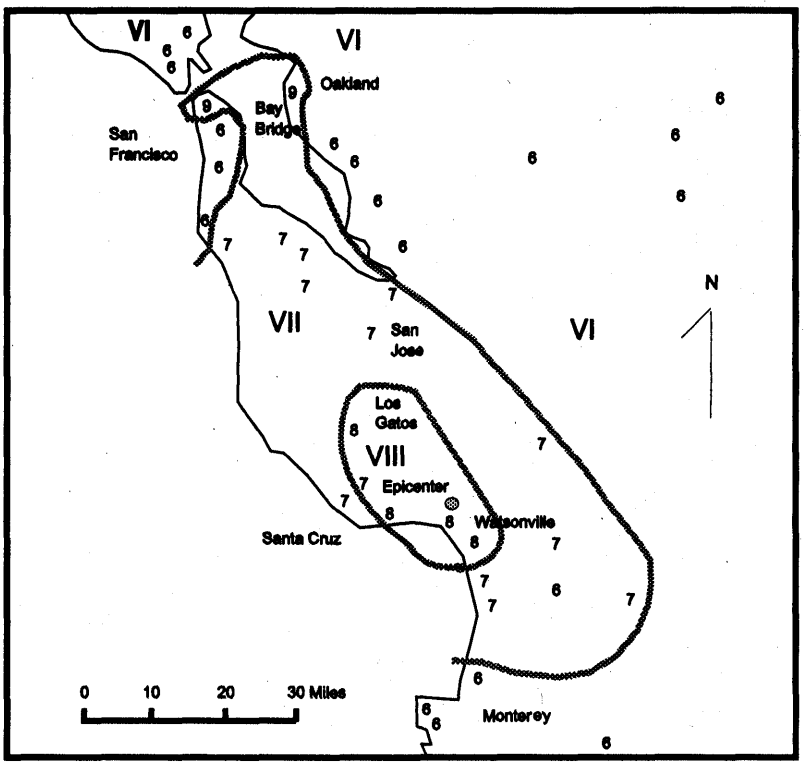


Figure 1.—Generalized isoseismal map of the damage impacts of the Loma Prieta earthquake according to the modified Mercalli intensity (MMI) scale. MMI VII is termed strong shaking and is described by the types of effects observed: weak unreinforced buildings damaged; unreinforced masonry chimneys broken at roof lines; disruption of building contents; plaster cracked. MMI VIII is termed very strong shaking: damage to nonearthquake-resistant structures can be significant, with some collapses, particularly those in poor condition; damage to nonstructural elements in modern, seismically resistant buildings; substantial disruption of building contents and toppling of unanchored equipment. From Housner and Thiel (1990).

Table 2.—Fatalities by structural type and location

[(From Durkin and others (1991)]

| Type of failure | Place of fatal injury | Fatalities | Percent of Total |
|---|---|---|---|
| Structural failure: | | | |
| Bridges: | | | |
| Reinforced concrete: | | | |
| Cypress Viaduct | Oakland | 42 | 65.0 |
| Steel truss: | | | |
| San Francisco Bay Bridge | San Francisco | 1 | 1.5 |
| Buildings: | | | |
| Unreinforced masonry: | | | |
| Exterior wall falls on cars | Downtown San Francisco | 5 | 8.0 |
| Exterior wall pieces: | | | |
| Strike victim outside | Watsonville | 1 | 1.5 |
| Roof collapse due to adjacent building collapse | Santa Cruz | 3 | 5.0 |
| Wood frame: | | | |
| Apartment building collapse | Marina District: San Francisco | 3 | 5.0 |
| Other structures: | | | |
| Transmission tower collapse | Los Altos | 1 | 1.5 |
| Water tower collapse | Monterey | 1 | 1.5 |
| Total related to structural failure | | 57 | 88.0 |
| Other causes: | | | |
| Landslide | Santa Cruz | 1 | 1.5 |
| Falls/stairway | San Francisco | 2 | 3.0 |
| Employee evacuation/heart attack | San Jose | 1 | 1.5 |
| Smoke inhalation/fire | San Francisco | 1 | 1.5 |
| Carbon monoxide inhalation/ generator | Oakland | 1 | 1.5 |
| Gunshot wound/ directing traffic | San Francisco | 1 | 1.5 |
| Vehicle collision with horses | Santa Cruz | 1 | 1.5 |
| Total related to other causes | | 8 | 12.0 |
| Total fatalities | | 65 | 100.0 |

distributions. Of these 65 earthquake-related fatalities, 43 (66 percent) were concentrated in Oakland at the Cypress viaduct collapse; 11 other deaths (17 percent) were confined to three other locations in San Francisco and Santa Cruz. Of these 11, 5 died within close proximity to each other in downtown San Francisco, 3 perished in a San Francisco Marina District residential building, and 3 others died in two separate buildings in the Santa Cruz central business district.

Structural failure was the underlying cause of most fatal injuries. Of the 65 fatalities, 57 (88 percent) were associated with some type of structural failure. All but one of the 18 work-related fatalities (94 percent) were the direct result of structural failure or its complications (for example, fire). Fatalities occurred in the collapse of a nonductile, reinforced concrete structure (the Cypress viaduct), the failure of two 50-ft spans of the San Francisco-Oakland Bay Bridge, the partial or complete failure of unreinforced masonry buildings, the collapse of a four-story wood-frame apartment building, the collapse of an agricultural water tower, and the collapse of a transmission tower (U.S. Centers for Disease Control, 1989; San Francisco County Coroner's Office, 1990).

Two-thirds of the fatal injuries and three-quarters of those related to structural failure occurred in the Cypress viaduct collapse (California Highway Patrol,1990). Table 3 provides a breakdown of the cause and place of fatalities, and their frequency and rate, for the two freeway levels and for surface streets in the collapse vicinity. One-quarter of the vehicle occupants involved in this collapse perished. However, table 3 shows a place differential, similar to that found in the collapse of reinforced concrete buildings, between fatalities on the upper and lower decks. Almost half of the vehicle occupants on the lower deck died, whereas less than 10 percent of upper deck occupants perished. Lower deck fatalities were primarily due to vehicles being crushed by falling spans or bent caps. Fire caused by exploding fuel tanks was also associated with some fatalities. Upper deck fatalities happened in vehicles that fell or were pitched off the upper deck and fell to the street be-

Table 3.—Casualty frequency and rates for the Cypress viaduct collapse

[Data from California Highway Patrol (1990). Injury index is interpretation of authors. Note that some data are for a range of injury indexes, which are described in text; therefore total numbers and percentages do not add up to the number of occupants. N, number of cases; Pct, percentage of total]

| Casualty | Injury index (table 9) | Lower deck ($N$ = 77) | | Upper deck ($N$ = 85) | | Surface streets ($N$ = 7) | | Total ($N$ = 169) | |
|---|---|---|---|---|---|---|---|---|---|
| | | $N$ | Pct. | $N$ | Pct. | $N$ | Pct. | $N$ | Pct. |
| Uninjured | 0 | 4 | 5.2 | 11 | 12.9 | 4 | 57.1 | 19 | 11.2 |
| Injured | 1-6 | 38 | 49.3 | 67 | 78.8 | 3 | 42.9 | 108 | 63.9 |
| Pain | 1 | 7 | 9.0 | 14 | 16.5 | 1 | 14.3 | 22 | 13.0 |
| Visible | 2 | 10 | 13.0 | 19 | 22.3 | 0 | 0.0 | 29 | 17.2 |
| Severe | 4-6 | 21 | 27.3 | 34 | 40.0 | 2 | 28.6 | 57 | 33.7 |
| Fatalities | 7 | 35 | 45.4 | 7 | 8.2 | 0 | 0.0 | 42 | 24.8 |

low. All of the 10 work-related fatalities occurred when the upper deck collapsed on vehicles: Apparently 8 were crushed in their vehicles by collapsing concrete; 1 person was killed when his truck toppled off the freeway; the tenth victim died from burns while trapped in wreckage.

In another "bridge-related" incident, which occurred 30 minutes after the earthquake, a 23-year-old female drove into the gap created by the collapse of the upper deck closure span of the San Francisco Bay Bridge suffering fatal injuries (Housner and Thiel,1991).

The failure of unreinforced masonry (URM) buildings contributed to nine fatalities, including six work-related deaths. In San Francisco, five motorists, in three separate vehicles, were killed when parts of the exterior wall of a five-story URM building collapsed on top of their vehicles. All of these fatalities were work related. In downtown Santa Cruz, two victims were inside a single-story URM commercial building when its roof collapse was triggered by a wall failure in the adjacent multistory URM building. Just down the street, a similar collapse incident killed a person inside a two-story department store. Finally, in Watsonville, falling exterior wall and parapet material fatally injured a woman outside of a bakery housed in a URM structure.

Three were killed when the top two stories of a four-story, wood frame San Francisco Marina District apartment building collapsed onto the first (residential) floor. Two were killed in an apartment while an infant, being evacuated by its mother, died in a collapsed stairwell. Two additional fatalities are related to the failure of other structures: A communications technician was killed by a falling transmission tower in Los Altos; the other victim died in the collapse of an agricultural water tower.

Eight deaths (12 percent) were related to causes other than structural failure. One of these was due to slope failure. The victim, discovered five days after the earthquake, was found buried under earth from a Santa Cruz cliff that apparently gave way during the earthquake.

Two San Francisco deaths were attributed to stairway falls either during or immediately after the earthquake. In one case, a 59-year-old man was observed to fall down a 10-foot flight of stairs. In the other instance, a 68-year-old female tourist was found lying on the floor of a darkened basement garage at the foot of the stairway leading to a hotel lobby.

Other fatalities included a public agency supervisor who suffered a fatal heart attack after evacuating his agency, a third San Francisco resident who apparently died from smoke inhalation during a fire caused by an earthquake-induced gas leak, a 34-year-old male who died from carbon monoxide inhalation from an emergency generator in Alameda County, and a civilian who was shot while directing traffic in San Francisco after the earthquake (this death was considered indirectly earthquake related by the San Francisco Coroner's office). Finally, perhaps the most bizarre death, attributed indirectly by the Santa Cruz Coroner's office to the earthquake, happened approximately 7 hours after the event when a pickup truck, traveling a darkened Santa Cruz freeway, crashed into three horses, killing the driver and all of the animals.

DIR data show that the 18 work-related fatalities (28 percent of all fatalities) were concentrated in five locations, all included within those deaths discussed above. Of the 18, 10 died in the Cypress viaduct collapse; 5 died within close proximity to each other in downtown San Francisco; one reported death was in the Santa Cruz central business district. An additional death was independently confirmed but not reported to DIR and therefore not discussed (or considered in our numbers) here. Two others died in Santa Clara County. All but one fatality was the direct result of structural failure or its complications (for example, fire). No work-related deaths were attributable to the performance of nonstructural elements or building contents.

## DISTRIBUTION OF HOSPITALIZED CASES

Next to fatalities, the most serious earthquake casualties were those requiring hospital admission, in addition to hospital emergency-room or outpatient treatment. The proportion of emergency-room cases that are actually admitted to a hospital, as opposed to being examined or treated or both and released, is one way to gage the relative severity of earthquake-related injuries. In the 72-hour period after the earthquake, the three Santa Cruz County hospitals, Dominican, Community, and Watsonville, admitted only 23 patients with serious earthquake-related injuries. This number stems from a medical record review, as part of a county and local hospital's postearthquake medical assessment, of the 981 cases seen in hospital emergency rooms during the 72-hour interval; 76 of these cases were seen more than once in the 72-hour period. Table 4 shows the probable medical cause of these emergency room cases. It shows that 55 percent of all cases were potentially earthquake related and 22 percent were clearly earthquake related. The geographic distribution of these 981 cases within the county shows a concentration in population centers.

A total of 115 patients (11.7 percent) of the 981 required hospital admission. Their case records contain significantly more detail than those cases not hospitalized. Table 5 provides a breakdown, by medical cause, of these 115 patients (11.7 percent of the total cases). This number includes both direct admissions to hospitals (81 percent) and transfers from other hospitals (19 percent). Of these 115 admissions, only 23 were judged earthquake related.

Data from tables 4 and 5 allow estimation of the frequency for earthquake-related injuries requiring hospital treatment from the total of earthquake injuries. Taking the 23 serious earthquake-related injuries, if only earthquake-caused injuries are considered, the frequency of serious injuries is 10.7 percent (23/215), whereas if all of the cause-uncertain injuries are assumed to be earthquake related, then the frequency is 4.4 percent (23/521). The California Department of Health Services, in association with Santa Cruz County, Johns Hopkins University, and the authors, is completing a detailed study of Santa Cruz County injuries. When completed this study will provide a means for more precise assessment of injury frequency.

Table 6 gives the probable medical cause of these 23 hospitalized cases. Heavy building contents, such as packing crates, were the source of the hospitalized injuries from building contents. Only one-fifth of the serious injuries was due to structural failure. Unlike the overall fatality distribution, falls were responsible for over half (13/23) of the Santa Cruz earthquake-related hospitalizations. Closer scrutiny reveals that the elderly were the most frequent fall victims. Whereas a younger individual might escape a fall with minor bruises, the elderly victims in this group were more likely to suffer a fractured hip requiring several days of hospitalization. In several cases, it appeared that the earthquake injury provided a convenient opportunity for the physician to treat a pre-earthquake condition.

These data clearly support the observation that serious injuries, those requiring hospitalization, did not represent a substantial fraction of all the injuries that occurred in the earthquake within Santa Cruz County and probably regionwide.

Research is now underway to further assess data from Loma Prieta and other worldwide earthquakes with the ob-

Table 4.—Probable medical cause for hospital cases during the 72-hour period after the earthquake

[N, number of cases; Pct, percentage of total]

| Medical cause | *N* | Pct. |
|---|---|---|
| Illness | 360 | 36.7 |
| Other (for example, OBGYN) | 6 | .6 |
| Unknown | 79 | 8.0 |
| Total | 445 | 45.4 |
| Injury | | |
| Clearly earthquake related | 215 | 21.9 |
| Clearly not earthquake related | 15 | 1.5 |
| Uncertain cause | 306 | 31.2 |
| Total | 536 | 54.6 |
| Total cases | 981 | 99.9 |

Table 5.—Cause of hospital admissions for the 72-hour period after the earthquake in Santa Cruz County

[Hospitals make a distinction between admissions and transfers from other hospitals; N, number of cases; Pct, percentage of total]

| Medical cause | Admissions | | Transfers | | Total | | Percent of hospital cases (table 4) |
|---|---|---|---|---|---|---|---|
| | *N* | Pct. | *N* | Pct. | *N* | Pct. | |
| Illness | 56 | 60.9 | 9 | 39.1 | 65 | 56.5 | 6.6 |
| Injury, earthquake related | 16 | 17.4 | 7 | 30.4 | 23 | 20.0 | 2.2 |
| Injury, not earthquake related | 13 | 14.1 | 7 | 30.4 | 20 | 17.4 | 2.0 |
| Other (for example, OBGYN) | 5 | 5.4 | --- | --- | 5 | 4.3 | 0.5 |
| Unknown | 2 | 2.2 | --- | --- | 2 | 1.7 | 0.2 |
| Total | 92 | 100.0 | 23 | 99.9 | 115 | 99.9 | 11.7 |

Table 6.—Earthquake-related hospitalized injuries in Santa Cruz County

[N, number of cases; Pct, percentage of total]

| Cause of injury | *N* | Pct. |
|---|---|---|
| Falls: | | |
| Direct | 9 | 39.1 |
| Indirect | 4 | 17.4 |
| Structural failure: | | |
| URM | 4 | 17.4 |
| Unknown | 1 | 4.3 |
| Building contents | 4 | 17.4 |
| Toxics (indirect) | 1 | 4.3 |
| Total hospitalized | 23 | 99.9 |

Table 7.—Distribution of nonfatal, disabling[1] work-related injuries and illnesses in Santa Cruz County

[(From Durkin and others (1991); N, number of injuries; Pct, percentage of total; leaders (--), no data]

| Cause of injury | During shaking | | After shaking | | Total | |
|---|---|---|---|---|---|---|
| | N | Pct | N | Pct | N | Pct |
| Due to structural collapse: | | | | | | |
| Cypress viaduct | 8 | 2.9 | 0 | .0 | 8 | 2.5 |
| San Francisco Bay Bridge | 2 | .7 | 0 | .0 | 2 | .6 |
| Unreinforced masonry related: | | | | | 0 | .0 |
| Falling wall material | 2 | .7 | 0 | .0 | 2 | .6 |
| Falling ceiling/ building collapse | 2 | .7 | 0 | .0 | 2 | .6 |
| Floor failure/burning building | 0 | .0 | 1 | 2.1 | 1 | .3 |
| Total | 14 | 5.0 | 1 | 2.1 | 15 | 4.6 |
| Not due to structural collapse: | | | | | | |
| Hit by falling object | 43 | 15.5 | 0 | .0 | 43 | 13.2 |
| Hit or bumped by overturning object | 36 | 13.0 | 0 | .0 | 36 | 11.1 |
| Thrown into or bumped into object | 57 | 20.6 | 0 | .0 | 57 | 17.5 |
| Fall-related injuries | 72 | 26.0 | 16 | 33.3 | 88 | 27.1 |
| Other stairway related | 0 | .0 | 6 | 12.5 | 6 | 1.8 |
| Sprains due to shaking | 6 | 2.2 | 0 | .0 | 6 | 1.8 |
| Strained taking evasive action | 23 | 8.3 | 0 | .0 | 23 | 7.1 |
| Holding on | 7 | 2.5 | 0 | .0 | 7 | 2.2 |
| Helping someone | 1 | 0.4 | 3 | 6.2 | 4 | 1.2 |
| Vehicle related | 2 | 0.7 | 1 | 2.1 | 3 | .9 |
| Toxic material exposure | 0 | .0 | 12 | 25.0 | 12 | 3.7 |
| Moving objects | 0 | .0 | 3 | 6.2 | 3 | .9 |
| Clean-up/repair | 0 | .0 | 2 | 4.2 | 2 | .6 |
| Stepped/slipped on object | 1 | .4 | 3 | 6.2 | 4 | 1.2 |
| Emotional | 2 | .7 | 1 | 2.1 | 3 | .9 |
| Other | 2 | .7 | 0 | .0 | 2 | .6 |
| Unknown | 11 | 4.0 | 0 | .0 | 11 | 3.4 |
| Total | 263 | 95.0 | 47 | 97.8 | 310 | 95.2 |
| Total Injuries | 277 | 100.0 | 48 | 99.9 | 325 | 99.8 |

[1]"Disabling" is defined in text in the section "Work-Related Casualty Data."

jective of developing empirically supportable casualty-estimation models.

## WORK-RELATED HOSPITAL ADMISSIONS

DIR data show that of the 25 work-related cases requiring hospital admission, 8 were related to structural failure, 10 were associated with building contents, 1 was connected to the failure of a nonstructural ceiling system, 5 were fall related and, 1 person was burned by cooking grease.

Six of the eight structure-related injuries occurred at the Cypress viaduct collapse; one at the San Francisco Bay Bridge failure; and one at a URM collapse. Heavy objects that toppled, including a roll of newsprint, a wine barrel, a metal locker, a file cabinet, and a store display, accounted for five building-content injuries. An airline employee suffered a possible paralysis when hit by a falling gate podium. Four injuries resulted when people were thrown into counters and other objects. Finally, two victims fell from some height (one from five stories); two others tripped and fell while evacuating a building, and a fifth felt that a fall may have complicated her pregnancy.

## DATA SHOWING CAUSE OF INJURY OR DEATH

DIR data are particularly useful in relating casualties to specific structures, environments, or actions. Despite their potential underreporting of injuries, these data offer a useful breakdown of types and causes.

### CASUALTY DISTRIBUTION BY PLACE

Table 7 summarizes the causes of the fatalities and injuries. While all but one fatality were associated with structural failures, only 7 percent of the injuries were related to such failures. Approximately 85 percent of the injuries were caused by earthquake shaking, while the other 15 percent occurred after the earthquake shaking. These latter casualties were associated with individual behavior or accidents that would not have occurred if the earthquake had not caused the damage or behavior associated with the injury. The fact that about 20 percent of after-earthquake injuries were caused by toxics is of some concern, especially since these are disabling injuries and few sites with non-agricultural chemicals were damaged. This percentage may suggest that future toxics-related injury rates can be expected to be much higher, both in absolute numbers and in proportions. The nature of these data are discussed below.

### WORK-RELATED INJURIES ASSOCIATED WITH STRUCTURAL COLLAPSE

Like fatalities, work-related injuries associated with structural collapse were concentrated at the Cypress viaduct and the San Francisco Bay Bridge and also scattered among a small number of URM buildings. There were 8 vehicle-related injuries at the Cypress viaduct collapse, 2 at the Bay Bridge, and 4 from URM failure. Two of the four documented URM-related injuries resulted from falling masonry hitting passersby; the other two victims were inside URM's when the ceiling collapsed. A fireman who fell when the floor of a burning building collapsed suffered the only postshaking injury due to structural failure.

### INJURIES NOT ATTRIBUTABLE TO STRUCTURAL COLLAPSE

Fall-related injuries comprised those most frequently reported to the DIR as unrelated to structural collapse. This type of injury accounted for almost 26 percent of those occurring during and after shaking. The four most common fall-related injuries during the shaking were due to stairway falls; falls off ladders, scaffolding, and loading docks; and simply being knocked down by the strength of the shaking. Falls were also responsible for 33 percent of the postshaking injuries. Postshaking fall victims were primarily individuals attempting to evacuate buildings through darkened stairways.

Being thrown into or bumping into a desk, doorway, or other object was reported by over one-fifth of the victims, making such impacts the second most frequent cause of shaking-related injuries. Although being hit by a falling object is commonly thought to be the predominant earthquake-injury mechanism, the DIR data support this assertion only for those injuries resulting from the structural failure of URM buildings. Only about 16 percent of the "nonstructural" injuries were due to falling nonstructural elements such as ceiling tiles or light fixtures. Furthermore, only 13 percent of the shaking-related injuries were associated with building contents, such as filing cabinets, overturning and striking building occupants. In addition, approximately 10 percent reported straining of the back or extremities while taking evasive action such as attempting to get under a desk.

### EVASIVE ACTION INJURIES

Many nonfatal injuries were associated with building occupants taking protective action. At least 60 percent of those injured during the period of shaking were engaged in some form of protective action at the time of their injury (table 7). A total of 43 percent of this number was either attempting to evacuate a building, move to a safer place within a building, or, if already outside, move away from a structure. Typical evacuation injuries included tripping while running down stairs, and jumping off loading docks while attempting to exit. One-quarter of those injured were either attempting to take shelter under a desk or table or were already underneath. A total of 14 percent was injured while standing in doorways or holding onto doors.

### INJURIES FROM TOXIC SUBSTANCES RELEASE

Emergency medical authorities are concerned about the health threat posed by hazardous-material releases during and after an earthquake. Our analysis of work-related injuries found 12 individuals exposed to toxic substances. The victims were predominantly managers and security and maintenance personnel who encountered or spent long periods of time in hazardous settings while searching buildings, directing evacuations, or participating in clean-up operations. The exposures were localized--confined to a single building area--and each involved one or two people. Two security guards evacuating a multistory college science building were exposed to unknown chemical fumes while passing through a science lab; a security guard in an industrial facility reported exposure to chemicals of unknown origin while conducting an evacuation. In addition, two workers at a semiconductor manufacturer and a janitorial supply warehouse employee inhaled chemical fumes while evacuating their respective facilities. The second group of toxic-related injuries happened during the post-earthquake cleanup period. Two janitorial supply warehouse workers reported exposure to spilled bathroom bowl cleaner; a hardware store clerk inhaled fumes from a spilled insecticide container; an electronics manufacturing manager was exposed to sodium hydroxide fumes when chemicals spilled from production line tubs; and a maintenance worker claimed to have inhaled dust particles while repairing damaged ceiling light fixtures. Finally, a retail store janitor slipped on spilled cleaning chemicals and suffered burns and blisters. All of these injuries were relatively minor, resulting in emergency room and physician visits for examination but no hospital admissions.

Table 8.—Frequency of disabling injuries during and after shaking in Santa Cruz County

[From Durkin and Thiel (1991); N, number of injuries; Pct, percentage of total]

| Disabling injury type | During shaking | | After shaking | | Total | |
|---|---|---|---|---|---|---|
| | *N* | Pct | *N* | Pct | *N* | Pct |
| Strains/sprains | 148 | 35.4 | 38 | 54.3 | 186 | 38.1 |
| Contusions | 97 | 23.2 | 12 | 17.1 | 109 | 22.3 |
| Fractures | 35 | 8.4 | 5 | 7.1 | 40 | 8.2 |
| Not specified | 40 | 9.7 | 0 | .0 | 40 | 8.2 |
| Lacerations | 31 | 7.4 | 5 | 7.1 | 36 | 7.4 |
| Pain/soreness | 29 | 6.9 | 2 | 2.9 | 31 | 6.4 |
| Inhalation | 6 | 1.4 | 6 | 8.6 | 12 | 2.5 |
| Multiple trauma | 10 | 2.4 | 0 | .0 | 10 | 2.0 |
| Concussions | 9 | 2.2 | 0 | .0 | 9 | 1.8 |
| Burns | 5 | 1.2 | 2 | 2.9 | 7 | 1.4 |
| Dislocations | 5 | 1.2 | 0 | .0 | 5 | 1.1 |
| Anxiety | 2 | .4 | 0 | .0 | 2 | .4 |
| Possible paralysis | 1 | .2 | 0 | .0 | 1 | .2 |
| Total | 418 | 100.0 | 70 | 100.0 | 488 | 100.0 |

## DIR DATA SHOWING CASUALTY DISTRIBUTION BY TYPE

DIR data also provide a useful breakdown of injury type, although limited to work-related injuries. Table 8 shows the distribution of nonfatal work-related injuries and illness by type. Strains, sprains, and contusions combined to constitute almost 60 percent of the shaking-related injuries and over 70 percent of the postshaking ones. Strains and sprains resulted mostly from falls and evasive action such as diving under a desk, bracing oneself in a doorway, or trying to hold onto something for stability. The chief causes of contusions were bumping against a wall, floor, doorway, or piece of equipment, or being struck by a falling or overturning object.

Fractures and lacerations added up to almost 16 percent of the total injuries reported by DIR. Most fractures were relatively minor, involving the hands, wrists, feet, and ankles. Over half of the fractures resulted from falls. Seven fractures were caused by falling or overturning objects. Two Cypress viaduct victims and one URM collapse victim sustained the most serious fractures. However, one office worker suffered a broken neck and back, requiring hospitalization, when struck by a filing cabinet. Most lacerations were also relatively mild.

## DIR CASUALTY INDICES

The casualty index (table 9) was applied to the DIR data. Table 10 gives the distribution of injury severity for the DIR data, using the definitions of table 9. The lowest two injury classes are certainly underrepresented because the DIR requirement for inclusion is that at least one day of work be lost after the injury. Category 1 and 2 injuries not resulting in one lost work day would be excluded. The current information available is not sufficient to make fine distinctions; however, it is sufficient to conclude that very few, no more than 7 percent, of the injuries required the use of hospitals, notwithstanding that many more people sought hospital attention for injuries. This frequency should be considered as an upper bound of the actual frequency since there is probably underreporting for Index 1 and 2. Significantly, none of the aftershaking injuries were sufficiently serious to require hospital care.

## CONCLUSIONS RELATED TO HEALTH-CARE DEMAND ANALYSIS

Our assessment of the characteristics of injuries, particularly serious injuries, in the Loma Prieta earthquake led to the following findings. These conclusions are the major findings of our research effort to date. They will be supplemented and revised as analysis continues and additional data now being collected and assessed are integrated.

*Earthquake Casualties*

1. Structural failure led to 98 percent of the direct earthquake fatalities and 88 percent of the total earthquake fatalities.
2. High-risk structures, especially the Cypress viaduct and unreinforced masonry buildings, were major sources of serious injuries.
3. Well-designed, modern, earthquake-resistant structures posed little casualty risk in this earthquake.

*Earthquake-related hospitalized injuries in Santa Cruz County*

4. Occupant contact with nonstructural building elements, especially building contents, was a major source of

Table 9.—Injury index scale for earthquake casualties in Santa Cruz County

[These index values are based on the seriousness of the initial injury, as determined from the services required to treat the injury; the index can be enhanced by incorporating the degree to which an injury will progress to a more serious level if medical attention is not provided]

| Injury index | Level of seriousness | Skill level of provider | Transportation of injured | Type of facility needed |
|---|---|---|---|---|
| 0 | None | -- | -- | -- |
| 1 | Nuisance | None; can be self administered | None | None |
| 2 | First Aid | Red Cross level training | None | None |
| 3 | Outpatient | Nurse, physician | To skilled person if not on-site; can convey self | Clinic, medical office, emergency room |
| 4 | Hospitalized | General practice physician | To skilled person if not on-site; needs assistance | Clinic or general services hospital: stay for observation |
| 5 | Serious | Specialized physician, surgeon | Attended care during transportation | General services hospital |
| 6 | Severe | Specialized physician, surgeon | Attended care during transportation; relocation to another facility possibly required | State-of-the-art hospital |
| 7 | Death | -- | -- | -- |
| 8 | Unknown | -- | -- | -- |

Table 10.—Work-related injuries by casualty index (table 9) that occurred during and after the earthquake in Santa Cruz County

[The injuries given for index 3 to 8 are estimated upper boundaries. The total injuries for index 1 and 2 are probably underrepresented; N, number of injuries; Pct, percentage of total]

| Injury index | During shaking | | After shaking | | Total | |
|---|---|---|---|---|---|---|
| | *N* | Pct. | *N* | Pct. | *N* | Pct. |
| 1 & 2 | 40 | 13.6 | 4 | 8.1 | 44 | 12.9 |
| 3 | 208 | 70.7 | 41 | 83.7 | 249 | 72.8 |
| 4,5,6 | 25 | 8.5 | 0 | .0 | 25 | 7.3 |
| 7 | 17 | 5.8 | 1 | 2.0 | 18 | 5.3 |
| 8 | 4 | 1.4 | 3 | 6.1 | 7 | 2.0 |
| Total | 294 | 100.0 | 49 | 99.9 | 342 | 100.3 |

minor injuries but was associated with few serious injuries.

5. Falls caused over half the Santa Cruz County hospitalizations.
6. The elderly were the principal fall victims.
7. Only 20 percent of the serious injuries in Santa Cruz County were due to structural failure, and these were principally caused by URM buildings.
8. Heavy building contents were associated with the few serious nonstructural injuries.
9. Total minor and first-aid level injuries (injury index 1 and 2; table 9) in the earthquake are underrepresented in the Loma Prieta injury data.

*Work-Related Injuries*

10. Most work-related injuries were relatively minor.
11. 60 percent of the shaking-related injuries and 70 percent of the indirect earthquake injuries were minor strains, sprains, and contusions.
12. Falls were the largest single source of work-related injuries.
13. Disabling work-related injuries, those causing 1 day or more lost work, were concentrated in a few locations. Half were building-failure related.
14. Nonstructural elements and building contents posed relatively little threat of serious injury. Heavy objects were responsible for the six serious injuries associated with building contents.
15. Only about 7 percent of DIR injuries required hospitalization.
16. 60 percent of DIR injuries were treated outside a hospital setting (emergency room, outpatient clinic, or

Table 11.—Index of treatment for nonfatal, disabling[1] work-related injuries and illnesses that occurred during or after the earthquake

[From Durkin and others (1991); N, number of injuries; Pct, percentage of total]

| Ultimate treatment setting | During shaking | | After shaking | | Total | |
|---|---|---|---|---|---|---|
| | N | Pct. | N | Pct. | N | Pct. |
| Self-treated (no formal treatment) | 40 | 14.6 | 4 | 8.9 | 44 | 13.8 |
| Physician's office or clinic | 120 | 44.0 | 23 | 51.1 | 143 | 45.0 |
| Hospital-based outpatient | 88 | 32.2 | 18 | 40.0 | 106 | 33.3 |
| Hospital inpatient | 25 | 9.2 | 0 | .0 | 25 | 7.9 |
| Total | 273 | 100.0 | 45 | 100.0 | 318 | 100.0 |

1 "Disabling" is defined in text in the section "Work-Related Casualty Data."

hospital-based physician); total number of DIR injuries was about 2 to 2A times the number of DIR hospital-treated injuries.

*Hospital case records*

17. From 22 percent to 54 percent of hospital cases seen were earthquake related.
18. Only about 2 percent of emergency-room contacts led to hospital admission and were earthquake related.

## CAPACITY OF THE HEALTH-CARE SYSTEM (SUPPLY)

Health-care supply is a combination of a number of components, which include local hospitals, emergency medical services, private clinics, and physicians. The adequacy of the supply in an emergency situation such as a major earthquake is a function not only of the physical condition of the supply, but also of its potential utilization. Our findings have three major implications for earthquake casualty modeling: First, structural damage potential remains the major predictor of serious earthquake casualties, but because nonstructural performance remains a key source of minor injuries and a potential risk for major ones, we should evaluate and prioritize nonstructural hazards in terms of their relative risk. Second, casualty estimates based exclusively on hospital utilization data may greatly underestimate the true medical demand. Third, future casualty models should estimate the resiliency of the entire regional health-care system. Table 11 provides a breakdown for DIR cases of the numbers and proportion of victims who treated themselves or sought treatment at various treatment settings. Of the 318 cases for which data is available, about 14 percent sought no formal medical care for their injuries, even though these injuries were sufficiently severe to cause at least one day's work loss, and 45 percent sought treatment at a private physician's office or nonhospital clinic. In sum, approximately 60 percent of the total DIR cases were treated outside of the hospital setting; of the remainder, about one-third received treatment at a hospital-based outpatient setting (for example, emergency room, outpatient clinic, hospital-based physician). Less than 10 percent of those injured during the shaking required hospital admission, and no postshaking injured needed such care.

The heavy utilization of private physicians and nonhospital-based clinics after the Loma Prieta earthquake is one indication of both the relatively low severity of most injuries and the absence of disruption to the normal health-care system. An analysis of injury type and severity (tables 10 and 11) indicates that most of the 106 injuries seen in the hospital setting could have been treated in physicians' offices or nonhospital clinics. That is, the vast majority of injuries (81 percent, 106/106+25) did not require the sophisticated technical environment of a hospital. These data suggest that about three-fourths of those who used a hospital may not have needed to do so.

The DIR data show heavy utilization of familiar, local, health-care resources and thus call into question the usefulness of setting up services in unfamiliar locations. It has been conjectured that an efficient way to manage earthquake medical services is to establish casualty collection points (CCP) at several locations within a community. However, when the Santa Cruz County emergency medical services officer was asked whether CCP's were needed, his response, based on patient behavior, corroborated findings from the DIR data:

> No. The public will always seek help where it is most familiar. The traditional focus of health care for the public are the hospitals and medical clinics. If casualty collection points were to be established, they would need to be located near hospitals and clinics. I believe CCP's would have been needed only if the hospitals had sustained enough structural damage to render the buildings unsafe. This was not the case for the Loma Prieta earthquake.

The total number of DIR injuries is about 2.5 times the number of DIR hospital-treated injuries. This observation has great potential importance for future casualty estimation and data collection. Since it was found that the county distribution of injuries was comparable to the OES distribution, then it is reasonable to assume that the actual number of total injuries may be approximately 2.5 times the number reported by studies that rely on hospital emergency room records as their only basis.

## SANTA CRUZ COUNTY EMERGENCY HEALTH-CARE DELIVERY

An analysis of one county, Santa Cruz, provides useful insights into the operation of major health-care components after a major earthquake. Santa Cruz County was selected for detailed analysis because it was the most severely impacted by the Loma Prieta event, data were available, and county officials were very cooperative. The following section reviews 9-1-1 emergency and hospital response. Health-care delivery systems in Santa Cruz County, including 9-1-1 emergency medical services, hospitals, clinics, and mental health agencies, were challenged beyond any previous disaster experience. At the time of the earthquake the county was served by three hospitals: Watsonville Community, Dominican (Santa Cruz), and AMI Community (Santa Cruz) Hospitals; AMI has subsequently been absorbed by Dominican. The County Emergency Operations Center (EOC) operated in the disaster mode for one week after the earthquake, coordinating a myriad of disaster operations. Although other studies are underway by the authors and other researchers, particularly those at Johns Hopkins University, only 9-1-1 emergency medical services and initial observations by medical administrators will be discussed below.

### 9-1-1 EMERGENCY RESPONSE

Requests for 9-1-1 emergency services reached unprecedented levels at the county communications center within minutes of the earthquake, even though many telephone lines were not functioning. Although there is not yet an accurate count, over 1,000 calls from the public were reported that night, many times the normal volume. Numerous requests for ambulance services were dispatched, but the number of victims who actually received their services is not known. Not all calls were for emergency purposes—some callers asked if there had been an earthquake. Despite the high volume of calls and confused radio communications, the emergency medical and rescue teams managed to respond to requests for their services.

The 9-1-1 system in Santa Cruz County is centrally organized and serves the entire county. Because of the earthquake, operators felt a sense of urgency to make sure that every call was taken, lest a major problem not be identified because of the busy 9-1-1 system. The usual careful, information-intensive inquiry process was foreshortened to a brief conversation to assure minimal time spent on each call. For medical calls, they reduced their inquiry to simply whether this was a medical emergency or not and, if so, the location where the ambulance should be sent. There was no interrogation to confirm the callers' response that it was a medical emergency and no information was obtained on the medical severity or other characteristics of the call. Using standard emergency-management procedures, the ambulance dispatcher was given a small card that only indicated the location to which an ambulance was to be dispatched and a time stamp indicating when the call was received. There were no notations that indicated severity, number of victims, and so forth that could have assisted in assigning priority. In most instances requests for ambulances were processed in the order that they were received. The dispatcher spread the unanswered calls out on a small table and made calls essentially in time order of receipt as ambulances became available.

During this period there were initially six EMS (emergency medical service) vehicles (ambulances) and crews on duty; this rapidly increased to 10 as additional crews were assembled. At the time of the earthquake, telephone technicians were in the process of some equipment work, a task rapidly completed once it was clear that an earthquake had occurred.

All 9-1-1 communications center ambulance dispatch cards and disaster report notes were collected to determine the volume and types of medical calls responded to during the earthquake. Each record was ordered sequentially by the date and time the call was received and the outcome was reviewed; that is, did the paramedic unit contact, treat, or transport a patient. A total of 230 dispatch requests were recorded during the 72-hour study period, including one duplicate. Determining the dispatch outcomes for the first 7 hours (up to midnight) after the earthquake proved problematic, as over 60 percent of the records did not include this information. These outcomes were of particular interest to this investigation, as nearly one-third of ambulance dispatches in the first 72 hours occurred from the time of the earthquake until midnight. After midnight, however, the unknown outcomes dropped to less than 10 percent as radio communications traffic decreased significantly and generally less chaos prevailed; this allowed for more complete documentation of dispatch information. This investigation then sought to reconstruct all dispatch outcomes from sources other than the 9-1-1 records.

Most of the 9-1-1 medical dispatch outcomes were reconstructed through interviews with the paramedics on duty the night of the earthquake and cross-referencing prehospital and hospital medical records. The results showed that for the period ending midnight the night of the earthquake, just over one in three dispatches resulted in a paramedic team transporting a patient or multiple patients to the hospitals. Most patients were brought to either Dominican Hospital or Watsonville Hospital; only three patients were transported to AMI Community Hospital. Initially, AMI was reported to have significant structural damage, and a diversion order was issued because field paramedics believed that the hospital was overloaded treating its own patients; subsequently, the order was canceled. The overall 9-1-1 call volume was significantly higher for 2 days after the earthquake but thereafter was near normal. The heaviest volume of ambulance transports was received by Watsonville Hospital on Wednesday (10/18/89), which was surprising because Dominican normally receives twice the volume of patients of Watsonville.

During the 72 hours after the earthquake a total of 229 calls was logged that resulted in ambulance dispatch. Figure 2 graphically locates the destination for ambulance runs during this 72-hour period.

Figure 3 shows the cumulative number of 9-1-1 calls resulting in ambulance dispatches for the 72 hours after the earthquake. The most substantial increase in call volume was during the hours after the earthquake. Time of day and seasonal experience from previous years were not available so that this volume could be compared. On the basis of aggregate data, table 12 shows that on an average day in late 1988 there were about 37 dispatches (3 per hour) that resulted from 9-1-1 calls; the dashed lines in figure 3 indicate the average slope for normal data. Clearly, the number of dispatches was unusually high, by a factor of three, during the 72 hours immediately after the earthquake, but quickly dropped to a rate only of about 50 percent above normal and stayed at this level for the 72-hour period. The responsible official on duty October 17 stated that until about midnight there were typically 5 to

Table 12.—Comparison of 9-1-1 outcomes for earthquake period to a previous normal period

[From Thiel and others (1992)]

| Location | Transports | Other[4] | Total runs |
|---|---|---|---|
| South county[1] | 8.6 | 2.9 | 11.5 |
| North county[2] | 19.3 | 6.2 | 25.5 |
| Average per day | 27.9 | 9.1 | 37.0 |
| | Pct. | Pct. | |
| Pre-earthquake | 75 | 25 | |
| October 17[3] | 59 | 41 | |
| 72 hours after earthquake[3] | 69 | 31 | |

1 Determined from total for last half of 1988.
2 Determined from total for last quarter of 1988.
3 Number of transports and dead-on-arrivals plus treat-and-release divided by total number dispatched less unknown dispositions.
4 Cancelled, unknown disposition, or unable to locate.

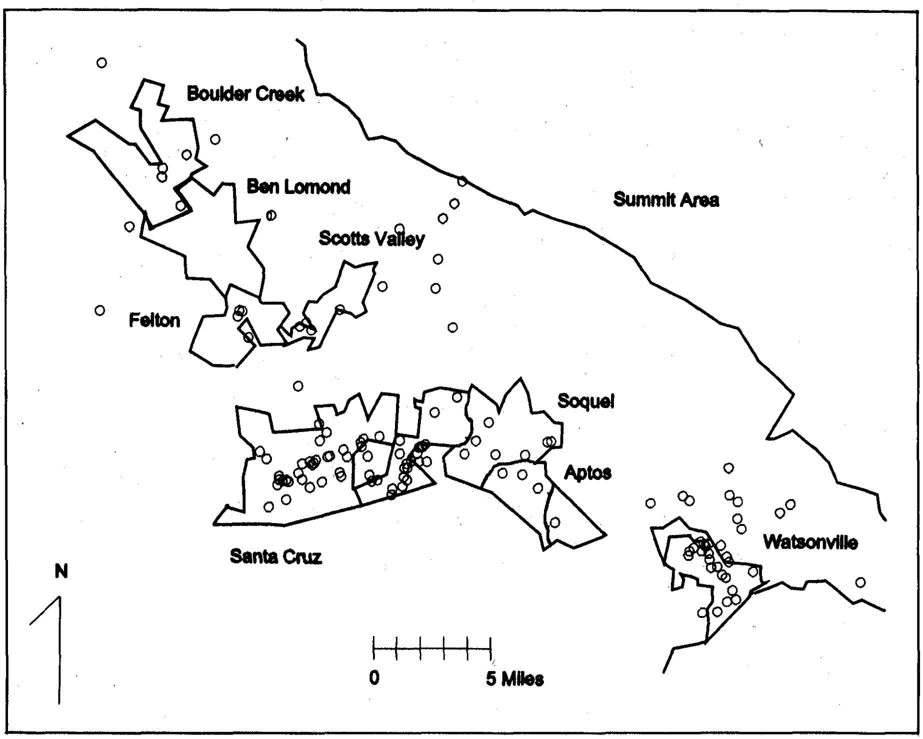


Figure 2.—Geographic distribution of Santa Cruz County 9-1-1 emergency dispatches during the first 72 hours after the earthquake. The distribution closely follows population centers; few midcounty, rural runs were made, in part due to road conditions and absence of calls for assistance. From Thiel and others (1992).

10 calls awaiting dispatch of an ambulance. Thus, it is reasonable to conclude that the system was saturated during the 7 hours after the earthquake. Figure 4 shows the processing sequence for a 9-1-1 call; an ambulance is dispatched to the site, unless the call is canceled in route. Table 13 gives the number of dispatches resulting in transport or cancellation for the 7-hour period after the earthquake and for the following 72-hour period. There are still a number of dispatches for which outcome is unknown.

The emergency response showed several ways that EMS personnel were resourceful in addressing abnormal circumstances: several patients were treated and released by the EMS crews; multiple individuals were transported in one run to a hospital; patients were directed to other means of transport if available; and no action was taken when the crew determined that their services were not critical. There was an unusually high number of dispatches where the ambulance arrived and found that other medical resources were already on the scene. The average time period from receipt of the call to completion ranged from 30 to 42 minutes for successive days (30, 35, 40, 42); however, the distribution indicated that the average was heavily affected by a few long cases, associated with victim extrication from automobiles.

One of the striking observations from table 13 is the unusually low number of advanced life support (ALS) trans-

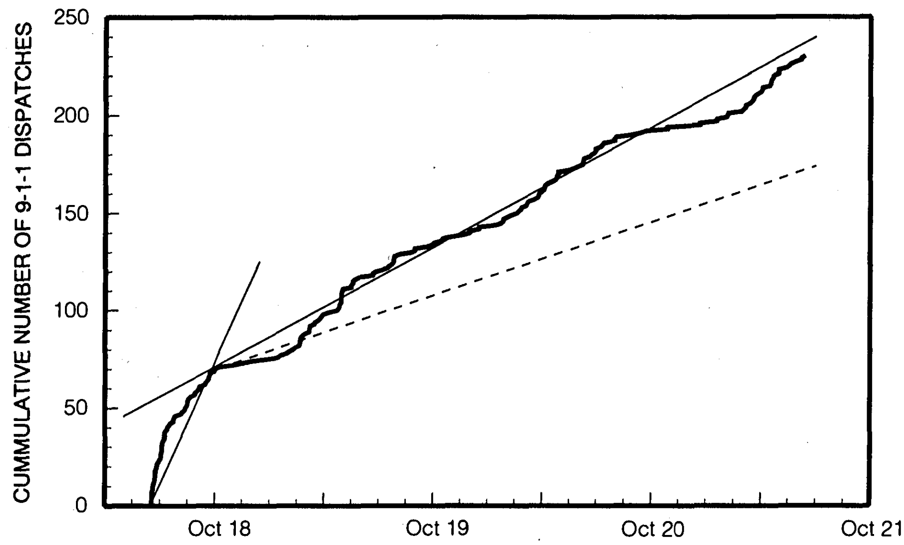


Figure 3.—Cumulative number of 9-1-1 calls that resulted in ambulances being dispatched for the 72 hours after the earthquake. The solid lines are average slopes for before and after midnight, October 17; dashed lines are estimates of average slope for normal rates based on data for late 1988. From Thiel and others (1992).

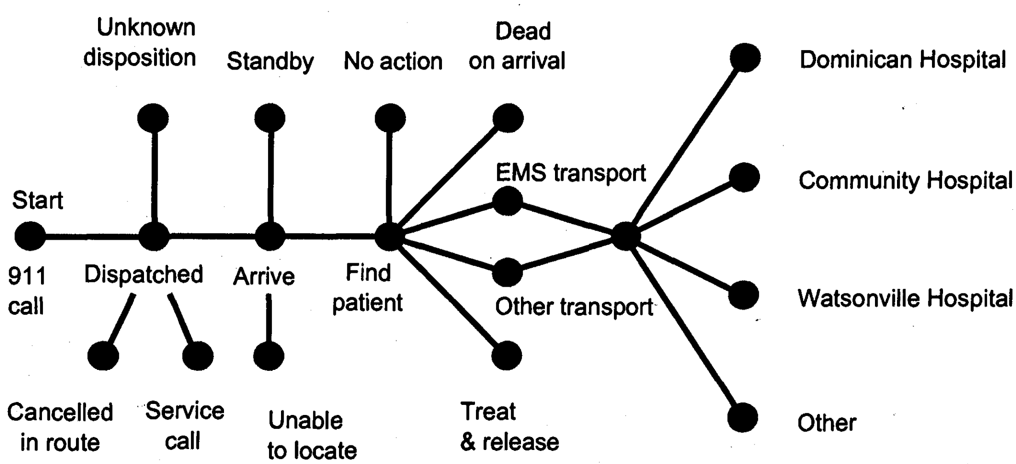


Figure 4.—Node diagram of processing and disposition of 9-1-1 calls; see table 13 for frequencies. From Thiel and others (1992).

Table 13.—Disposition of 9-1-1 calls in Santa Cruz County for October 17 and the 72-hour period after the earthquake

[From Thiel and others (1992). EMS, emergency medical services; ALS, advanced life support vehicle; BLS, basic life support vehicle]

| Disposition of 9-1-1 calls | October 17 (7 hours)[1] | 72-hour period[1] |
|---|---|---|
| Total 9-1-1 EMS dispatches[2] | 66 | 229 |
| Unknown disposition | 13 | 27 |
| Canceled in route | 5 | 22 |
| Service call | 1 | 3 |
| Arrive: | | |
| Standby | 0 | 1 |
| Unable to locate | 13 | 14 |
| Patient found: | | |
| No action | 3 | 22 |
| Dead on arrival | 3 | 3 |
| Treat and release | 3 | 3 |
| Transport: | | |
| EMS transport: ALS | 3 | 37 |
| EMS transport: BLS | 20 | 94 |
| Other transport | 2 | 3 |
| Location of transport: | | |
| To Dominican Hospital | 13 | 67 |
| To Community Hospital | 4 | 25 |
| To Watsonville Hospital | 6 | 39 |
| To other medical providers | 2 | 3 |

1 Electric power was out at the dispatch center for approximately 20 minutes at about 7:10 p.m. on October 17; therefore, no calls were received nor dispatched during this time.

2 This total represents only those calls evaluated as requiring EMS assistance; the total number of incoming calls is unknown.

Table 14.—Type of transport provided (advanced life support versus basic life support) by date and total admissions to each of the three hospitals in Santa Cruz County

[From Thiel and others (1992); leaders (--), no transport]

| Transports/ admissions | Date[1] (October 1989) 17 | 17A | 18 | 19 | 20 | 20A | Total 72 hours |
|---|---|---|---|---|---|---|---|
| Advanced life support | 3 | 10 | 10 | 18 | 6 | 8 | 37 |
| Basic life support | 20 | 69 | -- | -- | -- | -- | 94 |
| Total transports | 23 | 79 | 10 | 18 | 6 | 8 | 131 |
| Admissions: (postearthquake): | | | | | | | |
| Dominican | 13 | 45 | 14 | 26 | 14 | 20 | 67 |
| Community | 5 | 17 | 8 | 9 | 3 | 4 | 23 |
| Watsonville | 6 | 21 | 19 | 8 | 6 | 8 | 39 |
| Other | 2 | 7 | 1 | 0 | 0 | 0 | 3 |
| Total | 26 | 90 | 42 | 43 | 23 | 32 | 134 |
| Average admissions[2] | 8 | 28 | 28 | 28 | 20 | 28 | -- |
| Ratio[3] | 3.2 | 3.2 | 1.5 | 1.5 | 1.1 | 1.1 | -- |

1 A, results adjusted to reflect 24-hour equivalent values.

2 See table 12 for average pre-earthquake transports.

3 Ratio of total post-earthquake admissions to average admissions for each column.

Table 15.—Dispatch locations of 9-1-1 emergency calls for October 17 and 20

[From Thiel and others (1992); N, number; Pct, percentage of total; NA, not applicable]

| Location | October 17 *N* | October 17 Pct. | October 20 *N* | October 20 Pct. |
|---|---|---|---|---|
| Commercial building | 20 | 29.4 | 3 | 11 |
| Convalescent home | 6 | 8.8 | 3 | 11 |
| Medical/emergency services | 10 | 14.7 | 1 | 4 |
| Mobile home | 4 | 5.9 | 2 | 7 |
| Outdoors | 4 | 5.9 | 14 | 50 |
| Residence | 8 | 11.8 | 5 | 18 |
| Others, principally unknown | 16 | N.A. | 9 | N.A. |
| Total | 68 | 100 | 37 | 101 |

ports. All Santa Cruz ambulances and crews are ALS capable and trained. Table 14 indicates that when adjusted for the short day (7 hours on October 17 and 17 hours on October 20), the number of ALS cases is no higher during the last 7 hours of October 17 than for subsequent days; indeed it seems lower. For the first 7 hours, only 13 percent (3/23) of transports were ALS; for the subsequent 65 hours, 32 percent (34/168) of transports were ALS. It is likely that crews provided ALS treatment only in the most severe cases on October 17; on subsequent days, the reduced numbers of 9-1-1 dispatch requests allowed crews more time to treat individual patients. Another possible explanation is the low incidence of vehicular accidents on October 17, as discussed later.

The sources of 911-initiated EMS calls on October 17 and from October 17 to 20 are indicated in table 15. Commercial sites, convalescent homes, and medical service providers accounted for almost 70 percent of the calls on October 17.

Table 16.—Vehicular accidents resulting in 9-1-1 dispatches

[From Thiel and others (1992); A, results adjusted to reflect 24-hour equivalent values]

| Date | *N* |
|---|---|
| 17 after 5p.m. | 1.0 |
| 17A | 3.4 |
| 18 | 5.0 |
| 19 | 5.0 |
| 20 to 5 p.m. | 7.0 |
| 20A | 9.9 |

It is surprising that so few calls came from residences, where most people at risk are assumed to have been during the earthquake. Data for October 20, a more normal day for which such information is available, indicate a diversified mix of call locations, with calls substantially reduced from commercial sites and increased from outdoor accidents (such as vehicles). We consider this day to be more representative of a nondisaster period than are the previous two days. Table 16 reveals the number of vehicular accidents from the detailed 911 records of October 17 and 20. The one

October 17 accident, which occurred near midnight, involved one car running into three full-grown horses. Further, emergency personnel on-duty October 17 confirmed that few vehicular accidents appear to have occurred that day. In contrast, table 15 reveals a substantial increase in vehicular accident calls on October 20. It is possible that people were substantially more careful driving or chose not to drive during the immediate postearthquake period. If so, EMS services may not need to reserve significant resources after earthquakes to cover expected serious auto accidents.

The number of victims transported in response to 9-1-1 calls (table14) appears high on October 17 but decreases rapidly on subsequent days. Unfortunately, data on all transports are not yet available for analysis. Compared to normal ambulance transport rates, transport rates are substantially (75 percent) higher for the 7 hours after the earthquake and then are about 50 percent higher than normal for the next 2 days. These rates seem to indicate that the demand for 9-1-1 transport returned to normal very quickly. The actual rate would be somewhat higher for October 17, if an adjustment for time of day was made, because evening hours until midnight are typically a lower demand period.

Based on the findings of the 9-1-1 medical incidents, and information not herein reviewed, the following recommendations were made to the county:

1. Residents of the summit area or any remote area susceptible to road damage (for example, mountainous landslides) during an earthquake should consider the possibility of either a delayed response or no response at all from ground-based EMS units. In these areas, familiarity between residents and local fire departments should be encouraged so that they can have at least minimal medical aid provided for them until they are able to receive hospital treatment.
2. The county should consider whether the practice of simultaneously dispatching two paramedic ambulances to the same 9-1-1 incident should continue in disaster situations. (Of note: The very first medical dispatch by 9-1-1 following the earthquake sent two Santa Cruz paramedic units to an incident in the Aptos area. Fortunately, in this case, the private ambulance paramedics decided that it would be better for the Aptos Fire Department paramedic unit to handle their own transports so that the Santa Cruz units could remain available for what became a series of back-to back 9-1-1 incidents that followed this call.)
3. Consideration should be given to whether a public-information campaign should be used to inform the public not to call 9-1-1 following an earthquake unless they have an actual emergency. The 9-1-1 communications center received many unnecessary calls in the hours following the earthquake. Some victims, however, may take this notice to the extreme. Watsonville physicians reported that they treated patients for earthquake injuries who came to their clinics and hospital days after they were injured; by then, some of the injuries were infected. When the physicians asked the patients why they delayed seeking help for their injuries, they responded that they did not want to burden the doctors, whom they thought would be busy treating seriously injured victims.
4. The public should be encouraged to learn first aid and CPR because medical response teams may be delayed or unavailable during a disaster. A woman's life was saved immediately after the earthquake because a bystander provided her with CPR during what was a considerable length of time before a paramedic ambulance arrived.
5. The public should be made aware that driving following an earthquake may pose a risk to their safety because roads will be damaged, traffic control signals will not be working, and animals may be running loose on roadways. For example, a woman was seriously injured in Watsonville the day after the earthquake when the car she was in struck a protruding part of an earthquake-damaged bridge.

#### RECOMMENDED 9-1-1 EMS PROCESS FOR DISASTER PERIODS

Notable from the data in table 13 were the 13 calls (19 percent) in the first 7 hours where the patient was not located by the ambulance crew; that is, the patient was not at or near the dispatched location. This number would probably be higher if the 13 unknown disposition cases (table 13) could be resolved. In the following 65 hours there was only one additional "unable to locate" dispatch outcome. During this latter period the normal method of processing incoming 9-1-1 EMS calls had been reinstituted.

These data have implications for how 9-1-1 dispatch can be improved. The following findings relate to these management issues:

1. Immediately after the earthquake and for several hours thereafter, the 9-1-1 system was saturated with calls.
2. The volume of calls was so high that a short-cut procedure was used by the emergency medical dispatchers to process the calls in minimum time.
3. The ambulance dispatchers were only given the time the call was requested, as stamped, and the location for the dispatch. There were no notations on the cards that indicated severity, number of victims, and so forth that could have assisted in assigning priority.
4. There was an unusually small number, 34 percent, of the calls that resulted in a transport, compared to norm of 75 percent.
5. There was only a small number of ambulances, from 6 to 10, available during the earthquake; they had an average time from assignment to completion of 20 minutes. The backlog of waiting calls, at times, was 24 or more.

Clearly there was a conflict between the need for handling the incoming flood of calls and the need to manage effectively the use of the small number of emergency ambulances available. There is no evidence to suggest that any of the individual elements of the 9-1-1 EMS ambulance system performed poorly or were ineffective in carrying out their assigned and implied tasks. However, there is doubt as to whether the system on the whole effectively managed the small ambulance resource available. Fortunately the level of medical emergency associated with this earthquake in Santa Cruz County was modest and the inadequacies determined by our assessment did not result in serious medical consequences. The Loma Prieta earthquake caused a small number of casualties compared to that expected for major earthquakes expected near large urban centers (Federal Emergency Management Agency,1980). The system of 9-1-1 dispatch, as well as almost all emergency plans, used in Santa Cruz County could well have had major negative consequences if a more pressing medical emergency had occurred in the county.

The issue presented by these findings is how to maximize the provision of available medical services through the 9-1-1 system. This entails a process to—

1. Systematically handle unusually large call volumes quickly, and only process those with emergency needs.
2. Set priorities for management of a limited number of ambulances that results in provision of needed medical services.

Figure 5 shows the process used in Santa Cruz County after a 9-1-1 call was identified as being a medical emergency. It's simplicity allows for the maximum possible speed in processing incoming calls but provides for no information to assist ambulance dispatchers in establishing priority among requests.

The difficulty in determining priorities using the usual medical inquiry evaluation tools during the 9-1-1 call is that it consumes much more time than is reasonably available during a disaster, even for trained emergency medical dispatchers. An analysis of emergency medical records for Santa Cruz County indicates that only a small proportion of the earthquake injuries were medically severe and relatively few resulted in hospital admission (Durkin and others, 1991).

These findings and observations lead us to propose an alternative 9-1-1 medical services procedure, depicted in figure 6, for use during a medical emergency period. We believe that this process will shorten many, if not most, calls. The only calls that are lengthened are those for which an ambulance is needed. Of more than 1,000 calls during the first hours after the earthquake, only 66 resulted in ambulance dispatches. Given similar conditions, we believe that use of our procedure would not significantly increase 9-1-1 response time but would enhance proper allocation of medical resources.

The abbreviated procedure could be immediately invoked when the on-site EMS supervisor, or someone of comparable authority, determines that a disaster condition exists. The local supervisor must make this decision promptly on the basis of locally available information: The indicators could be felt shaking, confirming that an earthquake occurred, or large numbers of calls. It is recommended against waiting for State or regional notification that an emergency exists, because such a declaration is dependent, in part, on requests for emergency assistance (for example, 9-1-1 calls) and probably will occur some time after the earthquake and well into the emergency period. Although there appears to be no legal precedent for such a call-handling procedure, there also appear to be no legal restrictions to adopting such a procedure when a disaster exists, because such procedures are authorized and regularly employed within the medical community (triage, for example).

To reduce the large number of "unable to locate" dispatch outcomes, it is proposed that the first medical question put to a caller is whether the patient can be transported to care by other means. This is not meant to be an interrogation, and no medical advice or evaluation is intended, or given. The objective is to reduce the demand for ambulance service when there is an alternative. If the answer is "yes," the caller is told to move them there by this means and the call is terminated promptly, after possibly suggesting a nearby hospital based on where the call comes from. If the answer is "no," then the issue is what priority should be assigned to the call. Our experience with emergency conditions indicates that there is only the capacity to deal with two priority levels for dispatch of ambulances under these type circumstances. It is proposed to have the operator assign one of two priorities to the call:

- Priority 1: Life-threatening condition
- Priority 2: Non-life-threatening condition

Although there are very effective protocols for determining injury severity, the call volume does not allow for asking

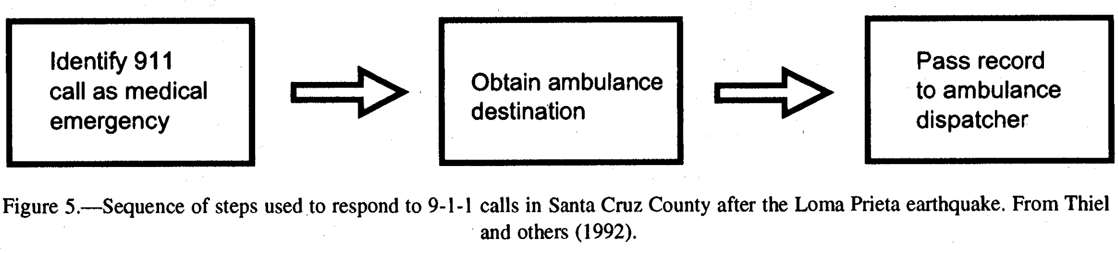


Figure 5.—Sequence of steps used to respond to 9-1-1 calls in Santa Cruz County after the Loma Prieta earthquake. From Thiel and others (1992).

and answering the battery of questions, with supporting descriptions, required to use them. It is proposed that the priority of the call be determined through a brief answer to the question "Why is an ambulance needed?" The operator is not to engage in discussion of terms, or to provide or offer advice. The purpose is to quickly gain the caller's perspective of why the ambulance is required. The operator then assigns the call a priority, without discussion with the caller or revealing the evaluation. An additional benefit of this procedure is that it also allows the operator to redirect those cases that require a different type of assistance. The operator then asks for the location information necessary for dispatch and asks the caller to call back if transport is provided some other way. The call is terminated and the dispatch card passed to the ambulance dispatcher. When there is substantial demand above capacity, priority should be given to the priority 1 cases regardless of the waiting time; ALS-capable units would preferentially be assigned to these cases. Possibly, the response protocol would increase a priority 2 case to priority 1 after a given length of time from receipt, say 1 hour.

It could be argued that callers are a poor judge of the medical characteristics required to make a judgment of whether a condition is life threatening. For this reason the caller is not asked to answer medical questions. Rather, the caller is asked to give a brief reason for the need for medical transportation, among which might be: has a severed arm; is bleeding from the mouth; is unconscious after being hit by a brick; fell off a bicycle and has a sore elbow. It is expected that the first thing the caller states will have sufficient content that an informed assessment of the category for dispatch priority can be made. Undoubtedly errors will be made, where individuals in need of ambulance service do not receive it because of the assignment priority. But it is even more likely that persons not needing service would tie up the 9-1-1 EMS system. The en-

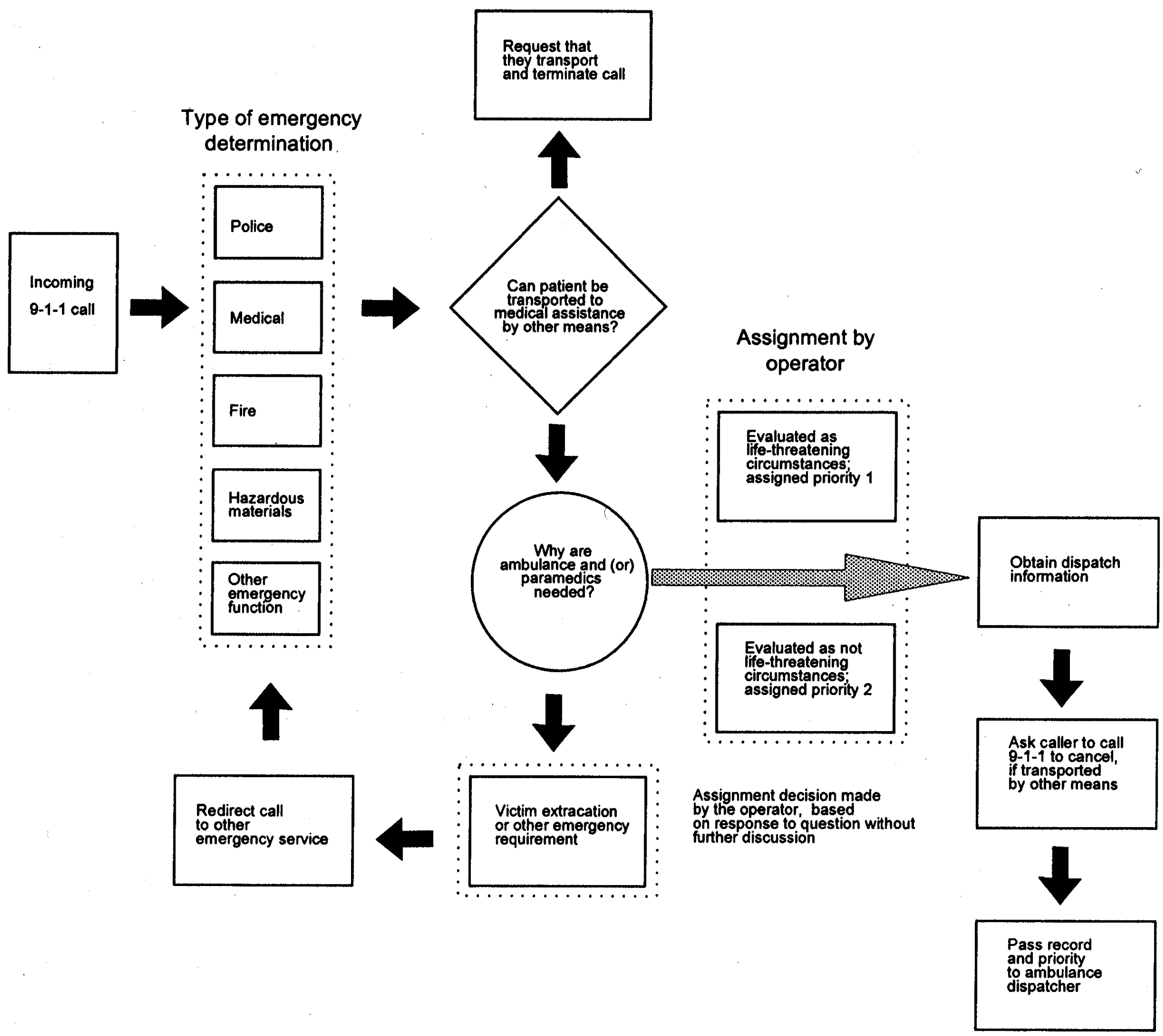


Figure 6.—Proposed sequence of steps to be used by 9-1-1 operators for medical needs during the emergency period after a damaging earthquake, or other large-scale disaster. From Durkin and Thiel (1992).

couragement to use other available transportation may cause some victims to suffer added injury by being improperly transported, but many more will be given timely assistance by the same process.

There are potentially serious medical consequences of improper movement of patients who have some types of injuries, particularly spinal, and our questioning procedure does not allow identification with certainty those patients who should be moved and transported only by trained personnel. There is the expectation that many callers will decline to move patient's with such injuries; however, this is conjectural. If the order of the questions were reversed, asking first "Why is an ambulance or paramedic services needed?", then the operator could assess whether it was appropriate to ask the transport question. This would help sort out the cases where severe injury would be caused by unskilled handling. However, the transport question is open ended and likely to add considerably to total call time not only to those for which the question is relevant. Evidence from 9-1-1 Santa Cruz data leads to the conclusion that any procedure that prevents some calls from being taken is likely to be abandoned quickly. Thus, the initial order of questions recommended is preferred, but with the recognition that the mix of serious injuries in this particular earthquake may not be representative of more severe earthquakes.

The recommended protocol has similarities to the widely discussed "Simple Triage And Rapid Treatment" (START) disaster medical treatment process. START is used when there are multiple victims at a site; the first step (simple triage) is to ask in a loud voice for everyone to stand up who can. These people are asked to get themselves to treatment off-site. Those remaining are then treated in priority order using standard emergency medical triage practices. The recommended 9-1-1 EMS procedure starts with the same type of transportation question, except that someone else does the transporting. The wide acceptance of the START process for field disaster treatment leads to the conclusion that our recommended 9-1-1 EMS process is sound.

Like other emergency management functions, training of the operators will be required for the system to function efficiently and effectively. That already takes place, yet it is the natural tendency of an individual to err on the side of assuming the worst when there is inadequate information to make considered judgments. The current 9-1-1 EMS protocols focus on the worst cases under normal operating conditions. However, the consequences of continuing to use such procedures during a disaster period could have catastrophic implications for many seriously injured. Training and the participant evaluations of performance in table-top exercises will quickly uncover the consequences of too great a proportion of high priorities. Such a system as proposed is an easily implementable approach to disaster period 9-1-1 medical dispatch management.

### CONCLUSIONS FOR EMS IMPROVEMENT

It is our judgment that adoption of the simple emergency procedure given in figure 6 for 9-1-1 medical calls offers the opportunity to substantially improve the performance of the emergency medical transport system at virtually no cost. Simply reducing the proportion of nontransport outcomes in Santa Cruz during the 7 hours after the earthquake from the 34 percent observed to the 75 percent usual proportion effectively increases the number of ambulances available by a factor of two! It is not often we have the opportunity to achieve a doubling of capacity by a simple, no-cost management change.

The findings and recommendations presented here were developed from experience in Santa Cruz County, where the telephone system continued to function in almost all areas and where there were relatively few major injuries. Other investigations are underway to determine whether those mostly rural areas that lacked telephone service had EMS needs that went unserviced. If the telephone system had been inoperative, either because of the intensity of the earthquake, power loss to the telephone system or damage to the response center, then the 9-1-1 response system would have been unavailable as a primary mode for providing EMS services. Experience shows that most serious injuries in earthquakes will be found in areas that experience the greatest concentrated building, particularly structural, damage. Such damage may eliminate local telephone service, thus, rendering the telephone 9-1-1 system ineffective as a means of identifying where EMS services are most needed. It is important that the EMS response plans include alternative, nontelephone-dependent approaches for locating the injured in heavily damaged areas and targeting emergency medical services to these areas. Identifying those areas and targeting immediate EMS response may be just as important to improving EMS effectiveness as is more effectively managing the 9-1-1 EMS response functions already discussed.

Although the focus has been on the problems of the emergency medical component of the 9-1-1 system during an earthquake disaster, the observations extend to all of the other services that the 9-1-1 system is designed to serve during an emergency, or other disaster. Large earthquakes are expected to have large demands, often dubious ones, for fire, search and rescue, toxics removal, and heavy rescue. These demands are typically larger than the capacity of the local service, even when augmented by resources from other communities. The same procedure suggested here for ambulance and paramedic services can and should be applied to these other emergency services.

## HOSPITALS

Almost immediately after an earthquake, all hospitals began triaging and treating patients who arrived by private vehicles, ambulances, and police and fire vehicles. Meanwhile, hospital-damage survey teams were reporting that they had lost essential services from the earthquake such as water supply and X-ray. A temporary loss of telephone and two-way radio communications at all three hospitals created confusion, as they were not able to accurately estimate resources needed, expected number of casualties, or exchange other vital information. Because of earthquake damage to equipment and facilities and high volumes of casualties, some patients received limited treatment and diagnosis and others with less than serious injury or illness were instructed to return the next day for treatment. The damage was so great at Watsonville Hospital that 17 patients had to transfer to other hospitals. Clearly, the hospitals were challenged well beyond any previous disaster experience.

Nonhospital medical facilities were called into action to assist emergency medical efforts in the county. In particular, Salud Para la Gente, a medical clinic located in Watsonville, treated many earthquake victims in the downtown area, perhaps greatly reducing the patient load at Watsonville Community Hospital. Their efforts, however, were not limited to medical treatment but included comprehensive assistance to the nonmedical needs of earthquake victims.

The emergency medical response to the earthquake was unprecedented by any previous disaster experience. Santa Cruz County had experienced five Presidentially declared disasters in the 1980's, but none had required the mobilization and actions of so many medical resources as did the Loma Prieta disaster.

A major effort is underway to review emergency department records at the three Santa Cruz County hospitals for the period ending 72 hours after the earthquake. A total of 1,057 patient records have been collected, reviewed, and abstracted, with the cooperation of the county, State, and Johns Hopkins University, in association with Durkin and Associates. The distribution of patients by hospital was 454 from Watsonville Community, 390 from Dominican Santa Cruz, and 213 from AMI Community. The total of 1,057 admissions from all sources, earthquake and nonearthquake causes, was drawn from a current county population of approximately 229,000. The follow-up data collection and reconciliation process is still in progress.

Over 95 percent of the patients seen at the local hospitals were residents of the county, and over 97 percent were from the normal patient catchment area for the county (less than 3 percent of the patients were not residents of the county or did not live within close proximity to the hospitals). Therefore, the transient population treated within the study period at the local hospitals was minimal compared with the resident population. Also noted was that patients who lived in the north county sought help almost exclusively in the north county—either Dominican or AMI Community Hospital—and south county residents sought help at Watsonville Hospital. Comparative data of normal volumes of injury versus illness patients is not yet available; however, the medical records managers at the three hospitals reported significantly higher volumes of emergency department admissions after the earthquake. Preliminary data suggest that over half of the earthquake-injured patients were treated in the hospital emergency departments in the hours beginning the morning of October 18 until the end of the study period October 20 at 5:04 p.m.

Seventeen patients, 13 injury cases and 4 medical cases, were transferred from Watsonville Hospital in the hours after the earthquake. Twelve patients were transported by helicopter—two to Dominican Santa Cruz Hospital (one medical, one trauma) and ten (two medical, eight trauma) to hospitals in Santa Clara and Monterey Counties. Five patients were transported by ground ambulances—four to Dominican Santa Cruz Hospital and one to a hospital in Monterey County. With one exception, all transfers were postearthquake, emergency-department admissions. All patients were classified as critical care transfers, and all received critical-level care at the receiving hospitals. All injury transfers were earthquake-caused injuries. One transfer patient later died as a result of her earthquake-caused injuries. Six transfer patients are known to have required major surgery because of their earthquake-caused injuries, and some of them were later transferred to other hospitals for further definitive care.

## HOSPITAL ADMINISTRATOR INTERVIEWS

Three hospital administrators were interviewed in person to determine their impressions of their hospital's operations during the disaster. Some special notes regarding the disaster response of the hospitals follow:

1. The hospitals enacted their disaster plans within 30 minutes after the earthquake and remained in the disaster mode from 4 days to 1 week.
2. Only Watsonville Hospital evacuated pre-earthquake patients.
3. Only Watsonville Hospital transferred patients from their facility, and only Dominican Hospital received transfer patients from other facilities (all from Watsonville Hospital).
4. Electrical power was lost at all three hospitals (as was the case in the entire county), but only Watsonville Hospital experienced difficulties with its generators as a direct result of earthquake damage.
5. Each hospital had staff and nonstaff volunteers spontaneously report for duty after the earthquake, and no management problems were reported regarding their actions.
6. Each hospital provided stress debriefing/counseling sessions for staff and their families within one week after the earthquake; attendance was voluntary.
7. Each hospital lost vital diagnostic services as a result of earthquake damage to equipment.

8. No problems were reported with patient transfers to Dominican Santa Cruz Hospital and Monterey and Santa Clara County hospitals from Watsonville Hospital, in spite of no formal transfer agreements to that effect.
9. No medical teams were sent to field sites from any hospital.
10. The hospital administrators predicted they could have seen between 50 and 100 percent more casualties in their emergency departments during the night of the earthquake, even though some of their essential hospital services became nonfunctional as a result of the earthquake.

## IMPLICATIONS FOR EMERGENCY MEDICAL SERVICES

Numerous implications for health-care supply and demand emerge from these data. For the Loma Prieta disaster, the demand was relatively small because the numbers were scattered and the severity was light. The supply was therefore adequate because the health-care system was extensive, the hospitals remained operational, and the demand for major medical care was light. Any future casualty estimation model should take into account an overall resiliency of the health-care system for various levels of demand.

Most earthquake fatalities and serious injuries (injury intensity 4 or higher; see table 1) resulted from structural failure. The majority of serious casualties came from a small number of damaged structures, consistent with experience in other recent earthquakes. Falling sections of URM buildings, striking other buildings, were once again sources of severe injuries.

Well-designed, modern, earthquake-resistant structures posed relatively little serious casualty threat to their occupants. Minor injuries constituted the bulk of injuries in these structures. A substantial threat is posed by structures with high collapse potential, even if they do not collapse. Experience worldwide suggests that a relatively small number of damaged structures provide the vast majority of serious casualties (Durkin and others, 1989a). Interior nonstructural elements have a relatively low likelihood of causing fatalities or serious injury. Building contents also have a relatively low likelihood of causing fatal or serious injuries. For example, no Loma Prieta work-related fatalities could be attributed to nonstructural elements or building contents. Although, 10 of the 25 Loma Prieta work-related injuries noted as requiring hospital admission were due to nonstructural elements or building contents, this number represents less than 8 percent of the total injured by such elements. However, despite the low overall probability for serious injury, some physical objects (for example, tall metal lockers, wine barrels, heavy filing cabinets, and so forth) and some settings are particularly hazardous and can cause serious injuries. In some cases, protective actions taken by building occupants increased their probability for minor and moderate injuries from physical objects. Thus there is still a need to (1) determine the probability for serious injury associated with all settings and (2) identify those settings which are most hazardous and prioritize them in terms of relative risk.

Most Loma Prieta injuries were treated by the normal health-care system. Emergency medical services were not overloaded. Most medical attention was provided by the local medical community, not by external resources.

What do some of these preliminary observations mean? For emergency medical planning, in particular, and the health-care system, in general, they suggest that there are three principal patient-demand sources after earthquakes. The first is from collapse of high-risk, high-occupancy structures that yield large numbers of serious, life-threatening injuries. The second is from the failure of high-risk, low-occupancy structures, like URM's, that are often distributed within the community in known places (Durkin and others, 1986, 1989b). The third is from the normal injury mix from low to moderate building damage, that is nonbuilding collapse; these injuries are probably distributed proportional to the population and do not create excessive demands on the health-care system, because there are not likely to be massive numbers of severe casualties concentrated in a local area.

The distribution of casualties for the Loma Prieta earthquake provides a rich source of data for future estimation of losses. The distribution shows the need for analysis by region, by building type, and by severity. Other indications may well emerge in future studies. However, casualty estimation still suffers from the absence of reported data on nonhospitalized injuries. Indeed, the strategies that currently estimate injuries ignore these doctor-treated injuries (for example, FEMA's casualty estimation for Memphis and St. Louis). Until ways of recovering these data are determined, reliable predictors of the larger injury effects of an earthquake will not be available.

Current Loma Prieta studies have adequate data on fatalities and hospitalized injuries. However, injury data based only on hospital-source data are likely to considerably underestimate injuries, particularly for the lower injury intensity. The number historically collected in the United States from such sources may be 2 1/2 times lower than actual numbers, if the ratios from Loma Prieta DIR injuries are characteristic of other nationwide earthquakes. Furthermore, the number of injuries attributable to an earthquake but occurring after the shaking may be significant.

It is important that strategies be developed for estimating these unreported injuries. Although some of these injuries might indeed be slight, others could be severe. More important, lesser injuries still use health-care resources. Furthermore, we project that a higher magnitude earthquake would have increased the severity of these minor injuries. Finally, the unreported injuries help us establish connections between building damage and injury types. Therefore, they are important for a number of estimating purposes.

Studies such as this are increasing our understanding of factors influencing casualty estimation in different building types. Such factors include a broad understanding of the relationship between shaking intensity, building damage, and casualty; of the relative influence of intervening variables such as occupant actions, space utilization, nonstructural elements, and building contents; and of the need in any casualty loss-estimation methodology to elaborate not only the causes of the loss but also the impact of the loss.

## CASUALTY-ESTIMATION MODELING

The casualty data collected, and still being analyzed at this writing, can provide a sound basis for development and widespread application of a comprehensive earthquake casualty-estimation methodology—one that combines and further develops the most effective existing casualty-estimation techniques, reflects current data, and is sensitive to different regional contexts of the United States. As part of a longer term U.S. Geological Survey-sponsored research effort, the authors are developing earthquake casualty-estimation procedures for a wide variety of potential applications. This section addresses the following three subject areas: (1) our initial research findings from an assessment of both Loma Prieta and other earthquake data; (2) deficiencies in currently available data bases and estimation methods; and (3) programmatic recommendations for future research and process development.

A scientifically based procedure for estimating earthquake casualties is potentially valuable to a variety of users—both public and private, including the health, design and construction professions—in the following areas of primary, secondary, and tertiary injury prevention:

1. Preparedness and response planning for providing emergency medical services after earthquakes, encompassing both health-care supply and demand issues. Supply issues include the availability of medical facilities (considering their degree of damage) and the management of available personnel, medications, and equipment in search and rescue and medical care delivery; demand issues relate to where casualties occur and what are their requirements (extraction, transportation, mix of injury types, types of diagnostic and treatment equipment needed).
2. Pre-earthquake preparedness programs, including information, education, and training, aimed at the general public and high-risk populations to reduce their vulnerability when earthquakes occur.
3. Mitigation actions that can reduce the likelihood of casualties when earthquakes occur. These are at two levels: those actions occupants can take to protect themselves from injury from contents (attaching cabinets, replacing brick chimneys) and those that design professionals (architecture, engineering, interior design) can incorporate into structures and interior space use.
4. Setting insurance rates, terms of coverage and financial reserves; for example, life, health, workman's compensation, and liability.
5. Determination, in legal actions, where earthquake casualty liability lies.

### CASUALTY ESTIMATION

Earthquake casualty estimates have been available for over 20 years. The majority of them were made in response to specific needs, usually preparedness, and focused on specific earthquake scenario's. They generally were gross estimates for use in policy determination, not for specific medical planning. The estimates were usually for large areas (Federal Emergency Management Agency, 1990) or for large numbers of buildings (National Academy of Sciences, 1988). These estimates typically had the following problems:

- They lacked a significant data sample on which to base the estimation procedure
- They have not been tested in accordance with what data has been available
- They were based on overly simplistic assumptions about casualties and health services

Unfortunately, there has been very little research or systematic data collection directed at developing more accurate and useful estimation procedures.

The major casualty-estimation approaches are (1) the nonbuilding-specific approach, (2) the building-specific approach, and (3) the composite approach. The nonbuilding specific approach is a "top-down" approach that develops casualty estimates for a geographic area which are based on gross mortality and morbidity ratios. The building-specific approach is a "bottom-up" approach that relates casualties to the performance of specific building types. The composite approach combines specific building-type loss estimates with gross mortality and morbidity casualty ratios. The more sophisticated casualty-estimation processes rely on fragility curves or damage probability matrices to express casualty rates as a function of shaking intensity and building damage.

The earliest casualty estimates were the widely circulated National Oceanic and Atmospheric Administration by Steinbrugge and others. They characterized casualties in three categories and determined the relative occurrence of casualties by ratios: for every death there are 4 injuries requiring hospitalization and 30 that do not. The number of fatalities was based on building type and the severity of shaking, with the ratio of fatalities to those exposed given per 10,000 occupants; for example, they assumed 4 fatalities in 10,000 for wood frame houses (1 in 2,500 chance of death) and 5,000 per 10,000 for URM buildings (1 in 2 chance). These procedures were applied first to the Berkeley campus of the University of California in late 1970, and subsequently to other University and State University campuses.

The ATC-13 project developed damage-estimation procedures for many different types of buildings (Applied Technology Council, 1985). Their approach yielded estimates of the probability of different damage levels for different ground motions (modified Mercalli intensity) by building type and height. They also estimated the likelihood of death and injury at different damage levels and provided a nominal differentiation of injuries: They were classified as either serious or not serious, with the assumption that the latter required hospitalization. Unfortunately, there were gross methodological difficulties in this approach to damage estimation.

The FEMA approach represents the most sophisticated study for a regional area to date; see the estimates for St. Louis City and County (Federal Emergency Management Agency, 1990) and the Six City Study (Federal Emergency Management Agency, 1985). Unfortunately these estimates categorize casualties as either fatalities or injuries, with no distinction for severity or degree of medical treatment.

In all these studies, having no information on the distribution by injury type, severity, and location, there is no way to know what medical resources will be needed and where; in the absence of such information, planning may well assume the worst. Also, significant gaps are present in conceptual approaches that restrict casualty estimates to building type and degree of damage; for example, recent studies have documented significant life loss and injuries from earthquake-induced landslides. Another limitation is that there has not been enough attention given to other built elements that might suffer significant damage and pose a significant safety threat; for example, property walls in Chile and bus kiosks in the Philippines were sources of fatalities. In addition, it was found in the 1985 Chile earthquake (Durkin and others, 1986) that many people successfully evacuated their homes only to be injured by falling unreinforced masonry property walls.

## PRELIMINARY ASSESSMENT OF EXISTING CASUALTY-ESTIMATION MODELS

The first two authors (Durkin and Thiel) are engaged in an ongoing research effort to develop casualty-estimation procedures, working toward an empirically and judgmentally based, maximum likelihood model to describe the types and severity of casualties likely for different building types, occupancies, and ground motions. This work is in progress, and conclusions and the specifics of the models are not yet appropriate for discussion. This research includes assessing an extensive data base, from domestic and foreign earthquakes, to determine relative injury rates due to:

- Damage to structural systems
- Damage to nonstructural systems
- Damage and performance of other physical setting elements, such as equipment or contents falling or moving, caustics, fire or other hazardous-materials release, and accidents such as tripping while exiting.

Injury sources and performance of a building and its contents are being classified as to where the injury occurred. Finally, the medical implications of the injury types are being assessed; for example, injuries are classified by the degree to which they would likely have been more severe if the earthquake had been more severe, using a classification system that indicates the typical level of emergency medical attention required. These results are being formulated to provide a qualitative, as well as quantitative, indication of the demand likely for the health-care assistance. Our (Durkin and Thiel) classification levels will be consistent with the types of qualitative damage scales developed for ATC-13 and by Thiel and Zsutty (1987) for historical building-damage studies.

During the initial phases of this research effort, a series of hypotheses was developed that provided the basis for collection and evaluation of historical injury data. Among the hypotheses were the following:

- Injuries in wood-frame dwellings are not usually life threatening.
- For any particular level of damage, measured as a percentage of replacement value, the severity of injury increases with the brittleness of the building lateral force resisting system.
- Falling sections from URM buildings striking other buildings are substantial sources of injury.
- Injuries caused by household and office equipment and furnishings are not usually life threatening.
- The occurrence of injuries from household and office equipment and furnishings increases with the flexibility of the building.
- First providers of medical assistance are typically not medical professionals.
- The current building code for emergency egress, based on fire requirements, does not provide adequate protection of escape routes from earthquake-damaged buildings (rows of lateral files are now prevalent in offices and often line corridors).
- "Duck-and-cover" recommendations lead to a heightened probability of minor injury but may reduce probability of major injuries.
- Broken glass and downed electrical lines are minimal causes of injury, and seldom cause higher classes of injury.
- Transportation of the injured can be a critical element for their survival.

- Search and rescue retrievals in the period right after damage occurs is critical for survival of the seriously injured; the success of such retrievals strongly diminishes over time.
- For modern, earthquake-resistant construction, minor injuries are a larger proportion of total injuries than most assume.
- For nonearthquake-resistant construction, major injuries are a large proportion of total injuries.
- Most critical medical attention is provided by the local community not by external resources.

These hypotheses indicate the types of data under examination by an empirical examination of historic data, most notably Loma Prieta, Coalinga, Mexico City, San Salvador, Japan and Chile: Housner and Thiel (1990), Durkin and others (1983), Durkin (1989a), Durkin (1987), Murakami and others (1989), and Durkin (1986). A comprehensive set of hypotheses, not all believed to be true, has been developed to assure that data collected is sufficiently complete to address the types of questions that are of potential importance to building design and management as emergency preparedness. Additional data are being collected from the Loma Prieta and Philippine (Roces, 1990a, b) earthquakes to supplement this analysis.

As pointed out by Steinbrugge (1982) in his seminal work on earthquake damage, casualties vary greatly, from a preponderance of scratches, cuts, and abrasions that can be self or nonprofessionally treated (a so-called Red Cross training level) to a relatively small proportion of injuries requiring specialized medical care. The first type do not degrade severely (become life threatening) with delays until treatment, whereas the latter can quickly become life threatening. Research to date suggests that there are three distinct components to categorizing injury severity: the type of assistance needed to rescue and move the patient to the medical provider, the skill level required to treat the injury, and the degree to which the injury becomes more serious with lack of treatment, which is an important element of the casualty-estimation procedure under development.

It is apparent that different building types pose different types of casualty risk. Data are not historically inclusive enough to determine risk for many types of construction, but they are sufficient to offer empirically defensible conclusions for a few building types: adobe, URM buildings, wood-frame residences, and nonductile concrete frames. These conclusions provide anchor points for estimation of the risk for other types of buildings, much in the manner that ATC-13 used information on performance of a few building types to determine risk for a larger range of building types. The clearest single casualty-related factor turns out to be the size and number of building elements likely to fall at a particular damage level during an earthquake; for example, URM building's propensity to shed parapets, nonductile frame's propensity to collapse, and brittle infill wall's tendency to topple. Buildings with great flexibility, particularly wood frame, appear to pose relatively low likelihood of serious injury.

Our analysis increases the understanding of factors influencing casualty estimation in various building types. Such factors include a better understanding of the relationships between shaking intensity, building damage, and casualty; the relative influence of intervening variables such as occupant actions, space utilization, nonstructural elements, and building contents; and the need in any casualty-estimation methodology to elaborate not only the causes of the loss but also the impact of the loss (for example, a building collapse can result in a range of fatal and nonfatal injuries that have varying immediate consequences for search and rescue and emergency medical response and longer-term consequences for health care).

## ANALYSIS OF EXISTING EARTHQUAKE CASUALTY-ESTIMATION APPROACHES

Normally, casualty-estimation processes determine earthquake casualties in the following manner. First, structural engineers or other trained personnel inventory buildings that fit prespecified conditions; for example, inventory all of the buildings in a particular geographic area or all critical facilities such as hospitals by structural type. Building-inventory techniques can range from simply documenting the presence and location of potentially hazardous buildings, through rapid, visual screening (Applied Technology Council, 1987a), to more detailed structural investigations of individual buildings (Applied Technology Council, 1987b). Second, ground-shaking levels and other geologic parameters in particular areas are estimated, either by relying on previous geotechnical studies or by commissioning such investigations. Third, researchers construct fragility curves for specific building types, ground motion, and geologic conditions. Fragility curves are then applied to the aggregated building inventory to determine how many buildings are likely to occupy each damage state in a particular earthquake scenario. Average occupancy rates are then used to determine the population at risk. Finally, planners incorporate a casualty coefficient, derived from expert consensus, to determine the expected number of casualties.

## NEEDS FOR REVISION AND EXTENSION OF MODELS

Our review of previous methods and empirical data from recent worldwide earthquakes found significant gaps in conceptual approaches that tie casualty estimates only to building type and expected degree of damage. This analysis revealed the following specific areas where present models can be revised and (or) extended to enable more comprehensive and meaningful earthquake-casualty estimations.

The first need is to incorporate a wider range of geotechnical factors. Present casualty estimates are based almost exclusively on structural failure caused by ground shaking, to the exclusion of potential casualties from other geologic events like landslides. This omission likely evolved from the United States having experienced relatively few casualties from earthquake phenomena other than simple ground shaking. Experience elsewhere suggests the importance of these other types of phenomena: Probably half of the fatalities in the 1990 Philippine earthquake were due to landslides sweeping buses, cars, pedestrians, and homes off mountainous roads and hillsides (Durkin and Thiel, 1992); many fatalities in the 1987 San Salvador earthquake occurred when single-family residences collapsed and fell down hillsides. Other types of earthquake phenomena may produce high structural damage with relatively little safety risk, as did the 1964 Turnagain slide in Alaska.

A second need, related to the impact of different earthquake phenomena, is to assess the relative extent to which different types of geotechnical performance and resultant structural failures contribute to earthquake casualties. For instance, liquefaction may cause significant structural damage but lead to few casualties, as was the case in the 1985 Chile and 1989 Loma Prieta earthquakes. Alternatively, structural collapse resulting from slope failure, also documented in the Philippines, may lead to significant fatalities.

A third need is to incorporate the numerous physical setting hazards other than complete building collapse. Irrespective of their validity, casualty coefficients used in past United States casualty estimations were applied only to occupants of collapsed buildings, to the exclusion of those at risk from other types and degrees of structural failure. These estimates assumed that the overwhelming majority of serious casualties would occur inside collapsed buildings and thus did not give enough attention to other physical setting types and elements that might experience significant structural damage and pose a significant life safety threat. One such type is the complete collapse of structures other then buildings; for example, the Cypress viaduct collapse caused most of the Loma Prieta earthquake fatalities. In the 1985 Chile earthquake, numerous residents evacuated their homes only to be killed and injured by collapsing masonry property walls. Partial building collapse is another important type of structural failure largely ignored by present casualty-estimation methods. The second major cause of Loma Prieta fatalities was falling parapets and sections of masonry exterior walls which fell on people outside of buildings.

A fourth need is to incorporate estimates of mortality and morbidity due to the performance of nonstructural elements and building contents. Although our recent research indicates that nonstructural elements such as ceiling tiles and building contents such as office equipment and household furnishings have a low likelihood of causing fatal injuries, such elements are responsible for numerous minor and moderate injuries that tax emergency health services and incapacitate individuals.

A fifth need is to develop better techniques for relating populations at risk to earthquake hazards. The threats posed by an entire physical setting need to be documented and incorporated, particularly urban design issues. The concept of physical setting is particularly useful in understanding factors that contribute to earthquake injuries because it combines physical elements with occupant behavior. Therefore, it is possible to evaluate the interaction of environment and behavior in terms of normal activity and space utilization, and in terms of emergency actions. The physical setting approach also has the advantage of including potentially hazardous physical elements outside the building itself, for instance the lethal Chilean property walls. In addition, the physical setting approach also allows a more comprehensive and detailed hazard assessment of specific geographic areas. For example, planners can analyze a specific intercity area by a number of different dimensions, including the proximity of specific medical resources to the areas of potential collapse, street width, population density, the probable ability of skilled medical personnel to reach victims, and the size of emergent groups that are likely to aid or hinder rescue efforts.

Ideally, casualty estimates should describe the damage potential of all physical setting elements, both natural and built. Specifically, better descriptions are needed of the exact mechanisms of structural failure that contribute to fatalities and injuries, beyond building collapse, to identify other causes of morbidity and mortality, including those injury-producing mechanisms that span the spectrum of non-contact/nondamage injuries to crushing injuries. Better documentation is needed of the circumstances surrounding typical injuries, and the personal characteristics and specific actions of building occupants that make them more or less susceptible to injury must be identified and described. Finally, a model is needed that interrelates how this information relates to different building types, building uses, and damage levels.

The sixth need is to expand our conceptual framework to include more supply-side issues (availability and management of health-care resources). It is clear that the rapid provision of appropriate medical care can save lives and reduce injury severity. Recent research shows that, even in building collapses, many seriously injured occupants are freed very quickly and can benefit from the rapid provision of specialized medical care. However, as discussed above, the Santa Cruz County EMS system response in the Loma Prieta earthquake shows that many ambulance trips were wasted because the disaster response system was not set up to deal adequately with injury severity. Unfortunately, most EMS approaches categorize casualties as either fatalities or injuries, with no distinction for severity of medical conditions. Thus, there is no way to know what medical resources are needed in a particular location. If it is known what the injury severity is likely to be, then the estimates can be adjusted. Other supply-side factors that existing estimation processes do not include are the impact of loss of transportation and utility systems. For example, medical conditions due to the inability of emergency medical equipment and personnel to reach the injured because of severed transportation arteries are not currently estimated. Similarly, the impact of interrupted utilities on the delivery of health-care services is not considered.

The seventh and final need is to redesign current loss and casualty-estimation processes so that they more fully assist policy formulation and implementation. Although processes used in the United States give planners gross building damage and casualty estimates (normally expressed in terms of expected numbers of deaths and serious injuries), these methods are not sufficiently developed. They fail to provide policymakers and emergency service agencies with an empirical basis for selecting among alternative policy strategies or for assessing the effectiveness of strategies once in place. For example, shaking of a URM building has a higher likelihood of causing serious injuries than the same level of shaking to a steel or wood-frame building. Therefore, given a program to decrease serious injuries, creating selective retrofit policies for URM buildings only is a more efficient use of limited resources than policies including all buildings, regardless of their level of damageability. Similarly, the ability to estimate the relative injury potential of different nonstructural elements and building contents is essential in allocating limited resources to fixing these facets only that have a likelihood of causing serious injuries, rather than all of them.

## FINDINGS ON THE SOURCES AND FREQUENCY OF EARTHQUAKE- CASUALTIES

This analysis increases our understanding of factors influencing casualty estimation in United States building types. Such factors include a better understanding of the relationships between shaking intensity, building damage, and casualty; the relative influence of intervening variables such as occupant actions, space utilization, nonstructural elements, and building contents; and the need in any casualty-estimation methodology to elaborate not only on the causes of the loss but also on the impact of the loss (for example, a building collapse can result in a range of fatal and non-fatal injuries that have different immediate and longer-term consequences). Although our work is in progress and therefore not ready to be fully documented, there are several important preliminary findings presented below that are organized by subject.

### FINDINGS RELATED TO CASUALTY-ESTIMATION METHODS

1. Past United States earthquake-casualty estimates were largely speculative, owing to the absence of an earthquake-injury data base. The estimates tended to be based first on simple ratios of casualties to damage and second on casualty ratios (minor, major, death) developed from other injury experience.
2. Recent United States earthquake-casualty estimates still lack a sufficient empirical basis; their casualty assumptions have not been tested with available data.
3. Recent United States earthquake-casualty estimates are based on overly simplistic assumptions about casualties and how the health-service delivery system works.
4. Casualty assumptions are not comprehensive.
5. Health-service assumptions ignore utilization patterns.
6. Hypothesized ratios of the number of fatalities to the number of casualties need revision and further refinement in light of current data. For example, Mexico City (1985 earthquake) results indicate more fatalities than hospital admissions, whereas Loma Prieta has many times more admissions than fatalities.
7. The problem of estimating casualties by degree of injury severity is one of statistical estimation, with associated probabilities for different levels of injury, not one of deterministic estimation.

### FINDINGS RELATED TO CASUALTY-RESEARCH METHODS

1. Early earthquake injury studies did not adequately categorize injury type and severity.
2. Few previous studies considered the role of physical setting in earthquake injuries.
3. Previous studies did not link earthquake injuries to physical setting elements.
4. Research has ignored the role of occupant behavior in earthquake-injury susceptibility.
5. Historical data has tended to record only specific injury data and not include what happened to others at risk in the same place or similar situations. This may have tended to inflate earthquake casualty rates.
6. Traditional, institutionalized methods for injury data collection (for example, medical record procedures) do not systematically collect information, such as injury location, contributing physical element, and injury circumstances, that is useful to earthquake-casualty estimation.

### FINDINGS RELATED TO PHYSICAL SETTING DATA

1. Current methods for describing physical setting performance (for example, building damage-classification schemes) are inadequate for explaining or predicting many earthquake injuries.
2. Methods for collecting postearthquake damage data lack sufficient detail to be very useful in casualty studies.
3. Preearthquake hazard-assessment methods (see Applied Technology Council, 1987a) need refinement to be useful in predicting earthquake casualties.

4. Physical settings are difficult to reconstruct after an earthquake. Documentation is often nonexistent for older buildings and for newer buildings, especially heavily damaged ones, is frequently restricted by the owners.

#### FINDINGS RELATED TO EARTHQUAKE CASUALTIES AND BUILDING PERFORMANCE

1. The majority of earthquake fatalities and serious injuries have resulted from structural failure.
2. A majority of serious casualties have come from a small number of damaged facilities, consistent with statistical experience from other disasters. This is apparent immediately in recent United States experience (50+ dead at the Cypress viaduct from the Loma Prieta earthquake and 40+ at the Veterans Hospital in San Fernando (1971) were the majority killed in their respective earthquakes; similar for foreign events) but has not become a basis for emergency planning.
3. Well-designed, modern, earthquake-resistant structures pose relatively little serious casualty threat to their occupants. The substantial threat is structures in classes that pose collapse hazards *even* if they do not collapse.
4. Nonstructural elements have a low likelihood of causing serious injury.
5. Building contents, such as office equipment and household furnishings, have a low likelihood of causing serious injury.

What do some of these preliminary observations mean? For emergency medical planning they suggest that there are two principal patient-demand sources. The first is from building collapse that yields large numbers of serious, life-threatening injuries. The second is from the normal injury mix from low to moderate building damage—that is, non-building collapse. These injuries are probably distributed proportionally to the population and do not create excessive demands on most health-care systems, because there are not likely to be massive numbers of severe casualties concentrated in a local area. This suggests that the primary emphasis of emergency medical planning should be first in areas where there are large numbers of high-hazard, structures and second where there are collapse-hazard structures, often widely distributed within a community.

The locating of collapse-hazard structures within a community is not overly difficult. The major contributors to building damageability include, among others, site location and characteristics, structural system, and architectural configuration. Classifying a structure and its site, however, is not the end of the hazard-determination process, because classification according to any one category (for example, unreinforced masonry) can be very misleading, giving either a false sense of security or peril. This is because earthquake engineering is not yet a precise endeavor; the identification of the damageability of a structure is a problem in statistics, with results given in rather broad ranges, not specific numbers.

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LOSS ESTIMATION AND PROCEDURES

# STUDY METHODS AND PROGRESS REPORT: A CASE-CONTROL STUDY OF PHYSICAL INJURIES ASSOCIATED WITH THE EARTHQUAKE IN THE COUNTY OF SANTA CRUZ

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## ABSTRACT

A case-control study in progress is examining the risk factors for physical injuries associated with the Loma Prieta earthquake. The study explores how the physical environments and personal behaviors of residents of the County of Santa Cruz contributed to their risk of being physically injured or killed during the shaking of the main earthquake and in the subsequent 72 hours. This paper describes in detail the study design and methods. Information on risk factors and injuries was collected in the County of Santa Cruz through a structured interview and review of medical records during the field period, which ended in August 1991. The risk factors for physical injury examined include age of building, type of structure, occupant behavior, and sociodemographic characteristics. Preliminary results of the data collection efforts (for example, the number of cases and controls targeted for an interview and ascertained) are reported here. The collected data are currently being coded for data entry and subsequent analysis. Final study findings will be published when available.

## INTRODUCTION

Obtaining reliable and accurate estimates of casualties associated with earthquakes has posed serious challenges.

Such estimates have varied, in part, because there is no universally accepted definition of earthquake-related deaths and injuries. Furthermore, documentation of injuries has generally taken a lower priority than rescue and treatment activities in the face of disaster. The Loma Prieta earthquake was no exception. Initial press accounts put the total death toll in the hundreds (Shilts and Sward, 1989a, b), an overestimate by a factor of three to four, and even the scientific literature could not agree on a final total count, offering a range of 60 to 67 deaths (Journal of Emergency Nursing, 1990; McNutt, 1990; Morbidity and Mortality Weekly Report, 1989; and Plafker and Galloway, 1989). One year after the event, there was still no reliable information on injury morbidity associated with the earthquake (Jones and others, 1990). The work described below attempts to overcome these and other problems that have characterized previous research in this area.

This paper describes recent efforts made, since the Loma Prieta earthquake, to assess, both qualitatively and quantitatively, the morbidity and mortality associated with that event. This study, when complete, will not only provide useful information relative to this specific event, but will also augment substantially the literature available in disaster—specifically earthquake—epidemiology. As the research is still in progress, the material and data presented herein must be considered preliminary only. Unfortunately, since most of the efforts to date have focussed on study design, data collection, and coding, few quantitative data are available for presentation at this stage. Reported herein, therefore, are descriptions of the study design, implementation, and future plans, as well as preliminary assessments made from the data processed to date. Specifically the authors are unable to report injury rates, risk factors, and so forth, at this stage, owing to the ongoing status of the project.

## PURPOSE OF STUDY

A case-control epidemiology study of the risk factors for physical injuries in the County of Santa Cruz, associated with the Loma Prieta earthquake, is being conducted. Earthquake-related injuries that occurred during the shaking of the main earthquake and the next 72 hours are being examined. The study population is restricted to persons who were residents of the County of Santa Cruz and were physically present in the County at the time of the earthquake.

The specific primary aims of this study are:

1. To assess the relative risk for physical injury associated with different physical environments (for example, buildings, vehicles, outside), with entrapment, and with personal behaviors in the disaster and postdisaster phases of the Loma Prieta earthquake.
2. To assess the relative risk for other potential risk factors for physical injury including preexisting medical conditions and mobility, drug and alcohol use, and sociodemographic characteristics.
3. To estimate the absolute risk of physical injury mortality and morbidity associated with the Loma Prieta earthquake in the County of Santa Cruz.

A secondary aim of this study is to determine if physically injured cases who sought treatment at a hospital were different from those who did not seek such care. For example, selection factors for treatment that will be examined include injury severity, possession of health insurance, and sociodemographic characteristics.

## BACKGROUND AND SIGNIFICANCE

Earthquakes are one of the most feared natural disasters, causing injury and physical damage in developing and developed nations alike. Despite the fact that earthquakes have killed at least 1.3 million people in this century (Smith, 1990), they have received scant attention from epidemiologists.

### PREVIOUS STUDIES

A critical review of the scientific literature on the causes of earthquake-related deaths and injuries leads to the following general conclusions. First, there is a paucity of epidemiological investigations of earthquakes, despite their great lethality (Smith, 1990). This dearth has arisen from inadequate funding and, until recently, from a relative lack of interest in the subject area by researchers (Tierney, 1990). Second, almost all of the published epidemiological studies on earthquake-related injuries are descriptive rather than analytical[1], precluding the ability to establish and quantify the magnitude of the relationship between significant risk factors and injuries. Only four earthquakes, prior to the Loma Prieta, have been examined through analytical studies of earthquake-related injuries: the 1976 Guatemalan (Glass and others, 1977); 1980 Italian (de Bruycker and others, 1983, 1985); 1988 Armenian (Armenian and others, 1992; Noji, 1990); and 1990 Philippine (Morbidity and Mortality Weekly Report, 1990) earthquakes.

Third, documentation of deaths and, in particular, nonlethal injuries is often incomplete in the aftermath of disaster,

[1]Descriptive injury studies investigate the experiences of injured or killed individuals only. The background rate of exposure to the same hazards (for example, collapsing buildings) in the noninjured persons is not considered. Analytical injury studies are superior to descriptive ones, in that they compare the experiences of injured persons to noninjured ones to identify and quantify significant risk factors for injury. Analytical studies permit researchers to test hypotheses that particular hazards are associated with injuries.

particularly in less-developed countries. Fourth, injuries are often vaguely and inconsistently defined in the previous epidemiological studies. For example, the definition of injuries may include conditions other than physical trauma (Sanchez-Carrillo, 1989), as well as any affliction treated after the disaster, whether or not it was earthquake-related (de Ville de Goyet and others, 1976). Investigators often employ different schemes to classify injury severity levels (Coulson, 1989). Fifth, most previous epidemiological studies of earthquakes have been conducted solely by health researchers, even though the topic calls for an interdisciplinary approach which draws on structural engineering, geology, architecture, epidemiology, and emergency medicine.

The majority of studies on the risk factors for earthquake-associated injuries actually appears in the earthquake engineering literature. These studies have generally been executed along strict disciplinary lines without input from health professionals. Thus, despite their quantitative approach, these engineering studies do not employ standard epidemiologic methods or meet minimal criteria generally required by epidemiologists to accurately and reliably assess risks. For example, some surveys of earthquake victims are not based on random probability samples of a clearly defined study population (Arnold, 1986; Durkin, 1985 (San Fernando earthquake)); others do not report sufficient information to evaluate the sampling methodology (Mochizuki, 1988; Miyano and Mochizuki, 1988; Ohta and others, 1980; Ohta and Omote, 1977); still others sample highly select groups (Mochizuki and others, 1988)[2], making it difficult to generalize the results to the rest of the population. Many of these studies either do not report or have unacceptably low case ascertainment or survey response rates.[3] The survey instruments, when described, do not always appear to measure well the stated variables of interest (Ohta and others, 1977, 1980), although this may result from inadequate translations of the questionnaires published in the English-language scientific literature.[4]

Despite these limitations, the literature has identified a number of potentially important risk factors for injuries associated with earthquakes. These include characteristics of the earthquake itself (magnitude, intensity, distance from the epicenter, time of day, and season), geological and topographic conditions (soil type, cliffs, or mountains), post-earthquake weather (rain which may cause landslides and extreme cold), the nature of the built environment (the degree of seismic resistance of buildings and other human engineered structures, such as bridges), the presence or absence of secondary hazards (fires, hazardous materials spills, tsunamis), sociodemographic features of the affected population (population density, age, and sex), and human behavior during and after the event (Stratton, 1989; Tierney, 1990). An extensive critique of the earthquake injury risk factor literature will be published later (Jones and others, 1993a).

## CASE-CONTROL STUDY OF THE EARTHQUAKE

This study in progress aims to build and improve upon previous work. It is being conducted by an interdisciplinary research team which includes epidemiologists (including an injury specialist), an engineer, and an architect. As an analytical epidemiological study, it will be able to explore and refine hypotheses of the contribution of the built environment and behaviors to earthquake-related casualties. Physical injuries are clearly defined with respect to qualifying medical conditions, severity level, time of occurrence, and earthquake-relatedness. Risks posed by structural and nonstructural components of buildings are distinguished from those associated with building contents.

The County of Santa Cruz was chosen for study rather than other regions affected by the Loma Prieta earthquake for the following reasons. Although the media concentrated on the San Francisco Bay area, the earthquake was centered in the County of Santa Cruz and caused widespread damage and destruction in the County. The County of Santa Cruz also presented unique opportunities for ascertaining persons injured in the County. The County had a relatively small total population at the time of the earthquake (approximately 235,000). It was difficult to leave the County by ground transportation after the earthquake, since it is isolated by natural barriers (the Pacific Ocean and Santa Cruz Mountains), and the few roads leading out of it were inaccessible for days, owing to earthquake-induced damage. Furthermore, medical treatment options in the County were thought to be restricted to the County's three hospitals, since doctor's offices and clinics were reportedly closed for several days after the earthquake.[5]

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[2]These researchers targeted college graduates because they thought respondents with higher education would have better memories than those with less schooling.

[3]For example, results based on case ascertainment rates of less than 30 percent were reported for building occupants in the 1985 Mexico and 1986 San Salvador earthquakes (Durkin and others, 1988).

[4]The Ohta questionnaires were administered in Japanese but translated into English for publication.

[5]An exception to this is that one clinic, Salad Para la Gente, which sustained serious structural damage during the quake, set up an outdoor temporary clinic in the downtown Plaza of Watsonville following the quake. The outdoor clinic provided limited services for minor injuries to a predominantly Hispanic clientele. According to Salud's Director, Barbara Garcia, persons with serious injuries were referred to a County hospital.

### PUBLIC HEALTH IMPACT OF THE STUDY

Injury prevention strategies can intervene at a number of different phases of an earthquake: the predisaster, disaster, and postdisaster phases (Noji and Sivertson, 1987). Interventions aimed at the predisaster phase prevent or limit people's exposure to the disaster; those directed toward the disaster phase limit the impact of the disaster while it is occurring; and those targeted at the postdisaster phase minimize the consequences of injuries incurred during the disaster. Examples of interventions for earthquakes include keeping people from living or working in seismically active regions and improving the design of buildings and (or) retrofitting them (for example, anchoring houses, bracing walls, and so forth) to prevent their collapse during the shaking (predisaster phase); instructing people on protective actions to take during the mainshock (disaster phase); and developing techniques to more rapidly rescue and treat victims trapped by rubble (postdisaster phase).

This case-control study will evaluate risk factors for the predisaster, disaster, and postdisaster phases. Thus, the lessons learned from this study can hopefully be used to design more effective injury prevention plans for future earthquakes.

Finally, this project is the first case-control study of earthquake-related injuries in a region in which many buildings have been designed or retrofitted to resist seismic forces. Thus, in contrast to the earlier studies which have concentrated on lesser developed nations, the results of this investigation are likely to be generalizable to future earthquakes in California and industrialized nations, such as Japan, which have well-conceived and enforced seismic building codes. This information should be valuable since there is a probability of approximately two-thirds that an earthquake at least as strong as the Loma Prieta earthquake will strike California in the next 30 years (U.S. Geological Survey, 1990).

## PRELIMINARY STUDIES

### BACKGROUND

This case-control study is one of several collaborative projects examining the health impacts of the Loma Prieta earthquake. The efforts of the participating research teams are being coordinated by the California Department of Health Services, the State's public health agency. This study builds on an ongoing descriptive, case-series study of the medical consequences associated with the earthquake in the County of Santa Cruz. The Johns Hopkins University team has played a leading role in the design and execution of both studies, in collaboration with California health authorities.

A major goal of the descriptive study is to determine the circumstances, causes, and nature of deaths and physical injuries requiring hospital treatment that occurred in the County of Santa Cruz and were associated with the earthquake. These cases are also part of the case-control study.

Hospital cases were identified by reviewing the medical records of all persons who visited the emergency room of any one of the three hospitals in the County of Santa Cruz—Dominican Santa Cruz, AMI Community, and Watsonville Community Hospitals[6]—for any reason in the 72 hours after the earthquake. County residents who were flown by helicopter to a hospital outside of the County were also identified as hospital cases. Helicoptered cases were identified through a review of the logs of all local helicopter ambulance services as well as through contact with the California Department of Forestry and Fire Protection. The latter agency used some of its helicopters to transport County residents to hospitals outside the County. Dead cases were identified by media reports and a visit to the County of Santa Cruz Coroner's Office. Dead cases and hospital cases whose medical records indicated they were "injured" or they visited the hospital for "unknown" (that is, unrecorded) reasons were targeted for a follow-up interview. Those with "unknown" diagnoses were targeted so as not to miss anyone who might have been injured.

The medical records of County of Santa Cruz hospital visitors were abstracted by 19 volunteers with medical training under the supervision of Santa Cruz County Office of Emergency Medical Services and Watsonville Community Hospital, collaborators in the project. Autopsy and coroner's reports were obtained from the Coroner's Office for the dead cases.

The interviewing phase of the descriptive study began on July 19, 1990, and was completed by March 31, 1991.

### PRELIMINARY RESULTS OF THE DESCRIPTIVE STUDY

During the case ascertainment period (the 72 hours after the main earthquake), six persons died from earthquake-related physical injuries that occurred in the County. The three County of Santa Cruz hospitals recorded 1,057 visits to their emergency rooms, representing 990 persons (some people went to a hospital more than once in the 72 hours after the quake). Of these 990, 630 visitors (64 percent) had diagnoses of "injured" or "unknown." The remainder (36 percent) had "illness" diagnoses. A critical review of all the medical abstracts resulted in some of the "injured" or "unknown" persons to be judged ineligible (that is, not earthquake-related) whereas a few from the "illness" category had sufficiently ambiguous diagnoses to be included for an interview. This review resulted in 565 persons who

[6]Dominican has recently acquired AMI and converted it into a drug treatment center, nursing home, and intermediate care hospital.

Table 1.—*Distribution of target population of County of Santa Cruz hospital cases by hospital and medical outcome recorded on the medical abstract*

| Hospital | Medical Outcome | | | |
|---|---|---|---|---|
| | Injury | Illness | Unknown | Total |
| Watsonville | 215 | 4 | 33 | 252 (44.6 pct) |
| Dominican | 193 | 0 | 14 | 207 (36.6 pct) |
| AMI | 104 | 0 | 2 | 106 (18.8 pct) |
| Total | 512 (90.6 pct) | 4 (0.7 pct) | 49 (8.7pct) | 565 (100.0 pct) |

Table 2.—*Distribution of ascertained County of Santa Cruz hospital cases that completed interviews as of December 26, 1990 by hospital and medical outcome recorded on the medical abstract**

| Hospital | Medical Outcome | | | |
|---|---|---|---|---|
| | Injury | Illness | Unknown | Total |
| Watsonville | 184 | 4 | 24 | 212 (45.6 pct) |
| Dominican | 163 | 0 | 10 | 173 (37.2 pct) |
| AMI | 79 | 0 | 1 | 80 (17.2 pct) |
| Total | 426 (91.6 pct) | 4 (0.9 pct) | 35 (7.5 pct) | 465 (100.0 pct) |

* $n$=463 and $n$=2 for totally and partially completed interviews, respectively.

Table 3.—*Distribution of ascertained County of Santa Cruz hospital cases that refused to be interviewed as of December 26, 1990, by hospital and medical outcome recorded on the medical abstract**

| Hospital | Medical Outcome | | | |
|---|---|---|---|---|
| | Injury | Illness | Unknown | Total |
| Watsonville | 6 | 0 | 1 | 7 (23.3 pct) |
| Dominican | 13 | 0 | 1 | 14 (46.7 pct) |
| AMI | 8 | 0 | 1 | 9 (30.0 pct) |
| Total | 27 (90.0 pct) | 0 (0.0 pct) | 3 (10.0 pct) | 30 (100.0 pct) |

* Includes final refusals (refusal conversion failed) ($n$=17) and refusals for whom refusal conversion process had not been completed ($n$=13).

visited a County of Santa Cruz hospital—including one of the six persons killed by the earthquake—or their proxies being targeted for an interview. Four additional persons were identified as injured and flown to an out-of-county hospital. Thus, the total pool of potential cases was 574 (565 County hospital cases (including 1 dead case) plus 5 other dead cases and 4 non-County hospital cases).

A total of 482 potential cases or proxies were interviewed (477 completed interviews and 5 break-offs), representing 83 percent of the total. Another 31 (5 percent) refused. About 11 percent were lost to follow-up.

Tables 1 and 2 show that the 465 County hospital cases who were interviewed as of December 26, 1990, (a final analysis is not yet available), were highly representative of the target population from which they came with respect to both medical outcome and hospital visited. Table 3 shows that refusals obtained as of December 26, 1990, were disproportionately higher than expected from the two north County hospitals (Dominican and AMI Hospital) and lower from the south County hospital (Watsonville). The reasons for this are unknown. However, Dominican Hospital acquired AMI in a highly publicized takeover during the interview phase, and this may account for some of the negative responses.

A more complete description of the case population and ascertainment methods is presented in the following section.

## STUDY DESIGN AND METHODS

### OVERVIEW OF METHODS

This case-control study examines how the physical environments and personal behaviors of the County of Santa Cruz residents contributed to their risk of being physically injured or killed in the County by the Loma Prieta earthquake. Physical environments are characterized broadly as being inside a building, in or on a vehicle, or outside (near a building or entirely away from one). Risk factors specific to each environment, such as collapsing chimneys or landslides, are also being explored. Within the building environment, hazards from structural and nonstructural components of buildings are being distinguished from dangers posed by building contents. Behaviors of interest include the protection and rescue of oneself and other people, pets, or things, as well as clean-up activities in earthquake-damaged areas. The outcomes of interest are earthquake-related physical injuries that occurred during the shaking of the main earthquake (the disaster phase) and the subsequent 72 hours (the postdisaster phase). Injuries are characterized by their type, affected body parts, cause, and level of severity.

Information on both injuries and risk factors was obtained through a structured interview of cases and controls, or their proxies if necessary.

Injury information on cases was also obtained from medical records and autopsy reports. Interviews were generally conducted by telephone. They were administered in English and Spanish.

Interviews are a standard tool in epidemiology (Schlesselman, 1982). They provide unique advantages over other methods of data collection for certain classes of information. For example, interviewing individuals is the best method currently available to investigate human behaviors during an unanticipated event (such as an earthquake) in a large-sized sample.

To be eligible for the case-control study, participants had to have been living and present in the County at the time of the earthquake. The case group consisted of hospital and dead cases. For comparison, a population-based sample of current County residents was selected using a random digit dial of listed and unlisted residential telephone numbers. The sample was divided into two groups: noninjured controls and population cases, the latter group comprising individuals who incurred an earthquake-related injury but were not treated at a County hospital or flown by helicopter to a hospital outside the County. The noninjured controls were frequency matched to hospital and dead cases on general area of residence at the time of the earthquake. Three residential strata were defined by aggregates of contiguous zip codes in the County. The goal was to interview two noninjured controls for each hospital or dead case.

The injury status of individuals from the population sample was not determined in advance of the interview. Injury information collected in the interview was used to assign persons post-hoc to the appropriate category. Based on the results of the pilot testing, 20 percent of the population sample was expected to have incurred an earthquake-related injury and thus qualify as population cases.[7] With such a background injury rate, it would be necessary to interview 2.5 members of the population sample for each hospital or dead case to achieve the desired 2:1 ratio of noninjured controls to hospital/dead cases. Population cases will be studied separately from hospital and dead cases.

Hospital and dead cases or their proxies were interviewed from July 19, 1990, to March 31, 1991. Noninjured controls and population cases were interviewed over the period of March 24, 1991, to August 31, 1991.

The collected data is currently being coded for data entry. Three basic types of analyses will be performed. First, hospital and dead cases will be compared to noninjured controls to assess the significant risk factors for injury. Second, hospital and dead cases will be compared to population cases to evaluate the selection factors for seeking medical care among the injured. Third, several descriptive studies will be undertaken to assess the total morbidity and mortality in the County of Santa Cruz associated with the earthquake.

### TARGET POPULATION

The case-control study target population was the residents of the County of Santa Cruz at the time of the earthquake. The County is highly diverse with respect to geography and the demographic composition of its population. At the time of the earthquake, the County's population was approximately 235,335 (California Department of Finance, 1990). Approximately two-fifths of the population lived in one of the four incorporated cities—Santa Cruz, Watsonville, Capitola, and Scotts Valley—whereas the remainder lived in unincorporated areas of the County (table 4). The two major cities are Santa Cruz ($n$=51,082) and Watsonville ($n$=30,882) which are located in the coastal parts of north and south County, respectively.

The populations in the north and south County are quite distinct. The residents of north County are predominantly white and English speaking and have a relatively high socioeconomic status. Many are employed in the computer and electronics industries. Nearby Silicon Valley and tourism drive the local economy. A large university, University of California at Santa Cruz, draws many students and professionals to the area.

[7]This background rate is in keeping with the results of the case-control study of the 1988 Armenian earthquake, in which 30 percent of the selected controls were found to have been injured but not hospitalized (Armenian and others, 1992).

Table 4.—*Population characteristics of the County of Santa Cruz, January 1, 1990, estimates*

[Source: California Department of Finance (1990, p. 51)]

| Location | Number (Percent) of People |
|---|---|
| Incorporated cities | |
| Santa Cruz (north County) | 51,082 (22 pct) |
| Watsonville (south County | 30,882 (13 pct) |
| Capitola (north County) | 10,450 (4 pct) |
| Scotts Valley (north County) | 9,460 (4 pct) |
| Total incorporated | 101,874 (43 pct) |
| Unincorporated areas | 133,461 (57 pct) |
| Grand Total | 235,335 (100 pct) |

In contrast, Watsonville has an agricultural economy with a large Hispanic population that fluctuates seasonally due to migrant farm workers. Many of the Hispanics are poor, and an undetermined number are undocumented. A significant fraction of the Hispanic community lives in severely overcrowded dwellings; often two or three families live in a house designed for one family. Others live in converted garages, shacks and labor camps.

The County of Santa Cruz can also be categorized by geography. Much of the County's population lives along the coastal regions in relatively urbanized cities. These coastal cities, running from north to south, include Davenport, Santa Cruz, Live Oak, Capitola, Soquel, Aptos, Rio del Mar, La Selva Beach, Freedom, and Watsonville. The rest of the population lives in the Santa Cruz Mountains, which run from the northwest to the southeast parts of the County. Cities in the mountains include Boulder Creek, Ben Lomond, Brookdale, Felton, Los Gatos, Mt. Herman, and Scotts Valley in the north, and Corralitos in the south. The mountainous population itself is quite diverse and different from the coastal residents. The residents range from wealthy growers, commune dwellers, and artists to persons in communities as poor as Appalachia.[8] Most are white and generally very self-reliant—an attitude which may affect medical seeking behaviors.

Geography also serves to isolate the population from neighboring counties. The County is bounded by the Pacific Ocean and the Santa Cruz Mountains. Only a few highways lead out of the County, and some of these were closed for days after the earthquake due to landslides and other damage.

This geographic and demographic diversity is likely to have influenced the types of risk factors for injury and opportunities for medical treatment experienced by the population during and after the earthquake.

In fact, the catchment areas for the three County hospitals—the main source of hospital cases—have almost no overlap. Watsonville Hospital serves the south County area. Dominican and AMI are located about 1 mile from one another in the Santa Cruz city area and serve the north coastal and mountainous regions. This can be seen in table 5, which presents the distribution of target population of the County hospital cases by hospital visited in the ascertainment period and city of residence at the time of the earthquake. Almost all of the potential cases from Watsonville went to Watsonville Hospital (184 out of 191), whereas the vast majority of Santa Cruz residents went to either Dominican or AMI Hospitals (155 out of 158).

[8]Personal communication from a number of local and Federal officials, including 1990 U.S. Census workers.

## DEFINITION OF STUDY GROUPS

The case-control study consists of a case group, comprising hospital and dead cases, and a population sample, divided into noninjured controls and population cases. The hospital and dead cases are a subset of those from the descriptive study, having to meet more stringent requirements for entry into the case-control study. The eligibility criteria for both studies are summarized and compared in table 6. The study group definitions for the case-control study are described in the following two sections.

### CASE GROUP: HOSPITAL AND DEAD CASES

Hospital cases were defined by the following criteria: (1) they were residents of the County at the time of the earthquake; (2) they were physically injured in the County during the shaking from the mainshock, or in the subsequent 72 hours as a result of the earthquake or its aftershocks; and (3) they were treated at a County hospital or were flown by helicopter to a hospital outside the County within 72 hours of the earthquake.

Dead cases met the following criteria: (1) they were residents of the County at the time of the earthquake and (2) they were killed in the County by physical injuries during the shaking from mainshock, or in the subsequent 72 hours as a result of the earthquake or its aftershocks.

Table 5.—*Distribution of potential cases by hospital visited and city of residence*

| Cities within County of Santa Cruz | Hospital | | | Total |
|---|---|---|---|---|
| | Watsonville | Dominican | AMI | |
| Aptos | 8 | 22 | 6 | 36 |
| Ben Lomond | 4 | 1 | 0 | 5 |
| Boulder Creek | 0 | 2 | 4 | 6 |
| Brookdale | 0 | 1 | 0 | 1 |
| Capitola | 0 | 14 | 6 | 20 |
| Corralitos | 0 | 1 | 1 | 2 |
| Felton | 0 | 6 | 4 | 10 |
| Freedom | 11 | 0 | 0 | 11 |
| La Selva Beach | 3 | 0 | 0 | 3 |
| Live Oak | 0 | 0 | 6 | 6 |
| Los Gatos | 0 | 3 | 1 | 4 |
| Mt. Herman | 0 | 0 | 1 | 1 |
| Santa Cruz | 3 | 102 | 53 | 158 |
| Scotts Valley | 0 | 5 | 4 | 9 |
| Soquel | 1 | 24 | 3 | 28 |
| Watsonville | 184 | 4 | 3 | 191 |
| Zayante | 0 | 0 | 1 | 1 |
| Cities outside County of Santa Cruz | 11 | 10 | 1 | 22 |
| No residence information | 36 | 6 | 8 | 50 |

To make the sampling frame for hospital cases and noninjured controls comparable, hospital cases were excluded if: (1) they lacked a home phone at the time of the interview or (2) they were living in institutional or commercial facilities at the time of the interview. These exclusion criteria will be waived if it can be determined from the interview that the case's condition is a consequence of the earthquake. For example, cases living in motels, shelters, or tents because the earthquake destroyed their homes are not excluded. The residential phone requirement will be waived for cases who usually had a home phone but who lacked one at the time of the interview because of earthquake-related circumstances.

### POPULATION SAMPLE: NONINJURED CONTROLS AND POPULATION CASES

A random sample of current County of Santa Cruz residents was taken for comparison to the case group. This population sample comprised two groups, noninjured controls and population cases.

Noninjured controls were defined by the following criteria: (1) they were residents of the County when the earthquake occurred; (2) they were present in the County when the earthquake occurred; (3) they were alive at the time of the interview; (4) they were residents of the County at the time of the interview; and (5) they were not injured because of the earthquake in the ascertainment period.

Population cases satisfied criteria (1) through (4) used for the noninjured controls, plus two additional ones: (5) they sustained an earthquake-related injury during the ascertainment period and (6) as a result of these injuries, they did not seek treatment at a County hospital or were not flown by helicopter to a non-County hospital during the ascertainment period. Individuals who met the population case criteria and who sought treatment at other medical facilities (for example, private doctor's offices, clinics) were classed as population cases.

Table 6.—*Comparison of case and control definitions in the case-series and case-control studies*

| Group Criteria | Case series study | | Case-control study | | | |
|---|---|---|---|---|---|---|
| | Cases | | Cases | | Population sample | |
| | Hospital | Dead | Hospital | Dead | Population cases | Noninjured controls |
| Injured during shaking and (or) in next 72 hours in County | Yes | Yes | Yes | Yes | Yes | No |
| Earthquake-related injuries | Yes | Yes | Yes | Yes | Yes | NA |
| Visited a County hospital or flown by helicopter ambulance to out-of-county hospital | Yes | Sometimes | Yes | Sometimes | No | No |
| Resident of County at time of quake | Not required | Not required | Required | Required | Required | Required |
| Resident of County at time of interview | Not required | Not required | Not required | Not required | Required | Required |
| Had home phone at time of interview | Not required | Not required | Required[1] | NA[3] | Required | Required |
| Living in an institutional facility at time of interview | Included | Included | Excluded[2] | NA[3] | Excluded | Excluded |
| Alive at the time of the interview | Not required | Not required | Not required | Not required | Required | Required |

[1]Cases without phones at the time of the interview will be included if their phone status was related to the earthquake (for example, they were institutionalized after their injuries, or they lived in temporary shelters because their homes were destroyed by the earthquake).

[2]Cases living in institutions at the time of the interview for reasons related to the earthquake will be included.

[3]NA means "not applicable."

## CASE ASCERTAINMENT (HOSPITAL AND DEAD CASES)

Hospital and dead cases in the case-control study are a subset of those in the case-series study. Thus, the former were ascertained in the same manner as the latter as described in the section, "Preliminary Studies."

As noted in that section, the review of medical records and helicopter logs resulted in 574 persons being targeted for an interview. Another five persons were ascertained in the process of tracing the cases who were identified from the medical records and helicopter logs. These five persons met the case definition and were interviewed. Thus, the final total population targeted for an interview was 579.

Reviews of the records of hospital and dead cases for whom an interview was obtained are underway to determine if they met the eligibility requirements for the case-control study. Preliminary results of this review are presented in the section, "Preliminary Progress Report on Case-Control Study."

## POPULATION SAMPLE SELECTION PLAN

A population-based stratified random sample of current County residents was selected using a random digit dial of listed and unlisted residential phone numbers in the County. Selected individuals were screened for eligibility on the residency requirements (that is, living and present in the County at the time of the earthquake) before being enrolled.

As indicated above, the population sample included both persons who were not injured by the earthquake (noninjured controls) and those who were injured but did not go to a hospital (population cases). The injury status of enrolled individuals was not determined before the interview began. Thus, participants were assigned to the appropriate study group after the interview was completed.

To increase statistical power, an attempt was made to select two noninjured controls for each hospital or dead case. It was estimated that 20 percent of the County population and selected sample would have been injured (see discussion below). Thus, it was deemed necessary to choose 2.5 eligible individuals to achieve the desired 2:1 ratio of noninjured controls to hospital and dead cases.

Noninjured controls were frequency matched to hospital and dead case on general area of residence at the time of the earthquake, which is likely to be an important confounder (see section, "Target Population").[9] Matching closely on residential location was not done because this could result in overmatching on building type, a primary risk factor of interest.

In theory, residential strata should be as similar within and as different between strata as possible with respect to the geography and sociodemographic characteristics. This ideal was approximated by creating three strata of contiguous zip codes which were geographically distinct (table 7;

fig. 1). Stratum 1 covered the north mountainous areas, where most of the County's mountain population lived. Stratum 2 corresponded to the north coastal region and included the cities of Santa Cruz, Capitola, Soquel, and Aptos. Stratum 3 covered the entire south County, including Watsonville, where most of the County's Hispanic population lived.

Noninjured controls were assigned to a stratum as part of the initial screening process. A random sample of listed and unlisted residential phone numbers for the County was computer generated.[10] Each number had an equal probability of being selected. Enrolled individuals were asked for their home zip code at the time of the earthquake before the interview began. Their answer determined the stratum into which they fell. Once the proper number of noninjured controls was selected for a stratum, additional persons initially selected from that stratum were not enrolled.

The matching information, home zip code at the time of the earthquake, was also obtained for hospital and dead cases from the questionnaire.

This sampling plan, unusual for a case-control study, was adopted because it was deemed both important and feasible. It was important because it would facilitate the study of persons injured by the earthquake who would not otherwise be ascertained as hospital and dead cases. The number of such persons was expected to be high. In the pilot test of the draft questionnaire—to refine the questions for inclusion in the final version—on a small random sample of County residents[11], it was found that 20 percent reported an earthquake-related injury of any severity level that was not treated at a hospital.[12] This rate, if borne out in the full-scale study, would translate into some 47,000 earthquake-related injuries in County residents.

The medical significance of injuries among population cases was also considered. Most population cases were expected to have minor injuries. However, the great majority

Table 7.—*Control selection strata by general area of residence in the County of Santa Cruz at the time of the earthquake*

| Zip code | City |
|---|---|
| Stratum 1: North Mountainous County | |
| 95005 | Ben Lomond |
| 95006 | Boulder Creek |
| 95007 | Brookdale |
| 95018 | Felton |
| 95030 | Los Gatos |
| 95041 | Mount Herman |
| 95066 | Scotts Valley |
| Stratum 2: North Coastal County (predominantly nonmountainous) | |
| 95003 | Aptos |
| 95010 | Capitola |
| 95017 | Davenport |
| 95060 | Santa Cruz |
| 95062 | Live Oak |
| 95064 | UC Santa Cruz |
| 95065 | Santa Cruz |
| 95073 | Soquel |
| Stratum 3: South County | |
| 95076 | Watsonville |
| 95019 | Freedom |

[9]A confounder (for example, residential stratum) for a risk factor of interest (for example, being in a building when mainshock began) can make it appear that there is a relationship between the risk factor of interest and the outcome of interest (for example, injury) when, in truth, there is none, and vice versa. Technically, a risk factor, C, is a confounder for the risk factor of interest, R, if: (1) C is an independent risk factor for the outcome of interest, I, and (2) C is distributed differently among the different levels or categories of R (for example, the distribution of residential stratum is different among those in a building and those not in a building when the shaking began), and (3) R does not cause C or vice-versa. One method to control or adjust for a confounder is to match cases and controls on that confounder. This is done when it is thought that a random sampling plan without matching may not produce enough cases and controls at each level of the confounder to examine the independent effect of other risk factors, holding the effect of the confounder constant, in the analysis phase. A disadvantage of matching is that one cannot examine the association between the confounder (for example, residential stratum) as a risk factor and the outcome of interest (for example, injury). Thus, in general, one tries to minimize the number of risk factors that are matched. In this study, matching on residential stratum was performed because this variable was thought to be a potential confounder, and a sampling plan was desired that would ensure an adequate number of cases and controls in each of the three strata. This matching will not preclude analyses of risks associated with other unmatched and potentially important risk factors (see section, "Purpose of Study"), including sociodemographic characteristics such as age, sex, and level of education.

[10]The telephone numbers were provided by the consulting firm Survey Sampling, Inc. (SSI), which had performed a Waksberg-like technique on all of the residential telephone prefixes in Santa Cruz County. SSI identified all "working blocks" of telephone numbers in the County. Details of the process will be provided in future reports.

[11]See section, "Questionnaire and Interview" for a brief description of the pilot testing procedures.

[12]An elevated background rate is consistent with the results of the case-control study of the Armenian earthquake, in which an even higher proportion (30 percent) of the selected controls was found to have been injured but not hospitalized (Armenian and others, 1992).

of all injuries caused by the earthquake was anticipated to be moderate to minor in nature. Only five County residents were killed[13], and only 33 persons had injuries serious enough to be admitted to a hospital. Most of the moderately injured were probably seen at a County hospital or helicoptered out of the County within the ascertainment period, since alternative care was largely unavailable. Furthermore, the medical abstracts indicated that many of the hospital visitors sustained relatively minor injuries. Thus, considerable overlap in the level of injury severity among the hospital and population cases with minor injuries was expected. Therefore, collecting information on the population cases was seen as essential in estimating the true earthquake-related injury burden in the County.

The sampling plan was deemed feasible because the expected 20 percent background injury rate was high enough to provide sufficient numbers of population cases to study in a meaningful fashion. In fact, population cases composed 15 percent of the population sample that was interviewed (see section "Preliminary Progress Report on Case-Control Study"). This injury rate was still adequate to produce enough population cases to study.

[13]The sixth person killed in the County was a resident of Napa, California.

## RISK FACTORS FOR PHYSICAL INJURY

Table 8 presents an outline of the risk factors for physical injury that were examined in the interview. The primary risk

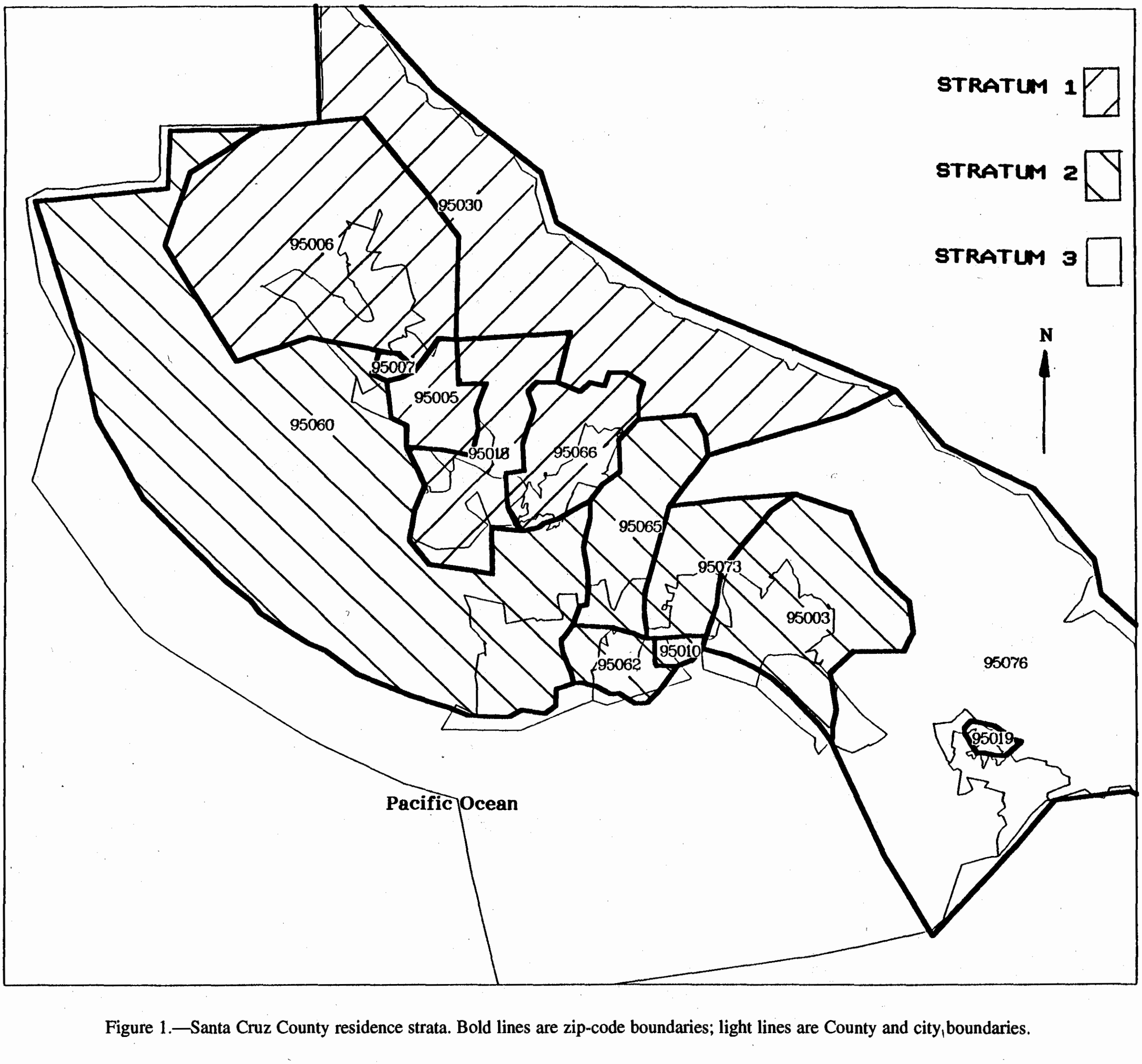


Figure 1.—Santa Cruz County residence strata. Bold lines are zip-code boundaries; light lines are County and city boundaries.

Table 8.—*Risk factors for physical injury*

| During the shaking of the main earthquake | In the 72 hours after the shaking of the main earthquake stopped |
|---|---|
| Physical environment | Physical environment |
| Inside a building | Inside a building |
| Inside a vehicle | Inside a vehicle |
| Outside, within 20 feet of a building | Outside |
| Outside, further than 20 feet from a building | Other |
| Other | |
| Being trapped | Being trapped |
| Protective/rescue behaviors | Rescue/retrieval behaviors |
| Oneself | Oneself |
| Other people | Other people |
| Pets | Pets |
| Things/belongings | Things/belongings in buildings |
| | Clean-up activities |

factors of interest were physical environments, entrapment, individual behaviors, and their interactions. Potential confounders, including demographic characteristics, were also explored. Risks posed during each time period—during the shaking of the mainshock and in the next 72 hours—were examined separately.

Physical environments were broadly defined as being inside a building, in or on a vehicle, outside and within 20 feet of a building, outside and further than 20 feet from a building, and "other." The category of "other" would include, for example, persons in a car which is inside an enclosed garage. Risk factors within each environment will be explored through subgroup analysis. For example, for those within a building during the shaking, the hazards associated with falling furniture, collapsing walls, gas leaks, exposed live wiring, and so forth will be examined. The type of building will also be explored (that is, buildings were broadly classified as residential, commercial, industrial/farm, or public/institutional). The age, construction materials, and number of floor levels of the building, as well as respondent's location within it (floor level, room, and so forth) will be determined. Respondents were also asked whether or not the building was bolted to its foundation. The year of construction is considered a potential risk factor because seismic building codes changed and improved over time; thus, for example, older brick buildings (which have not been retrofitted) are expected to be more hazardous than newer ones. For practical reasons (for example, knowledge limitations of layperson respondents), the only attempt made through the questionnaire to infer structural type was through a description of building materials (for example, wood, brick, and so forth).[14] For those outside further than 20 feet from a building, the dangers posed by landslides, floods, and human-made structures such as collapsing bridges and fences will be explored.

Entrapment, or inability to move, can be caused by both physical objects which restrict movement, or by injuries (which themselves could be the result of physical objects). The interview distinguished between these two types of entrapment, which will be treated separately in analysis. Elements of entrapment which were examined include the causative agent(s), the duration of entrapment, and the place of entrapment. The duration of entrapment was broken down into the intervals between first being trapped, discovered by others (when relevant), and rescued or self-freed.

Personal behaviors examined include actions taken to protect oneself, other people, pets, and belongings or things. Rescue or retrieval of other persons, pets, and things were also explored as well as clean-up in earthquake damaged areas. Behaviors specific to each environment were scrutinized. For example, for those in a building during the shaking, standing in a doorjamb, holding onto to something, getting under a table or desk, and running outside were examined. For those in a moving vehicle during the shaking, actions evaluated included continuing to drive, pulling over and stopping, getting out of the vehicle, and so forth.

Demographic characteristics which were collected include age, sex, marital status, occupation, ethnic origin, level of education, number of dependents, and home ownership. The importance of being with other people, including dependents or disabled persons, during the shaking was examined. Other risk factors which were explored include preexisting medical conditions and mobility, prescription drug use, and alcohol consumption in the 2 hours before the mainshock.

## OUTCOME MEASURES FOR PHYSICAL INJURY

Injuries directly and indirectly associated with the earthquake were included in the study but will be analyzed sep-

[14] Verification of building type required a field follow-up after preliminary data analysis (Jones and others, 1993b).

arately. Directly related injuries were defined as those caused by the seismic forces during the shaking of the mainshock or its aftershocks. This class of injuries also included persons injured in the postdisaster period while engaged in protective, rescue, retrieval, or clean-up activities because of the earthquake. For example, this category would include persons injured while cleaning up or retrieving belongings from their earthquake-damaged homes. Indirectly related injuries were those whose relationship to the earthquake is less clear. For example, a person injured in a car accident because of excess alcohol consumption due to stress brought on by the earthquake would fall into this category.

Outcomes which were excluded from this study are: (1) intentional physical injuries, that is, injuries that were self-inflicted or caused by assaults, and (2) medical conditions other than injuries which may or may not have been associated with the earthquake, including but not limited to psychological trauma, communicable diseases, cardiovascular events, and complications of pregnancy.

The outcomes of interest are earthquake-related physical injuries that occurred during the shaking from the mainshock and the subsequent 72 hours. Injuries were defined as physical trauma of any severity level. Multiple injuries to the same person were described individually. Information collected on each injury included the type of injury, affected body part, the cause of the injury, and the location of the person when the injury occurred. Injuries that occurred during the shaking from the mainshock will be analyzed separately from those that occurred in the subsequent 72 hours.

Each injury will be coded using the Abbreviated Injury Scale 1990 Revision (AIS) (Association for the Advancement of Automotive Medicine, 1990). The 1990 AIS assigns a unique seven digit number to each injury diagnosis. The code describes an injury according to body region where it occurs, the type of anatomical structure affected (nerves, and so forth), the specific nature of the injury or anatomic structure (for example, abrasion, amputation, loss of consciousness, cervical injury, and so forth), the severity level of injury, and the AIS severity score.

The AIS severity score is an anatomically based system that categorizes injuries by six body regions using a six point ordinal scale ranging from minor (AIS=1) to currently untreatable (AIS=6) injuries. The other four scores are AIS 2=moderate, AIS 3=serious, AIS 4=severe, and AIS 5=critical. A score of nine is assigned for injuries of unknown severity. AIS scores reflect not only potential lethality but also diagnostic certainty, as well as the expected duration and degree of recovery with or without medical treatment (Association for the Advancement of Automotive Medicine, 1990).

The AIS severity scores are based on only anatomical injury and not physiological status. This property means that a particular injury can have only one AIS score that does not change with time. In contrast, injury severity systems which include physiological parameters, such as the Trauma Score, may produce many scores for the same injury as the patient's physiological status changes with time. The AIS' anatomical basis also means that it is a measure of the severity of the injury itself and not of the consequences of injury such as death or disability, the latter which may be affected by availability and efficacy of treatment (Association for the Advancement of Automotive Medicine, 1990).

AIS scores will be computed from interview data (all case groups) and from medical abstracts and autopsies (hospital and dead cases only). The scoring from each source (interview and medical records) will be done separately and blinded. AIS scoring employs precise medical information of sufficient detail usually found only in medical records.

Injury Severity Scores (ISS's) will be computed separately from AIS's derived from the interview data (all case groups) and from medical records/autopsies (hospital and dead cases only). Analyses which rely on the ISS will be done twice, using each set of ISS's.

For the purposes of analysis, outcomes for each individual will be described in two ways: (1) the absence or presence of physical injury of any level and (2) the overall level of injury severity. Overall injury severity is a measure of the total impact of all injuries a person may have. It will be assessed using the ISS (Baker and others, 1974). The ISS is the sum of the squares of the highest AIS severity code in each of the three most severely injured ISS body regions. The ISS body regions are slightly different from the AIS classifications but are intraconvertable. The ISS has a range of 1 to 75. The maximum score of 75 is produced in one of two ways: either a person has three AIS level 5 injuries, or at least one AIS level 6 injury.

## DATA COLLECTION PROCEDURES

### MEDICAL ABSTRACTS

The majority of relevant County hospital records were abstracted by the team described above from November 1989 to June 1990; the rest were abstracted in September 1991. The helicopter-mediated visits to out-of-County hospitals will be abstracted by the same team in future work. The summary judgment of medical diagnosis was used to determine which County hospital visitors to target for a follow-up interview.

### HELICOPTER AMBULANCE LOGS

The premedical care logs of all local ambulance services were reviewed for the ascertainment period by the California Office of Emergency Services. In addition, the California

Department of Forestry and Fire Protection was contacted for a list of persons they helicoptered to neighboring County hospitals. Persons whose premedical care record indicated they were injured or did not list a diagnosis were targeted for a follow-up interview.

## QUESTIONNAIRE AND INTERVIEW

Information on potential hazards, injuries, and other factors of interest was collected through a structured interview. The same questionnaire was administered to cases and controls, and their proxies when necessary.

The questionnaire was developed in English, and translated into Spanish to accommodate the large Hispanic population that lives in the southern part of the County. The translation was done by a doctoral student in public health who has extensive experience in health survey design and translation. Like most of the Hispanic residents of the County, the translator is of Mexican descent and was able to translate the questionnaire into an appropriate Spanish dialect. The Spanish version was back-translated into English by two qualified persons selected by the translator. The English version was pilot tested in June and July 1990 on a random sample of approximately 30 County residents who were not hospital cases; the Spanish version was comparably tested on a sample of 10. The versions were modified based on the lessons learned from pilot testing.

The questionnaire had eight parts, sections A to H. Section A collected demographic information and determined the physical environment (in a building, in a vehicle, or outside) in which the case or control was when the main earthquake began. The answers given in section A directed the respondent to either section B, C, or D. These sections asked about exposures, human behaviors, and injuries during the 15-second shaking period of the mainshock for those in a building (section B), in or on a vehicle (section C), or outside (in close proximity to a building or away from buildings entirely) (section D) when the earthquake began. Section E gathered information about hazards and injuries in the 72 hours after the mainshock. It also queried about being trapped and rescued during the shaking and subsequent 72 hours and evaluates the use and efficacy of the 911 emergency response system. Section E was administered to all respondents. Section F collected information on health care utilization. It was given only to those who reported an injury during the shaking or the next 72 hours. Section F also collected information on disabilities associated with the reported injuries. Section G gathered more demographic information, and data on drug and alcohol use, physical mobility, health insurance and preexisting medical conditions. Section H was the closing section of the interview and asked for future contact information.

The questionnaire took approximately 30 minutes to an hour to administer depending on the experiences of the respondent. The interview was conducted by a staff of trained bilingual interviewers located in the County. It was done in either English or Spanish depending on the preference of the respondent. It was generally administered by telephone at the respondent's home. However, interviews were conducted at a work phone, or in person through home visits if the respondent requested it. In-person interviews were also done for hospital and dead cases (or their proxies) who could not be reached by home phone because either they lacked a home phone or the study could not trace the phone number.

Proxy interviews were obtained for dead cases or for hospital cases who died since the ascertainment period. Proxies were sought for hospital cases who were unavailable during the interviewing phase, or who refused to do the interview. Proxy interviews were also done for study subjects who were under 13 years old, or who were too mentally or physically disabled to do the interview.

For respondents under 13 years old, proxy interviews were requested of parents or guardians. For other categories, proxy interviews were sought from adult next of kin. However, when next of kin were unavailable, other adults who were knowledgeable about the respondent were solicited.

Minors between 13 and 17 years old were interviewed directly. However, permission to do the interview was first obtained from parents or guardians.

## RECRUITMENT AND ENROLLMENT OF HOSPITAL AND DEAD CASES

The recruitment and enrollment of hospital and dead cases began on July 19, 1990, and was completed on March 31, 1991. The process involved tracing, contacting, and obtaining informed consent from cases or their proxies in order to administer the interview.

### TRACING METHODS AND COMMUNITY OUTREACH EFFORTS

Tracing efforts began with the information contained in the medical records. However, phone numbers and addresses were either missing or outdated for many cases. Therefore, the following additional sources were employed to trace cases or their proxies: (1) individuals including neighbors, friends, relatives, and apartment managers; (2) private and public agencies (for example, nonprofit social service groups, the Red Cross, churches, and government agencies including U.S. Postal Service, Voter Registration, California Department of Motor Vehicles, Planning Departments of the incorporated cities and unincorporated areas of the County); (3) a national credit bureau; (4) former and current employers; (5) Federal Express, (6) publicly available sources (newspapers, Directory Assistance, hard-bound and on-line criss-cross directories); and (7) a prominent Hispanic community organizer hired as a consultant to the study.

Tracing methods were chosen to protect the confidentiality of cases. No information about the study or the case was divulged to past or current employers. When speaking with other categories of individuals, or public and private agencies, interviewers identified themselves as from the study but did not reveal that the case was injured or visited a hospital.

A bilingual community outreach campaign was initiated in August 1990 with the assistance of the community organizer. The purpose of the campaign was to familiarize the community with the study, and to encourage people who met the hospital case definition to contact the study for an interview. Flyers in Spanish and English were prepared and distributed to social service agencies, labor camps, churches, employment agencies, supermarkets, and other public places. Radio and television public service announcements on the study ran on local stations. The major County newspapers donated advertisement space to explain the study. The authors were also interviewed by local radio stations and newspapers.

### CONTACT AND ENROLLMENT

In general, the study first contacted cases or their proxies at their homes by phone. When this was not possible, initial contact was made through other phone numbers (when available), home visits, or mailings which asked the targeted individuals to call the study, collect if necessary. Phone contact and home visits were made by the interviewers.

When a household was contacted, the interviewer asked to speak to the case or his or her proxy, if necessary. Once the desired person was reached, s/he was read an introductory script describing the study. To confirm that the proper person had been contacted, the interviewer asked for the case's age. When relevant, the interviewer also asked if the case visited the appropriate hospital in the 72 hours after the earthquake. If the reported age was within three years of that noted on the medical record or autopsy, and (or) the respondent confirmed a recorded hospital visit, the respondent was read an informed consent statement which describes the study's purpose, risks, and benefits. Respondents who granted consent were considered enrolled. The questionnaire was administered immediately after consent was given whenever possible. If this was not possible, the interview was scheduled for a later time.

If the reported age or hospital visit did not match the information in the medical records or autopsy report, the respondent was thanked, the session was ended, and the search for the correct respondent was continued.

## RECRUITMENT AND ENROLLMENT OF THE POPULATION SAMPLE

The population sample was recruited starting in the middle of March 1991 and was continued through August 1991. The selection protocol was pilot tested in the first half of March 1991.

In general, the recruitment and enrollment process involved identifying eligible households by calling lists of randomly generated County telephone numbers.[15] Each randomly generated phone number was called up to six times, before it was discarded in favor of another one. The six calls were made at different times of day and on different days of the week. The interviewers proceeded down a list of such numbers until an eligible participant from a residence was enrolled. Persons reached at nonresidential numbers—businesses, government offices, jails, hospitals, nursing homes, and so forth—were not eligible for enrollment.

When a household was reached, the interviewer asked to speak to an adult. Once an adult was on the phone, the interviewer confirmed that the correct number was dialed and that it was a home phone. If the number was nonresidential, the session was terminated. If it was residential, the interviewer determined whether the household was eligible, that is, whether it was located in the County. If the household was eligible, the adult—the informant—was asked to list all the current residents in the household in descending order of age. The sex and relationship to the informant was also obtained for each listed member. The interviewer recorded this information on a numbered roster form. A potentially eligible respondent from the numbered list was selected using a random number table. A proxy was obtained for selected respondents who were physically or mentally unable to answer questions, or who were under 13 years old.

When the selected person or proxy came to the phone, s/he was asked the questions on residency which determined eligibility. If the selected individual did not meet the residency requirements described earlier, another person on the list was randomly selected. The same steps were repeated until an eligible person was identified from the household. The selected individual was read the informed consent statement. If consent was granted, the interview began or was rescheduled. If consent was denied, the interviewer attempted refusal conversion. If this failed, contact with the household was terminated.

## DATA MANAGEMENT AND QUALITY CONTROL

### MANAGEMENT OF INTERVIEW DATA

Each study participant was assigned a unique identification number. A packet of materials was assembled for each hospital and dead case that included tracing information, interviewing materials, and a tracking sheet to record the

[15]See section "Population Sample Selection Plan" for a description of how the numbers were generated.

time, day, and outcome of contacts. The packet for population sample members included the interview as well as materials for the selection of an eligible household member.

Once an interview was completed, the interviewer filled out a final disposition summary sheet and reviewed his or her work for accuracy, neatness, and completeness. The interviewer supervisors and (or) study coordinator then edit-checked the interview and went over any problems with the interviewer who conducted it. When information was incorrectly or incompletely ascertained, the interviewer was instructed to call the respondent back. The specific questions asked or reasked were noted on the final disposition sheet.

A DBASE file was created to assist in tracing cases and monitor interviewing progress in cases and controls. Once a final disposition was reached, the information was recorded on the hard copy and was later transferred to the data base. After the interviewing phase was completed, the data base was stripped of identifying information (names, and so forth) to protect the confidentiality of those interviewed.

#### INTERVIEWER TRAINING

All interviewers received two days of training at the time of hire on general interviewing techniques, and procedures specific to the study. They received another two days of training on the population sample selection protocol in March 1991. The importance of maintaining the confidentiality of information collected was highly stressed. The training included role playing with the interview and doing practice interviews on noncase County residents. Additional experience was obtained during the pilot testing phases. The interviewers were periodically monitored while interviewing to improve quality control.

#### CODING QUESTIONNAIRES

The answers to close-ended questions on the questionnaires were precoded. Coding of the open-ended questions is currently being done by the Johns Hopkins team. Spanish comments have been translated into English before being coded with the English responses. For a subset of the data, coding assignments to each open-ended question will be made independently by at least two persons so that interrater reliability can be assessed. Coders will also be asked to assign codes to the same data on different days to assess intrarater reliability.

#### DATA ENTRY

Data entry of the coded questionnaires and the medical abstracts was subcontracted to a data entry firm in Baltimore, Maryland. The data was keypunched twice and verified for accuracy. The Johns Hopkins team is currently doing additional analyses of the data tape to check for consistency and accuracy.

#### ASSESSMENT OF BIAS IN SELF-REPORTED INFORMATION

Information collected in the interview has two sources of potential bias, bias in the accuracy and in the repeatability of self-reported information. Accuracy for hospital and dead cases will be assessed by comparing the degree of correspondence between injury information reported in the interview and that contained in the medical records or autopsies.

Medical records are generally considered to be more accurate and complete than retrospective self-reports. However, this assumption is questionable for the first 12 to 24 hours after the earthquake, when the hospitals (especially Watsonville) were overwhelmed with visitors and treatment took a higher priority than keeping records. The hospitals reportedly resumed their normal routines after the first 24 hours. To adjust for variable degrees of completeness of the medical records, the accuracy analysis will be stratified by hospital and day of arrival at the emergency room.

Accuracy for all study groups will also be assessed by comparing self-reports of successfully reaching the 911 system to another dataset containing the logs of all 911 calls received in the 72 hours after the earthquake. The 911 dataset was compiled by study collaborator, Jim Schneider.

## STATISTICAL ANALYSIS

Three basic types of analysis will be performed on the collected data: (1) a case-control analysis, which compares hospital and dead cases to noninjured controls to evaluate the significant risk factors for earthquake-related injury; (2) a study of selection factors for seeking medical treatment among the injured, which compares hospital cases to population cases that did not seek medical attention; and (3) descriptive analyses which estimate total injury morbidity and mortality in the County of Santa Cruz related to the earthquake.

### CASE-CONTROL ANALYSIS

The relationship(s) among the injury and various risk factors will be analyzed through a series of steps. Exploratory data analysis will be employed to identify significant risk factors. Injury outcomes for each case will be characterized in two ways: (1) the presence or absence of injury (a binary outcome variable) and (2) the overall level of injury severity as measured by the ISS (an ordinal outcome variable). Separate analyses will be performed for cases who were injured during shaking, versus those who were injured in the next 72 hours. Some cases were injured in both time periods, and attempts will be made to model the dependence of being injured in the postshaking phase on being injured during the mainshock. Separate analyses will also be conducted for injuries directly and indirectly related to the earthquake.

When the outcome variable is the presence or absence of injury, odds ratios can be computed. Univariate and bivariate analysis will first be performed followed by multiple logistic regression to characterize the independent risk factors and their interactions adjusted for confounders. The relative odds associated with being in different physical environments, broadly defined (that is, building, vehicle, outside) will be evaluated. Subgroup analyses will also be performed for risks within each physical environment.

The ISS has a range of 1 to 75, with higher values representing greater injury severity. When the ISS is the outcome variable, it will be used to create categories of injury severity (for example, mild, moderate, severe, lethal, and so forth). ISS ranges will define each category. Logistic regression will be done where the outcome variable is defined as injury severity class (for example, severe vs. moderate; severe vs. all other) and the dependent variables are the same as before. Several categorization schemes have been used by other investigators and will be explored here (MacKenzie and others, 1986; Copes and others, 1988).

### MEDICAL TREATMENT SELECTION FACTORS ANALYSIS

The selection factors for medical treatment among the injured will be evaluated in several ways. Injury severity as a selection factor will explored by comparing the distribution of ISS's for hospital cases to the distribution for population cases with back-to-back stem and leaf plots. Multiple logistic regression will also be performed where the outcome variable will be sought or did not seek medical treatment (that is, y=1 for hospital cases and y=0 for population cases). The independent variables will be the various potential selection factors including but not limited to perceived and actual injury severity level, possession of health insurance, entrapment due to the earthquake, preexisting medical conditions and mobility, the needs of others, and sociodemographic features such as age, sex, and ethnic origin.

### DESCRIPTIVE ANALYSES

The total burden of physical injury in County of Santa Cruz residents associated with the Loma Prieta earthquake will be estimated. Both hospital and population cases, appropriately weighted, will be used to this end. Total morbidity and mortality will be calculated as well as age-, sex-, ethnic origin- and injury severity level-specific rates in the County population. Casualty rates for the disaster and post-disaster phases will be calculated, as will rates for injuries directly and indirectly related to the earthquake.

The ability to estimate rates is a special feature of this study. It is not possible to do this with most case-control study designs. However, it is possible to estimate rates in this study because estimates are available for both the size of the total population at the time of the earthquake and the fraction of the total sampled for each of the three geographic strata.

Spatial analyses of injuries will also be performed in collaboration with study collaborator, Jim Schneider. Spot maps which distinguish cases by injury severity, physical environment, time period of injury, and so forth will be made. The relationship between injuries, distance from the epicenter, and zone of earthquake intensity will be investigated.

## PRELIMINARY PROGRESS REPORT ON CASE-CONTROL STUDY

The following preliminary results should be interpreted with caution as they have not yet been thoroughly validated. Validation efforts are currently underway, the results of which will be reported in the future.

### HOSPITAL AND DEAD CASES

As noted in section "Preliminary Results of the Descriptive Study," the size of the target population of potentially eligible hospital and dead cases was 579. Interviews were obtained for 482, or 83 percent of the target population. Another 31, or 5 percent refused to do the interview, and 66, or 11 percent were lost to follow-up.

Completed interviews were provisionally reviewed to evaluate which respondents were eligible for the case-control and descriptive studies. Recall that the eligibility criteria are more stringent for the former than for the latter study. Nearly three-fourths of those interviewed ($n$=358) are definitely eligible for both studies, including 10 percent ($n$=48) who moved out of the County of Santa Cruz after the earthquake. Twelve percent ($n$=58) are ineligible for either study because they were not injured or their injuries were clearly not earthquake related. About 5 percent ($n$=26) are eligible only for the case-series study because they were not County residents at the time of the earthquake or they lacked home phones at the time of the interview. Seven percent ($n$=36) met the residency and phone requirements of the case-control study but had injuries whose relationship to the earthquake is questionable. This last group will be included in the case-control study but will be analyzed separately from other cases. Finally, less than one percent ($n$=4) are possibly eligible for the case-series but not the case-control study.

Thus, the number of hospital and dead cases which qualify for the case-control study ranges from 310 to 394, depending on the stringency of the case definition. The most stringent definition includes only those definitely eligible cases who had not moved outside the County by the time of the interview (that is, 358-48=310). The most lenient definition includes those who are definitely eligible for the case-control study, including those who moved out of the County, plus those for whom the earthquake relatedness of their injuries is unclear (that is, 358+36=394).

To date, all but 3 (0.8 percent) of the 394 hospital and dead cases have been assigned to one of the three residential strata used to match noninjured controls to cases (the remaining three cases require additional information to classify). At the time of the earthquake, 38 cases (9.6 percent) resided in the north mountainous part of the County (stratum 1), 179 (45.4 percent) lived in the coastal northern and midcounty area that includes the city of Santa Cruz (stratum 2), and 174 (44.2 percent) lived in the southern part of the County that includes Watsonville (stratum 3).

### POPULATION SAMPLE: NONINJURED CONTROLS AND POPULATION CASES

The reader is again cautioned that the figures, provided below, are preliminary and await verification.

A total of 2,749 telephone numbers were called as part of the population sampling plan. Of these numbers, 780 (28.4 percent) were nonhousehold numbers (for example, businesses, disconnected numbers, FAX or modem numbers, and so forth). Another 1,823 (66.3 percent) were determined to be households. The status of another 146 numbers (5.3 percent) was unknown because no answer was ever obtained upon calling them.

Of the 1,823 households contacted, 538 (29.5 percent) were ineligible because they were either located outside of the County boundaries or contained residents who had moved to the County after the earthquake. Another 432 households (23.7 percent) were ineligible because they were contacted after the residential stratum from which they came was filled (see section "Population Sample Selection Plan"). Four households (0.2 percent) posed a language barrier which precluded doing the interview, six eligible households (0.3 percent) had otherwise eligible respondents who were not available during the study period (for example, were serving in the Persian Gulf War), and five households (0.3 percent) contained a person who had been previously interviewed by the study.

One hundred thirty-six households (7.5 percent) refused to cooperate with the study, despite efforts to persuade them to do otherwise. An unknown proportion of these refusals almost certainly came from ineligible households, as many of them occurred before household eligibility could be determined; nearly a third of the cooperating households were found to be ineligible, suggesting that some of the uncooperative ones were ineligible as well. Study efforts at refusal conversion—conducted within the appropriate guidelines of informed consent—were quite successful. Initially, 299 households refused to participate in the study. It was eventually possible to convince 163 of them (54.5 percent of the refusals) to cooperate.

Finally, 701 of the 1,823 households were eligible (25.5 percent) and provided one eligible person each to interview (resulting in 696 completed interviews and 5 break-offs). These 701 respondents comprise the population sample for the case-control study.

The population sample was distributed in the following manner. At the time of the earthquake, nearly 20 percent ($n$=138) lived in stratum 1, 45.6 percent ($n$=320) lived in stratum 2, and 34.7 percent ($n$=243) resided in stratum 3. Just over 15 percent ($n$=106) of the population sample reported an earthquake-related injury and thus were classed as population cases. The majority of these injuries were minor, although a systematic review of injury severity has not yet been done. The remainder were noninjured controls ($n$=594) or had an unknown injury status ($n$=1).[16]

The proportion of reported earthquake-related injuries varied by stratum. The northern and mid-County coastal area had the lowest proportion of injuries, with 12.2 percent ($n$=39) of the 320 stratum 2 respondents reporting one. The northern mountainous region had the highest percentage of injuries, with 18.1 percent ($n$=25) of the 138 stratum 1 respondents saying they were injured. The heavily Hispanic south County area followed closely behind, with 17.3 percent ($n$=42) of the 243 stratum 3 respondents reporting an injury.

### FUTURE DIRECTIONS

Further characterization of injuries and their associations with potential risk factors is underway. These results will be reported when available.

## SAMPLE SIZE AND STATISTICAL POWER

The maximum sample size of the case group (that is, hospital and dead cases) was fixed by design. Of the 482 interviewed to date, almost 400 hospital and dead cases were provisionally found to qualify for the case-control study.

Statistical power increases as the ratio of noninjured controls to cases increases to about four when the prevalence

[16]One break-off interview ended before the injury status was determined.

of exposure to a risk factor of interest is low in controls[17]. Balancing additional costs of doing extra interviews against a desire for greater power, a ratio of 2:1 noninjured controls to each hospital/dead case was sought with a 1:1 ratio as an absolute minimum. Because controls were matched to cases on residential stratum, this translated into seeking a 2:1 ratio in each stratum.

Due to resource constraints, the 2:1 goal was met only for stratum 1. The minimum goal of a 1:1 ratio was exceeded for strata 2 and 3. The ratios that were achieved were 3.0 (113/38), 1.6 (281/179), and 1.1 (200/174) noninjured controls per case for strata 1, 2, and 3, respectively. The total sample size for noninjured controls was 594. Thus, the overall ratio of noninjured controls to hospital and dead cases was 1.5 (594/394).

The statistical power actually achieved is likely to be somewhere between having one and two controls per case, all other relevant factors held constant (for example, sample size of cases, type 1 error, exposure rate of risk factor in controls, relative risk). Therefore, power calculations discussed below are presented as a range, assuming the control:case ratio of 1:1 and 2:1, all other factors held equal. A 5 percent significance level (type 1 error) is also assumed.

Most analyses will be conducted on subgroups of the total. For example, cases injured during the shaking will be analyzed separately from those injured in the next 72 hours. Approximately 75 percent, or 300, of the cases are expected to have been injured during the shaking.[18] One might wish to estimate the relative risk of injury among those in a building versus other physical environments when the earthquake began. The power to detect a significant relative risk of injury with 300 cases for a variety of relative risk values (1.25-20.0) and levels of exposure to a risk factor in controls (0.1-0.9) was calculated.[19] The power lies between 82 percent and 99.8 percent to detect any relative risks greater than or equal to two for any background exposure rate in controls of 80 percent or less.

Sample size will be further reduced when doing subgroup analyses restricted to each physical environment. The power to detect a significant relative risk of injury with 100 cases was calculated for the same range of relative risks and exposure rates in controls, and the same significance level as for the preceding example. The power lies between 80 percent and 99.4 percent to detect a relative risk of three or more for exposure rates in controls less than or equal to 70 percent. For a relative risk of 2.0, the power ranges from 24 percent to 80 percent for exposure rates in controls between 0.1 and 0.9.

[17]Personal communication with Dr. Walter Stewart, Associate Professor of Epidemiology, Johns Hopkins University, Baltimore, Md.

[18]This conclusion is based on a preliminary analysis of a subset of cases eligible for the case-control study.

[19]Power calculated from the formula (6.9) in Schlesselman (1982, p. 151).

# STUDY LIMITATIONS

## CASE ASCERTAINMENT ISSUES

Not all County hospital cases were ascertained because some visits to the hospitals made in the 72 hours after the earthquake were not recorded. An estimated 30 to 40 people were treated at Watsonville Hospital, and some small but unknown number were seen at Dominican Hospital for whom no record was made. All of the missing persons are likely to have had minor injuries (they were treated and discharged). A few of these cases may have been picked up in the population sample, a determination which awaits further analysis.

People who were injured in the 72 hours after the earthquake but who went to the hospital after 72 hours will not be ascertained as hospital cases. The magnitude of this problem is unknown but is expected to be small according to anecdotal reports of hospital personnel (Jim Schneider, County of Santa Cruz Office of Emergency Medical Services, 1990, personal commun.). Again, a few of these people may have been selected in the population sample. In contrast, all injuries that occurred in the population sample during the 72-hour ascertainment period will potentially be detected.

## SAMPLING FRAME ISSUES

For practical reasons, the sampling frames were slightly different for hospital cases and the population sample. Noninjured controls and population cases had to be County residents at the time of the interview to get into the sampling frame, whereas hospital cases did not have to satisfy this criteria. As a result, hospital cases who left the County after the earthquake were included in the study. However, noninjured controls and population cases who have moved out of the County since the earthquake were not included. The frames could be made comparable by excluding outmigrating hospital cases from the case-control study. This option was rejected since outmigration may be related to both risk factors (for example, earthquake-damaged residence) and injury severity levels. Although it is not possible to obtain a probability-based sample of noninjured controls who have left the County, it is possible to evaluate the importance of outmigrators in the hospital case group by studying how risk estimates change, if at all, by their inclusion or exclusion.

Another difference in the sampling frames between hospital cases and controls is that a small subset of cases did not have a home phone at the time of the interview whereas all controls did. Similarly, a few hospital cases lived in institutions at the time of the interview (for example, in jail, hospitals, and so forth), whereas all controls lived in private residences when interviewed. These distinctions arose from the different sampling methodologies used to ascertain cases and controls: cases were ascertained from medical records, independent of their home phone status or type of residence, whereas controls were ascertained from private residences using a randomly generated list of phone numbers. To make the sampling frames comparable, cases without home phones or living in institutions at the time of the interview will be excluded from the analyses. This exclusion could result in some bias; it is well known that individuals who have home phones or who live in private residences may differ significantly from those who do not. One way the study will try to measure the degree of bias introduced by excluding hospital cases that lacked a home phone or lived in institutions at the time of the interview will be to examine how risk estimates change, if at all, by their inclusion or exclusion.

It is important to note that the exclusion of persons who lack home phones or who live in institutions is an inherent limitation of the random digit dial sampling method. It is a commonly employed method, however, because it is relatively inexpensive and it generates a nonbiased, random sample of persons who have residential phones, which constitute the vast majority of the population.[20] The standard alternative sampling method—multistage sampling of first blocks, then households within selected blocks, and then individuals within selected households—is far more expensive in time and money. The latter method requires sending staff into the field to do an up-to-date census of all residential units within selected blocks. Interviewers then must attempt to contact households in person, a task which to successfully complete may require many visits to homes spread out over a large geographic area. The study employed the random digit dial method for selecting controls for practical reasons—that is, resource limitations.

## INTERVIEWING TIMETABLE ISSUES

Noninjured controls and population cases were interviewed after hospital cases and proxies for dead cases. Several potential biases are introduced by this situation. There may be differential recall bias in self-reported information provided by the respondents. Many hospital cases or proxies were interviewed less than one year after the disaster, whereas all controls were surveyed at least 17 months after the event. It can be argued that recall bias is less likely in this situation because the earthquake was a point source environmental exposure experienced by everyone in the County. In the field work, virtually everyone contacted indicated that people told their earthquake experience to others over and over again. This may enhance recall of the event. In any case, potential recall bias in the hospital case group can be examined by comparing the information contained in the medical records to self-reports to see if correspondence between the two sources declines with calendar time.

There may also be interviewer bias because the interviewers were not blinded to the injury status of the hospital and dead cases. However, the effects of nonblinding should be mitigated in part by the fact that both injured and noninjured persons from the population-based sample were interviewed in the same time period—and injury status was not determined before the interview began.

## INFORMATION BIAS ISSUES

Medical records were less complete in the first day following the earthquake when the emergency rooms of the County hospitals, especially Watsonville Hospital, were overwhelmed with patients. For some cases, no diagnosis information was recorded. Missing or incomplete information will preclude or compromise the ability to compute ISS's from medical records. One possible solution to this problem is to evaluate the degree of record completeness by day of arrival at the emergency room. A stratified analysis by day of arrival at the hospital can be done to see if and how risk estimates are affected.

Another form of information (and recall) bias may also affect the computation of AIS scores. The injury questions on the questionnaire were designed to solicit the same types of information necessary to assign AIS codes to them. However, most respondents are unlikely to be able to report their injuries at the detailed level the AIS can accommodate. This problem should not preclude using the AIS on the interview data but may result in systematically underestimating true injury severity; when details on an injury are not specified, the AIS usually assigns a lower severity score. The accuracy of self-reports of injury severity will be assessed by examining the degree of correspondence between AIS scores based on interview data and those computed from medical records and autopsies. The latter procedure can be done only on hospital and dead cases.

While the medical records-based ISS's are expected to be more accurate, their use will reduce the sample size for hospital cases since the medical records for at least 10 percent of these cases had no diagnostic details. The assumption of greater accuracy of medical records recorded during a disaster over interview data may also be incorrect. This is

[20] In fact, the 1980 U.S. Census indicated that 96 percent of County residents had a home phone. The comparable statistics from the 1990 Census, which coincides more closely with the time period of the study, will be evaluated when available.

especially true for hospital visits made in the first 24 hours after the disaster, as noted above.

### OTHER ISSUES RELATED TO THE ISS

The use of the ISS to measure injury severity presents several advantages. First, it has biological relevance in that it has been shown to correlate well with the probability of death (Greenspan and others, 1985). Second, it is the most widely used anatomically based injury severity scale, facilitating comparisons across injury studies (MacKenzie and others, 1986). Third, it has been shown to have relatively high inter- and intra- rater reliability for both blunt and penetrating injuries, even among persons without medical training (MacKenzie and others, 1985).

A limitation of the ISS is there is some heterogeneity in mortality associated with some of the same value ISS scores. This heterogeneity may be the result of several factors: (1) the ISS measures only the most severe injury within a given body region, ignoring the effect of multiple injuries to that part; (2) combinations of injuries of different severity levels—with different mortality experiences—can produce the same ISS score; and (3) the ISS gives equal weight to each body region even though same level injuries to some regions (that is, head injuries) appear to be more lethal than others (Copes and others, 1988). This heterogeneity may be reduced by aggregating ISS scores into categories (Copes and others, 1988) as proposed in the "Statistical Analysis" section above.

## CONCLUSIONS

Despite the limitations discussed in the preceding sections, it is believed that the studies described herein will provide a wealth of information relative to morbidity and mortality in the Loma Prieta earthquake, and for earthquakes in general.

It is clear from literature reviews that there is a shortage of quality, quantitative data in this area. In conducting this study, at least some of the reasons for this scarcity became evident. Even in the U.S., collection of both the case and control data was difficult. The research team is most encouraged by the support it received in most phases of the study from a broad range of people (see "Acknowledgments" section).

Successful completion of the analysis phase of the study will provide useful quantitative information to epidemiologists, engineers, planners, emergency medicine personnel, and so forth, relative to earthquake preparedness for future events. In addition, while it is recognized that this study provides a single-event perspective of injury patterns, it is hoped that it will form the basis for future studies in earthquakes in this country and abroad, thereby enabling comparative studies among events to be made.

## ACKNOWLEDGMENTS

A large number of collaborators and consultants have participated and will continue to participate in the study. The authors would like to identify and gratefully acknowledge their contributions to the effort.

The case-control and case-series studies are a collaborative effort among the Johns Hopkins University, the California Department of Health Services (California's public health agency), and various consultants; the three County of Santa Cruz hospitals, Dominican Santa Cruz, AMI Community, and Watsonville Community Hospitals; and the County of Santa Cruz Office of Emergency Medical Services and its consultants. The Hopkins research team also hired two consultants, Ms. Mary Lou Gutierrez, who translated the questionnaire into Spanish, and Ms. Celia Organiste, who orchestrated the community outreach campaign in the County.

Dr. Kirsten Waller is the California Department of Health Services' principal scientific advisor on the descriptive study. She wrote the medical abstract form in consultation with Prof. Gordon Smith, and co-authored early drafts of the questionnaire. She has been involved with the study since its inception and continues to provide assistance and advice on the collection of case data. Drs. Alex Kelter and Roger Trent are responsible for coordinating the efforts of the various study collaborators. They also oversee the sizable California Department of Health Services' budget allocated to the study.

Peter Roeper, a consultant to the California Department of Health Services, acted as Study Field Coordinator from June through September 1990. He managed the interviewing operation and field staff in the first months of the study. He had primary responsibility for hiring and training the first group of interviewers in June 1990. He also contributed to the development of the questionnaire.

Jim Schneider and Lisa Angell, emergency medical care specialists, organized and directed the medical abstraction of hospital case records. Mr. Schneider conducted a parallel study of the utilization of emergency medical services in the County in the 72 hours after the earthquake. Ms. Angell, the hospital base coordinator for Watsonville Hospital, is the primary liaison between the cooperating County hospitals and the descriptive and case-control studies.

The Santa Cruz field staff consisted of the study coordinators, and 21 interviewers (their names are not listed here for brevity). Most of the interviewers were local college students. Three of the interviewers also served as interviewer supervisors. All of the interviewers were fluent in Spanish and English except for five. An additional student was hired to assist in translating Spanish interviews into English for coding.

It would be negligent if the authors did not thank the people of the County of Santa Cruz for their support and cooperation. Without their willingness to provide the necessary data, this study would not have been possible.

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LOSS ESTIMATION AND PROCEDURES

# PRELIMINARY STATISTICS ON LOSSES ASSOCIATED WITH GROUND DEFORMATION

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### ABSTRACT

Loss estimates made for buildings affected by ground deformation due to earthquakes have had limited reliability. As a consequence, public policy questions on the equity and efficiency of various earthquake-related landuse alternatives have been subject to considerable speculation. In this report, we develop, largely from secondary sources, earthquake loss data in four ZIP code areas of San Francisco. The many significant studies on ground deformation resulting from the Loma Prieta earthquake greatly assist in delineating hazards within these four areas. Moreover, data are available, at some expense, for estimating the replacement costs and general structural categories of buildings at risk. We review the loss data collected from more than 700 buildings. Data suggest that for buildings suffering losses, the degree of building loss as a percentage of replacement value is weakly correlated with the degree of ground failure in the general vicinity. Because these study results are preliminary, we further indicate ways in which these data may be improved and future studies developed to compile improved loss data.

## INTRODUCTION

This report surveys losses associated with ground deformation from the 1989 Loma Prieta, Calif., earthquake. We confined our study to structures located in four San Francisco ZIP code areas (fig. 1), which experienced significant ground deformation. This report emphasizes strengths and weaknesses of alternative approaches to gathering earthquake loss data for areas of ground deformation and presents preliminary loss statistics derived through this project.

## PREVIOUS WORK

Loss data for buildings subjected to earthquakes characterized by strong ground motion are limited (Eguchi and others, 1989). Loss data are even more limited with respect to buildings affected by permanent ground deformation (here used to mean permanent soil displacement and also used interchangeably with ground failure).

A partial review of previous loss data associated with ground deformation is provided in Rojahn and others (1985). Their study quotes Wood (1908) in reporting that in the 1906 San Francisco, Calif., earthquake, structures built on soft, moist sands and sediments near the shoreline or on filled swamps suffered damage five to ten times greater than similar structures built on hard ground or thinly covered ridges of rock. Rojahn and others (1985) also cited Youd (1978) in discussions of losses associated with ground deformation in the 1964 Alaska earthquake, the 1920 Kansu, China, earthquake and the 1970 Peruvian earthquake. Based on an interpretation of Wood's (1908) data from the 1906 San Francisco earthquake, Rojahn and others (1985) proposed that a multiplicative factor of five be used to estimate increases in structural damage expected in areas prone to ground liquefaction. This factor applies only if the mean building-loss estimate, owing to ground shaking, is less than 20 percent of the building replacement value.

Loss data from the 1971 San Fernando Valley, Calif., earthquake (McClure, 1973) were re-examined by Wiggins and Taylor (1986). In the 1973 study, structural reviews were made for 169 dwellings in heavily damaged areas and 217 factors were analyzed for each dwelling. As support for this previous research, Ralph Goers (Ralph Goers and Associates, unpub. commun., 1984) made available detailed field notes, which often clarified evidence of permanent ground displacement. These factors included actual repair-cost estimates as well as damage estimates for a large number of structural and nonstructural components. Although statistical biases were evident in the selection of the structures, the biases were partially overcome through normalization of loss data in a more expansive study of losses to single-family dwellings in California earthquakes by Stein-

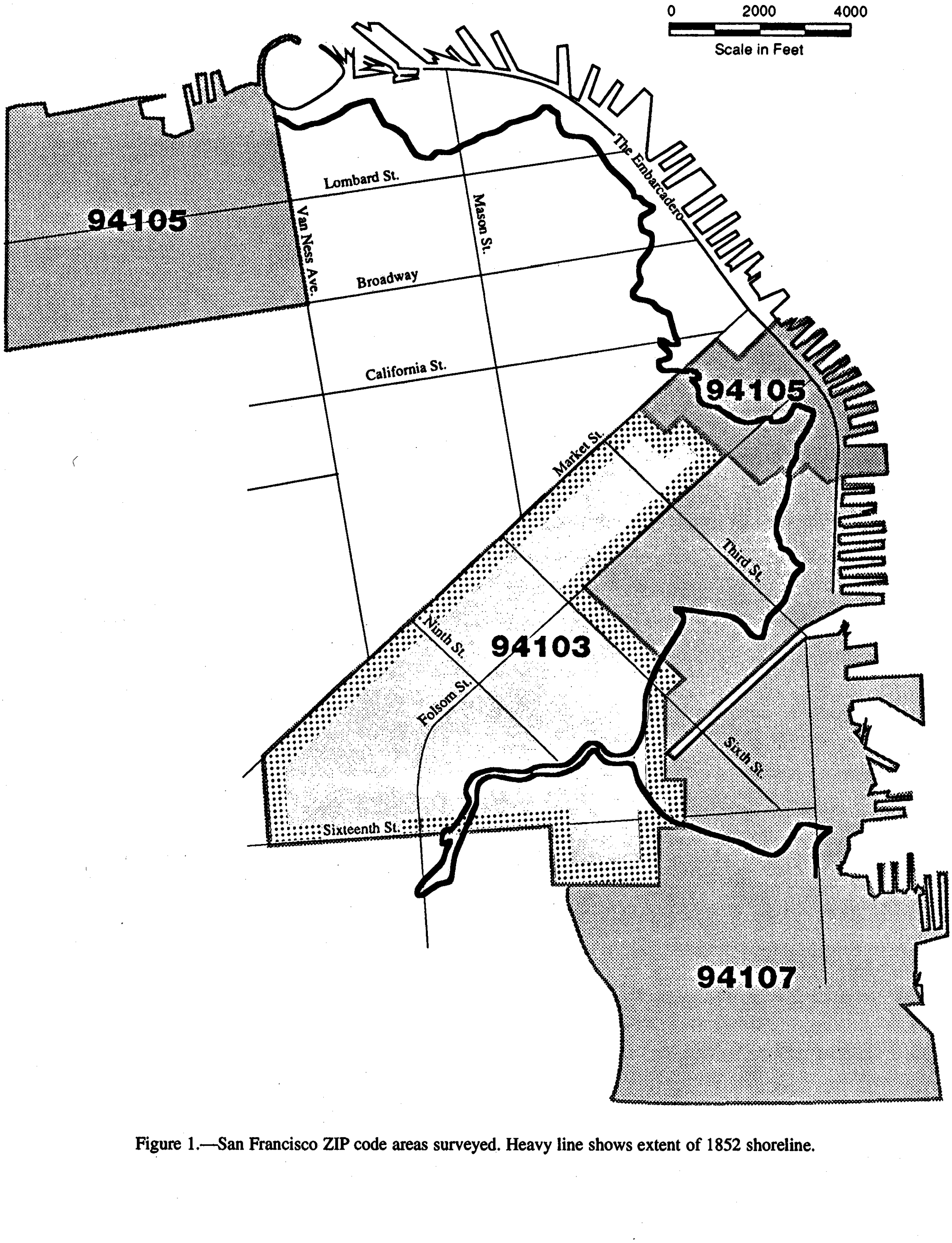


Figure 1.—San Francisco ZIP code areas surveyed. Heavy line shows extent of 1852 shoreline.

brugge and Algermissen (1990). Wiggins and Taylor (1986) used regression analyses on these data to confirm that a statistical correlation exists between higher observed structural damage and the following dwelling characteristics:

- exterior wall framing of wood stud and cripples,
- no visible connection of wood sill or ledger to footings,
- interior partition finish of gypsum lath and plaster or metal lath and plaster,
- site grading of fill, engineered or not, and
- crawl space or split level below first floor.

As part of the review and augmentation of McClure's data for the Wiggins and Taylor (1986) study, M. Legg (written commun., 1984) used geologic data on ground displacement, along with field notes by surveyors, to identify structures whose damage was affected by permanent ground displacement. Legg (written commun., 1984) identified additional structures as being in fault rupture zones based on the map of surficial fault ruptures in Oakeshott (1975). These additional cases could, on occasion, be compared with the surveyor field notes when the actual location of fissures was identified.

Dwellings affected by ground failure were then separated according to type of ground failure: dwellings in tectonic fault-rupture zones; dwellings in landslide areas or areas of significant lateral spread; dwellings that suffered differential settlement ground-failure effects; and dwellings identified as being in areas with minor ground cracking, such as lurch cracks or minor liquefaction effects. Differences between these categories were in some instances gradational, such as when a minor lateral spread appears as lurch cracking or even differential settlement. Wiggins and Taylor (1986) devised the following measures of severity of ground failure: For fault rupture areas, maximum displacement of a given fault segment was used (Sharp, 1975; Legg and others, 1982); for landslide/lateral spread, maximum displacement width of individual cracks at the site (Ralph Goers, unpub. data, 1972) was used, and for differential settlement and minor liquefaction, a modified Mercalli intensity (MMI) scale was used only as it pertains to shaking intensity.

A comparison of the data showed that the amount of structural damage associated with fault rupture and landslide/lateral spread appears to correlate with the degree of ground displacement (fig. 2; Wiggins and Taylor, 1986) and that the use of MMI as a measure of severity for differential settlement and minor liquefaction/lurching does not correlate well with the associated amount of structural damage for the limited cases examined (figs. 2, 3; Wiggins and Taylor, 1986). Figures 2, 3, and 4 all show that when detailed field survey loss data are gathered, it is sheerly speculative to maintain that building loss resulting from ground deformation is a multiplicative factor of normal building loss at the same intensity. Figures 3 and 4 appear to show that structural damage associated with minor liquefaction/differential settlement is similar to damage that would otherwise be expected as a result of strong ground shaking at MMI X.

Steinbrugge and Algermissen (1990) provided less detailed data on a much larger sample of dwellings for the 1971

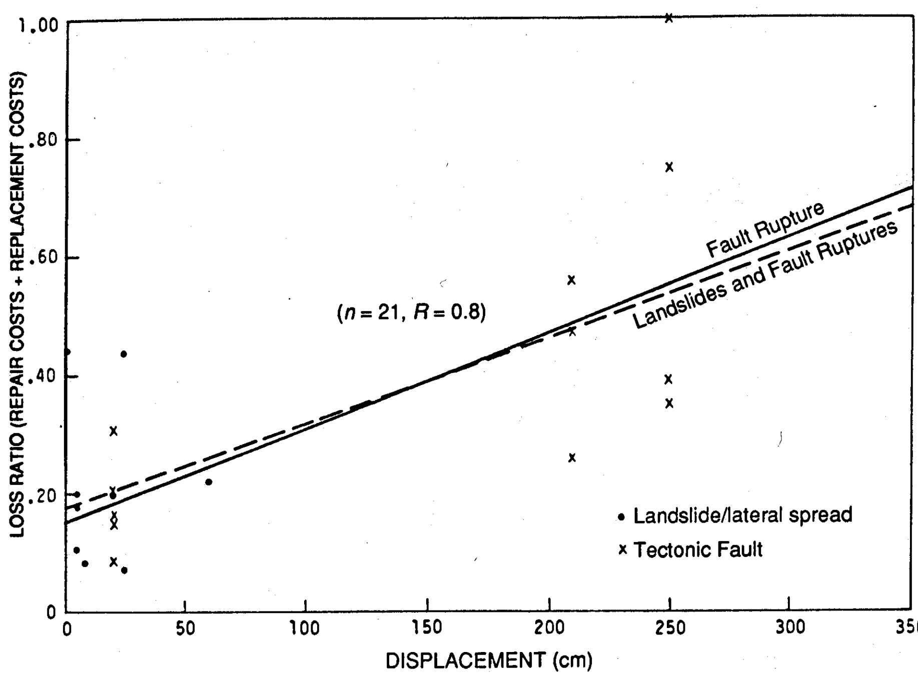


Figure 2.—Loss ratios versus displacement for structural damage associated with ground failures related to tectonic faulting and landslides (Wiggins and Taylor, 1986).

Table 1.—*Dwelling loss ratio as a percentage of market value in high intensity areas of the 1971 San Fernando Valley earthquake*

| Construction date | Areas without ground deformation | | Areas with ground deformation | |
|---|---|---|---|---|
| | Number of dwellings | Loss ratio (percent)[2] | Number of dwellings | Loss ratio (percent)[2] |
| Pre-1940 . . . . . . . . | 589 | 10.4 | 45 | 30.3 |
| 1940-49 . . . . . . . . . | 4,117 | 8.0 | 424 | 18.0 |
| Post-1949 . . . . . . . . | 5,596 | 8.0 | 1,056 | 13.6 |
| Total [1] | 10,515 | 8.1 | 1,560 | 15.3 |

[1] Includes dwellings not categorized by construction date.

[2] Average loss (building and contents) as a percentage of market value.

San Fernando Valley earthquake than did Wiggins and Taylor (1986). Steinbrugge and Algermissen's (1990) loss data are limited by (1) the lack of detailed structure distinctions, especially structural foundation details; (2) the use of market value rather than replacement value as a basis for loss ratios; (3) the use of total dwelling losses (losses for both building and contents); (4) the use of subjective estimates for damage (for example, for slight damage to interior finishes) rather than actual repair costs; and (5) the absence of clear descriptions as to how geologic effects (ground deformation) were categorized. With these restrictions in mind, table 1 can be derived from tables 2 and 6 in Steinbrugge and Algermissen

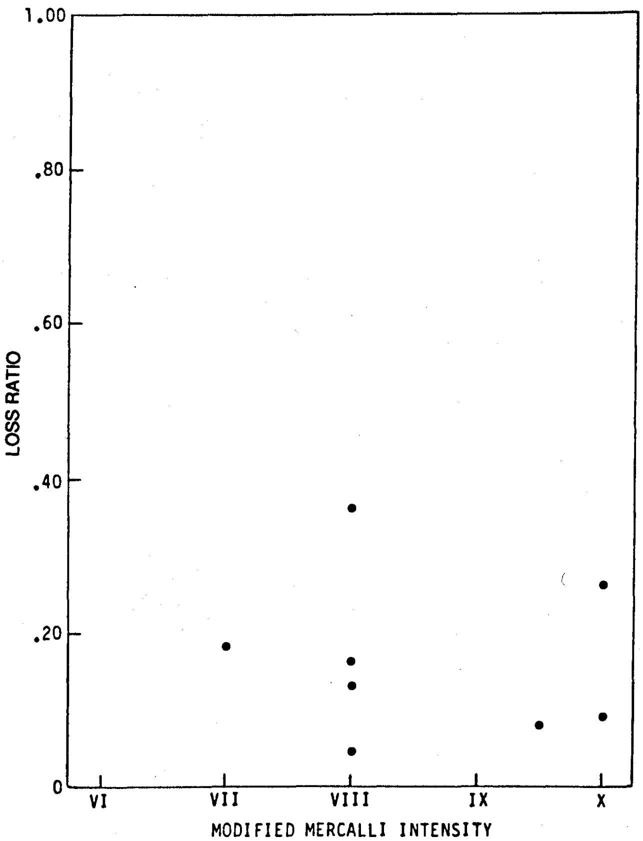


Figure 3.—Loss ratios versus modified Mercalli intensity for structural damage associated with ground failures related to differential settlement (Wiggins and Taylor, 1986).

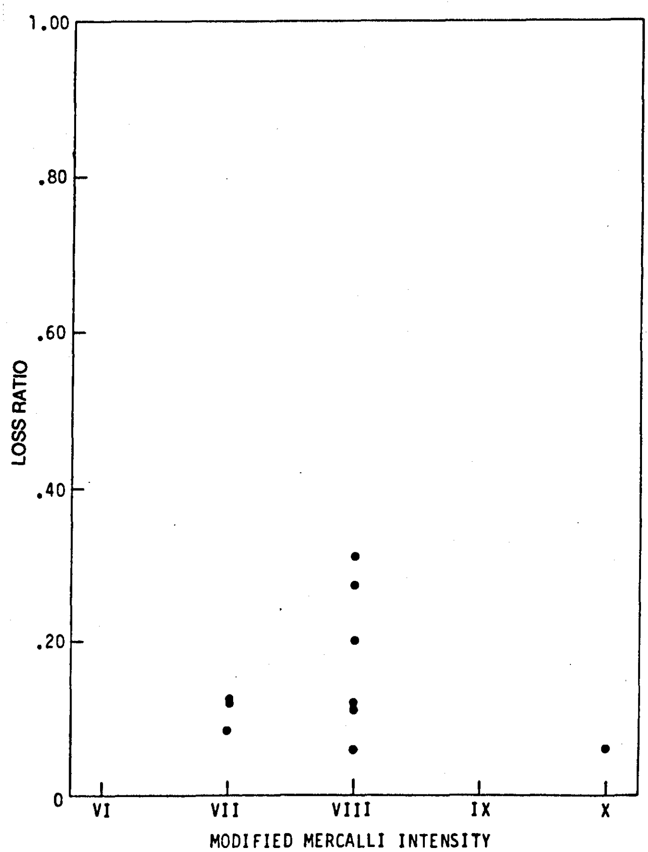


Figure 4.—Loss ratios versus modified Mercalli intensity for structural damage associated with ground failures related to liquefaction/lurch cracking (Wiggins and Taylor, 1986).

(1990). We derived multipliers from table 1 for comparison between areas with and without ground deformation. Total dwelling losses in areas with deformation were 2.9 times higher for pre-1940 buildings, 2.3 times higher for 1940 through 1949 buildings, and 1.7 times higher for post-1949 buildings. The overall average multiplier of 1.9 is far below the multiplier of 5.0 proposed by Rojahn and others (1985) for the 1906 San Francisco earthquake. Because the dwellings surveyed by Steinbrugge and Algermissen (1990) were in the highly damaged regions of the 1971 earthquake, the use of a simple multiplier approach for estimating effects of ground deformation is further called into question.

The lack of more extensive studies of earthquake loss data has far-reaching implications. Controversies, such as those in a workshop on loss-control measures in a Federal earthquake insurance context (see Taylor and others, 1989; Taylor, Petak, and others, 1990), present special practical concerns because:

- Section 404 of the 1989 Robert T. Stafford Disaster Relief and Assistance Act requires that applicants produce cost-effective mitigations (these may require weighing benefits against costs; estimation of benefits for many landuse policies requires estimation of losses associated with ground deformation);
- earthquake insurance ratings depend on reliable data; and
- reliable data are required to evaluate the comparative practical worth of strong motion versus ground-failure studies and of structural loss-reduction measures versus landuse and geotechnical planning measures.

Without more extensive data, informed judgments are difficult to make in establishing Federal, state, and local priorities and in determining the cost effectiveness of proposed mitigation measures.

## IDENTIFYING PERMANENT GROUND DEFORMATION WITHIN THE FOUR ZIP CODE AREAS

Ideally, for each structure evaluated within the four San Francisco ZIP code areas (fig. 1), one would have actual measurements of ground displacement at the site along with structural models that explain and clarify the types and amount of damage associated with the ground displacement. This would be in contrast to the types and amount of damage resulting from strong ground motion alone. For the Loma Prieta earthquake, detailed maps were developed of sand boils within the Marina District. Moreover, evidence exists, such as the Federal Emergency Management Agency's Damage Survey Reports (DSRs), for the usefulness of street and gutter damage as indices of permanent ground displacement.

We selected Bennett's (1990) general contour map of long-term sediment settlement as one basis for analyzing losses associated with ground deformation in the Marina District (ZIP code 94123). Contours on this map are associated with four different artificial fills (fig. 5). Most sand boils are found in the area of fills laid down between 1906 and 1917. Bennett (1990) plotted the ratios of 1974 through 1989 settlement to 1961 through 1974 settlement for regions in the Marina District (fig. 6); ratios greater than one indicated that more vertical settlement of sediments occurred in the 1974 through 1989 period. (Bennett, 1990, primarily attributed settlement during this period to the Loma Prieta earthquake.) We used rapid evaluation forms filled out for the City and County of San Francisco to augment this general background mapping (see R.P. Gallagher and Associates, 1989; Oaks, 1990; and Seekins, in press, for survey details). (A general history of Marina District developments is found in Bonilla, 1990.)

For the South of Market area (SOMA) (ZIP codes 94103, 94105, and 94107), we used Seed and others' (1990) map (fig. 7). The liquefaction areas on this map roughly correspond to similar areas in the 1906 earthquake. However, massive and catastrophic liquefaction did not occur in the shorter duration, more distant 1989 earthquake. Instead, the map shows areas of "minor liquefaction and (or) pore-pressure generation and associated ground softening representing incipient or near liquefaction over much of this region" (Seed and others, 1990).

The modified Mercalli intensity assigned to the Marina District is IX; the intensity assigned to the SOMA area is VII (Stover and others, 1990; Plafker and Galloway, 1989); and an intensity of IX is ascribed to a portion of the SOMA area by Oaks (1990). These intensities are sometimes determined by strong motion data alone; however, some authors suggest that shaking and ground failure sometimes inextricably contribute to damage.

## EARTHQUAKE DAMAGE DATA

For gathering earthquake damage and loss data for the four ZIP code areas, we have used numerous data sources, including:

- the city of San Francisco, which performed a rapid evaluation screening analysis based on Applied Technology Council Procedures for post-earthquake safety evaluation of buildings, commonly referred to as ATC-20;
- the Federal Emergency Management Agency (FEMA), which provided DSRs for public and private nonprofit applicants for Federal disaster assistance grants and loans;
- the Small Business Administration (SBA), which provided loss data relative to loans to small business and individuals adversely affected by the earthquake;
- the Individual and Family Grant Program (IFGP), State of California, which provided loss data for applicants;
- private insurers, who provided detailed data on losses to their insured properties;
- the State of California Department of Insurance (DOI), which requested detailed loss data from all primary insurers

(only preliminary DOI data were available for use in this study);

- the State of California Office of the State Architect; and
- comments by other investigators.

## OTHER PRELIMINARY FINDINGS

Preliminary findings by other investigators provided a valuable background for the systematic collection of earth-

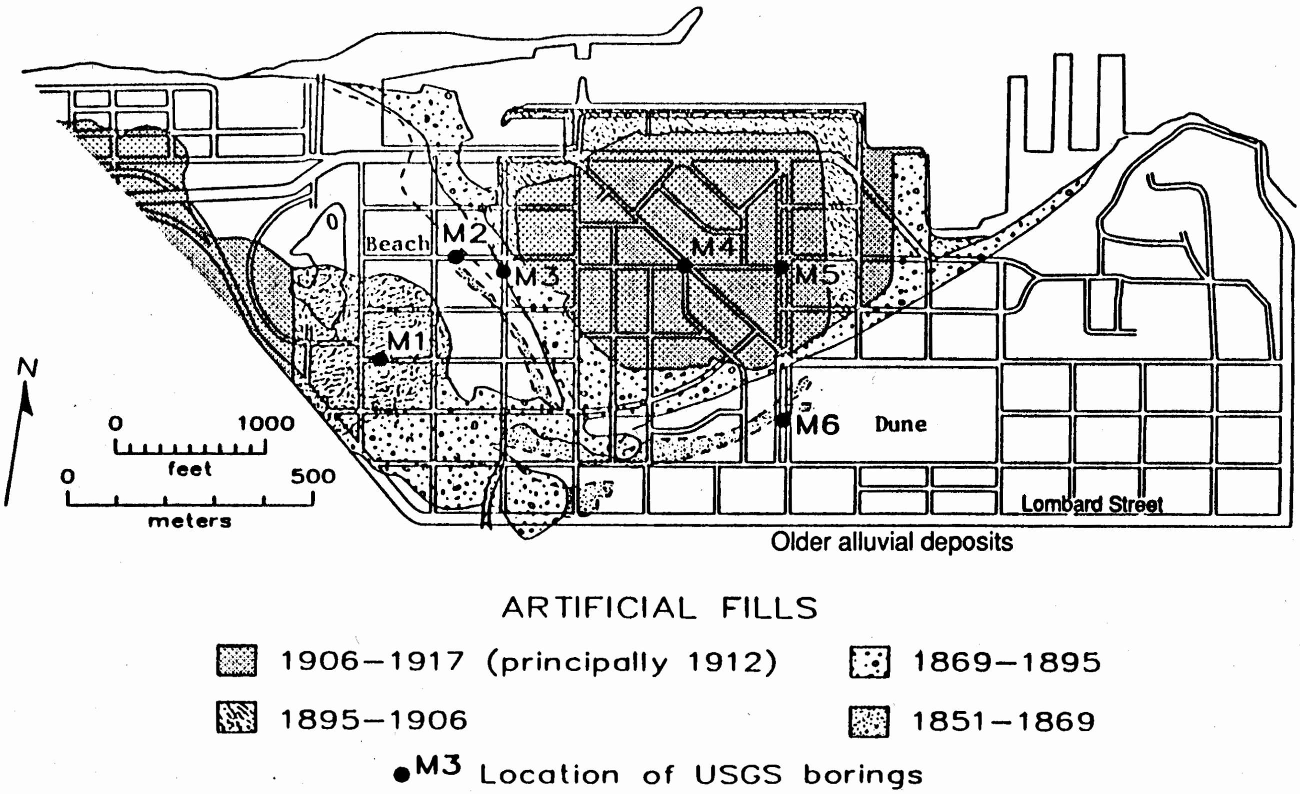


Figure 5.—General locations of geologic units (the older alluvial deposits are generally south of Lombard Street) and the location of the different fills used to reclaim the Marina District. The central fill area is referred to as Marina Cove. (Data from Bennett, 1990.)

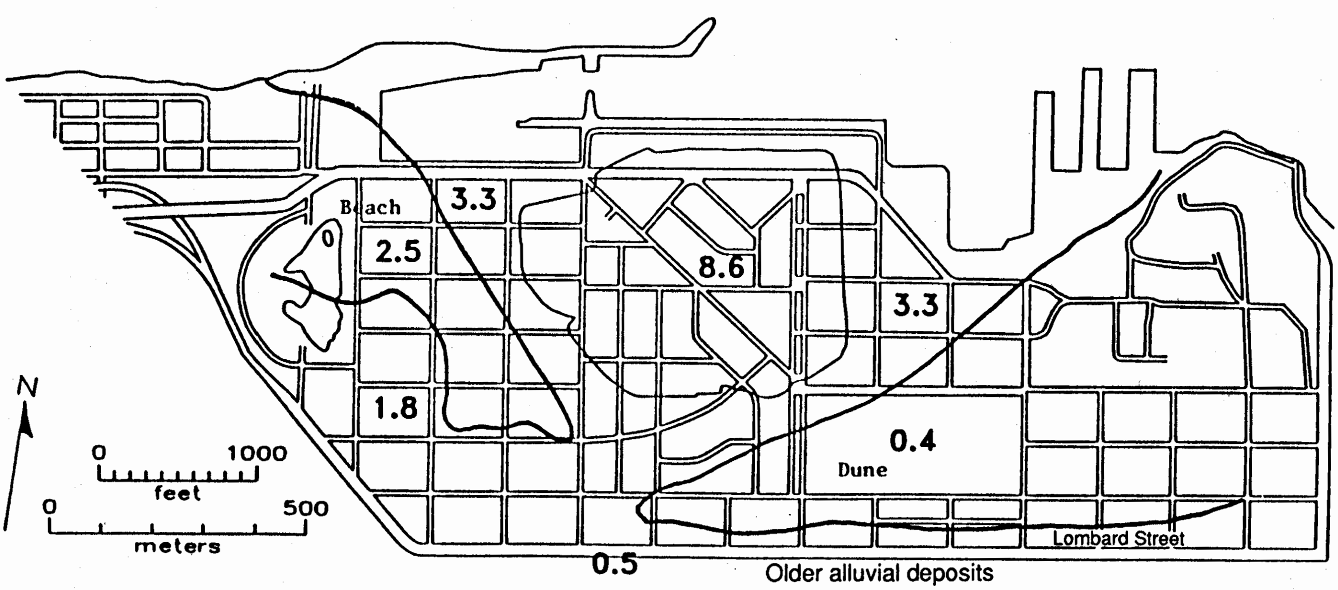


Figure 6.—Ratios of 1974-1989 settlement to 1961-1974 settlement in the Marina District. Ratios less than one indicate that more vertical settlement of sediments took place before 1974 than after 1974. (Data from Bennett, 1990.)

quake loss data. We reviewed damage patterns for the Marina District and the SOMA.

Celebi (1990) attributed damage in the Marina District to two main causes: structural deficiencies including foundations (for example, lack of strength and stiffness at the first story of many buildings) and soil-related phenomena (settlement and amplification). Other contributing causes were structural deterioration of concrete or timber members, buildings out of plumb owing to long-term settlement, deficient building-to-foundation anchorage, and pounding of structures against one another. In short, assessment of damage patterns must consider both structural and soil-related parameters.

Diverse opinions have been expressed on the relative importance of liquefaction versus strong ground motion in causing damage. Tissel (1990) noted structural deficiencies

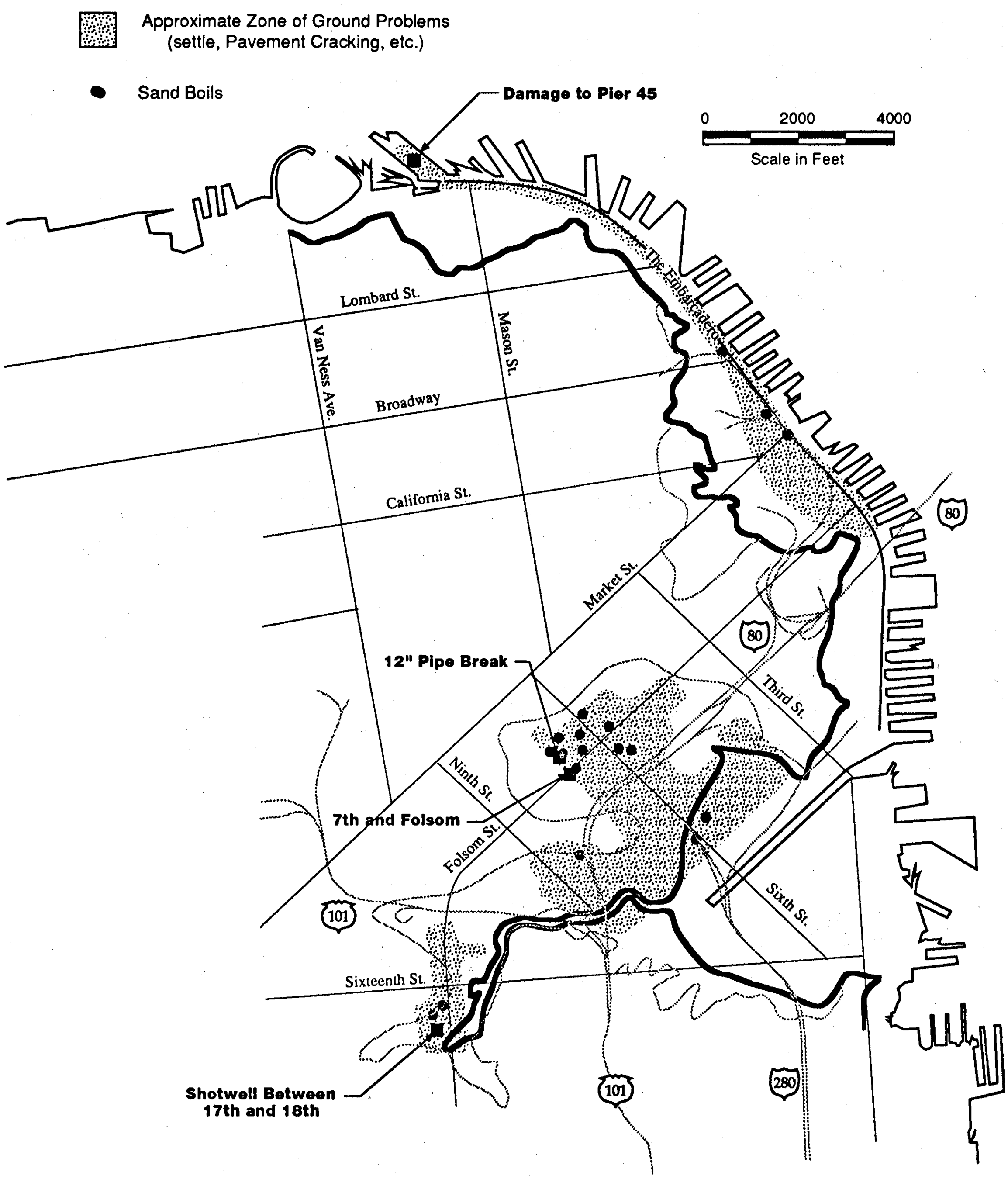


Figure 7.—Apparent extent of soil liquefaction in San Francisco's Embarcadero and Old Mission Bay regions on October 17, 1989. Light, unlabeled lines show landward limit of bay mud deposits. Heavy line shows extent of 1852 shoreline. (From Seed and others, 1990.)

of wood-frame buildings in the Marina District: soft story problems, no anchor bolts from the sill plate to the foundation, and lack of ties between brick veneer and the frame. In a survey of posted buildings (red, unsafe; yellow, limited entry; and green, no restrictions), Seekins and others (1990) maintained that the boundary of the hydraulic fill region of the Marina does not correlate with damage patterns. Much of the damage in the Loma Prieta earthquake resulted from shaking alone (in other words, much damage was not related to the liquefaction of the fill). Boatwright and others (1990) maintained that, other than the blocks between Marina Boulevard and Beach Street, to the end of Scott Street, "the area underlain by the 1912 hydraulic fill was less severely damaged than the areas to the west and south." Boatwright and others (1990) suggested that the small liquefaction settlements were part of a process that dampened the strong ground motion in the hydraulic fill area, so that strong-motion amplification and associated damage was actually less in this area. Baringer (1989) also noted that liquefaction contributed little to the damage because of the short duration of the earthquake. In a follow-up study based on revised City of San Francisco damage postings, Seekins (in press) reiterated that "while some of the structural damage in the Marina was due to liquefaction, or a combination of liquefaction and shaking, much of it was due to shaking alone." However, Bennett (1990) maintained that all demolished buildings and most tilted buildings are in areas of fill. "Seventy-three percent of the red tag [sic] buildings are located in the areas that have been filled, and except for the red-tagged buildings on the beach deposit, ninety one percent of the red-tagged buildings are located where settlement was at least 25 mm."

Astaneh and others (1989) reported that much of the structural damage in the Marina District had been initially attributed to strong shaking, but on closer inspection, they found that many structures suffered partial bearing failures, differential settlement of interior column footings, and sand intrusions in garages and basements. In the SOMA, they found pockets of settlement-induced damage, especially to unreinforced concrete buildings and buildings not supported on deep piles.

## VARIATIONS IN THE MEANING OF LOSS

Discussions of loss-data surveys and findings often make important distinctions among the various meanings of the term "loss." Steinbrugge and Algermissen (1990), for instance, draw a distinction between "personal" and "impersonal" viewpoints on loss. As an example, minor interior and exterior plaster damage can be an out-of-pocket cost for the homeowners who make their own repairs. If a professional is hired, the repairs and painting may cost $1,000. What constitutes a minor crack to one observer may be a major eyesore to another and entail considerable cash outlays. For those who are covered by insurance, grants, or loans, incentives exist not to perform the work on one's own and to repair and restore as much as outside funds will permit. The regulatory environment may also require that specific repairs be made, which increase repair costs. (Issues such as these are elaborated in Arnold, 1990.) The relationship between loss and hazardous conditions is also complex. For example, some buildings that suffer significant losses may not be posted as either extreme hazards or dangerous to enter. In contrast, some buildings may be posted as hazardous even though they have not suffered direct loss but are at risk from adjacent damaged buildings, glass damage, broken gas mains, or asbestos exposure (Seekins, in press).

From the standpoint of the secondary survey of losses that we have performed, additional complications arise: (1) Loss estimates may be based on different methods or different intents, (2) loss estimates from one information source may be incompatible with those from another, and (3) loss estimates from various sources may not be representative—data from insurance companies, for example, only cover insured losses, not losses to all affected buildings. Also, the actual loss may depend on regulations that are in place to govern repairs required; losses exceeding 50 percent of replacement value may require total replacement. Depending on the municipality, repairs or replacement may be required to comply with current building regulatory standards (Lizundia, Rutherford and Chekene, written commun., 1992). SBA loss estimates, which are the most complete data sets available, depend on estimator's assessment of repair costs; these estimates may vary from the actual costs. FEMA's estimates depend on actual approved costs, based on receipts and detailed information on damage. Insurance company estimates reflect not only actual approved repair costs, but deductible levels, types of losses covered, and limits of liability. An insured building with a 10 percent deductible may have no insured losses recorded if actual approved repair costs are less than the 10 percent deductible. If insurance covers only building contents, structural damage may go unrecorded; also if policy limits are below the replacement value of the structure, the insured loss will not represent the actual loss.

The rapid ATC-20 evaluation performed by the city and county of San Francisco provided data on ground deformation and other data observed at the time the structures were posted as hazardous. As such, these data assist in loss estimation to the extent that they clarify what damage surveyors observed in comparison with final loss estimates.

Potential discrepancies between ATC-20 postings and loss estimates are a concern. Other concerns arise from discrepancies in loss estimates from different sources. Comparisons between SBA loss estimates and insurance company estimates showed that some discrepancies could be explained by the deductible levels and (or) limits of

Table 2.—*Initial summary of Loma Prieta earthquake damage estimates*

[SBA, Small Business Administration; FEMA, Federal Emergency Management Agency]

| Zip code area | Zone of ground displacement[1] | SBA/FEMA damage estimates (total $) | No. of buildings damaged | Average loss ($) | Buildings posted red or yellow[2] | |
|---|---|---|---|---|---|---|
| | | | | | No. | Percent |
| South of Market area | | | | | | |
| 94103 | Yes | $10,226,790 | 63 | $162,330 | 22 | 34.9 |
| | No | $11,892,942 | 58 | $205,051 | 19 | 32.8 |
| 94105 | Yes | $787,322 | 5 | $157,464 | 0 | 0 |
| | No | $2,652,199 | 22 | $120,555 | 11 | 50.0 |
| 94107 | Yes | $10,355,710 | 37 | $279,884 | 19 | 51.4 |
| | No | $978,362 | 32 | $30,574 | 3 | 9.4 |
| Marina District | | | | | | |
| 94123 | A | $18,686,400 | 156 | $119,785 | 41 | 26.3 |
| | C | $16,353,256 | 112 | $146,011 | 47 | 42.0 |
| | $B_1$ | $8,849,921 | 67 | $132,088 | 33 | 49.3 |
| | D | $5,991,400 | 63 | $95,102 | 24 | 38.1 |
| | $B_2$ | $5,352,264 | 111 | $48,219 | 15 | 13.5 |
| Grand total ......... | | $92,126,566 | 726 | $126,896 | 234 | 32.2 |

[1]Sand boils in the Marina were concentrated in areas A and C. A, Hydraulic fill placed principally in 1912 (ratio 8.6); C, older fills (1869-1895; ratio 3.3); $B_1$, beach sands (Strawberry Island; ratio 2.5); D, filled tidal slough/draining marsh (1895 to 1906; ratio 1.8); $B_2$, dune field (ratio 0.4). (Higher ratios are attributed to greater ground displacement; data from Bennett, 1990.)

[2]Buildings posted red (no entry) or yellow (limited entry) during initial damage survey by the city of San Francisco.

liability on insurance policies or by the fact that full insurance payment amounts had not been determined at the time of the SBA survey. However, other discrepancies were very large and could not be explained without a detailed followup. In the HUD survey of residential structures damaged by the 1971 San Fernando Valley earthquake, actual documented repair costs were used as the standard for estimating earthquake losses (McClure, 1973). Therefore, it was assumed that actual payouts by insurers or Federal agencies would effectively serve as the final loss estimates for both groups (McClure, 1973). However, even if loss estimates are objective in the sense that they are the result of the application of various uniform standards, the actual payouts may differ depending on who pays for the claimed losses and in the extent to which the judicial system is involved in claims adjudication.

## THE NEED FOR REPLACEMENT COST ESTIMATES

Based on data collected through the secondary surveys previously discussed, we developed table 2, which provides a summary of SBA/FEMA total dollar estimates of structural damage in the four San Fernando ZIP code areas. These estimates are further broken down by location in or out of ground-failure zones, and average losses are calculated. These average losses were used to determine that losses are higher in zones of ground failure. However, it is also possible that the average cost of buildings in zones of ground failures is greater. For this reason it is necessary to normalize losses to some value at risk such as structural replacement cost.

The current standard for value at risk is building replacement value. This implies additional costs to restore a building to its original condition—including possible costs of upgrades to comply with current codes. Also, regulatory standards may need to be taken into account so that losses do not exceed replacement value. The use of building market value is less satisfactory than the use of replacement value, because building depreciation, which makes comparisons between damage to older and newer buildings difficult, must be taken into account. The use of appraised land values and improvements is an extremely indirect means of assessing building value. The land value is generally speculative, whereas structural replacement costs are ordinarily less speculative. In addition, building losses may depend on such factors as building type and age. The presence of more seismically vulnerable buildings in one locality may contribute to larger aggregate earthquake losses in that locality. To overcome these problems, we gathered data from the city and county of San Francisco on the 726

Table 3.—*Summary of estimates of replacement cost estimates per square foot*

[Leaders (- -), not applicable]

| General building usage type[1] | Replacement cost ($) per square foot | | |
|---|---|---|---|
| | Low rise | Medium rise | High rise |
| Houses, condominiums, duplexes | 70 | 70 | 70 |
| Apartments, dormitories (not elsewhere specified) | 80 | 80 | 80 |
| Public buildings: libraries, educational institutions, jails, police and fire stations | 90 | 105 | 115 |
| Commercial buildings (generally with no specific breakdown) | 95 | 100 | 110 |
| Restaurants, bars, banks, hotels and motels, convalescent hospitals, clubs, churches, theaters, service stations | 95 | 104 | 117 |
| Garages | 33 | 65 | 65 |
| Hospitals | 124 | 124 | 124 |
| Offices, convenience stores | 72 | 85 | 111 |
| Industrial offices | 72 | 85 | 111 |
| Warehouses | 52 | 72 | - - |
| Heavy industrial factories | 59 | 78 | - - |

[1]Omits the San Francisco land-use codes with which each of the general building-usage types were correlated.

buildings for which loss data were available. Data include: year of construction, number of stories, square footage, landuse, building class (frame system), ZIP code, land value, improvements value (building market value after subtracting land value), tax valuation, notes, and damage inspection category (red, yellow, or green).

In order to develop replacement costs, we first correlated San Francisco landuse codes with categories found respectively in Means Square Foot Costs (R.S. Means Company, Inc., 1991) and in Rojahn and others (1985, table 4.6). Next, we used the Local Cost Index table in Means Square Foot Costs to set prices at January 1990 (close to October 1989) levels. This very approximate process resulted in broad categories for estimating replacement values of surveyed buildings for which square footage data were available. A more detailed valuation approach would only be justified for extremely high-value or unique buildings.

A summary of the replacement costs per square foot basis that we used to estimate replacement costs is listed in table 3. We have chosen not to use city and county of San Francisco estimates of improvements values as the basis for estimating building values at risk. Compared with the replacement values that we have calculated, improvements values show a wide scatter or variation relative to usage categories and square footage estimates (fig. 8). Almost half of the 726 buildings surveyed have improvements value estimates of less than 40 percent of replacement cost as estimated from table 3 and square footage data. While most improvements-value estimates are low relative to replacement-value estimates, more than 10 percent of the estimates of improvements values exceed estimates of replacement values, and a few exceed replacement values by more than a factor of two. Thus a wide scatter exists in estimates of improvements values, which in general are low relative to replacement values.

A further test of the use of estimates of improvements values, replacement costs, and insurance liability limits, as estimates of building values at risk, is derived from examination of a small sample group from the database in which two or three of these factors were present in the database we have examined. In some cases, loss estimates of building values at risk may significantly exceed insurance policy estimates of limits of liability. Even for insurance policies that cover replacement costs, the basis for estimating limits of liability may depend on estimates of replacement costs per square foot; our gross-scale estimates in table 3 are similar to these estimates of replacement costs per square foot. Ratios of improvements estimates to insurance estimates had a mean value of 0.55 with a standard deviation of 0.13 (32 cases). Ratios of replacement values estimates derived from table 3 and square footage data to insurance estimates had a ratio of 1.14 with a standard deviation of 0.14. These suggest that some degree of variability is to be expected in replacement-cost estimates (similar conclusions are drawn in Taylor, Elliot, and others, 1990).

## CONDITIONAL LOSS ESTIMATES AS PERCENTS OF REPLACEMENT VALUE

The loss and replacement-cost estimates developed in our project mostly relate only to building-damage cases in which damage claims are made to some party, whether a governmental agency or a private insurer. Until we assimilate further data such as California DOI data, biases are possible in our results because not all cases are included in our database.

Alternative data sets may be compared in order to discern the possible biases in the loss data we have examined. For example, early data collected by the California DOI after the Loma Prieta earthquake contain data sets (2, 4 and 10 claims, respectively) on personal lines insurance claims in ZIP code areas 94103, 94105, and 94107. However, a large data set of 370 insurance claims was compiled for ZIP code area 94123. The average earthquake insurance claim payout amount in these 370 building damage cases was $21,700. To determine an average replacement value of $174,000 for these buildings, we used their fire policy insured values because fire policies have low deductibles and therefore have insured values that approximate actual building replacement values. (Our study does not cover earthquake losses that are due to fires.) If the typical earthquake insurance deductible in these cases was 10 percent of the replacement value, then the average claim payout represents a loss of $39,100 (about 22 percent of the replacement value). At the time of the Loma Prieta earthquake, 966 buildings were insured against earthquake damage in the 94123 ZIP code area. Because only 370 of these 966 insured buildings had adjusted losses above their policy deductibles, the average loss for the entire sample of 966 buildings was well below 22 percent of building replacement value. (Source of information: R. Roth, Jr., California DOI, written commun., 1991.) In contrast to the DOI data, the loss data surveyed in our study show an average loss for small residentially zoned properties (city and county of San Francisco zone R-1) (74 in sample) in ZIP code 94123 with $98,000 on an average replacement value of $222,000. The average claim in data we surveyed for these properties is about 44 percent of replacement value, which is well above the 22 percent estimated from DOI claims data. It should be borne in mind that the preponderance of claims data we surveyed were from the Small Business Administration. Only limited overlap with insurance data exists within our database. These overlaps may not include building contents losses and temporary living expenses and may reflect different loss estimation criteria. Our limited comparison of SBA and DOI loss data strongly suggests that a more comprehensive comparison of these loss data should be made in order to clarify potential biases and to improve future earthquake loss projections for both the SBA and private insurers.

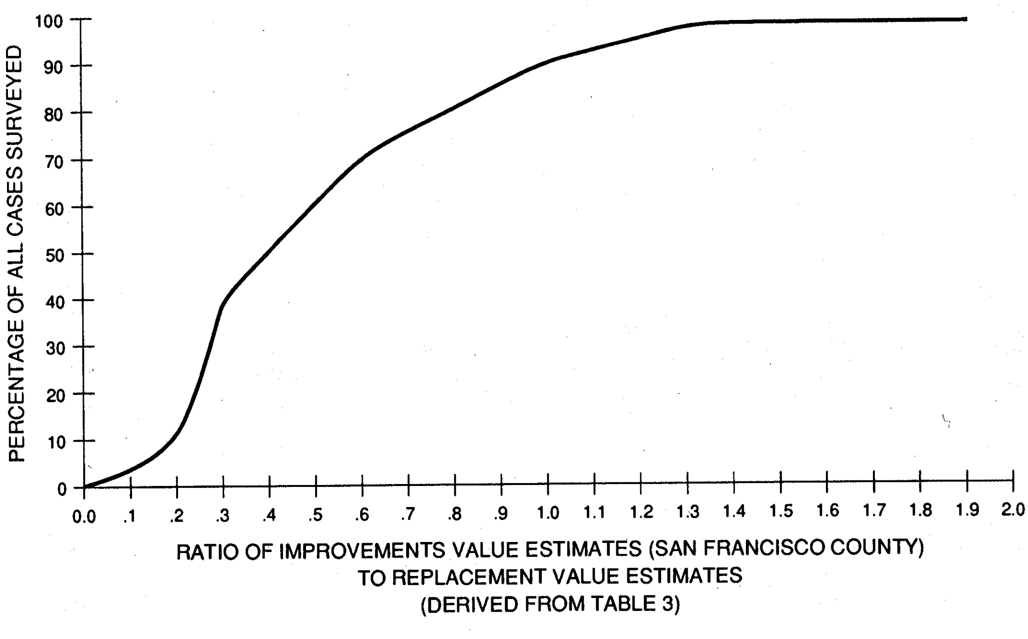


Figure 8.—Cumulative distribution of ratio of improvements value estimates to replacement value estimates. Replacement value estimates derived from table 3.

A key question in our study was whether or not liquefaction-induced ground displacement was a significant contributing factor in overall building losses. We indirectly approached this question by aggregating the buildings surveyed into groups based on ground displacements (see table 2); yes and no zones of displacement were used for buildings in the SOMA (data from Seed and others, 1990; fig. 7), and buildings in the Marina district were grouped on the basis of the ratio of 1974 through 1984 settlement to 1961 through 1974 settlement and the type of underlying artificial fill/sediment (data from Bennett, 1990; figs. 5, 6).

Our loss data show that mean damage ratios (losses as a percent of replacement value) are greater for wood-frame buildings located in zones in which ground failure is generally more severe (fig. 9).

Figure 10 compares cumulative loss distributions for three general ground-failure zones, a high zone (combining the South of Market ground failure zones, and the Marina A, C, and $B_1$ zones), a moderate zone (consisting of the Marina D zone), and a low zone (combining the Marina $B_2$ zone and the South of Market zones with no ground failures).

The cumulative loss distributions in figure 10 show that, regardless of percentile rank, greater losses are expected to occur as ground failure severity increases. For example, at 40 percent of all cases (on the vertical scale) losses are 8 percent, 14 percent, and 20 percent of replacement value, respectively, for the low, moderate and high ground-failure zones.

The loss patterns shown in figures 9 and 10, however, need to be qualified because of three issues: (1) Unanalyzed hazard factors such as more severe ground shaking may or may not have been present in the higher ground-failure zones; (2) losses are conditional only—a thorough data set including all zero losses will modify the distributions and may modify any conclusions drawn; and (3) other structural vulnerability factors such as poor seismic resistance may have contributed to damage.

In this project, our current data set does not permit us to address the first and second issues. We address the third issue only partially by using a multiple-regression analysis of the form

$$Y = A_1X_1 + A_2X_2 + A_3X_3 + \varepsilon \qquad (1)$$

where

- $Y$ is the building damage ratio (loss as a percentage of replacement value),
- $X_1$ is the degree of ground displacement, approximated by the yearly sediment settlement ratios listed in table 2 (the ground-failure region in the SOMA is assigned an 8.6, analogous to the Marina A zone, and the no-ground-failure region in the SOMA is assigned a 0.4, analogous to the Marina $B_2$ zone),
- $X_2$ is the building story height, subdivided into low-, medium-, and high-rise buildings;
- $X_3$ is the building age; and

A1, A2, A3, and $\varepsilon$ are coefficients to be determined.

Application of this linear-regression model to our data base led to the following conclusions:

- Age had a zero coefficient of determination with respect to the damage ratio, or loss as a percentage of replacement value (nearly all the buildings surveyed were at least 50 years old).
- Height category had a zero coefficient of determination with respect to the damage ratio (most buildings were low rise).

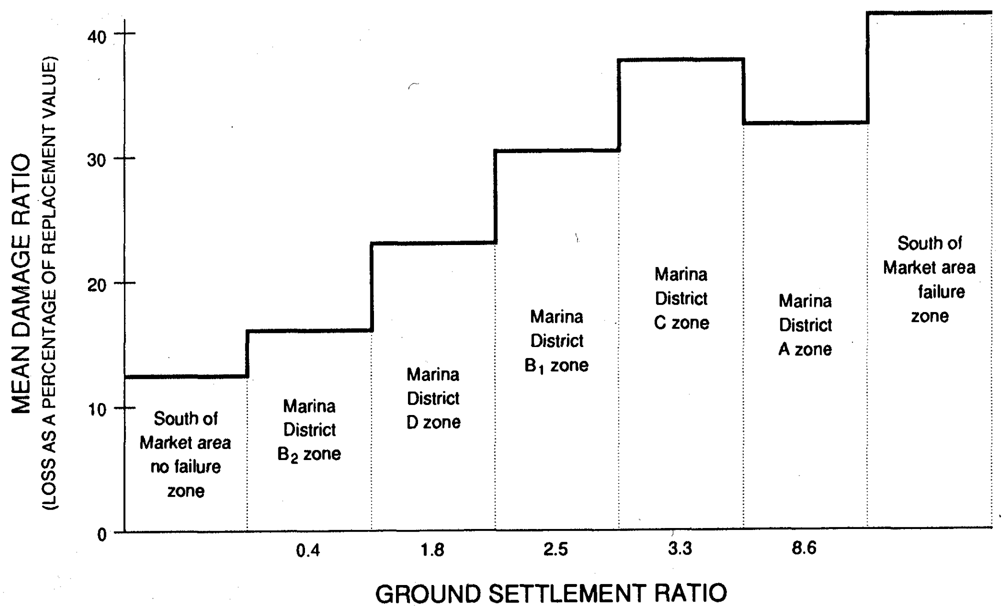


Figure 9.—Mean damage ratio (average of damage ratios for wood-frame buildings surveyed) plotted against ground settlement ratios (discussed in table 2) for ground failure zones.

- Sediment settlement regions had a small coefficient of determination with respect to the damage ratio, which for the analyses evaluated was highest ($\gamma^2 = 0.097$) when both the settlement categories and the damage ratios were transformed by natural-logarithm functions (for example, $\ln Y = a_1 \ln X_1 + \varepsilon$).

To determine the effects of using a real variable $X_1$ (continuous in theory, polychotomous in application) to estimate degree of ground deformation, we also regressed the logarithm of $Y$ with a dependent indicator $X$ (0 for no settlement in the vicinity or if $X_1 < 0.5$, and 1 for settlement). Figure 11 summarizes the results; the coefficient of determination

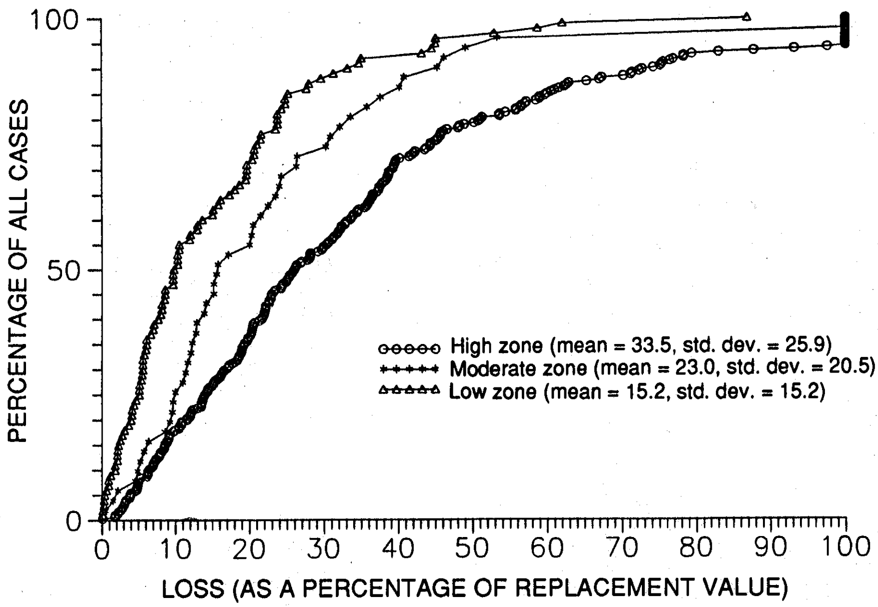


Figure 10.—Cumulative loss distribution by general ground failure zones for buildings having losses in San Francisco ZIP code areas surveyed. The high zone of ground failure combines the South of Market ground-failure zones and the Marina A, C, and B, zones; the moderate zone consists of the Marina D zone; and the low zone combines the Marina $B_2$ zone and the South of Market zones with no ground failures.

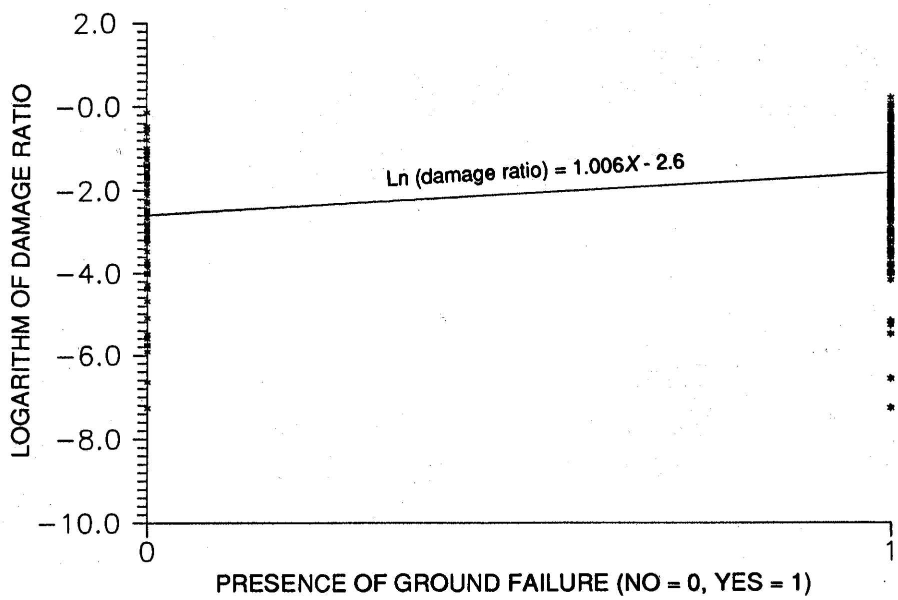


Figure 11.—Line regressing natural logarithms (Ln) of damage ratios (loss as a percentage of replacement value) for damaged buildings in the San Francisco ZIP code areas surveyed plotted against the presence of ground failure in the general vicinity.

($\gamma^2 = 0.12$) is somewhat better, and the regression shows that the presence of settlement appears to influence the loss ratios.

Our analyses show that considerable scatter exists in our loss data and that detailed follow-up studies are required to reduce this scatter.

## CONCLUSIONS

Currently, for a public policy study, loss data from the SBA constitute the most comprehensive data on incurred losses. The quality of data available from insurance companies varies depending on their specific data-collection practices. Some insurers do not wish to release data and some do not systematically gather loss data. The California DOI's call for insurance loss data following the Loma Prieta earthquake resolves the data-release problem. However, the DOI analysis of the loss data had only begun when this paper was written. Insurance regulators seem to be in the best position to improve the gathering of loss statistics. Still, only a portion of buildings at risk are voluntarily insured; and unfortunately, we do not know if the insured building stock is representative of the larger building stock.

Losses are relative to whomever pays. Actual repair costs may be one standard of loss incurred. This standard is considered by governmental agencies or insurers. The actual loss to a governmental agency or insurer is the amount paid for the damages through the claims adjustment process.

Improvements value estimates (estimates of the building market value after subtracting land value) can be exceptionally misleading in developing a normalized loss ratio (one in which losses are related to a standard measure of exposure at risk). In this project, we used cost-per-square-foot estimates along with data on square footage to derive estimates of building replacement values. These replacement value estimates compare well with insurance industry limits of liability estimates. However, variations arise with respect to estimates of values at risk, even though more detailed cost and bid procedures could reduce these variations.

Tax assessor data assist in estimating building square footage and often contain additional information, such as building frame system and landuse category. If tax assessor improvements value estimates were regularly updated, these could be useful proxies for replacement value estimates.

Our preliminary analysis of building loss data from the San Francisco ZIP code areas we surveyed show that a pattern can be developed to distinguish loss ratios (as a percentage of replacement value) for buildings in ground-deformation areas from loss ratios for buildings in areas that have little or no ground deformation. Considerable variability exists in individual building losses sustained relative to mean building losses for a given sample.

The regression analyses of our building loss data shows only a small coefficient of determination ($\gamma^2 = 0.097$), which indicates a weak correlation, between the logarithm of loss (as a percentage of replacement value) and the logarithm of degree of sediment settlement (by ground-failure zone). A slight improvement ($\gamma^2 = 0.12$) occurs if the presence of sediment settlement is treated as an indicator variable (with values of 0 and 1). Scatter in our data can be further removed by (1) use of a broader data base of building loss data, covering newer structures, undamaged structures, and higher rise structures and (2) more detailed followup evaluations of specific building structures to improve data development and to augment data with site-specific and building-specific hazard and vulnerability data.

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