CASE STUDIES OF 25 BUILDINGS SUBJECTED TO STRONG SHAKING IN THE NORTHRIDGE EARTHQUAKE

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ABSTRACT

This paper summarizes the key findings and recommendations from a Seismic Safety Commission publication titled *Northridge Buildings Case Studies Project* (SSC 94-06) and how it influenced the Commission's report titled *Turning Loss to Gain* (SSC 95-01). The paper also describes how the ground motions recorded during the 1994 Northridge Earthquake were characterized by engineers during short seismic evaluations of 25 buildings.

INTRODUCTION

We are all fortunate that relatively few people were killed or injured in the January 17, 1994 Northridge Earthquake. While the media focused its attention on the event, the public policy arena in Sacramento was not nearly as engaged as it was after the 1989 Loma Prieta earthquake. This unusually mild reaction was puzzling considering that the Northridge event had easily an order of magnitude more population in the regions of MMI VIII or greater than the Loma Prieta Earthquake. Had the Northridge event occurred at another time of day, easily 10 times as many people would likely have been killed in collapsed buildings including some of the buildings that were later chosen as case studies by the Seismic Safety Commission. After the Loma Prieta Earthquake, the focus of public policy attention was on hundreds of new seismic safety laws proposed in Sacramento. In contrast, after Northridge, much of the focus was on the adequacy of building codes and practices.

Members of the public and the media raised serious questions about the ability of the building industry to design and construct reliable, earthquake-resistant buildings. Their concerns were influenced more by large economic losses than by the earthquake's actual or potential human losses. Since our building codes are intended to provide life safety and not economic protection from earthquakes, two schools of opinion emerged. School “A” felt that on the whole, buildings affected by the Northridge earthquake provided acceptable levels of risk as evidenced by the low life loss, which met the limited objectives of the building code seismic provisions. School "B" opined that Northridge was just a moderate earthquake that occurred at an opportune time and that both economic losses and the potential for life loss was unacceptable. On February 9, 1994, Governor Pete Wilson issued an Executive Order (W-78-94) asking that the Seismic Safety Commission examine the adequacy of building codes and practices.

This Executive Order set the stage for several information collection efforts by the Commission. The Commission knew it needed to base its assessment of the adequacy of building practices on more specific information than it had collected in the two months of hearings and interviews following the earthquake. So in May 1995, the Commission issued an emergency $242,000 contract to Rutherford and Chekene to gather information about the seismic performance of two dozen or so buildings in the region of strong ground shaking. Rutherford and Chekene's team develop specific findings and recommendations for each building that would later influence the Commission's general conclusions and recommendations about the adequacy of the state's building codes and practices.

The subject of this paper was funded in large part by a state general obligation bond, Proposition 122, that is a seismic retrofit program for state and local government buildings. This $300 million measure passed shortly after the Loma Prieta Earthquake in 1990. The Seismic Safety Commission is authorized to spend up to one percent of the bond fund to help improve seismic retrofit practices. The author manages this effort for the Commission.

Rutherford and Chekene and the Commission eventually selected 26 case study proposals that were significant from a public policy and structural engineering viewpoint. A special effort was made to include buildings retrofitted prior to the earthquake and instrumented buildings. Twenty-nine damaged and undamaged buildings in 25 case studies were eventually published, ten of which were retrofitted. Both large and small structural engineering firms that practiced in the region of damage were selected. Each had different levels of experience and expertise in earthquake engineering. The selection of individual buildings was influenced greatly by the limited availability of local firms to perform the work during the summer of 1994 since all local firms were involved in recovery efforts. Also some candidate buildings were not selected because building owners were reluctant or declined to allow their buildings to be included when told of the nature of the investigations. By August 1994, Rutherford and Chekene had hired 30 investigators in 18 separate firms to undertake case studies with individual budgets ranging from $2500 to $10,500 each. The Commission had hoped to complete the studies within two months, that is, by the end of September 1994.

CHARACTERIZATION OF GROUND MOTION IN THE CASE STUDIES

Each case study investigator was asked to "summarize the effects of site geology, geotechnical improvements, soil failure, and response to ground motions and their impact on building response"(SSC 3032, 1994). However, since the Commission relied on each individual investigator to obtain ground motion records that were relevant to their buildings, the preliminary results were mixed. The Commission realized in late August that investigators were taking several different approaches to characterize ground motions. Some quoted peak ground accelerations, some spectral response acceleration values consistent with the predominant periods of vibration for the subject buildings. One investigator estimated "effective peak acceleration" using personal observations of downed chimneys and masonry walls. Several investigators stuck to simple building code approaches arguing that periods of vibration could not be estimated for their buildings.

So the Commission arranged a meeting in late August 1994 with Bill Holmes and Helen Ferner of Rutherford and Chekene, as well as Bruce Norton, Kevin Coppersmith, Geoff Martin, Joe Penzien, Tom Tobin, Tony Shakal, and Commissioners Lloyd Cluff, Paul Fratessa, and Jeff Johnson to get a meeting of the minds on how to characterize ground motion in both the Case Studies and the Commission's response to the Governor's Executive Order. More directly, an e-mail message to Tom Tobin suggested that:

> We need a knock-down bolted-door meeting to arrive at a consistent way to characterize ground motion parameters with engineering significance at each case study site. (Anon)

After some very frank discussions about the shortcomings of earthquake engineering ensued, this group agreed to reference linear elastic spectral response accelerations in the ranges of the first periods of vibration for each building. At the time, this seemed to be the direction that future building codes and practices would be taking. Dr. Tony Shakal of CSMIP was very helpful as he then directed his office to prepare response spectra from stations in the region of strong ground shaking.

Unfortunately some of the case studies had already been completed by the time investigators received SMIP's response spectra, so the final report still contains references to more distant records and peak values. However, the introduction to the case studies has much of the relevant response spectra available in late 1994, so readers can still piece together building performance using nearby records with a little effort.

Rutherford and Chekene described the difficulty of characterizing ground motions in their introduction to the Case Studies :

> Definition of ground motions at the various building sites proved to be the most vexing difficulty for the investigators. Only one case study building, the Holiday Inn on Orion Boulevard, was instrumented. Estimating the ground motion at a particular building site from a recorded motion several miles away is fraught with uncertainty. Ground conditions, topography, basin edge effects, and directionality may affect the earthquake record and duration at any building site in unpredictable ways. These concepts are further complicated by considerations of vertical accelerations and their phasing with the horizontal accelerations and the acceleration and velocity pulse shapes. California Division of Mines and Geology staff assisted the project by providing ground motion acceleration response spectra from the nearest available recording station for each of the case studies.
>
> In cases where the recorded ground motion is located very close to the case study building and the ground conditions are sufficiently similar that the investigator felt the recorded ground motion was representative of the motion at the case study building site, this record is included in the case study report. For the other buildings where the recorded ground motions are not very close to the case study building, the nearest ground motion is noted in the report and the response spectra are given in Figures in the Introduction.
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> Table 1 indicates how close the nearest response spectra is to the case study building. Engineers can draw their own conclusions about the likely ground motions at any particular case study site based on proximity and ground conditions.
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> The Area Map, shown in Figure 1, was prepared by the California Governor's Office of Emergency Services. This map indicates the location of the California Strong Motion Instrumentation Program recording stations and MMI contours in addition to the case study building locations. All except three of the buildings are located in areas with reported shaking intensities of MMI VIII or higher. (SSC 94-06)

The Van Nuys Holiday Inn, a seven-story reinforced concrete frame constructed in 1996 was instrumented by SMIP prior to the 1971 San Fernando Earthquake. Additional instruments were added after that event and worked well in the 1994 Northridge earthquake. However, there were no free-field sensors located near the site. This greatly hampered the ability of case study investigators to compare free-field ground motions with building response. As a further example:

> There were few free-field instruments in the immediate vicinity of damaged steel-frame buildings, so the levels and character of shaking experienced by these buildings are not well understood. (SSC 95-01)

Table 1. Distance of Response Spectra to Case Study Building

Case Study	Building, Location	Recording Station	Distance from Case Study Building
1.1	Sherman Oaks Towers, Sherman Oaks	322	0.9
1.2	Saint John's Hospital and Health Center, Santa Monica	538	1.8
1.3	Precast Building, Van Nuys	386	4.0
1.4	Eight Story Concrete Shear Wall Building, Van Nuys	386	0.3
1.5	Retail Facility, Topanga Plaza, Canoga Park	C246	0.6
1.6	Bullock's Department Store, Northridge Fashion Center, Northridge	C130	1.8
1.7	Department Store, Northridge Fashion Center, Northridge	C130	1.0
1.8	JFK Senior High School, Administration Building A, Granada Hills	Rinaldi	0.3
1.9	CSU Northridge Oviatt Library, Northridge	C130	1.3
1.10	Santa Monica College Precast Concrete Parking Structure, Santa Monica	538	1.0
1.11	CSU Northridge Parking Structure C, Northridge	C130	1.5
1.12	The Newhall Land & Farm Building, Santa Clarita	279	1.6
1.13	Ductile Concrete Frame Building, Sherman Oaks	322	0.3
1.14	Holiday Inn, Van Nuys	386	4.0
1.15	Concrete Tilt ups, Chatsworth	C130	3.6
2.1	Moment Frame Building, Sherman Oaks	322	2.5
2.2	Division Office Building Moment Frame, Santa Clarita	279	1.6
2.3	Concentric Braced Frame, North Hollywood	C083	0.75
3.1	Unreinforced Masonry Building, Hollywood	303	1.9
3.2	St. Monica's Parish Elementary School, Santa Monica	538	0.9
3.3	Unreinforced Masonry Building, Los Angeles	655	3.1
3.3	Unreinforced Masonry Building, Hollywood	303	1.3
4.1	Three Story Wood Apartment Building, Northridge	C130	2.2
4.2	Multi Story Wood Condominium, Sherman Oaks	322	1.7
4.3	Two Story Damaged Dwelling, Granada Hills	Rinaldi	3.6
4.4	One Story Retrofitted Dwelling, Hollywood	303	1.1

Table 1. Distances (miles) from Ground Motion Recording Stations to Case Study Buildings

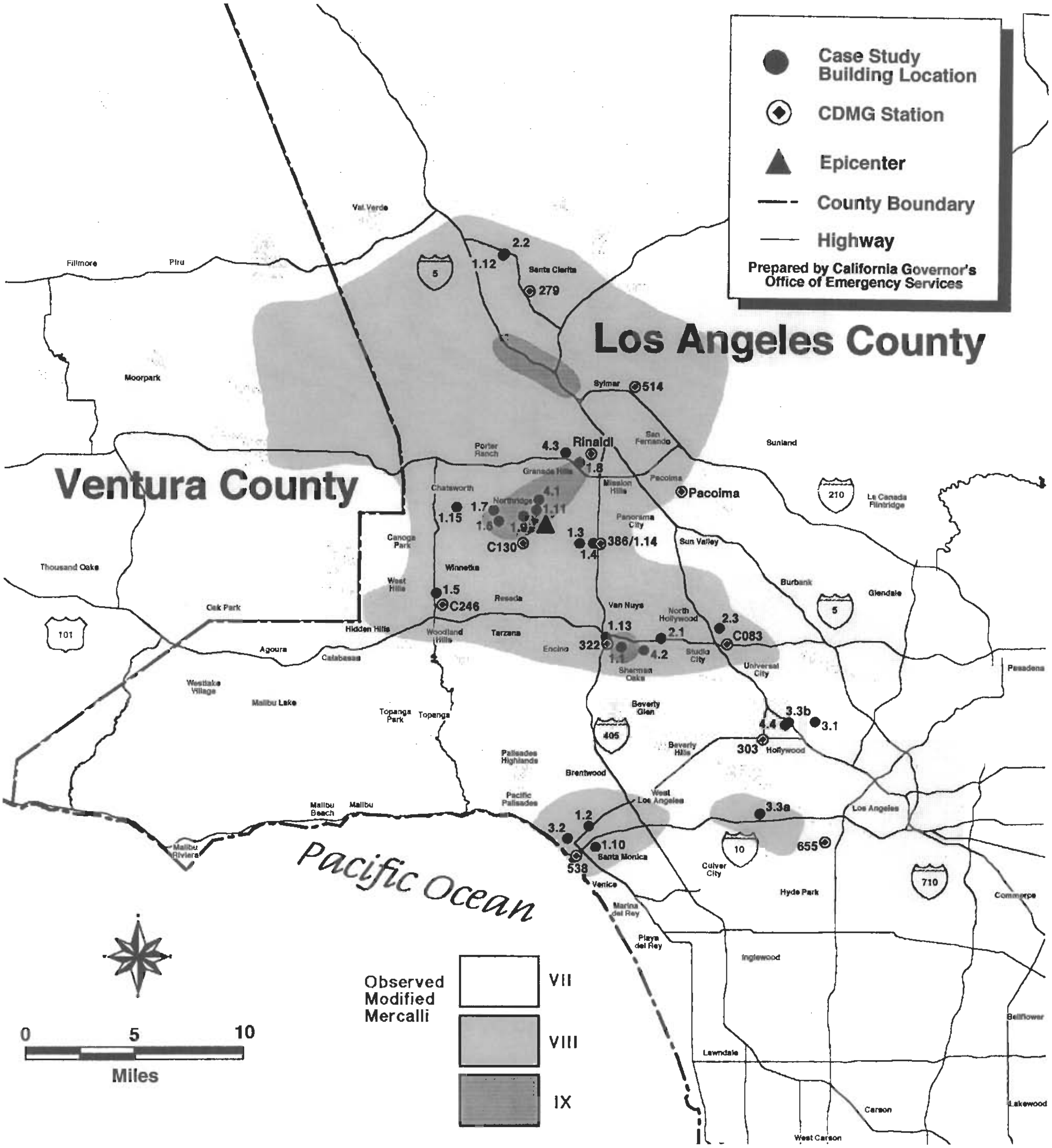

Figure 1. Area Map of Case Study Buildings, ground motion recording station locations, and Observed Modified Mercalli Intensity (Prepared by Cal OES)

The lack of free field sensors or "reference stations" is perhaps one of the best lessons SMIP and other strong motion instrumentation programs can capitalize on from the Northridge earthquake. The Commission later recommended in its response to Governor Wilson's Executive Order, *Turning Loss to Gain* , that:

> SMIP give high priority to establishing a network of reference stations to measure ground motions in major urban areas of California. (SSC 95-01)

Since then, SMIP increased its emphasis on installing reference stations and submitted a TriNet proposal to FEMA that, if funded, would further accelerate such installations.

Still other case study investigators encountered problems securing ground motion records in time to compare them with actual building response. For example, the John F. Kennedy High School, which suffered only nonstructural damage in the 1971 San Fernando earthquake, sustained major structural damage in 1994. The nearest free field station was the LA DWP Rinaldi station, but the investigator was not aware of response spectra's availability until late September, well after the case study was written. Other instruments funded by USGS, NSF and private owners also had data that were not processed and disseminated in a timely manner. As a result of these and other similar experiences, the Commission recommended that:

> SMIP should exert leadership by organizing a workshop involving the other operators of strong-motion instrument networks in California to coordinate the deployment and operation of these networks.
>
> As a result of these workshops, SMIP should compile a list of all strong-motion instruments and their locations in the state and find ways to improve the overall performance of the systems. Furthermore a mechanism should be developed to provide the processed data from earthquakes in a timely manner. These tasks should be completed by July 1995.
>
> Public funds should not be used for the purchase, deployment, or upgrading of strong-motion instrument networks operated by private organizations unless there is a plan for the maintenance of the instruments and an agreement for the timely release of data to the public. (SSC 95-01)

In February 1995, SMIP met with representatives of instrumentation networks to start on this effort to improve communications. In spite of SMIP's limited resources and the shortcomings of other networks, the Commission strongly endorsed SMIP as a valuable part of California's effort to reduce the risk from earthquakes:

> The Commission believes that SMIP proved its worth during this earthquake and its aftermath. Within a day of the main shock, SMIP had issued a Quick Report... SMIP also processed data from five stations during the first week of February. Processed data for more than 70 stations were released by December 1994. The timeliness and quality of these data were extremely valuable. (SSC 95-01)

Two case study investigators independently suggested that the effects of high modes of vibration may have played roles in damage to buildings. The Sherman Oaks Tower, a 12 story concrete shear wall building had only minor damage to reinforcing steel at the end of a wall just below the sixth floor. Similarly the Holiday Inn in Van Nuys experienced its most severe damage in columns at the fourth and fifth floors. The investigator noted that the lateral force capacity at the fourth floor was less than at lower floors and surmised that the second mode may have contributed significantly to the building's response placing a high shear demand in the upper floors.

> These case studies raise questions about analytical techniques and lateral force distribution assumptions that certainly merit further investigation. (SSC 94-06)

The Commission in 1995 drew several conclusions regarding Northridge Earthquake ground motions from its case studies and other Executive Order investigations:

> Although some recorded accelerations in this earthquake were especially high, most spectra generally agreed with those recommended by site-specific geotechnical studies as the basis for the design of special structures. Similar response spectra have been calculated from data from numerous earthquakes since the 1971 San Fernando earthquake and should be expected in future events.
>
> Because of damage from this earthquake, questions have been raised concerning the adequacy of the building code's definition of the forces that earthquakes can impose on buildings. Code writers and designers know that code spectral values will likely be exceeded in large earthquakes and that this was anticipated when the code was written.
>
> The recorded data from the Northridge earthquake are still being evaluated and subject to different interpretations. Strong motion instruments also were not located in many areas that suffered the most severe damage. Generally speaking, the motions recorded near the Northridge epicenter were compatible with those used as the basis for the code, but the motions exceeded those assumed in the code in some cases. At some locations, particularly in the near-source area and in areas with unique local geology, shaking exceeded the assumptions underlying design values in the short-to mid-period range. This shaking appears to have affected low- and mid-rise buildings and caused response in higher modes of vibration for tall buildings. Velocity- and displacement-sensitive structures also may have been affected by the velocity pulses described earlier. Near-source and local geologic effects must be considered in the design of structures. There is no compelling evidence that changes to the code's assumed force levels are necessary. However, changes are necessary regarding the treatment of the effects of near-source and local geologic conditions.

OBSERVATIONS AND RECOMMENDATIONS ABOUT BUILDING PRACTICES

By and large, poor quality in design and construction was the biggest source of earthquake damage in the Northridge Earthquake, as observed in other earthquakes throughout the world. Only a few building case study investigators suggested that low original design force levels were primary contributors to damage. The case studies provide first-hand examples of the adverse effects of, among other things, design omissions, questionable installation practices, and incomplete load paths:

> Case Study 1.14, Holiday Inn, presents an example of reinforcing in a beam-column joint that was specified on the original plans but was apparently not present in a column damaged by the Northridge earthquake. Improved inspection practices for construction could significantly reduce occurrences of this type of omission.
>
> Case Study 1.15, Three Tilt-Up Buildings, indicates that a variety of wood connection hardware details and installation practices, including gaps between wood framing, may have contributed to partial collapses.
>
> Assumptions that were made by the designer of a URM retrofit (presented in Case Study 3.1) were apparently never verified in the field and contributed to the partial

> collapse of this building. Improved plan checking, field inspection, and observation of construction by the designer could have caught this discrepancy before the retrofit was completed. This is also an example of damage caused by building elements that are not well tied together.
>
> Case Study 3.3, Two Unreinforced Masonry Buildings, shows that the lack of URM wall braces and inadequate veneer ties were responsible for out-of-plane failure of wall elements. This condition was further exacerbated by poor mortar quality in the second building. Inadequate out-of-plane anchorage was responsible for damage to another URM, presented in Unretrofitted URM Saint Monica's Parish Elementary School, Case Study 3.2.
>
> Case Study 1.6, Bullock's Department Store, Northridge Fashion Center, presents a graphic example of what can happen to a partially retrofitted building with an incomplete load path.

The case studies also provide examples of damage that the Structural Engineers Association of California and the International Conference of Building Officials have since begun to address with changes to the building code. These include steel moment frame joints, steel braced frames, and tiltup wall-to-roof connections.

Several building systems suffered from deformations during the Northridge earthquake far in excess of that estimated by their original designers. In some cases these deformations caused failure in parts of the buildings that were not intended to act as part of the earthquake force-resisting systems. In effect, these large deformations were not compatible with the building vertical load carrying systems and caused collapse or otherwise incipient situations. Recent code changes will require designers to make more realistic estimates of building deformations and to protect from collapse those parts of buildings such as concrete columns that are susceptible to incompatible deformations.

Many building components have not been thoroughly tested for earthquake resistance. The Northridge event served to confirm or call their future use into question. For example, observations of concrete walls indicate that staggering horizontal steel splices is most likely not a necessary expense. But sliding failures at horizontal construction joints in non-load bearing concrete walls indicated a need for a subsequent change in the code. Case studies of wood buildings provide clear examples of the generally unacceptable performance of drywall panels.

SUMMARY AND CONCLUSIONS

The Northridge Buildings Case Studies provide an anecdotal, but nevertheless informative summary of the many ways buildings performed and of different ways engineers evaluate buildings after earthquakes. The Seismic Safety Commission relied heavily on the specific examples in case studies to substantiate its general recommendations and overall conclusions regarding the adequacy of the building codes and practices as stated below:

> At the heart of Governor Wilson's executive order is the question: "Is the building code safe enough for earthquakes?" With few notable exceptions, the UBC provides an adequate level of life safety for new construction as long as the code is strictly applied during the design and construction of buildings and as long as the code is enforced with thorough plan reviews and inspection. As long as the current performance objectives are acceptable, the building code itself is not in need of a major overhaul, but far more attention to strict adherence to the code and the elimination of shoddy design and construction is clearly needed for earthquake-safe

> buildings. Recent changes to the earthquake requirements in the building code have not been adequately substantiated and do need to be more comprehensively verified in the future.
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> In light of the extensive, albeit non-life-threatening, damage to modern buildings, the state should more actively support efforts to develop future codes, establish acceptable levels of earthquake risk in buildings, and develop design guidelines for meeting seismic performance objectives. (SSC 95-01)

The Seismic Safety Commission's actions reaffirmed the importance of California's Strong Motion Instrumentation Program. As future building codes become more transparent with a greater scientific basis, our collective reliance on SMIP to calibrate both ground motions and system response will undoubtedly grow.

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