# SEISMIC SAFETY ADVISORY COUNCIL

## STATE OF UTAH

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# SEISMIC RISK ASSESSMENT OF FIRE STATIONS, POLICE FACILITIES, AND OTHER CRITICAL MUNICIPAL FACILITIES IN UTAH AND RECOMMENDATIONS FOR RISK REDUCTION

January, 1981

Issued By

SEISMIC SAFETY ADVISORY COUNCIL
STATE OF UTAH

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FOREWORD

The Utah Seismic Safety Advisory Council, established in 1977, is charged to prepare assessments of earthquake hazards and associated risks to life and property in the State of Utah, and to make recommendations for mitigating hazards which may be found.

This report presents an assessment of seismic risk for existing fire stations, police stations, and other critical municipal facilities in Utah and provides recommendations for abatement or mitigation of hazards identified in the study. The recommendations are set forth as judgements of the Advisory Council in terms of (1) effectiveness of the suggested action for reducing risk to life and property losses and (2) economic feasibility for the particular action. Effectiveness and economic feasibility are addressed in combination through "benefit-cost" methods.

The report is divided into a summary of findings, a set of recommendations for seismic hazards reduction, an in-depth discussion of findings, and a technical section on methods of analysis and results. The technical section utilizes current seismicity data in Utah and state-of-the-art methods for earthquake damage and risk assessments. The reader must bear in mind that earthquake risk assessment is an inexact science built upon limited understanding of earthquake phenomena and their effects upon buildings. The technical results presented here are probabilistic in nature and carry all of the imperfections implied by this term. Notwithstanding these fundamental limitations, the Advisory Council deems the conclusions to be founded on reasonable data and analytical methods.

The report presents an overview of seismic risk for fire stations, police stations, and other critical facilities in Utah. Most, if not all, of these facilities are owned and used by local governments. Thus, recommendations that are made, even though some are directed to State agencies, are intended to provide assurance that these important local facilities remain functional during and after moderate to strong earthquakes.

In every community, there are some services and associated facilities that are more important than others. Importance may be defined in many ways, such as in terms of special life-safety considerations for occupants of particular buildings, or in terms of the critical nature of the service rendered. Fire stations clearly fit the second definition; for fire-fighting capability is an essential after-earthquake need. Effective law enforcement services also are especially needed following damaging earthquakes to control traffic movement, secure damaged businesses, and facilitate disaster response and recovery activities by others. Emergency operations centers, by their very concept, are intended to serve as the focal points of government during and after disasters and other abnormal situations. Special measures therefore are warranted to ensure that these services and the facilities in which they are housed will not be rendered nonoperational by an earthquake event.

In general, conclusions in this report are drawn and recommendations are made for classes of fire stations, police stations, and other critical municipal facilities in accordance with the severity of the earthquake environment of the region of location. Although construction data about individual buildings were used in the study analysis, this was for the purpose of classifying the buildings according to their risk rather than for identifying problems for specific buildings. In general, then, the report is not intended for application to specific buildings.

We have presented an overview of the seismic safety for fire stations, police stations, and other critical municipal facilities from which we have developed general program directions for mitigation of hazards. From such an analysis, the Seismic Safety Advisory Council has been able to identify pervasive seismic risk conditions among these types of facilities and to recommend actions leading to remedies of unfavorable conditions.

Responsibility for any mitigation programs that might be undertaken is recognized to lie with local governments that own and operate the fire stations, police stations, and other critical facilities. However, the State of Utah can provide helpful assistance to local governments by identifying hazardous conditions and by suggesting cost-effective mitigation actions. It is hoped that this report will serve a two-fold purpose--first, to focus attention on high-risk earthquake hazards among these types of facilities, and, second, to suggest appropriate State actions that will assist local governments to recognize, identify, and mitigate those risks that may be too great.

The Seismic Safety Advisory Council urges adoption and implementation of the recommendations contained herein.

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SECTION 1

## INTRODUCTION

The primary purpose of this report is to provide direction for State and local governments concerning the operational reliability and earthquake vulnerability of particular classes of facilities used to house essential services that we here call "critical facilities." Critical facilities here primarily are fire stations, police stations, and emergency operations centers. Jails and municipal buildings are included also to the extent that fire and police services may be housed in them.

These particular classes of buildings have been targeted for special attention regarding their earthquake resistance because of the special importance of the functions they house during emergencies. Two services of local governments--fire and police--typically are fully mobilized and utilized in any type of emergency that causes widespread social disruption or loss, be it an accident, a tornado, or an earthquake. Indeed, anxious citizens typically telephone one or both of these agencies for assistance, even when the appropriate type of response actually is provided by some other agency or organization. Hence, services from both of these types of agencies are expected by the public and are essential after any damaging earthquake event.

The concern of the study leading to this report was whether or not those facilities housing fire and police services and equipment are especially vulnerable to damage in Utah's earthquake environment and the extent to which any resulting damage might be detrimental to fire-fighting, law enforcement, or other similar capabilities. A fire truck, immobilized because the fire station roof fell on it during an earthquake, is of little use to a community. A police communication center that cannot continue to function after an earthquake because the building collapsed around the radios, likewise, is a critical loss immediately after an earthquake.

Evaluation of the vulnerability of such critical facilities is one of three principal elements of this report. The second element consists of an evaluation of the alternatives to correct safety deficiencies that are observed in facilities and which could affect the reliability of the functions if an earthquake were to strike. The third element of the report consists of policy recommendations made by the Utah Seismic Safety Advisory Council. The recommendations are intended to indicate courses of action for mitigating the hazards to these critical facilities posed by earthquakes.

In the report, we first present, in Section 2, an overview of the findings from detailed evaluations of earthquake vulnerability and mitigation alternatives. Section 3 lists and discusses recommendations by the Advisory Council for reducing earthquake vulnerability of the facilities and for procedures that would lead to their improved reliability. These policy recommendations are for consideration and adoption by State and local government agencies. In subsequent sections, Utah's seismic environment is described, the extent and degree of earthquake hazards are established, locations of critical facilities relative to seismic zones of differing degrees of hazards are examined, and construction characteristics of the critical facilities are classified according to their seismic resistances. After identifying the various degrees of vulnerability of these critical facilities, we apply a "benefit-cost" technique to evaluate the economic merits of alternative mitigation programs.

The acceptability of any mitigation program will be decided in the main after consideration of trade-offs between degree of risk and cost to remove the risk. We do not now, and we never will, live in a risk-free world. Even if we knew how to remove all risks, we could not afford the dollar cost of doing so. It is no different for mitigation of earthquake hazards. Any hazards mitigation effort will have an associated cost. In some cases, that cost to remove the hazard is greater than the hazard itself. In this report, then, we have attempted to suggest policy guidelines and sufficient information for use by government agencies that might help local governments to make these sorts of judgements about safeguarding their essential facilities.

In benefit-cost terms, the dollar value of any fire station to a community is dependent upon a number of factors, such as the number of other fire stations in the vicinity, the condition of the equipment, the skill of the fireworkers, and the availability of the water supply (Cf. [1]). Determination of such values was beyond the scope of this study, and so herein no definite dollar value was placed on any given fire station. Rather, we have tacitly assumed that fire stations are indispensible to each community, especially immediately after disasters, and so our risk analysis has focused only upon building vulnerability to earthquakes and the costs to reduce high vulnerability. For this report, priorities are suggested for fire stations in regard both to those that should first be examined for replacement purposes and to those that should first be examined for retrofitting purposes.

Although location and construction data exist on almost all fire stations in Utah, this report does not include any recommendations as to whether or not a given fire station should be either retrofitted or replaced. Such a decision would need to be made by the municipalities concerned. The information contained in this report, which relates expected costs of construction to expected collapses (classified by seismic mazrozones and structural types), should be useful in making any such decision.

A benefit-cost type of analysis is more feasible with regard to other critical facilities covered in this report. Such facilities, primarily including police stations, jails, and some ambulance operations, are mostly high-occupancy facilities whose critical function in the event of an earthquake, while important in many cases, is not so indispensible as that of fire stations. Fire stations house critical personnel, equipment, and communications capabilities. Much police work during emergencies, in contrast, goes on outside police stations. Equipment, too, often is not endangered by structural failure at the police stations. Communications during post-disaster operations may be housed in police facilities, but, unless evidence to the contrary is available, it is presumed that special attention already has been given to the safety of the emergency operations communications areas in buildings. In addition, the total issue of the effectiveness of the communications network, including the capacity to use alternative means of communication when some segments of the regular system break down, lies beyond the scope of this paper.

So, for this paper, fire stations are regarded as indispensible facilities after an earthquake, whereas police facilities are not. However, if, in a given locale, police workers often occupy a facility which also houses major police equipment, including communications equipment and rescue equipment, then the distinction here made does not hold, and the police station should be regarded as being as critical as a fire station.

For readers especially interested in the risk analysis techniques that were applied in this study, we have included, in Appendix C, a detailed discussion of the methodology as well as pertinent numerical values that were derived. We emphasize that earthquake risk assessment is an inexact science built upon incomplete understanding of earthquake phenomena and their effects upon buildings. To overcome deficiencies in scientific knowledge, we have relied upon probabilistic analysis techniques regarding the occurrence of earthquake events and upon statistical data from buildings damaged by past earthquakes for our estimates of expected structural losses. The conclusions are believed to be valid for both aggregate groups of earthquake events and classes of buildings, but the analytical techniques do not allow specific conclusions to be drawn for individual buildings. Hence, the report is not intended for application to specific buildings but, instead, should be used as a guide to probable vulnerability and as a means to determine which buildings ought to be evaluated more thoroughly.

## SECTION 2

## SUMMARY OF FINDINGS

Principal findings resulting from the seismic risk assessment of existing Utah fire stations, police stations, and other critical facilities reported herein are presented first, without elaboration or extensive discussion. More detail is provided in subsequent sections. A full description of the analytical methodology is provided in Appendix C. Recommendations for dealing with principal findings of earthquake hazards are provided in Section 3 which is organized so as to allow its separation from the report without seeming to be incomplete.

The report is organized to provide the reader with constant overview of study concerns while developing and describing a complex analysis of earthquake safety in certain classes of existing critical facilities in Utah.

This study addresses the seismic risk only for existing fire stations, police stations, and other similar critical facilities in Utah. The principal findings and recommendations which follow are limited accordingly. Seismic hazards mitigation in the construction of new facilities involves conditions which are completely different from existing facilities and, consequently, remedies which also are different. New construction is treated only tangentially in this report. Here, it is enough to observe that seismic safety can be achieved relatively simply in new construction in contrast to the high cost and difficulty of remedying safety deficiencies in existing buildings, and that providing seismic safety in new construction is inexpensive if current seismic standards are followed.

Principal findings of this study are listed below. Importance of the topic was not a basis for the list sequence. Readers will note that the findings are listed more or less in order of their appearance in the discussion sections of the report, with findings pertinent just to fire stations, just to police stations, and just to other critical facilities separately listed.

### Seismicity In Utah And Earthquake Effects On Buildings

- Seismicity is common in most of the State of Utah with the possible exception of the easternmost portion. The most severe and frequent earthquakes historically have occurred along a central region extending from the north central border to the southwest border. This seismic region is a part of an area that has become known as the Intermountain Seismic Belt. Geologic evidence suggests that severe seismicity in the future most likely will occur within this same region, with the Wasatch fault zone being the zone of greatest risk. Although the probable frequency of strong earthquakes is expected to be very low, the Wasatch fault is said to be capable of producing earthquakes in the 7.3 Richter magnitude range. Earthquakes in the 6+ Richter magnitude range have occurred in historic time in the State. Utah can expect to experience more such events in the future, and the possibility always is present that an even stronger one may occur.

- Earthquake damage to buildings is determined primarily by three factors: (1) earthquake strength, (2) earthquake location relative to the building, and (3) building construction characteristics. Damage is found to appear in ordinary buildings at an earthquake threshold level of 4.5 to 5 Richter magnitude. As the earthquake strength increases, so does the building damage. Earthquakes in the 6+ Richter magnitude range can cause severe damage and create severe hazards to life safety, although building collapse is uncommon. Earthquakes in the 7+ Richter magnitude range assuredly will cause collapse of many non-seismically designed buildings and could even damage some that are seismically designed.

- All buildings are not equally resistant to earthquake forces. Resistance is influenced not only by the quality of construction but also by the type of construction, i.e., the selection of materials and their assembly configuration. Age of the building is a measure of quality in the sense that building techniques generally have improved over the years and, particularly, are increasingly subject to building codes and standards.

- Although individual building characteristics affecting earthquake resistance are rarely the same, a few generalities about construction types can be made to give one a rough idea about earthquake vulnerability. For non-seismically designed buildings, those that have framed primary structural systems typically have better earthquake resistances than do buildings with bearing walls as the primary support system. Unreinforced brick masonry, often used for bearing wall construction, is especially vulnerable to the lateral forces induced by earthquake motion. Brick masonry construction traditionally has been widespread in Utah, and so, given the fact that only recently have earthquake forces been considered in their design, there are numerous vulnerable buildings of this type throughout the State, not exluding a fair number of fire stations, police stations, and housing for other critical facilities.

- Some general observations regarding building vulnerability may be made, drawing upon knowledge of past construction practices in Utah. Buildings constructed before 1950 universally were unreinforced when masonry was used, and this was the case for nearly all large buildings. Multistory buildings of such construction typically have poor seismic resistance. Pre-1940 buildings typically were not governed by construction codes. Hence, their seismic resistances are even less certain. As recently as the 1960's, little attention was given to seismic-induced lateral forces in Utah construction, and critical facilities were no exception. While these newer buildings generally had better quality control in their construction, and while the applicable newer code provisions typically result in stronger buildings, lateral-force resistance remains an uncertainty for these post-1960 buildings. Seismic safety and seismic design standards received wider attention during the 1970's but, even so, there were no policies or procedures in force or use in Utah which allows one to say with confidence that all such structures meet the seismic standards of their era. With a few exceptions, it is fair to conclude that few existing critical facilities in Utah have deliberately designed seismic lateral-force resistance, and few of the buildings have been analyzed rigorously to determine their vulnerability.

Earthquake Risk For Fire Stations

- One hundred forty four fire stations were identified and included in the surveys of this study. Most, if not all, of Utah's fire stations are included. Gross floor area of these 144 facilities totals 640,000 sq. ft. The value of these facilities (1978 dollars) is estimated to be over $34 million. (Given the recent high inflation in construction costs, this estimate is rapidly becoming much too low.)

- Eighty seven of the 144 fire stations surveyed lie in Utah's seismic zone of highest risk. Of these 87 facilities, 40, or 46 percent (27.8 percent of the total surveyed), have construction characteristics that place them in the most seismically vulnerable class of buildings. A few of these buildings are situated astride or nearly astride known fault lines and so are doubly jeopordized.

- Damage to present fire stations resulting from earthquakes is estimated at $1.64 million per 100 years, or an annual average loss of $16,400. However, due to the fact that damaging earthquakes are infrequent, annual loss estimates have little meaning except in terms of averages. Actual losses will be aggregated according to the occurrence of strong earthquakes, and it might be necessary to compile loss data for several centuries before the average smoothens.

- Damage to present fire stations can be reduced in two ways: (1) by replacement of hazardous facilities, or (2) by strengthening (retrofit) of existing facilities. Replacement as a strategy has a very high associated cost. Replacement value of the 144 surveyed facilities is estimated at $34 million (1978 dollars). Benefit/cost analysis indicate that the total 100-year loss estimate is but 4.8 percent of the total replacement value of all fire stations. Even for the worst seismic zone, the benefit/cost relationship is just 6.3 percent of the replacement value. Thus, without even considering the current cost of money, a replacement strategy for hazards reduction would be economically marginal. When the cost of money is included in the analysis, any economic argument for a replacement strategy is destroyed. A selective retrofit strategy gives more favorable benefit/cost data. If one could, through detailed review, select those fire stations with the most hazardous conditions and strengthen them, and assuming retrofit costs at 25 percent of replacement value, then the total 100-year loss estimate improves to less than 1.4 percent of the total replacement value, with a corresponding damage loss reduction to about one-fifth of the estimated loss to present facilities.

- Cost-effective reduction of seismic risks in fire stations can be accomplished only in a limited number of cases, and even then decisions to do so will be influenced additionally by two special factors-- namely, the criticality of the facility to a community and the ability by a local governmental unit to obtain the capital funds for the replacement or retrofit. It is worthy of note here that larger cities, i.e., cities with several fire stations, may be less burdened by the loss of one or more facilities than would a community with just one fire station whose loss could be locally disastrous if fire fighting capability were lost.

- Construction of earthquake-resistant fire stations when new ones are built is the most cost-effective means for earthquake hazards reduction. Since new stations are built for replacement as well as for growing neighborhoods, this strategy clearly excels over other strategy alternatives in the long run. If this strategy were to be combined with a policy for retrofit or replacement of the most vulnerable facilities, in order of their priority of risk, over several decades, Utah could extricate itself from earthquake risk situations that have grown since settlement.

<u>Earthquake Risk For Police Stations And Other Essential Facilities</u>

- One hundred twenty eight municipal facilities housing police stations and other essential emergency services of government were identified and included in the surveys of this study. The value of these facilities (1978 dollars) is estimated to be over $88 million.

- Seventy two of the 128 municipal facilities surveyed lie in Utah's seismic zone of highest risk. Of these 72 facilities, 24, or 33 percent (18.7 percent of the total surveyed), have construction characteristics that place them in the most seismically vulnerable class of buildings.

- Damage to present municipal facilities resulting from earthquakes is estimated at $3.5 million per 100 years, or an annual average loss of $35,000. About 11 percent of essential municipal facilities are expected to suffer damage causing nonfunctionality of the facility over 100 years.

- Damage to present essential municipal facilities can be reduced either by replacement with seismically resistant facilities or by strengthening existing facilities. Replacement is the more costly alternative, both in total capital outlay and in benefit/cost terms where loss reductions are compared with total outlay. Damage estimates, if all facilities were replaced with seismically resistant ones, are $7,700 annually and 2 percent nonfunctional. Retrofit for earthquake safety applied to all facilities, at a cost of about $10 million, produces damage estimates of $20,000 annually and 3 percent nonfunctionality. Retrofit clearly is the more cost-effective alternative. Since both replacement and retrofit can be applied selectively to the most hazardous facilities, the benefit-cost ratios can be improved. However, even for the most favorable retrofit conditions, the ratio of benefit to cost is less than 16:100. So, for no essential facility can replacement or retrofitting be justified solely in economic terms, and other reasons must be present to justify the replacement or retrofit. In the case of police services housed in these municipal facilities, and speaking generally, only the communications function appears important enough to safeguard from nonfunctionality due to earthquake damage.

- Construction of earthquake-resistant municipal facilities when new ones are built is the most cost-effective means for earthquake hazards reduction. Although such a program has only long-term benefits, since new municipal facilities are not built very frequently, it still appears to be the most feasible of the alternatives from a political economics point of view. Moreover, Utah's seismic environment does not seem to provide an ample argument for a more agressive mitigation effort.

SECTION 3

## RECOMMENDATIONS FOR MITIGATION OF EARTHQUAKE HAZARDS IN EXISTING FIRE STATIONS, POLICE STATIONS, AND OTHER CRITICAL MUNICIPAL FACILITIES IN UTAH

The following recommendations result from a benefit-cost analysis of earthquake safety for selected critical facilities in Utah. These selected facilities are classified as critical for reason of their importance to post-disaster recovery activities. The study provides information on the extent and the nature of earthquake hazards in existing fire stations, police stations, and selected other essential municipal facilities and also guidance as to feasible remedies for identified problems. Since such essential facilities are in the main under the jurisdiction of local municipalities, and since some such facilities are housed in municipal centers, recommendations here should be used as guidelines for planning purposes to ensure that the indispensible functions of these facilities remain operational during and after severe earthquakes. Consideration is given in the recommendations to the fact that these essential facilities may be separate buildings or may be a part of community complexes which house several government activities.

Fire stations are here regarded as being indispensible within a community in terms of their critical personnel, equipment, and communications. The degree to which the functioning of a particular fire station is indispensible to a community depends also upon the number of other fire stations functioning and the extent to which their personnel can respond promptly during emergencies.

Police stations, often housed in municipal centers, likewise contain critical communications centers that should be so constructed as to remain functional during critical times. But many police workers and much needed equipment spend only limited periods within such structures. So, the police stations themselves, apart from their communications facilities, are not here regarded as being indispensible to a given community.

In recent years local governments have been encouraged to establish "emergency operations centers" intended for use as centers of governmental coordination during emergency periods. Sometimes these centers are located in existing police or fire stations where communications systems are already in place; sometimes they are located in designated spaces within municipal or county buildings; and sometimes the centers are separate buildings. While the seismic risks very likely are different in these various locations of emergency operating centers, such facilities share a common purpose which requires that they remain functional during emergencies. Although earthquake safety typically has been considered in the designation of emergency operations facilities, many of them within existing structures are as vulnerable as those structures. Consequently, separate earthquake safety review is justified.

Given the special considerations for fire stations, police stations, and other critical facilities, respectively, the following recommendations are based upon an assessment of the seismic risks in various parts of Utah.

## Fire Stations

1. It is recommended that the State Fire Marshall should encourage all local governments to apply diligently and thoroughly to the construction of all fire stations the earthquake safety provisions adopted by the State Building Board.

   Given the indispensibility of fire stations during post-earthquake response periods, the State Fire Marshall's office should include earthquake safety recommendations whenever it provides assistance to local governments in construction or remodeling of fire stations. Geoseismic criteria also should be used among other criteria when new fire stations are sited.

2. It is recommended that local government jurisdictions in the State's most seismically active zone be encouraged to carry out an inspection/review program for the purpose of identifying existing fire stations which may be vulnerable to earthquake-induced damage, that detailed analysis be made for those facilities with apparent limited lateral-load resistance, that those structures likely to be rendered non-functional by moderate earthquake forces be retrofitted promptly, that those structures likely to be rendered non-functional by large earthquake forces be retrofitted as expeditiously as possible, and that the State Fire Marshall publish yearly a report which summarizes progress of local jurisdictions to identify and mitigate these earthquake hazards.

   Of 144 surveyed fire stations, 87 lie in Utah's zone of greatest seismic activity, of which about 45 appear to be unreinforced concrete or masonry systems. About 31 of these structures merit special seismic safety inspections and removal of identified hazardous conditions. A geolgoical site inspection of one structure in Salt Lake County that appears to be within a zone of deformation is also in order so that it may be known whether or not to rely upon such a station in the event of a major earthquake. Monitoring by the State Fire Marshall's office of progress by local governments to identify and remedy seismically hazardous conditions in fire stations is suggested as a means to keep this need before Utah's citizens where there is opportunity for expressions of concern to be made.

## Police Stations

3. It is recommended that the State Department of Public Safety should encourage all local governments to apply diligently and thoroughly to the construction of all police station communications centers the earthquake safety provisions adopted by the State Building Board.

   Given the indispensibility of police communications during post-earthquake response periods, the Department of Public Safety should undertake a program to encourage that facilities used to house these communications centers be capable of resisting earthquake-induced forces that might cause them to be rendered dysfunctional. During emergencies, communications are needed much more so than in normal times. Building damage and equipment dislocation resulting from earthquakes should be guarded against. This may be accomplished by detailed analysis of existing communications housing in each community, followed by appropriate problem corrections or relocation of equipment to safer quarters.

4. It is recommended that jail and other confinement facilities maintained by local governments should comply with earthquake safety standards adopted by the State Building Board or with similar standards as contained in the building code adopted by the particular local government jurisdiction.

   The study of police stations which forms the analytical basis of this recommendation indicates that jails typically are a part of local government law enforcement facilities. Given that there are obligations placed upon local governments to ensure the safety of persons confined in such facilities, where the potential hazards are greater than for those occupants of similar buildings who are not confined, and given evidence that some jail facilities in the State are in older, possibly hazardous masonry buildings, there is ample justification for this recommendation.

## Municipal Centers Housing Critical Operations

5. It is recommended that the State Building Board undertake a preliminary survey of seismic safety conditions for local public buildings and facilities in the State's zones of greatest seismic activity, that seismic safety deficiencies which may be identified be compiled in report form, and that the findings be published and made available to the local governments and the

public in general.

A number of public buildings and other facilities owned by local governments throughout the State appear to have characteristics which may make them unsafe in moderate to large earthquakes. It is possible that these vulnerable conditions are not recognized by the local governments.

Of 128 such buildings surveyed during preparation of these recommendations, 36 were built before 1930. Twelve of these buildings lie in the State's highest seismic risk zone. Another 14 lie in the second highest seismic risk zone. Some of these older structures (primarily those of unreinforced masonry construction) pose special life-safety risks which should be fully assessed and disclosed.

Since such structures typically serve as local centers of government activity, thereby exposing the general public as well as employees to seismic risks, identified risk conditions should be disclosed so that local governments may undertake remedial or replacement action as they may decide and as they are able.

It is to be noted that older government buildings often have special community significance and value and therefore are preserved for historic or sentimental reasons. Hence, replacement often is not a viable option. In preparing this recommendation, no broadly acceptable methodology was discovered for correcting seismic hazards in buildings that have outlived their normal life-use period yet are being preserved. Given the high costs for retrofitting such buildings to correct seismic safety deficiencies, no specific and acceptable remedial steps are known or suggested at this time other than disclosure of identified risk conditions.

## SECTION 4

## RISK TO FIRE STATIONS, POLICE STATIONS, AND OTHER CRITICAL MUNICIPAL FACILITIES IN RELATION TO EARTHQUAKE ACTIVITY IN UTAH

### PART A: SEISMICITY IN UTAH

Two typical ways to assess earthquake risk for a given situation are, first, to examine the consequences of a postulated worst-case earthquake and, second, to examine the historical record of past earthquakes and their long-term damage effects.

In a report on earthquake losses in the Salt Lake City area prepared by the U.S. Geological Survey, the first approach is taken (Cf. [2], p. 58). Such an approach allows one to estimate the difficulties that could occur as a result of a large earthquake. The hazards posed by a damaging earthquake depend upon many factors, such as how many people are occupying the various buildings at the time and where the epicenter of the earthquake happens to be. If preparations are made for a comparatively worst case, such as when the epicentral location of a large earthquake is in Salt Lake City, then, presumably, preparations also have been made for all earthquakes that would cause less damage.

However, since such a postulated large earthquake may occur very infrequently, an overall assessment of the earthquake risk in a given area also requires that one estimate the frequency and severity of the entire range of earthquakes, both large and small, in the area.

The primary source for the overall earthquake activity in Utah is the historical record.

In a report by S.T. Algermissen and D.M. Perkins, the United States is divided into 71 seismic source areas based on expected seismicity in each area ([3], pp. 17, 18). Expected earthquake rates in the report are based chiefly on historical records of occurrences.

Utah is one of the most seismically active states. According to the report, only a few areas of the United States have higher expected earthquakes rates than does Utah.

Utah has four major seismic source areas and one non-active area, according to the Algermissen and Perkins report. Three specific source areas are of special interest, namely, zones 32, 33, and 34 (See Figure 1). One can compare the Algermissen and Perkins zonation map published in 1976 with the map still in use in the Uniform Building Code, 1979 Edition (UBC) (See Figure 2). It can be seen that the UBC map oversimplifies Utah's seismic environment as it currently is understood by scientists. In Figure 1, Zone 33 is the most seismically active, followed by Zone 34. Zones 32 and 43 are least active. Part of the State along the east side lies in a zone where little seismic activity has occurred or is expected (See Figure 3).

Zone 33, which extends through Utah's most densely populated areas, ranks seventh among the 71 Zones in the continental United States (Algermissen and Perkins data) in terms of expected number of Modified Mercalli Intensity V earthquakes per 100 years[1], and ties for nineteenth in terms of its expected maximum Mercalli intensity. Zones that exceed Utah's seismicity levels lie predominantly in California, Nevada, and Montana, although expected maximum magnitudes are equal in the St. Louis area and in South Carolina.

In another study of the historical record from 1850 through June, 1965, Kenneth L. Cook and Robert B. Smith identified at least seven earthquakes that would register at least 6 on the Richter Magnitude Scale ([5], pp. 703-718). From 1853 to 1975, an estimated 17 Utah earthquakes had an Intensity VII or greater ([6], p. 156). Two earthquakes, one in Richfield in 1901 and one in Kosmo in 1934, were identified as having an intensity of IX (Cf. [2], pp. 9-20). So, the historical record indicates considerable seismic activity in Utah.

Even though the historical record provides important data for assessing the earthquake environment in Utah, the use of the historical record alone has several shortcomings. One shortcoming is that future epicenters are not likely to occur exactly where past epicenters have occurred, so that a simulation of the past record alone does not predict future hazards. Another is that the historical record, which in geologic time reference is very short, may be misrepresentative of the much longer geological record.

Further evidence disclosed by Robert Bucknam at the U.S. Geological Survey (USGS) in Denver indicates that the geological record may imply even greater estimated seismic activity along the Wasatch fault than is indicated by the more limited historical record. In line with USGS findings, which have been reported in several technical papers, a revised map has been used in this study in which Zone 33 in Figure 1 has been subdivided into two sub-zones, 33A and 33B. Zone 33A with higher expected seismicity rates, extends approximately 20 kilometers on each side of the Wasatch fault (See Figure 4).

More detailed delineation of the Wasatch Front seismic zone is shown in Figure 5. Borrowing from the Algermissen and Perkins seismic source zone data and the Bucknam geologic evidence of higher seismicity in Zone 33A, a modified seismic zone map has been used in this study to indicate variations in expected seismicity (See Figure 6). The modified map renames the Algermissen and Perkins zones as follows:

| Algermissen and Perkins Source Areas | Modified Zone Designations |
|---|---|
| Zone 43 | Zone U-0 |
| Zone 32 | Zone U-1 |
| Zone 34 | Zone U-2 |
| Zone 33B | Zone U-3 |
| Zone 33A | Zone U-4 |

[1]For a partial explanation of the Modified Mercalli Intensity Scale, see Appendix A.

Increasing numbers on the modified seismic zone map correspond with areas of increasing seismicity, with Zone U-4 being the most severe in the State of Utah.

As is explained in Appendix C on methodology, seismicity rates for the zones in Utah have been developed on the assumption that, except for major earthquakes on the Wasatch fault, earthquakes of lesser intensity may have their epicenter anywhere within the given zone.

Location of structures relative to these zones of varying seismicity provides one measure of their vulnerability. In general, only those facilities in Zones U-4, U-3, and U-2 deserve special attention for seismic hazards, since seismicity rates are very low in Zone U-1 and are assumed to be negligible in portions of the State Zoned U-0.

## PART B: LOCATION OF ESSENTIAL FACILITIES IN EARTHQUAKE ZONES

Figure 7, which shows the distribution of fire stations surveyed, indicates that 60 percent lie in the State's worst seismic zone. Figure 8 indicates the distribution of other critical facilities surveyed. Once again, the majority of the facilities (56 percent) lie in the most severe seismic zone. Table 1 indicates distribution in the seismic zones of the buildings, classified according to their use or purpose.

Seismic zones, as depicted in Figure 6 and other preceding figures, provide a relative indication of expected earthquake strength for a region. These seismic zones usually are correlated with design standards for buildings and other structures and provide the criteria for degree of strength that should be designed into a structure. By indicating relative earthquake strength, seismic zones also imply relative earthquake frequency, but one cannot determine from such zones the actual or estimated frequencies for earthquakes of all strengths. Thus, information about seismic rates that is implied by seismic zones needs to be supplemented with other information about frequency in order to estimate the earthquake risk.

Estimates of earthquake recurrence rates, explained in greater detail in the appendix on methodology, are an important factor in assessing long-term earthquake risks. Such estimates depend heavily both upon geological and historical studies, some of which are yielding new results. According to current seismological research, Utah's earthquake environment is less severe than in many parts of California but is more severe than in most of the rest of the United States.

Information about recurrence rates is useful for estimating degrees of damage to structures, which is the major cause of deaths and injuries, and for evaluating the relative risks of multiple earthquakes of moderate size that occur more frequently in comparison with more devastating large earthquakes that are infrequent. For example, one may wish to know if the building losses that might be caused by earthquakes of Richter magnitude 6 every ten or so years are greater or less in the long run than the more severe losses that might be caused by a large earthquake of Richter magnitude 7 every 475 or so years. Since it is far more costly to provide resistance to earthquakes of Richter magnitude 7 than for Richter magnitude 6, such information is valuable in evaluating the relative merits of one approach over the other, at least in cost terms.

The location of facilities relative to zones of seismicity, then, is a major measure of their vulnerability to earthquakes. However, seismic rates as used in this study limit the conclusions to buildings on an aggregate level and in a statistical sense. Uncertainties in earthquake occurrences preclude accurate application to individual buildings. Further geological investigations of soil and other conditions would be needed in order to provide a more accurate site-specific account of the vulnerability of various facilities.

## PART C: CLASSIFICATION OF ESSENTIAL FACILITIES IN ACCORDANCE WITH THEIR COMPARATIVE SEISMIC RESISTANCES

Another major factor in assessing the vulnerability of a facility to earthquakes is the type of construction of the structure. Given such information and the distribution of earthquake activity, it is possible to estimate the comparative earthquake resistance of structures.

There are two methods used in this report to assess the earthquake resistance of particular types of structures. Both methods are discussed in detail in Appendix C on methodology.

The first method derives from a classification scheme used by S.T. Algermissen and K.V. Steinbrugge in their studies of earthquake losses in California (Cf. [7], p. 3). Algermissen and Steinbrugge developed their classifications from observed damaged and undamaged structures resulting from several earthquakes. They observed that the type of construction, particularly the structural system of a building, greatly influences the amount of damage that will be sustained, and they have correlated these observations with various earthquake strengths.

The classification includes five basic structural types that are commonly found, with subclasses to differentiate the quality of the construction and other unique characteristics. The five main classes are:

(1) Wood-frame and frame-stucco buildings.
(2) All-metal buildings.
(3) Steel-frame buildings.
(4) Concrete buildings.
(5) Buildings with mixed construction, and masonry bearing and non-bearing walls.

The five main classes are further subdivided into subclasses in accordance with particular characteristics or features that give different vulnerabilities to earthquake forces. The entire classification is given in Appendix B.

Of the five main classes, the first two classes contain the safest buildings in terms of their earthquake resistance, even when such buildings are comparatively old. In the third class, two subclasses are of special interest.

(3B) Steel-frame buildings with ordinary damage-control features.

(3D) Steel-frame buildings with floors and roofs not concrete.

Due to unique structural characteristics, such buildings are more earthquake resistant than most other framed structures and especially are superior to bearing-wall systems.

In the fourth class, a subclass of special interest is:

(4D) Precast reinforced-concrete buildings and lift-slab structures.

Structures of these types are especially vulnerable to seismically-induced lateral forces unless special precautions are taken in connection details.

In the fifth class, a subclass of special interest is:

(5E) Buildings having unreinforced solid-unit masonry of unreinforced brick, unreinforced concrete brick, or unreinforced stone, or buildings of unreinforced concrete, where the loads are carried in whole or in part by the walls and partitions.

Structures of these construction types seem to be the least resistive to earthquake forces, and considerable damage often is observed due even to small and moderate earthquakes. Damage can range from minor to serious cracking of walls, which may cause large economic losses, and from partial to total building collapse, which endangers life safety as well as causes property losses.

Generally speaking, steel-frame and wood-frame buildings are safer than are older concrete or masonry structures subjected to earthquake forces.

The other building classification scheme is derived from work of the H.C. Hughes Company, structural engineering consultants that prepared the USGS report on earthquake losses in the Salt Lake City area [2]. The Hughes classification consists of seven main classes of buildings in order of their comparative seismic resistances. Roughly speaking, the seven classes are as follows:

(1) Small frame and metal buildings; and small specially designed structures with reinforced-concrete bearing walls.

(2) Large frame and metal buildings; large low-rise reinforced-concrete or steel-frame structures with reinforced-masonry or concrete shear walls, and built after 1970; and small specially designed structures with reinforced-masonry bearing walls.

(3) Large low-rise reinforced-concrete or reinforced-masonry

structures built in the 1970's; and multistory reinforced-concrete or steel-frame structures, with reinforced-concrete or reinforced-masonry shear walls, built in the 1970's.

(4) Multistory high-rise steel-frame structures built in the 1970's; multistory masonry bearing-wall structures built in the 1970's; large reinforced-concrete or reinforced-masonry structures built in the 1960's; and multistory reinforced-concrete or steel-frame structures, with reinforced-concrete or reinforced-masonry shear walls or bracing, built before 1970.

(5) Large reinforced-concrete or steel-reinforced-masonry buildings using precast elements on walls or floors and roof, and built after 1970; large reinforced-concrete or steel or reinforced-masonry structures built prior to 1961; and multistory steel-frame or masonry bearing-wall structures built between 1961-1970.

(6) Multistory reinforced-concrete structures built after 1970 and with lift-slab construction; multistory masonry bearing-wall structures built before 1961; and small structures with unreinforced-masonry bearing walls, and wood floors and roof.

(7) Large multistory structures with unreinforced-masonry bearing walls, and wood floors and roof; precast-concrete frame or wall structures built prior to 1970; and any category with apparent structural design weakness.

The significance of the dates in the foregoing classification scheme depends upon the presumption that the structure was built in accordance with the Uniform Building Code in effect at the time, unless site inspection or other data indicate otherwise. On such an assumption, structures built before 1961 are designed only for gravity loads and wind forces, those built from 1961 to 1970 are designed for earthquake forces in accordance with UBC seismic zone 2[2] provisions or less, and those built in the 1970's are designed in accordance with the more recent UBC seismic provisions and zone map (see Figure 2) (Cf. [2], p. 91).

Site inspection may, in particular cases, override these general assumptions.

An examination of both building classification schemes also leads to the conclusion that their use requires judgement and some guesswork. Users of the first classification scheme must employ the notions of ordinary, intermediate, and superior damage control features for earthquake resistance, and these are not readily apparent in most structures. The second classification scheme contains some 13 structural characteristics which, if the scheme were complete, would lead to a matrix containing at least $2^{13}$ separate categories. Practically speaking, such a large number of classes would be

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[2]Zone 2 is designation of seismic hazard contained in the pre-1971 editions of the Uniform Building Code. The UBC zone designations and associated seismic design standards have been changed since then for the Wasatch Front.

unmanageable, and it would be nearly impossible to classify buildings correctly. For this report, then, the classification schemes are used basically to grade given structures on their comparative seismic vulnerability, and it is accepted that some error of classification may occur in a few cases. Also, the incompleteness of the categories leads to possible alternative classifications of given structures, even though the user has a general notion of what features make a structure more or less vulnerable to earthquake effects.

Both building classification schemes have been utilized in this study, but for different reasons. The Algermissen and Steinbrugge classification scheme was used for the purpose of estimating property losses caused by a range of earthquake intensities and for a variety of construction types. There is no comparable information from which to make similar estimates using other available building classifications. The Hughes classification scheme, as used in the USGS study of earthquake losses in the Salt Lake City area, was the basis for estimating life losses and injuries due to building failures. Again, no comparable information from which to make similar estimates is available that would permit use of some other building classification scheme. Thus, in order to utilize available research data and to avoid additional research, we have utilized portions of both classification methods to separately derive property loss and life safety estimates. Tables 2 and 3 indicate the distribution of fire stations and police facilities in accordance with the classification systems described above, each by seismic zone.

## PART D: ESTIMATED EARTHQUAKE LOSSES TO BUILDINGS GENERALLY

Using data on the location of various structures and on their structural types, on can estimate long-term losses due to ground-shaking for classes of buildings according to construction type and use. Since there are two classification schemes for structural types, two separate estimates can be made for any given facility. The first estimate, based upon Algermissen and Steinbrugge taxonomy, is used to determine expected dollar loss. The second estimate, based on the USGS taxonomy, provides information on expected number of structural failures that is used to estimate life loss and injuries. Failure is defined here as occurring when loss due to damage exceeds 50 percent of replacement cost and is an indication of extent of damage from which casualty estimates may be made.

Details of specific calculations for estimates are made available in Appendix C on methodology. Those structures in Zone U-4 have the greatest estimated structural losses, and structures of unreinforced-masonry construction have higher expected losses than those of any other class. For one set of estimates, the average 100-year expected dollar loss to buildings in class 5E, (unreinforced-masonry construction) exceeds 9% of the replacement cost. For the other set of estimates, one can expect almost 29% of the structures in class 7 (multistory buildings with unreinforced-masonry bearing-wall construction) in Zone U-4 to suffer from structural nonfunctionality over a century.

If one takes all five classes and their subclasses as defined by

Algermissen and Steinbrugge and compares the expected loss in each category and zone against that subclass having the maximum expected loss, which occurs in category 5E and in Zone U-4, one derives the comparative expected dollar losses to buildings as shown in Table 4. The numbers given are comparative against a base of 100 and so also may be viewed as comparative percentages--that is, for each $100 loss to class 5E structures in Zone U-4, there would be, comparatively speaking, just $20 loss to class 4E structures in Zone U-3, or 20 percent of the base line loss.

Several conclusions can be drawn from Table 4 that are confirmed by other means as well. In the first place, the expected loss to structures in Zone U-1 is very small in comparison to the expected loss in the other three zones. Losses to structures in Zone U-1 add little to expected total ground-shaking losses in the State. In the second place, the average expected loss to a structure in Zone U-3 is less than one-third of what it would be if it were in Zone U-4, and the expected average loss to a structure in Zone U-2 is about one-sixth of what it would be if it were in Zone U-4. For purposes of comparison, then, the approximate ratios of one-third and one-sixth give one a rough idea of how the zones differ in seismicity. As a result, some steel-frame structures in Zone U-4 have higher expected losses than any type of structure in any other seismic zone. In the third place, wood-frame and metal-frame structures can be expected to fare considerably better than other structures, and steel-frame structures, except for those in the worst subcategories, are also comparatively safe.

A similar table can be constructed on the basis of the Hughes taxonomy. Table 5 shows the results abbreviated to Zone U-4.

The Hughes taxonomy, to repeat, is gradated in terms of comparative seismic resistance.

Tables 4 and 5, based on comparative estimates, indicate which types of structures are most preferable in a given seismic zone and also, by implication, how the zones compare in seismicity. Tables 4 and 5 do not, though, directly indicate which specific structures are either most economically replaced or retrofitted. Only classes of structures are treated.

In order to consider comparative suitability for replacement, one must take into account the seismic zone and type of structure that serves as the replacement. If all structures could be moved from a zone of high seismic risk to one of lower or no risk, then, of course, tables 4 and 5 would indicate that nearly all expected losses or structural failures due to earthquakes could be eliminated. Since such relocation is not practical, it is here assumed that the hypothetical replacement structure remains within the same earthquake zone as the original structure. Consequently, earthquake losses or structural losses can only be minimized within the zone rather than eliminated altogether. As regards the Algermissen and Steinbrugge taxonomy, it is here assumed that a building of class 5 will be replaced by the most earthquake-resistant building of class 5, that a building in class 4 will be replaced by the most earthquake-resistant building in class 4, and so on. Hence, the most earthquake-resistant structures in a given class are not considered as being suitable for replacement.

Given such assumptions, one can define the preventable loss to a given structure by replacement as the difference between its expected loss and the expected loss to the most earthquake-resistant structure in its class. It turns out that the maximum preventable loss through replacement is for buildings in class 5E in Zone U-4, and amounts to 8 percent of the replacement cost of the structure over 100 years. Using the maximum preventable loss as the standard, one can compare the loss reduction benefits of replacing various structures in various seismic zones. If, further, one uses the ratio of one-third for Zone U-3 and one-sixth for Zone U-2, one can abbreviate the comparisons to a table for Zone U-4. Table 6 gives such an abbreviation.

From Table 6, one can identify those structures that would be most worth replacing in terms of structural losses. For example, it would be more beneficial to replace some steel-frame structures (classes 3B and 3D) in Zone U-4 than any structures in the other seismic zones (the maximum for any other zone is 1/3 times 100, or 33). Using the ratios of one-third and one-sixth, one can conclude that it would be more beneficial to replace even class 5D structures in Zone U-4 than any structures in Zone U-2 (the maximum for Zone U-2 is 1/6 times 100, or approximately 17).

A similar abbreviated table can be constructed based on the Hughes taxonomy, on the assumption that any replaced structure remains within its seismic zone and turns out to be at least a class 2 structure. On such assumptions, the standard for replacement consists of class 7 structures in Zone U-4, which would have expected reduced cases of nonfunctionality of about 25 percent of the replacement cost over 100 years. Table 7 gives such data, again only for seismic Zone U-4. Ratios of one-sixth for Zone U-2 and one-third for Zone U-3 can be applied here also for comparsions.

Table 7 implies that replacement of even the worst sort of structures in Zone U-3 would barely have more expected seismic safety benefits than replacement of class 4 structures in Zone U-4. Once again, seismicity of the location is a dominant factor in evaluating the benefits of replacement.

Suitability for being retrofitted, though, produces a different set of rankings than does suitability for being replaced, because certain types of buildings can be retrofitted much more cheaply than others. So, the preventable loss per dollar spent on retrofitting also will depend upon how many dollars need to be spent to retrofit a given type of structure.

Based upon assumptions clarified in Appendix C on methodology, masonry structures were considered to be retrofitted at a cost of 22 percent of the replacement value of the building, concrete structures at 13 percent of the replacement value of the building, and steel-frame structures at 9 percent of the replacement value of the building. The comparative ease of retrofitting steel-frame structures, as implied by the lower cost, means that, if the benefits of such retrofitting were equal with the benefits of retrofitting other sorts of structures, then the value of such retrofitting per dollar spent would be greater for steel-frame structures.

In order to estimate the benefits of retrofitting various buildings, the following assumptions are made in terms of what can be achieved through retrofitting.

-- Class 5E multistory (3 or more story) structures can be converted into Class 5C (equivalent) structures.

-- Other Class 5E, and all Class 5D and 5C structures can be converted into Class 5B structures.

-- Class 4 structures can be converted into Class 4C structures.

-- Class 3B and 3D structures can be converted into Class 3C structures.

Such assumptions, based partly upon the fact that the taxonomy used can be regarded as being gradated and upon the view that less can be done to multistory masonry structures, imply that only selected structures are considered as being suitable for retrofitting. Just as retrofitting structures in Zone U-1 would yield few returns, retrofitting wood-frame or metal-frame structures also would produce few benefits.

A similar set of assumptions is made in terms of the Hughes taxonomy.

-- Masonry structures can be converted into Class 3 structures.

-- Steel-frame and concrete structures can be converted into Class 2 structures.

Such assumptions result in another set of priorities as to which sorts of facilities should be examined first for the purposes of being retrofitted. If one lets retrofitting of class 5E buildings in Zone U-4 be the standard for retrofitting, so that one can compare structures by class and zone for preventable loss per dollar spent, than one develops the abbreviated data for Zone U-4 shown in Table 8.

Here also, Zones U-3 and U-2 can be estimated by means of the ratios of one-third and one-sixth, respectively. Table 8 suggests that, in some cases, retrofitting steel-frame structures may have almost as much benefit per cost as retrofitting masonry structures. This information contained in Table 7 is further developed in Table 9 to give information about comparative structural failures, based upon the Hughes classifications.

Table 9 indicates that, given different price estimates to retrofit different types of structures, the most seismically vulnerable steel and concrete structures can be retrofitted with more expected benefits per dollar spent than can masonry structures. Steel-frame structures, it is true, are comparatively safe from collapse when subjected to earthquake forces. In the 1906 San Francisco earthquake, none of the 17 high-rise steel-frame structures collapsed ([2] p. 86). Yet, hazards may exist even where structures are fairly safe from collapse, such as may be caused by falling ceilings, fixtures, etc., and Tables 8 and 9 take into account the comparative safety of steel-frame structures as well as the comparative ease with which they can be upgraded.

Hence, ranking of buildings for retrofitting is not identical with ranking of buildings for replacment, since cost estimates for retrofitting vary with the severity of the problems faced in retrofitting. How ever one may choose to evaluate the information presented in Tables 4 through 9, the highest priorities for either retrofitting or for replacement are for the vulnerable buildings in Zone U-4.

## PART E: VULNERABILITY ASSESSMENT OF FIRE STATIONS TO EARTHQUAKE DAMAGE AND MITIGATION ALTERNATIVES

Owing to the fact that fire stations house critical personnel, fire-fighting equipment, and communications equipment, fire stations are here treated as being indispensible in a major earthquake. To justify this position, one might attempt to analyze the dollar value of the loss of a given fire station in terms of resulting increases in total insurance costs, or by some other means. However, such an attempt would be highly speculative and depend upon many factors, such as the expected quantity of the water supply, that are beyond the scope of this report. For this report, we have simply begun with the view that fire stations remain functional, based upon experiences by other communities that have experienced earthquakes. During the San Fernando Valley earthquake, for instance, the need for major services, such as those provided by fire personnel, increased between 300 and 700 percent ([9], p. 1).

The main concern in this part of the report is to provide an assessment of the comparative structural functionality of fire stations and to provide rankings of those fire stations that most beneficially could be replaced or retrofitted in order to reduce structural losses due to earthquakes.

In accordance with the characterization made by Richard Hughes, structural engineer, the definition of "functionality" used in this report will be that 50-percent structural damage renders structures non-functional (see Appendix C of this report). We shall regard non-functionality, then, chiefly in terms of structural damage.

Such a definition of non-functionality covers almost all, but perhaps not all, emergency problems that earthquakes might cause to fire services. Total functionality covers protection of personnel, essential or critical equipment, access routes, and centricity for disaster efforts in regard to medical, communication, and other services. If the structure does not collapse, then most other problems will be averted. Yet, some problems, such as when the large overhead doors are jammed due to racking, are not covered under the definition used (Cf. [2], p. 196).

It is here assumed that problems of egress, whether caused by parapets that have fallen, power generators that have ceased to work, or problems of racking, can be handled by the workers on the spot, so that only time will be lost in clearing away debris or finding some means to open the doors. In some instances, it is admitted, such problems not due to structural non-functionality may render the fire service inoperative. These are not directly considered in our analysis.

One hundred forty four fire stations in Utah were surveyed in this study. Base data were drawn from a Statewide survey of public buildings by

Einar Johnson at the Utah State Building Board and from information provided by Richard Hughes. All surveyed fire stations were evaluated both in terms of structural type and location. Figure 7, which indicates the location of fire stations surveyed, shows that the majority of such fire stations lie in the most seismically active zone. Of the surveyed fire stations, 87 lie in Zone U-4, 18 in Zone U-3, 19 in Zone U-2, 13 in Zone U-1, and 7 in Zone U-0. Since the State Building Board survey by Einar Johnson attempted to include all major public facilities in Utah, and since there were only four known facilities for which data were insufficient, it is expected that those surveyed yield a reliable picture of the distribution and general structural features of fire stations in the State. A few of the fire stations were examined in more detail, but this report only purports to provide policy information on an aggregate rather than a building-by-building basis.

Tables 2 and 3 provide more detailed counts of the surveyed structures by zone and by structural type.

Table 2 indicates that almost half of the fire stations are in class 5E. Almost 30% are in class 5E and in Zone U-4. Table 3 indicates that the fire stations are distributed among all the main categories, and so have a wide range in their capacity to withstand earthquakes.

The results here developed to reflect expected collapses do not also take into account nonfunctionality due to faulting. As a specific case, in Salt Lake City, one recently built fire station is on the Wasatch fault. The methodology used herein does not consider this additional aspect of vulnerability.

Fire stations included in this survey range widely in size. This is partly because it was decided to include as fire stations those municipal structures that house local fire departments plus other governmental services. Some stations were less than 500 sq. ft. in gross area; others covered more than 20,000 sq. ft.

Gross area of surveyed fire stations was about 640,000 sq. ft., of which over 70% lies in Zone U-4. Almost half the gross area lay in class 5E structures, and over 30 percent lay in class 5E structures in Zone U-4. Almost 13 percent lay in category 7, and another 28 percent lay in category 6.

Based on figures provided by Bill Erickson (at Boyd Blackener and Associates, Architects), the cost of a fire station was $53 per sq. ft. in July, 1978. Based on cost per square foot, the overall replacement cost of all fire stations exceeds $34 million (July, 1978 dollars).

Based on estimates developed in Appendix C on methodology, Tables 10 and 11 indicate expected earthquake losses to fire stations in Utah. Table 10 loss estimates are in dollars; Table 11 loss estimates are in numbers of buildings.

Buildings surveyed in Zone U-4 have more mean square footage than in the State as a whole. Hence, the estimated area loss due to nonfunctionality is estimated at about 10.7 percent.

The prinicpal ways that are available to minimize nonfunctionality in fire stations are to replace them or to retrofit them. Note is made that, on a statistical basis, even replaced or retrofitted buildings also have some chance of being damaged, although much less so than for the non-earthquake-resistant original structures. If all fire stations were replaced, then one derives losses to hypothetical replacement structures as shown in Tables 12 and 13.

The data thus indicate that replacement of all fire stations by structures more seismically resistant would reduce expected groundshaking losses by almost $1.3 million, and would prevent about 10 failures in functionality over a 100-year period. These reduced losses do not justify a Statewide effort of replacement or retrofitting of all or nearly all existing fire stations, at a cost expected to exceed $34 million, to accomplish the goal of greater earthquake safety for Utah citizens.

There is, however, other helpful information to be drawn from the data. Most of the benefits of replacment come from replacement of unreinforced masonry structures in Zone U-4. Sixty seven percent of the total preventable dollar loss exists in class 5E buildings in Zone U-4. If one replaced only the 60 structures in classes 5E, 4D, 5D, and 5C in Zone U-4, then one would have reduced the preventable loss by almost 93 percent of what is possible. Similarly, if only those structures that are in categories 5, 6, 7 in Zone U-4 were replaced, 83 percent of the preventable cases of nonfunctionality would be included. In short, concentrated replacement efforts would appear to be more cost-effective than a blanket replacement effort, provided the concentrated effort were first directed toward the worst class of structures in Zone U-4.

Cost-effective retrofitting, though, is determined in accordance with a different list of priorities, as was explained in previous sections. Nonetheless, data available do not suggest that there are any steel-frame fire stations in the worst category and in Zone U-4. So, for surveyed fire stations, the priorities for replacement and for retrofitting are practically identical.

The estimated 100-year preventable structural losses through retrofitting is over $1.2 million, or almost as much as is preventable through replacement. Yet, the estimated cost of retrofitting is about $5 million, or $29 million less than comparable replacement cost. Almost 95 percent of the preventable losses exist in Zone U-4, and over 70 percent of the Statewide preventable losses come from retrofitting class 5E structures in Zone U-4. The cost of retrofitting structures in Zone U-4 is about $4 million, and the cost of retrofitting class 5E structures in Zone U-4 is about $2.4 million.

Based upon the Hughes classification system, 88 structures could be strengthened through retrofitting. There could be 9 preventable structural failures per century at a cost of slightly less than $5 million. About 7.9 of these preventable collapses lie in Zone U-4, where the retrofitting cost is estimated at $3.3 million. In Zone U-4, there are 9 concrete structures in categories 5, 6, and 7 that could be retrofitted at about $1.7 million to prevent an estimated 5.7 structural failures.

So, retrofitting produces more estimated seismic benefits per dollar than does replacement, and emphasis upon the worst categories of concrete and masonry structures in Zone U-4 removes most of the estimated preventable loss.

## PART F: VULNERABILITY ASSESSMENT OF BUILDINGS HOUSING POLICE STATIONS TO EARTHQUAKE DAMAGE AND MITIGATION ALTERNATIVES

Whereas fire stations are regarded in this report solely in terms of their potential for collapse, or for structural loss, police stations are here considered, like other public structures, in terms of their overall vulnerability to earthquake damage, including nonstructural loss, and as compared with the costs of replacing or retrofitting such structures.

Police facilities include several operational funtions that have implications for earthquake safety. Foremost among these are the communications systems that police departments operate. In fact, it often is the case that the police communications center serves as the dispatch center for a variety of other governmental communications, including any emergency operations center that the government unit might have established. Police facilities also sometimes house vehicles, although most often these either are in use or are parked in open areas. Safeguarding of the communications systems and personnel and the emergency vehicles, then, are the more important considerations in ensuring the operational capabilities of police departments.

Most police facilities also include confinement facilities for prisoners. Sometimes, the jail occupancies are very large for larger communities. The possibility of earthquake damage to such facilities poses numerous problems, involving prisoner safety, security, and legal liability considerations.

Experience in the San Fernando Valley earthquake at the San Fernando Juvenile Hall indicates some possible consequences to jails if structural failure occurs:

> Partial roof collapses jammed heavy security doors. Power failure rendered locking systems inoperative, security window screens prevented access to or egress from many rooms, lights were out, halls blocked, lockers and other furniture were scattered about, dangerous crevices (1 1/2" wide) existed in the floors, a jammed lock made emergency lights inaccessible, telephone lines were inoperative, fire warning lights were activated, and leaking gas began to concentrate (Cf. [11], Vol. II, p. 290).

Evidently, a variety of problems may exist in connection with jails, especially older or more vulnerable ones. In this report, however, we have not addressed these problems, other than to point them out.

From data derived from surveys by Einar Johnson at the Utah State Building Board and supplemented by data from Richard Hughes, structural engineer, 128 buildings were surveyed within which are located police stations. Such buildings range considerably in size, inasmuch as some police stations are separate structures and very small, and other police departments are housed in large municipal centers.

In terms of building types, Table 3 summarizes the buildings surveyed in terms of the building classifications already referred to.

As can be seen in Figure 8, many of these facilities lie in the worst Utah earthquake zone, Zone U-4, but not all. A number also are located in less active seismic zones that must be considered to be potentially vulnerable.

Many of the structures are very old. In Zone U-4, 12 of the structures appear to have been built during or before 1930. In Zone U-3, 14 structures were built during or before 1930; 8 such older structures exist in Zone U-2. In the State as a whole, of the 128 surveyed structures, 37 appear to have been built during or before 1930. Age, of course, provides a good indication of earthquake vulnerability for certain types of construction, such as masonry construction.

For benefit-cost analysis purposes, assumptions must be added concerning occupancy rates for such structures. Building losses alone cannot, in principle, justify in benefit-cost terms replacing structures. As also is explained in Appendix C on methodology, building losses alone are most unlikely to justify the retrofitting of structures for seismic safety. Life safety considerations necessarily are a part of any such evaluation.

For the general class of buildings housing police stations, we have assumed that during the normal working time of the day there would be one occupant every 150 square feet. For the rest of the day, larger structures are considered to have one-fifth as many occupants, and smaller structures (under 2,000 square feet) are considered to have just one occupant. Resulting occupancy rates are thus fairly high. But, just as larger earthquakes that cause considerable damage occur infrequently, so too, a larger earthquake that occurs at peak hours and when occupancy loads are at a maximum may cause more injuries than if the earthquake occurs at other times. Short-term histories of earthquake fatalities and casualties, thus, may be very misleading owing to the numerous factors affecting deaths and casualties that may cause wide variations over the long term.

Three broad alternatives were selected for evaluation in this study: (1) the existing structure is left as it is; (2) the structure is fully retrofitted to be seismically stronger; and (3) the existing structure is fully replaced by one that is earthquake resistant. As concluded from photographs taken for the Utah State Building Board survey, a number of other possible earthquake hazards could be pointed out for correction in existing facilities, such as porticos that might fall, unsafe parapets or cornices, potential egress problems, and facades that may fall. However, these are random occurrences that require analysis on a building by building basis. Although remedies for such potential hazards are far less costly than major replacement or retrofitting operations, the scope of this initial study of essential facilities was not planned to furnish such detailed information.

The benefit-cost results are clear for the three alternatives named above: On the aggregate level, the alternative of allowing structures to continue in use to the end of their life-span is more economic than either replacing them or retrofitting them. This is so even if allowance is made for replacement costs due to any estimated future earthquake damage.

For the State as a whole, the replacemet cost of critical facilities surveyed is over $88 million. Just over 4 deaths and 67 injuries are expected in such buildings every 100 years. Based upon Steinbrugge-Algermissen data, estimates of this study are that the present expected value of long-term losses is $350,000. Based upon the Hughes taxonomy for loss estimates, about 11 percent of all police stations and other essential facilities are expected to suffer from nonfunctionality over 100 years. If all structures were replaced, then the estimates are $77,000 and 2 percent, respectively. So, in order to justify replacement, the value of life would need to be set at almost $600 million. These estimates, of course, disregard the potential life loss in other facilities if needed emergency services could not be provided after an earthquake. Tables 14, 15, and 16 summarize some of this statistical data according to seismic zones.

Retrofitting is the more economic alternative. If all existing structures are retrofitted, then the cost of retrofitting would be around $10 million. Based upon data from Steinbrugge-Algermissen, this study estimates the present value of losses prevented by retrofitting to be about $200,000. From estimates based upon the Hughes taxonomy, long-term structural failures prevented by retrofitting would apply to about 8 percent of all police stations and other essential structures over 100 years. In order to justify retrofitting, one would still need to set the value of life at above $30 million.

One likely would want to evaluate the cost of other programs for the prolongation of life before committing oneself to a costly program of replacement or retrofitting all police facilities and other essential facilities for earthquake safety. Although we have not here made other such studies, the benefit-cost ratios obtained do not appear to be favorable for the alternatives that were considered.

If the value of life is set at an economic estimate of $1 million, then benefit-cost ratios for replacement are still less than 1:100 and those for retrofitting are about 5:100. Even for the most favorable case, that of retrofitting a vulnerable steel-frame structure, the ratio still lies below 16:100. So, for no class of essential facilities or no single essential facility in Utah can replacement or retrofitting be justified in benefit-cost terms. The question then arises: Can improved earthquake safety be accomplished for any essential facility in any cost-effective manner? Selective and limited retrofit of the most hazardous buildings affords such opportunities.

Selective and limited retrofit, as used here, refers to selective identification and removal of isolated hazardous conditions in a building that may be unique to that building. Such an effort requires that each and every building be reviewed for the purpose of identifying those construction elements most likely to fail when subjected to earthquake forces. While the process of identifying such elements requires a special kind of expertise and is costly to do, the findings of this study regarding poor benefit-cost ratios for full retrofit or replacement lead to the conclusion that selective and limited retrofit is, in the long run, more appropriate. Moreover, a selective and limited retrofit effort can be applied so as to ensure cost-effective investment while improving the earthquake safety of essential fire stations and police facilities.

For some structures, other hazards may, when combined with earthquake hazards, justify either replacement or retrofitting, at some added cost. This study does not consider such comprehensive examinations of buildings for all sorts of hazards. Here, just seismic benefits and costs are considered in relative isolation from other benefits and costs.

Less costly seismic adjustments to structures also may be justified by future technological developments that may prove to provide inexpensive means to improve the earthquake resistances of buildings. This study also does not cover such possible developments.

Idiosyncracies of the data were analyzed for the purpose of evaluating the validity of the conclusions reported above. One observation is that the large number of older structures may lead to an underestimate of expected losses, and to a bias in the benefit-cost analysis where it is assumed that older structures are replaced when their normal life-span is over. The age of buildings is only an indication of earthquake resistance, and sometimes older structures may be weaker than assumed. In at least one case, comparatively small earthquakes have been surmised to cause structural damage as a result of the weak condition of the structure (Cf. [10], especially p. 5).

## PART G: SOURCES OF DATA

In addition to sources of data listed in the references, of special mention is that data on essential facilities which comes chiefly from a survey made by Einar Johnson at the Utah State Building Board. Data exist, or almost every publicly owned building, on the following matters: Building number, location, number of stories, construction date(s), floor area, type of structural frame, and type of exterior wall system. Given such data, it is possible to use the methods described in Appendix C, provided that the information on building types is translated into the building classifications suggested in the report.

Richard Hughes, structural engineer with the H.C. Hughes Company, also was a source of valuable information on Utah construction, and much of his data was introduced both directly and indirectly into the report.

With the help of Ronald Ivey, building inspection supervisor with the Salt Lake County building department, we were able to obtain all copies of the Uniform Building Code back to 1949, except for the 1955 edition. This information also has been useful for estimating the earthquake-resistant characteristics of buildings constructed during particular eras.

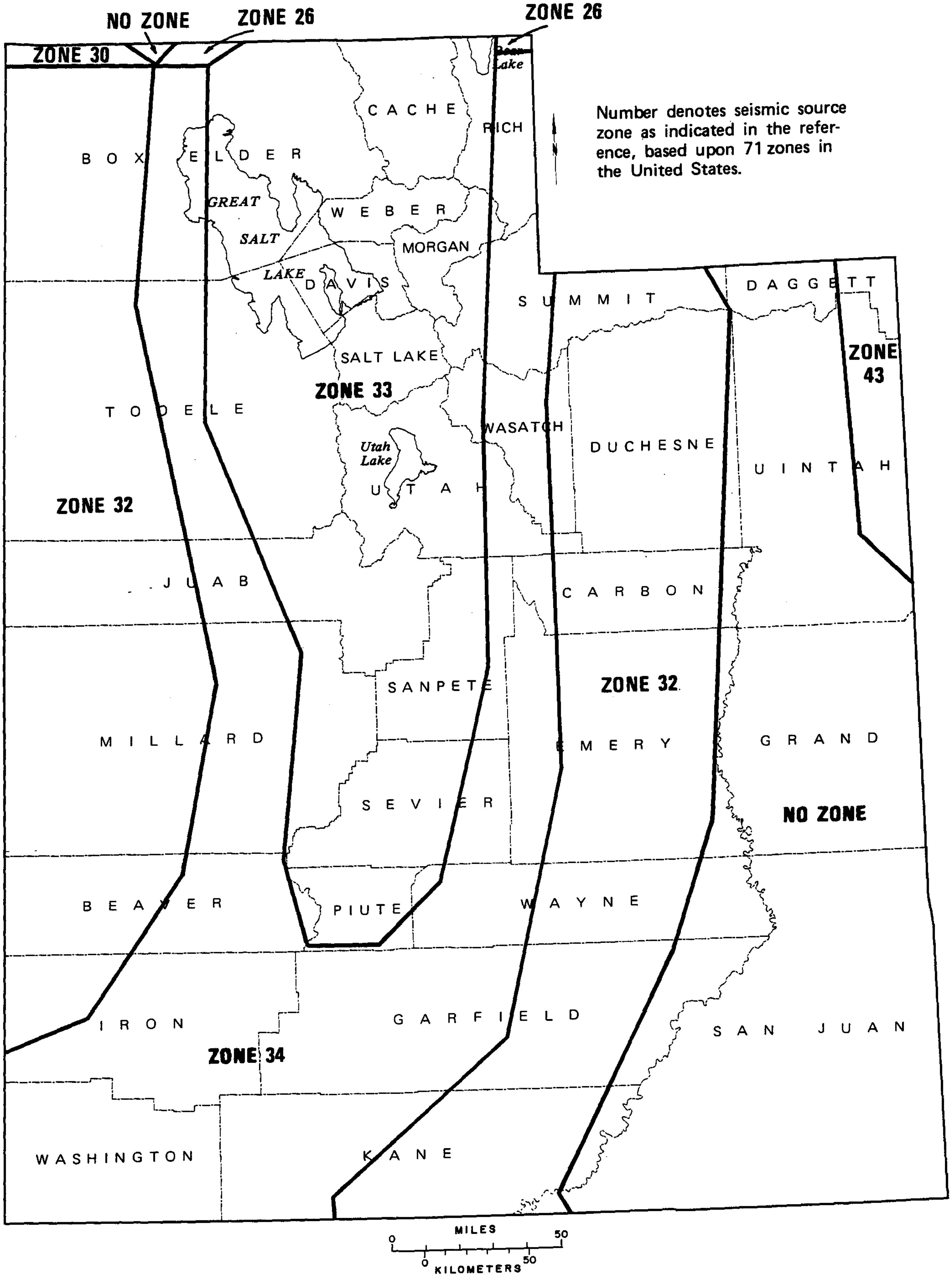



Figure 1

SEISMIC SOURCE AREAS IN UTAH

(Reference: S.T. Algermissen, and D.M. Perkins, USGS Open File Report 76-416)

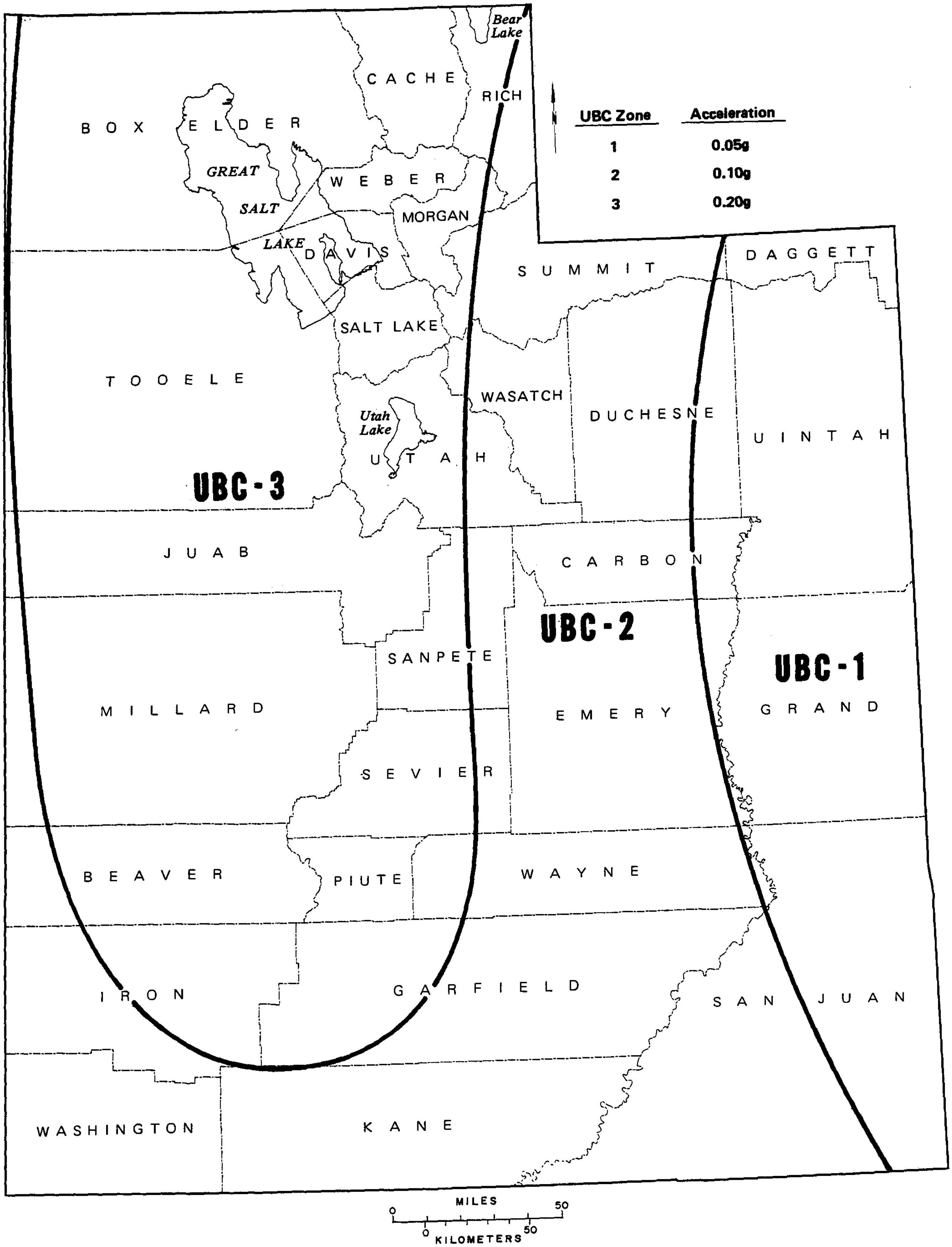



Figure 2
SEISMIC ZONES—1976 UNIFORM BUILDING CODE
STATE OF UTAH

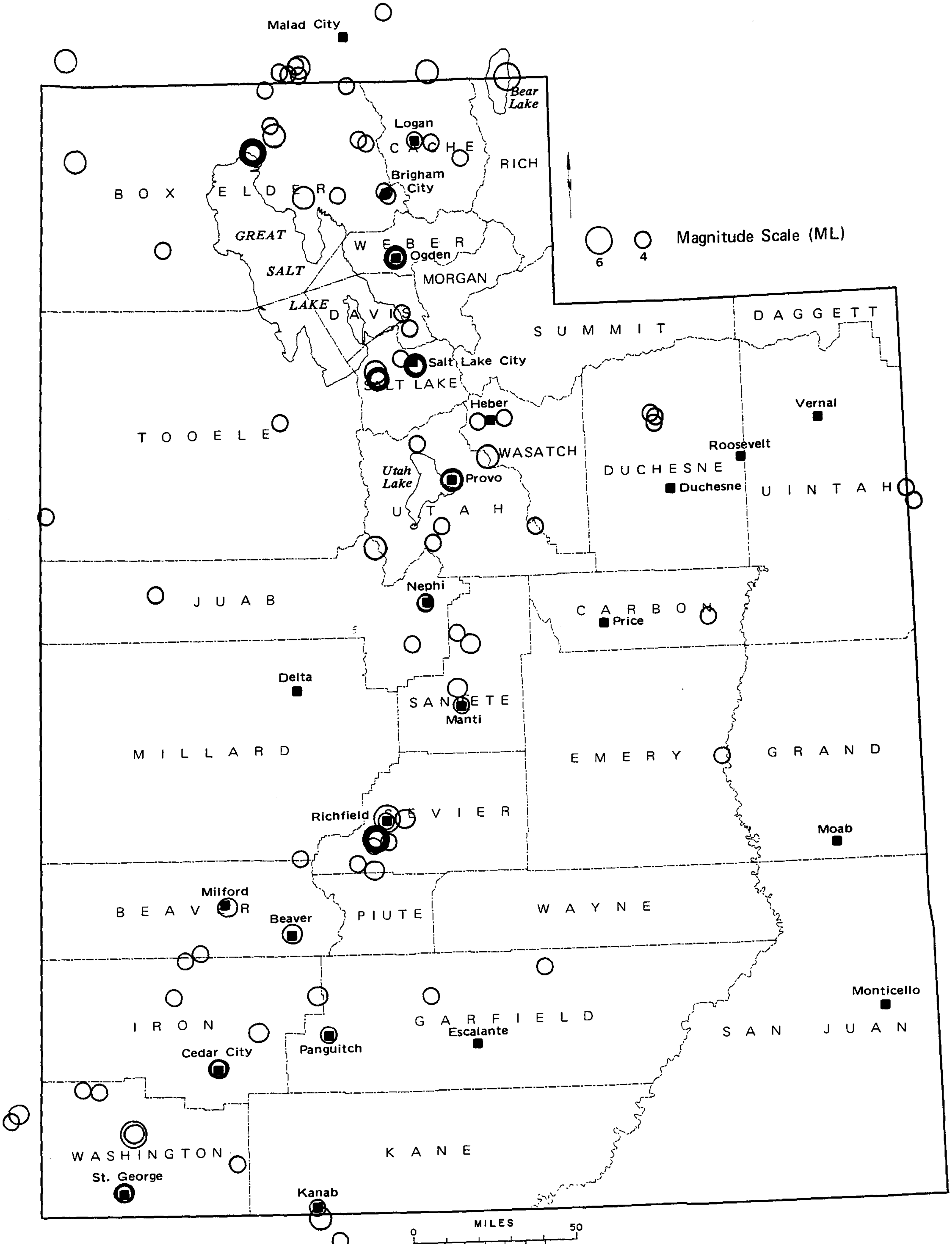



Figure 3

HISTORICAL SEISMICITY IN UTAH -- 1850 - JUNE 1978

MAGNITUDE 4.0 (INTENSITY V) OR GREATER

(Reference: *Earthquake Studies In Utah,* W.J. Arabasz, R.B. Smith, and W.D. Richins)

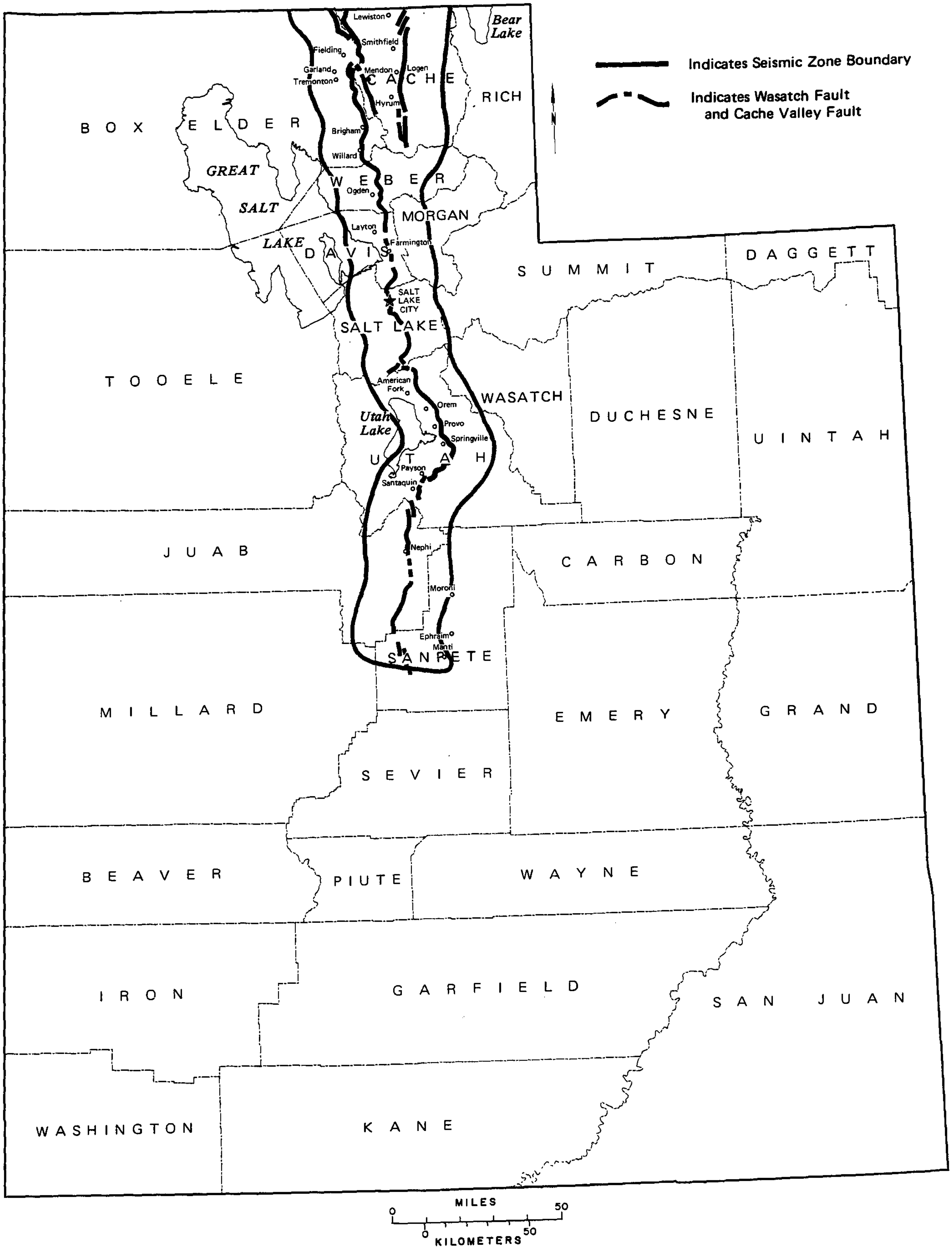
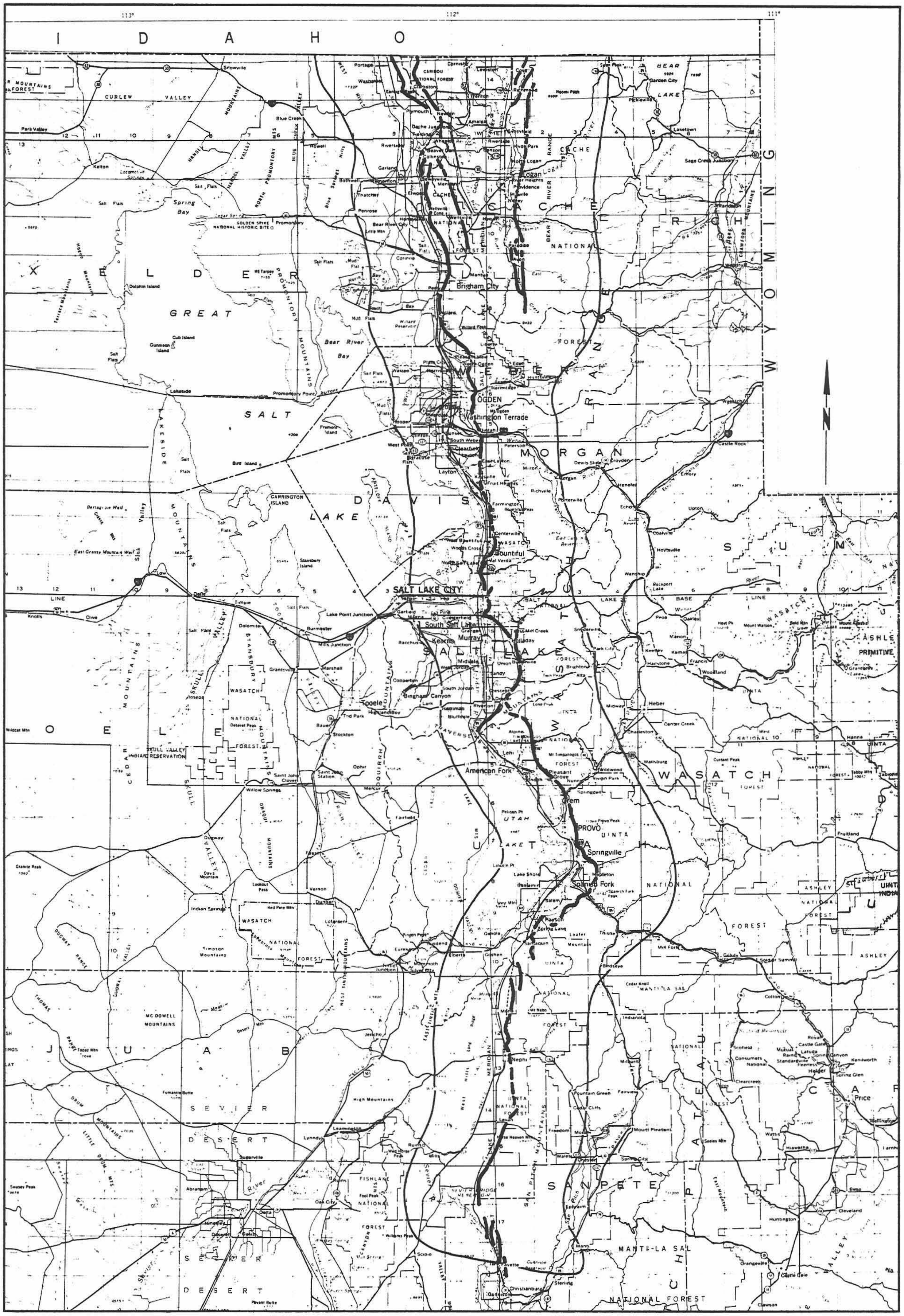



Figure 4
WASATCH FRONT SEISMIC ZONE, WASATCH AND CACHE VALLEY FAULTS
STATE OF UTAH



0 10 20 30 40 Miles
0 10 20 30 40 50 Kilometers

Figure 5

**WASATCH FRONT SEISMIC ZONE**

**STATE OF UTAH**

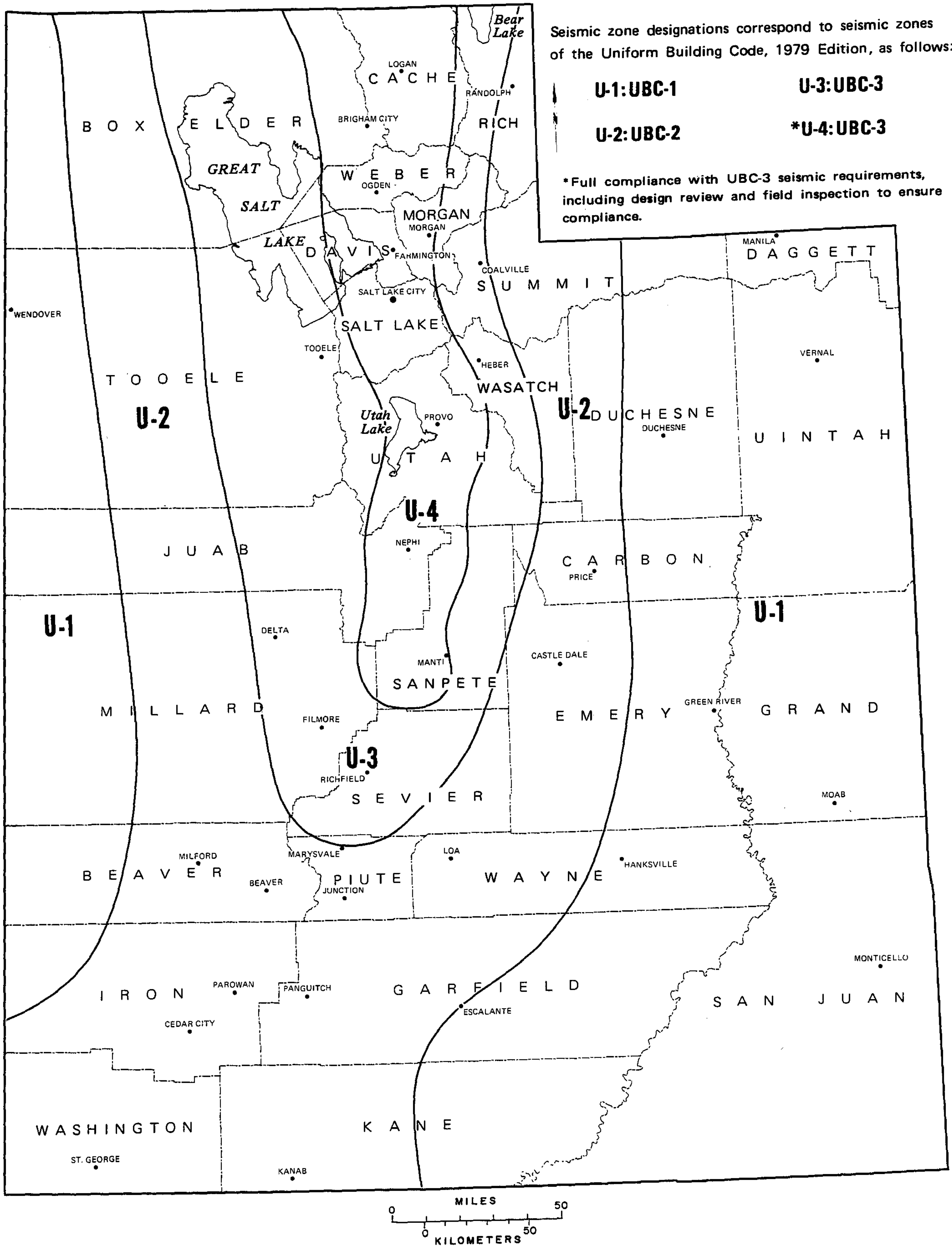



Figure 6

**SEISMIC ZONES**

**January 1980**

(Recommended by the Utah Seismic Safety Advisory Council)

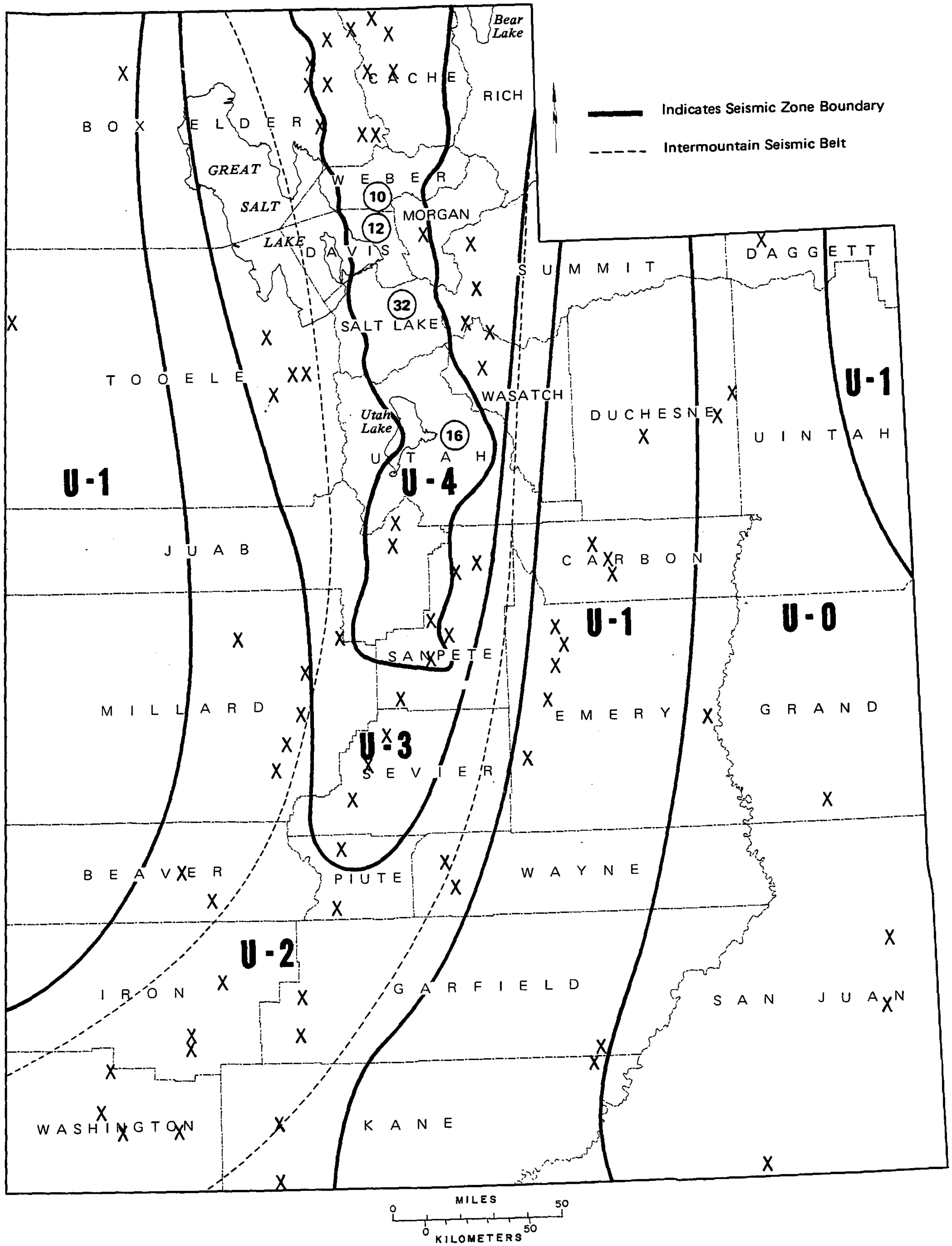



Figure 7

LOCATION OF FIRE STATIONS INCLUDED IN STUDY
STATE OF UTAH

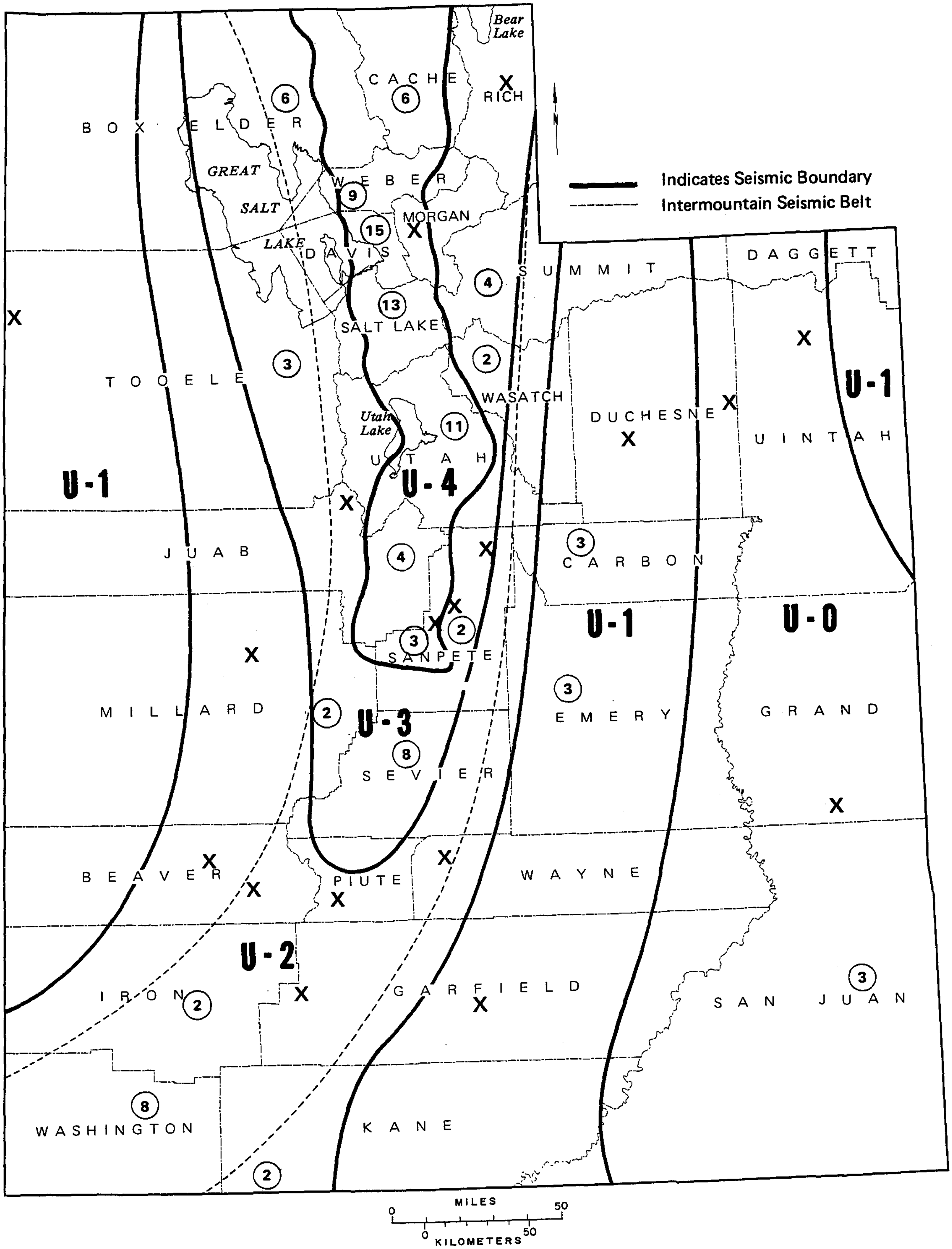



Figure 8

DISTRIBUTION OF POLICE STATIONS, JAILS, AND EMERGENCY OPERATIONS CENTERS SURVEYED BY SEISMIC ZONES AND COUNTY STATE OF UTAH

Table 1

DISTRIBUTION OF SELECTED ESSENTIAL GOVERNMENT FACILITIES IN UTAH BY SEISMIC ZONE AND BY TYPE OF USE

| Use of Facility | Seimsic Zone | | | | | Total |
|---|---|---|---|---|---|---|
| | Zone U-0 | Zone U-1 | Zone U-2 | Zone U-3 | Zone U-4 | |
| Fire Stations | 7 | 13 | 19 | 18 | 87 | 144 |
| Buildings Housing Police Stations | 6 | 8 | 17 | 25 | 72 | 128 |
| TOTALS | 13 | 21 | 36 | 43 | 159 | 272 |

TABLE 2

CLASSIFICATION OF SURVEYED FIRE STATIONS AND POLICE FACILITIES
IN ACCORDANCE WITH THE
ALGERMISSEN AND STEINBRUGGE CLASSIFICATION SYSTEM
AND BY SEISMIC ZONE

FIRE STATIONS

| Seismic Zone | Building Classification | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2A | 2B | 3A | 3C,4A 5B | 3B,3D 4C,5C | 5D | 4B | 4D | 5E | |
| Zone U-0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 7 |
| Zone U-1 | 0 | 1 | 0 | 0 | 2 | 2 | 0 | 0 | 8 | 13 |
| Zone U-2 | 1 | 0 | 3 | 0 | 5 | 3 | 0 | 0 | 7 | 19 |
| Zone U-3 | 1 | 0 | 1 | 0 | 5 | 3 | 0 | 0 | 8 | 18 |
| Zone U-4 | 2 | 3 | 8 | 13 | 8 | 9 | 1 | 3 | 40 | 87 |
| TOTALS | 5 | 5 | 12 | 13 | 20 | 17 | 1 | 4 | 67 | 144 |

BUILDINGS HOUSING POLICE STATIONS

| Seismic Zone | Building Classification | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2A | 2B | 3A | 3C | 3B,3C 4C,5C | 5D | 4B | 4D | 5E | |
| Zone U-0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 | 6 |
| Zone U-1 | 0 | 1 | 0 | 1 | 3 | 0 | 0 | 0 | 3 | 8 |
| Zone U-2 | 3 | 0 | 0 | 2 | 2 | 1 | 0 | 0 | 9 | 17 |
| Zone U-3 | 10 | 0 | 2 | 3 | 0 | 0 | 0 | 0 | 10 | 25 |
| Zone U-4 | 11 | 2 | 0 | 6 | 16 | 8 | 3 | 2 | 24 | 72 |
| TOTALS | 24 | 3 | 2 | 12 | 21 | 10 | 3 | 2 | 51 | 128 |

TABLE 3

CLASSIFICATION OF SURVEYED FIRE STATIONS AND POLICE FACILITIES
IN ACCORDANCE WITH THE
H.C. HUGHES COMPANY CLASSIFICATION SYSTEM
AND BY SEISMIC ZONE

FIRE STATIONS

| Seismic Zone | Building Classification | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | 1A | 1B | 2 | 3 | 4 | 5 | 6 | 7 | |
| Zone U-0 | 1 | 1 | 0 | 0 | 0 | 2 | 3 | 0 | 7 |
| Zone U-1 | 0 | 1 | 2 | 0 | 1 | 4 | 4 | 1 | 13 |
| Zone U-2 | 3 | 0 | 5 | 1 | 3 | 1 | 5 | 1 | 19 |
| Zone U-3 | 1 | 0 | 5 | 1 | 3 | 2 | 5 | 1 | 18 |
| Zone U-4 | 4 | 4 | 20 | 5 | 9 | 14 | 24 | 7 | 87 |
| TOTALS | 9 | 6 | 32 | 7 | 16 | 23 | 41 | 10 | 144 |

BUILDINGS HOUSING POLICE STATIONS

| Seismic Zone | Building Classification | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | 1A | 1B | 2 | 3 | 4 | 5 | 6 | 7 | |
| Zone U-0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 0 | 6 |
| Zone U-1 | 1 | 0 | 2 | 0 | 1 | 2 | 2 | 0 | 8 |
| Zone U-2 | 0 | 1 | 6 | 0 | 1 | 2 | 5 | 2 | 17 |
| Zone U-3 | 0 | 1 | 14 | 0 | 0 | 1 | 5 | 4 | 25 |
| Zone U-4 | 3 | 7 | 14 | 6 | 8 | 12 | 17 | 5 | 72 |
| TOTALS | 4 | 9 | 36 | 6 | 10 | 19 | 33 | 11 | 128 |

Table 4

COMPARATIVE PERCENTAGES OF EXPECTED DOLLAR LOSSES TO BUILDINGS BY STRUCTURAL TYPE AND SEISMIC ZONE

(Algermissen and Steinbrugge Categories)
(Loss to a Building of Class 5E in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2A | 2B | 3A | 3C,4A 5B | 3B,3D 4C,5C | 5D | 4B | 4E | 4D | 5E |
| Zone U-1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zone U-2 | 2 | 1 | 1 | 2 | 8 | 10 | 11 | 11 | 13 | 16 |
| Zone U-3 | 2 | 1 | 2 | 2 | 14 | 18 | 19 | 20 | 24 | 30 |
| Zone U-4 | 11 | 9 | 12 | 15 | 49 | 63 | 67 | 71 | 82 | 100 |

Table 5

COMPARATIVE PERCENTAGES OF EXPECTED STRUCTURAL FAILURES TO BUILDINGS BY STRUCTURAL TYPE IN SEISMIC ZONE U-4

(Hughes Taxonomy)
(Losses to Class 7 Structures in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1A | 1B | 2 | 3 | 4 | 5 | 6 | 7 |
| Zone U-4 | 4 | 7 | 12 | 22 | 38 | 60 | 78 | 100 |

Table 6

COMPARATIVE PERCENTAGES OF PREVENTABLE LOSSES THROUGH REPLACEMENT BY CONSTRUCTION CLASS IN SEISMIC ZONE U-4

(Algermissen and Steinbrugge Taxonomy)
(Preventable Losses to Class 5E Structures in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2A | 2B | 3A | 3C | 5B | 3B,3D | 5C | 5D | 4D | 5E |
| Zone U-4 | 3 | -- | -- | 4 | -- | 44 | 40 | 56 | 83 | 100 |

Table 7

COMPARATIVE STRUCTURAL FAILURES TO BUILDINGS IN SEISMIC ZONE U-4 THROUGH REPLACEMENT OF THE ORIGINAL STRUCTURAL TYPE WITH AN EARTHQUAKE RESISTANT STRUCTURE OF THE SAME TYPE

(Hughes Taxonomy)
(Preventable Losses for Class 7 Structures in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Zone U-4 | -- | -- | 11 | 30 | 54 | 74 | 100 |

Table 8

COMPARATIVE PERCENTAGES OF PREVENTABLE LOSSES TO BUILDINGS IN SEISMIC ZONE U-4 PER DOLLAR SPENT ON RETROFITTING BY BUILDING CLASS

(Algermissen and Steinbrugge Categories)
(Preventable Losses for Class 5E Structures in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | |
|---|---|---|---|---|---|---|---|
| | 3B,3D | 4D | 4E | 5C | 5D | 5E Lowrise | 5E Highrise |
| Zone U-4 | 98 | 66 | 44 | 40 | 56 | 100 | 72 |

Table 9

COMPARATIVE PERCENTAGES OF PREVENTABLE STRUCTURAL FAILURES IN SEISMIC ZONE U-4 PER DOLLAR SPENT ON RETROFITTING BY BUILDING CLASS

(Hughes Categories)
(Preventable Structural Failures for Class 7 Structures in Zone U-4 = 100%)

| Seismic Zone | Building Classification | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 |
| | Masonry | Concrete | Masonry | Concrete | Masonry | Concrete | Steel | Masonry | Concrete | Steel | Concrete | Steel |
| Zone U-4 | 100 | 169 | 71 | 141 | 57 | 103 | 149 | 22 | 57 | 82 | 18 | 27 |

Table 10

ESTIMATED 100-YEAR DOLLAR LOSSES TO FIRE STATIONS
BY SEISMIC ZONE AND AS A PERCENT OF REPLACEMENT COST

(1978 Dollars)

| Seismic Zone | 100-Year Total Loss | 100-Year Loss As A Percent Of Replacement Cost |
|---|---|---|
| Zone U-0 | $ 0 | 0.0% |
| Zone U-1 | $ 4,000 | 0.1% |
| Zone U-2 | $ 21,000 | 1.1% |
| Zone U-3 | $ 51,000 | 1.9% |
| Zone U-4 | $1,560,000 | 6.3% |
| TOTALS | $1,636,000 | 4.8% |

Table 11

ESTIMATED 100-YEAR TOTAL AND PERCENT OF
FIRE STATIONS RENDERED NON-FUNCTIONAL DUE TO EARTHQUAKES
BY SEISMIC ZONE

| Seismic Zone | Number | Percent Of The Total |
|---|---|---|
| Zone U-0 | 0 | 0.0% |
| Zone U-1 | 0.02 | 0.3% |
| Zone U-2 | 0.46 | 2.4% |
| Zone U-3 | 0.65 | 3.6% |
| Zone U-4 | 12.18 | 14.0% |
| TOTALS | 13.31 | 9.2% |

Table 12

ESTIMATED 100-YEAR DOLLAR LOSSES TO FIRE STATIONS
IF ALL ARE REPLACED BY EARTHQUAKE-RESISTANT STRUCTURES
BY SEISMIC ZONE

| Seismic Zone | 100-Year Total Loss | 100-Year Loss As A Percent Of Replacement Cost |
|---|---|---|
| Zone U-0 | $ 0 | 0.0% |
| Zone U-1 | $ 400 | 0.0% |
| Zone U-2 | $ 4,000 | 0.2% |
| Zone U-3 | $ 6,000 | 0.2% |
| Zone U-4 | $ 347,000 | 1.4% |
| TOTALS | $ 357,400 | 1.1% |

Table 13

ESTIMATED 100-YEAR TOTAL AND PERCENT OF
FIRE STATIONS RENDERED NON-FUNCTIONAL DUE TO EARTHQUAKES
IF ALL ARE REPLACED BY EARTHQUAKE-RESISTANT STRUCTURES
BY SEISMIC ZONE

| Seismic Zone | Number | Percent Of The Total |
|---|---|---|
| Zone U-0 | 0 | 0.0% |
| Zone U-1 | 0 | 0.0% |
| Zone U-2 | 0.08 | 0.4% |
| Zone U-3 | 0.13 | 0.7% |
| Zone U-4 | 2.96 | 3.4% |
| TOTALS | 3.17 | 2.2% |

Table 14

ESTIMATED 100-YEAR DOLLAR LOSS TO BUILDINGS HOUSING POLICE STATIONS BY SEISMIC ZONE AND AS A PERCENT OF REPLACEMENT COSTS

(1978 Dollars)

| Seismic Zone | 100-Year Total Loss | 100-Year Loss As A Percent Of Replacement Cost |
|---|---|---|
| Zone U-0 | $ 0 | 0.0% |
| Zone U-1 | $ 2,600 | <0.1% |
| Zone U-2 | $ 51,400 | 0.6% |
| Zone U-3 | $ 111,400 | 0.7% |
| Zone U-4 | $3,353,000 | 6.0% |
| TOTALS | $3,518,400 | 4.0% |

Table 15

ESTIMATED 100-YEAR TOTAL AND PERCENT OF BUILDINGS HOUSING POLICE STATIONS RENDERED NON-FUNCTIONAL DUE TO EARTHQUAKES BY SEISMIC ZONE

| Seismic Zone | Number | Percent Of The Total |
|---|---|---|
| Zone U-0 | 0 | 0.0% |
| Zone U-1 | <0.01 | 0.1% |
| Zone U-2 | 0.14 | 0.8% |
| Zone U-3 | 0.36 | 1.4% |
| Zone U-4 | 10.63 | 14.8% |
| TOTALS | 11.14 | 8.7% |

Table 16

ESTIMATED 100-YEAR DOLLAR LOSSES TO BUILDINGS HOUSING POLICE STATIONS IF ALL ARE REPLACED BY EARTHQUAKE-RESISTANT STRUCTURES BY SEISMIC ZONE

| Seismic Zone | 100-Year Total Loss | 100-Year Loss As A Percent Of Replacement Cost |
|---|---|---|
| Zone U-0 | $ 0 | 0.00% |
| Zone U-1 | $ 200 | <0.01% |
| Zone U-2 | $ 12,600 | 0.16% |
| Zone U-3 | $ 28,300 | 0.18% |
| Zone U-4 | $ 733,600 | 1.30% |
| TOTALS | $ 744,700 | 0.88% |

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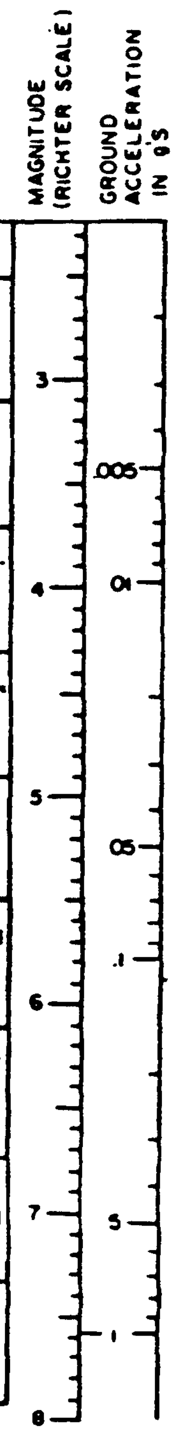
# MODIFIED MERCALLI INTENSITY SCALE APPROXIMATE RELATIONSHIP WITH MAGNITUDE AND GROUND ACCELERATION

## ABRIDGED MODIFIED MERCALLI INTENSITY SCALE

| | |
|---|---|
| I | Not felt except by a very few under especially favourable circumstances. |
| II | Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. |
| III | Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated. |
| IV | During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. |
| V | Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop. |
| VI | Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. |
| VII | Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars. |
| VIII | Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed. |
| IX | Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. |
| X | Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. |




[a]Modified Mercalli Intensity Scale after Wood and Neumann, 1931. (Intensities XI and XII not included).

[b]Magnitude and acceleration values taken from Nuclear Reactors and Earthquakes, TID-7024, United States Atomic Energy Commission.

# APPENDIX B

## BUILDING CLASSIFICATIONS FOR ESTIMATING EARTHQUAKE LOSSES

(As Suggested by K.V. Steinbrugge, et al.)

CLASS I: WOOD FRAME:

Class I-A:

1. Wood frame and frame stucco dwellings regardless of area and height.
2. Wood frame and frame stucco buildings, other than dwellings, which do not exceed 3 stories in height and do not exceed 3,000 sq. ft. in ground floor area.
3. Wood frame and frame stucco habitational structures which do not exceed 3 stories in height regardless of area.

Class I-B: Wood frame and frame stucco buildings not qualifying under Class I-A.

CLASS II: ALL-METAL BUILDINGS:

Class II-A: One story all-metal buildings which have a floor area not exceeding 20,000 sq. ft.

Class II-B: All-metal buildings not qualifying under Class II-A.

CLASS III: STEEL FRAME BUILDINGS:

Class III-A: Buildings having a complete steel frame with all loads carried by the steel frame. Floors and roofs shall be of poured-in-place reinforced concrete, or of concrete fill on metal decking welded to the steel frame (open web steel joists excluded). Exterior walls shall be of poured-in-place reinforced concrete or of reinforced unit masonry placed within the frame. Buildings shall have a least width to height about ground (or above any setback) ratio of not exceeding one to four. Not qualifying are buildings having column-free areas greater than 2,500 sq. ft. (such as auditoriums, theaters, public halls, etc.)

Class III-B: Buildings having a complete steel frame with all loads carried by the steel frame. Floors and roofs shall be of poured-in-place reinforced concrete or metal, or any combination thereof, except that roofs on buildings over three stories may be of any material. Exterior and interior walls may be of any non-load carrying material.

Class III-C: Buildings having some of the favorable characteristics of Class III-A but otherwise falling into Class III-B.

Class III-D: Buildings having a complete steel frame with floors and roofs of any material and with walls of any non-load bearing materials.

CLASS IV: REINFORCED CONCRETE, COMBINED REINFORCED CONCRETE AND STRUCTURAL STEEL FRAME:

Note: Class IV-A, B, and C buildings shall have all vertical loads carried by a structural system consisting of one or a combination of the following: (a) poured-in-place reinforced concrete frame, (b) poured-in-place reinforced concrete bearing walls, (c) partial structural steel frame with (a) and/or (b). Floors and roof shall be of poured-in-place reinforced concrete, except that materials other than reinforced concrete may be used for the roofs on buildings over 3 stories.

Class IV-A: Building having a structural system as defined by the note (above) with poured-in-place reinforced concrete exterior walls or reinforced unit masonry exterior walls placed within the frame. Buildings shall have a least width to height above ground (or above any setback) ratio of not exceeding one to three. Not qualifying are buildings having column-free areas greater than 2,500 sq. ft. (such as auditoriums, theaters, public halls, etc.)

Class IV-B: Buildings having a structural system as defined by the note (above) with exterior and interior non-bearing walls of any material.

Class IV-C: Buildings having some of the favorable characteristics of Class IV-A but otherwise falling into Class IV-B.

Class IV-D: Buildings having (a) a partial or complete load carrying system of precast concrete, and/or (b) reinforced concrete lift slab floors and/or roofs, and (c) otherwise qualifying for Classes IV-A, B, or C.

Class IV-E: Buildings having a complete reinforced concrete frame, or a complete frame of combined reinforced concrete and structural steel. Floors and roofs may be any material while walls may be of any non-load bearing material.

CLASS V: MIXED CONSTRUCTION:

Class V-A:

1. Dwellings, not over two stories in height, constructed of poured-in-place reinforced concrete, with roofs and second floors of wood frame.
2. Dwellings, not over two stories in height, constructed of adequately reinforced brick or hollow concrete block masonry, with roofs and floors of wood.

Class V-B: One story buildings having superior earthquake damage control features including exterior walls of (a) poured-in-place reinforced concrete, and/or (b) precast reinforced concrete, and/or (c) reinforced brick masonry or reinforced concrete brick masonry, and/or (d) reinforced hollow concrete block masonry. Roofs and supported floors shall be of wood or metal diaphragm assemblies. Interior bearing walls shall be of wood frame or any one or a combination of the aforementioned wall materials.

Class V-C: One story buildings having construction materials listed for Class V-B, but with ordinary earthquake damage control features.

Class V-D:

1. Buildings having reinforced concrete load bearing walls with floors and roofs of wood and not qualifying for Class IV-E.

2. Buildings of any height having Class V-B materials of construction, including wall reinforcement; also included are buildings with roofs and supported floors of reinforced concrete (precast or otherwise) not qualifying for Class IV.

Class V-E: Buildings having unreinforced solid unit masonry of unreinforced brick, unreinforced concrete brick, unreinforced stone, or unreinforced concrete, where the loads are carried in whole or in part by the walls and partitions. Interior partitions may be wood frame or of the aforementioned materials. Roofs and floors may be of any material. Not qualifying are buildings with non-reinforced load carrying walls of hollow tile or other hollow unit masonry, adobe, or cavity construction.

Class V-F:

1. Buildings having load carrying walls of hollow tile or other hollow unit masonry construction, adobe, and cavity wall construction.
2. Any building not covered by any other class.

CLASSES VI-A, B, C, D, AND E: EARTHQUAKE RESISTIVE CONSTRUCTION:

Any building or structure with any combination of materials and with earthquake damage control features equivalent to those found in Classes I through V buildings. Alternatively, a qualifying building or structure may be classed as any class from I through V (instead of VI-A, B, C, D, or E) if the construction resembles that described for one of these classes and if the qualifying building or structure has an equivalent damageability.

APPENDIX C

## METHODS OF ANALYSIS AND TECHNICAL RESULTS

### PART A: SUMMARY OF METHODS AND RESULTS

The chief function of a benefit-cost analysis is to provide information relevant to the determination of which of several courses of action is most economic. In this methodology, three alternatives for existing buildings are examined in terms of seismic safety: leaving the structures as they are, replacing the structures with earthquake-resistant buildings, and retrofitting the structures to improve their earthquake resistance.

Numerous other alternatives have been omitted from detailed evaluation, such as implementing disaster-preparedness programs, selective mitigation as by removing hazardous cornices and parapets, devising ways to mitigate associated fire hazards, and securing equipment that might fall as a result of ground shaking.

Since at present there is no way to predict with reasonable certainty the date or exact location of an earthquake, assessment of the losses due to earthquakes requires one to make estimates of the likelihood of occurrences. Herein, earthquake source zones are used so that the likelihood of an earthquake within a given zone is estimated. Such probabilities and frequencies are developed here in terms of earthquake intensities, since earthquake intensities are so closely associated with building damage.

Because the seismic zones here used are extensive in area, results for particular buildings would no doubt be different if seismic microzones were constructed based upon such factors as local soil conditions and position relative to faults.

Building damage also depends upon the type of construction. Masonry structures with unreinforced-brick exterior bearing walls, for instance, are more vulnerable to earthquake damage than are wood-frame structures. Expected damage resulting from an earthquake of a given intensity is thus a function of building construction.

In this study, data on building classes are limited to secondary sources. Site inspections of particular structures would lead to improved estimates regarding the vulnerability of specific facilities to earthquake damage.

Given the location and construction type of a building, its expected damage can be determined for various seismic conditions. The expected damage for such a building either retrofitted or replaced likewise can be determined from a characterization of the seismic resistance that the building would have were it either retrofitted or replaced. Hence, one can compare damages for the three alternatives.

Such damages are those due to ground shaking, and do not include estimated fire loss that might follow a large earthquake, or damage due to other factors, such as liquefaction or rockslides.

Property damages, though, form only a part of a benefit-cost analysis of replacing or retrofitting buildings. Costs of retrofitting a structure commonly are out-of-the-pocket costs, and costs of replacing a structure now rather than later involve borrowing rates. As shall be shown, property costs of replacing a structure now rather than later are of necessity greater than property costs of leaving the building as it is, even if an earthquake should cause the original building to collapse. Moreover, it is highly unlikely that it will be less costly, in terms of property losses alone, to retrofit a structure rather than to leave it as it is.

Due to the economic conditions indicated above, losses due to deaths and casualties also must be considered in order to overcome the prejudice in favor of waiting to spend later, when the building needs to be replaced, rather than spending now. Even though there are important reasons for not considering the value of life in economic terms, there are also important reasons for assuming that life has economic value. First, to disregard the value of life is to assume tacitly that life has an economic value of zero. Second, if one derives an economic value for the prolongation of life, it is possible to consider the value as being limited to economic terms. So, one can discuss matters pertaining to the prolongation of life in non-economic terms as well as in economic terms, and estimates involving life-saving and injury-reduction can be useful for either sort of discussion. Given, then, data on construction types and occupancy rates, life and casualty estimates can be constructed for each of the three alternatives. Life and casualty estimates can be used also to determine the risks taken on each of the alternatives.

Hence, for a particular building, either retrofitting or replacing a structure is economic if the lesser damage and life and casualty estimates overcome, in dollar value, the prejudices in favor of waiting to spend money later.

In Part B of this section, the benefit-cost method, assumptions, and theoretical results are expressed mathematically. Such a presentation allows for a condensation of the mathematical implications of the use of discount rates, so that the key factors in the analysis may be seen in their most mathematically direct relationships. In Part C of this section, the method for estimating earthquake intensities are explained. In Part D, the method for deriving damage estimates from earthquake intensities is explained. Different results are obtained from different classification schemes for buildings, where different estimates are relied upon for the vulnerability of structures to loss at given earthquake intensities. In Part E, the method for arriving at speculative life and casualty estimates is explained. In Part F, improvements in the methodology, as suggested by reviewers, are introduced. In Part G, particular results from the analytical studies are interpreted for the benefit of readers.

PART B: THE GENERAL METHOD EXPRESSED MATHEMATICALLY

Let us consider three alternatives.

(a) The original building is left as it is (until its life-span ends).

(b) The original building presently is replaced with an earthquake-resistant building.

(c) The original building is fully retrofitted to improve its earthquake resistance.

We shall employ symbols as follows.

Let $C$ = the present replacement costs for a given building.

Let $y$ = its age.

Let $z$ = the number of years that the building is expected to remain in use.

Let $i$ = the appropriate discount rate.

Let $d$ = the expected annual damage loss due to earthquakes. "d" is determined as a percent of C, and d includes only losses to the structure (and excludes losses to the contents) due to ground shaking. Let $d_a$ refer to the annual damage for the first alternative, $d_b$ for the second alternative, and $d_c$ for the third alternative.

Let $L$ = the expected annual loss due to deaths and injuries, so that $L_a$ refers to the percent loss for the first alternative, and $L_c$ for the third alternative.

Let $R$ = the retrofitting cost.

There are numerous assumptions made in assigning or computing values for the listed variables, any of which may warrant fresh examination.

Since we do not know how building prices are going to change, we shall assume that they are going to change at the same rate as all prices. In assuming that building prices rise at the same rate as overall prices, we recognize that there are occasions when some people will be privy to information that building prices are going to rise, say, faster than the rate of overall prices. We have, though, no grounds for predicting long-term discrepancies between changes in building prices and changes in overall prices. Hence, we shall be assuming that, if building prices are determined in 1978 dollars, then such money values do not need to be adjusted upwards or downwards for projects undertaken in the future.

So, we shall assume that the replacement costs of a building today are, in constant dollar values, equal to the discounted replacement costs of the building at a later date.

We shall presuppose also that the recorded present value of a building, where the term "present value" refers to something other than the replacement cost, is not relevant to our considerations. Fire stations, as such, have no market value. Conversion of police stations into, say, offices, does not alter their principal factors of earthquake risk, namely, structural damage and life-safety losses. The only determinants of the present value of essential facilities are the life span of the buildings, their present age, their replacement cost, and their present capacity to serve their function until the life-span of the building is over.

The expression "present capacity to serve their function" can include a variety of considerations, many of which are tangential or only distantly related to the aims of this study. Replacing a building can improve the use of space, can reduce utility costs and result in energy savings, and can make a building more suitable for other possible uses, such as being a place of refuge during critical periods. In this study, we assume that earthquake-resistant design itself does not contribute much to the reduction of utility costs, etc. A further study would be needed if the benefits of a reduction in utility costs or other benefits were to be added to earthquake safety benefits, since such added benefits would presumably entail added costs.

Even though some data exist to the contrary, we shall assume, in the main, that buildings are presently suited for their purposes. Where it is known that a given building is dysfunctional, the life span of the building can be adjusted accordingly. In addition, repairs for fire safety or other matters not directly related to repairs for earthquake safety are not considered part of the costs either of retrofitting or of losses due to earthquakes.

One possible assumption is that each essential facility has a 50-year life span, or that $z = 50-y$. Since, though, so many essential facilities in Utah are older than 50 years, such an assumption was not found to be satisfactory for all buildings.

We further shall assume that the expected damage to the contents of the building is the same, no matter which alternative is decided upon.

We also shall assume that the cost of money, as a function of the discount rate, is a social cost, and so is not influenced by different ways of financing. So, even if the local municipality can borrow at a 6 percent rate, the discount rate, the rate of borrowing, is nonetheless higher, since the source of funds to the local municipality has a higher discount rate. Likewise, the discount rate shall be applied to funds spent, even if such funds happen to be financed in any of the following ways.

(a) A percentage of funds is provided by the State or federal government.
(b) The cost is paid off immediately.
(c) Funds are borrowed for twenty years at a rate of 12 percent on the remaining balance.

The reason for adopting a constant discount rate is that the additional money raised still has a long-term social borrowing cost, in constant dollar values. One function of a benefit-cost analysis is to determine whether or not the benefits of borrowing now, rather than later, exceed the costs, from which reasonable alternative courses of action may be identified.

It is here assumed that the bulk of relocation costs will be minor when a police station suffers considerable damage. Police personnel may work out of other stations (if there are any), but the costs of renovating other sorts of buildings, leasing them, and stocking them, is an alternative so cumbersome and so costly in many cases that other remedies likely would be sought first. In addition, there also are relocation costs from replacing or retrofitting police stations, and so the alternatives appear to have a similar cost element in this regard.

Given these numerous simplifying assumptions, it is possible to derive various conclusions and to express the analysis mathematically. Sources of data and further clarification of terms are given later.

If a earthquake occurs t years from now, and the earthquake destroys the original building, but would not have affected at all a replaced building, then there still would be the following property loss for having replaced the building now rather than at time t.

(1) $C\,[(1+i)^t - 1]$ = money costs of replacing now rather than when the building collapses.

Therefore, if such human factors as potential life and safety hazards are not considered, it is more economic to replace a building later. Equation (1) represents the worst case for alternative (a) as opposed to alternative (b). So, if one fails to consider deaths and casualties, then, no matter how low one estimates the discount rate as being, alternative (b) would be more costly than alternative (a).

In general, the borrowing cost of selecting (b) rather than (a) is

(2) $C\,[(1+i)^z - 1]$ = the borrowing loss of alternative (b) as opposed to alternative (a).

Given that $d_a - d_b$ equals the annual difference between damages estimated for the two alternatives, and that $L_a - L_b$ equals the difference between casualty and life estimates, then the damage and casualty loss of selecting (a) rather than (b) is

(3) $[(d_a-d_b) + (L_a-L_b)] \sum_{j=0}^{z-1} (1+i)^j$ = damage and casualty loss of selecting (a) rather than (b).

Equation (3) represents the total of such annual differences discounted for remaining expected years of the original building. Since

(4) $\sum_{j=0}^{z-1} (1+i)^j = [\frac{(1+i)^z-1}{i}]$,

it follows that

$$(5) \quad [(d_a-d_b) - (L_a-L_b)] \left[\frac{(1+i)^z-1}{i}\right] = \text{damage and casualty}$$

loss of selecting (a) rather than (b).

Thus, it is economic to replace the building, rather than to leave it as it is, only when the damage and casualty loss of selecting (a) rather than (b) exceeds the borrowing loss of alternative (b) as opposed to alternative (a), that is, when

$$(6) \quad [(d_a-d_b) - (L_a-L_b)] \left[\frac{(1+i)^z-1}{i}\right] > C\ [(1+i)^z-1].$$

Equation (6) can be simplified algebraicly to read that replacement is justified as opposed to leaving the building as it is when

$$(7) \quad (d_a-d_b) + (L_a-L_b) > C \times i.$$

Otherwise, the two alternatives are identical, or alternative (a) is more economic.

The ratio of benefits of replacement to costs of replacement may thus be expressed as follows:

$$(8) \quad \frac{(d_a-d_b) + (L_a-L_b)}{Ci} = \text{ratio of benefits of replacement}$$

to costs of replacement.

When such a ratio exceeds unity, then it is economic to replace a given structure.

When one considers retrofitting costs, one conceives that the building retrofitted will have roughly the same life span as the building left as it is. So, apart from damages and casualties, alternative (c), as opposed to alternative (a), is a loss in the amount of

$$(9) \quad R\ (1+i)^z = \text{money costs of retrofitting now, as}$$

opposed to leaving the building as it is.

Damage and casualty losses are greater for alternative (a) than for alternative (c) by the amount of

$$(10) \quad [(d_a-d_c) + (L_a-L_c)] \frac{(1-i)^z-1}{i} = \text{damage and casualty}$$

losses for leaving the building as it is rather than retrofitting it.

So, alternative (c) is more economic than alternative (a) when damage and casualty losses for leaving the building as it is rather than retrofitting it exceed money costs of retrofitting the building. That is, alternative (c) is more economic when

$$(11) \quad (d_a-d_c) + (L_a-L_b) > R \times i.$$

Equations (7) and (11) represent, then, the mathematical outlines of the benefit-cost analyses here undertaken.

If a discount rate of 10% is used, then one can multiply either the replacement or retrofitting costs by 10% in order to determine how much the annual differences in damage and casualty estimates must be in order to justify either replacement or retrofitting.

The present value of annual losses of value v and at discount rate i equals

$$(12) \quad \frac{[(1+i)^j-1]v}{(i)(1+i)^j} = \text{present value of annual losses of value } v \text{ at discount rate } i.$$

As j becomes very great, given i = 10%, the present value approaches 10 x v. So, for purposes of presentation, we shall assume that the present value of annualized losses is ten times the annual value. However, if buildings are replaced in a very short time, such losses, of course, decrease in present value.

Throughout this report a discount or borrowing rate of 10% is assumed. According to one economist, Frank Hachman, Associate Director of the Bureau of Economic and Business Research at the University of Utah, 10% is presently the absolute minimum discount rate for this study, and higher rates might be more reasonable. In other words, a 10% discount rate minimizes the prejudice in favor of waiting to spend money later. Even though no formula has been developed here for calculating a discount rate, and choice of discount rate can be a very controversial matter, the general benefit-cost results of this study would not be changed substantially if higher or somewhat lower discount rates were chosen (Cf. [12], pp. 243-332).

## PART C: METHOD FOR CONSTRUCTING SEISMIC MACROZONES

The equations employed in the previous subsection presuppose that there is some way to determine both damage estimates and life and casualty estimates for a given building.

Both sorts of estimates depend in turn upon estimating the seismicity at various sites.

In the Algermissen and Perkins study referred to earlier (Cf. [3]), the United States is divided into 71 zones. Three zones, Zones 32, 33, and 34, are specially applicable to Utah. For each zone, the values of the coefficients a and $b_I$ are developed and implicitly available so that one can employ the following equation.

$$(13) \quad \log N = a + b_I I_o,$$

wherein N is the number of yearly earthquake occurrences with maximum intensity $I_o$, such that $I_o$ is either the observed historical maximum intensity, or is determined from the equation

$$(14) \quad M_c = 1.3 + 0.6\, I_o,$$

wherein $M_c$ is the Richter magnitude corresponding to $I_o$ in equation (13). That is, $I_o$ can be derived from data about Richter magnitudes.

For each zone, we are given the estimated number of earthquakes of Intensity V per 100 years. We also are given $b_I$ for each zone ([3], pp. 17, 18). So, at the 90% probability level, we have the following information.

| Zone | Number of Modified Mercalli Maximum Intensity V's Per 100 Years | $b_I$ |
|---|---|---|
| Zone 32 | 17.0 | -0.56 |
| Zone 33 | 126.8 | -0.56 |
| Zone 34 | 71.0 | -0.56 |

If we assume that there is an equal distribution of earthquakes over the years, or that the above estimates of earthquakes of Intensity V can be reduced suitably to annual estimates (where, say, there are 1.268 such earthquakes expected annually in Zone 33, at 90% probability level), then we can use the above information, in conjunction with equation (11), in order to derive values of the coefficient a. Given such assumptions, we have the following values for the coefficient a.

| Zone | a |
|---|---|
| Zone 32 | 2.03 |
| Zone 33 | 2.90 |
| Zone 34 | 2.65 |

Hence, for each zone, we can derive the expected annual frequencies for earthquakes of a given intensity if we employ the following equations.

| Zone | Frequency (N) |
|---|---|
| Zone 32 | $10^{2.03-0.56\ I}$ |
| Zone 33 | $10^{2.90-0.56\ I}$ |
| Zone 34 | $10^{2.65-0.56\ I}$ |

Given the assumption that the occurrence of an earthquake having a given intensity is equiprobable for each year during a 100-year period, then, with a 90% probability, we can derive the following 100-year expected earthquake occurrences by zone and by maximum intensity.

| Zone | Maximum Intensity | | | | | |
|---|---|---|---|---|---|---|
| | X | IX | VIII | VII | VI | V |
| Zone 32 | 0.03 | 0.10 | 0.35 | 1.29 | 4.68 | 16.98 |
| Zone 33 | 0.20 | 0.72 | 2.63 | 9.55 | 34.67 | 125.89 |
| Zone 34 | 0.11 | 0.41 | 1.48 | 5.37 | 19.50 | 70.79 |

So, for example, in Zone 33, about 35 earthquakes of every 100 occurrences can be expected to have intensities with a maximum of VI, about 10 with a maximum of VII, and so on.

The information derived from the Algermissen and Perkins study, however, is based primarily upon historical records adjusted for gaps in data. Geological evidence, in contrast, as revealed by Robert Bucknam of the U.S. Geological Survey (USGS), indicates that the expected activity along the Wasatch fault, in Zone 33, may be greater than that expected in terms of historical records.

In particular, in order to appraise the effects of such increased activity as indicated by new geological evidence, we may assume that, along the fault line, which is about 350 kilometers in length, about one earthquake between 7.0 and 7.6 on the Richter scale may be expected to occur every 500 years. Such an earthquake would not have an epicenter, but would create an assumed 50-kilometer break along the fault line.

In order to estimate seismicity of sites based upon such information, we shall construct a zone, called Zone 33A, that extends approximately 20 kilometers on each side of the fault. Zone 33A thus covers 350 km. x 40 km. Very crudely, we approximate the areas of the other zones as being 261,000 sq. km. for Zone 32, 43,200 sq. km. for Zone 33, and 76,400 sq. km.

for Zone 34. If the remainder of Zone 33 is labeled Zone 33B, then Zone 33B covers about 29,200 sq. km.

An examination of the limited historical data indicates that about one-half of all earthquakes of Intensity V or greater that have occurred in Zone 33 have been located in Zone 33A. So, too, about one-half of all Intensity V's in Zone 33 have occurred in Zone 33A (Cf. [2], pp. 9-20).

In Zone A, we shall assume, then, that about 63.4 earthquakes with a maximum Intensity V are expected to occur in 100 years. Also, the slope chosen for the logarithmic curve (13), -0.52, is such that values of X and over will barely exceed a frequency of 0.20. That is, if one expects one maximum Modified Mercalli Intensity X (about 7.3 on the Richter scale) every 500 years, then one expects 0.20 every 100 years. Hence, we have constructed 100-year frequencies for Zone 33A.

| Zone | Intensity | | | | | |
|---|---|---|---|---|---|---|
| | X+ | IX | VIII | VII | VI | V |
| Zone 33A | 0.22 | 0.52 | 1.8 | 5.8 | 19.2 | 63.4 |

In order to estimate the frequencies for Zone 33B, one first subtracts the frequencies of Zone 33A from the frequencies in Zone 33. Then, because frequencies at higher intensities will be too low, since geological evidence has increased those values for Zone 33A and hence for the zone in general, one fits the lower values to a logarithmic curve. So, for Zone 33B, one derives the following expected maximum frequencies.

| Zone | Intensity | | | | |
|---|---|---|---|---|---|
| | IX | VIII | VII | VI | V |
| Zone 33B | 0.30 | 1.15 | 7.8 | 16.5 | 63.4 |

So far, then, estimated frequencies have been derived for each main macrozone. However, the estimate of frequencies at maximum intensities does not by itself give specific information about the expected frequencies of a given intensity at some site within a given zone. The seismicity at specific sites is needed in order to estimate property and human losses for a particular structure.

In order to use the information about the seismicity in a zone to derive conclusions about the possible seismicity at a specific location within the zone, one needs to estimate how earthquakes with certain epicentral or maximum intensities will attenuate.

Attenuation curves have been developed in order to determine the intensity of an earthquake at a certain distance from the epicenter. From the USGS study of the Salt Lake City area (Cf. [2], p. 39), one finds the following curve:

(15) $I_o - I = n \, Log_{10} [(\Delta^2 + h)^{0.5} / h]$, wherein

$\Delta$ = the epicentral distance (km.) from $I_o$ to I,

h = depth of focus (km.),

$I_o$ = maximum intensity at the epicenter,

I = intensity at $\Delta$ from the epicenter, and

n = an exponent determined empirically.

According to Dr. Walter Arabasz, geophysicist at the University of Utah, a good approximation for Utah can be constructed if we let n = 4.0.

The assumption for h can make a substantial difference. In terms of area covered, the assumption of 10 km. in depth as opposed to 5 km. in depth makes a difference of four times the area covered.

From a list of recent earthquakes in Utah that was supplied by Walter Arabasz and Bill Richins at the University of Utah Department of Geology and Geophysics, the mean and median of focal depths are less than 6 kilometers. A more relevant notion to the consideration of areas, the root mean square, the square root of the mean of squares, is also less than 7 kilometers. Focal depths did not seem to vary with intensity, although the sample was skewed with a preponderance of lower intensities. So, for this study, 7 kilometers was chosen as the focal depth.

Hence, for Utah, one can determine $\Delta$ for $I_o$-I = 1, for $I_o$-I = 2, and so on.

We shall assume that a given intensity ceases to exist at the midpoint between two numerically successive $\Delta$'s. That is, if $I_0$-$I_1$ = 1, and $\Delta$ = 10 kilometers, then the maximum intensity, $I_o$, extends for a distance of 5 kilometers. So, too, if for $I_o$- I, $\Delta$ = 21 kms., then the second highest intensity, $I_o$- I, extends from 5 kms. from the epicenter to 15.5 km. from the epicenter.

Given the abovementioned assumptions for Utah, and equation (15), then we have the following values for $\Delta$, given various differences in intensity.

| $I_o-I$ | (km.) |
|---|---|
| 1 | 10.3 |
| 2 | 21.0 |
| 3 | 38.7 |
| 4 | 69.7 |
| 5 | 124.3 |
| 6 | 221.3 |
| 7 | 393.6 |
| 8 | 700.0 |
| 9 | 1,244.8 |

Given the assumption about the use of a midpoint in order to determine the distance covered by the maximum intensity, we can, with other suitable assumptions, determine the area covered by each intensity.

In the general case, for all earthquakes except for those major earthquakes that cause a 50-kilometer break along the Wasatch fault, we shall assume that intensities can be mapped as a group of concentric circles, with the epicenter at the center, with the maximum intensity covering the inner circle, and with each lesser intensity found in each next outer circle. Given such a mapping of intensities, along with assumptions made about the use of the midpoint, one can estimate the area for each intensity, given a value for the maximum intensity. For a given $I_o$, the areas covered by $I_o-I$, for $0 \leq I_o < 10$, are as follows.

| $I_o-I$ | Area (sq. km.) |
|---|---|
| 0 | 83 |
| 1 | 686 |
| 2 | 2,034 |
| 3 | 6,424 |
| 4 | 20,310 |
| 5 | 64,230 |
| 6 | 203,100 |
| 7 | 652,700 |
| 8 | 2,021,000 |
| 9 | 6,423,000 |

For a given value of $I_o$, one can use the above areas. If, say, $I_o$, the maximum intensity of an earthquake, is V, then 83 sq. km. are covered with an Intensity V, 686 sq. km. by Intensity IV, and so on.* Likewise, whatever the maximum intensity is assumed to be, it covers 83 sq. km., the next lower intensity covers 686 sq. km., and so on.

For Zones 32 and 34, which are more extensive in area, we shall assume that all of the relevant attenuated area (down to a Mercalli Intensity VI) lies within the zone. In other words, we shall assume that the impact of earthquakes originating outside the zone is counterbalanced for our purposes by the attenuated areas of earthquakes that go outside the zone even though the epicenter lies within the zone.

For all cases where we can suitably regard the attenuation pattern as a sequence of concentric circles, we can derive the approximate areas covered at a given intensity as a result of attenuation. Given expected epicentral frequencies, such areas can be derived. If, for instance, 0.11 is the expected frequency of earthquakes having Intensity X, then one can expect such earthquakes to cover 0.11 x 83 sq. km. at Intensity X, 0.11 x 686 sq. km. at Intensity IX, 0.11 x 2,034 sq. km. at Intensity VIII, and so on. In general, for Zone 32, one can use the same method to derive a table analogous to the one shown below for Zone 34 which gives the values used to estimate areas covered per 100 years at given intensities.

| Epicentral Intensity | Expected Frequency of Epicentral Intensity | Area for Attenuated Intensity -- Zone 34 | | | | | |
|---|---|---|---|---|---|---|---|
| | | X | IX | VIII | VII | VI | V |
| X | 0.11 | 9 | 75 | 224 | 707 | 2,234 | 7,065 |
| IX | 0.41 | | 34 | 281 | 834 | 2,634 | 8,327 |
| VIII | 1.48 | | | 123 | 1,015 | 3,010 | 9,508 |
| VII | 5.37 | | | | 446 | 3,684 | 10,923 |
| VI | 19.50 | | | | | 1,619 | 13,377 |
| V | 70.79 | | | | | | 5,876 |
| Cumulative Areas in Zone 34 Covered at the Given Intensity | | 9 | 109 | 628 | 3,002 | 13,181 | 55,076 |

This table illustrates how the contribution of each epicentral intensity to intensities at lower levels can be established.

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*Attenuation curves are generally imprecise very close to the epicenter. The result here that the epicentral intensity extends about 5 km. is at least consistent with the general conclusion of William Gordon (member of the Utah Seismic Safety Advisory Council and a geotechnical engineer) that attenuation curves have not been defined precisely for the first 5 kilometers.

So for any given intensity, the expected area covered is the expected area covered at such an intensity as a result of the attenuation of higher epicentral intensity earthquakes plus the expected area covered at the given intensity given its expected epicentral frequency. Since expected epicentral frequencies vary from zone to zone, so too will vary expected frequencies of areas covered by given intensities. For Zone 32, there are the following expected areas (in square kilometers) covered at various intensities.

| Zone | Intensity | | | | | |
|---|---|---|---|---|---|---|
| | X | IX | VIII | VII | VI | V |
| Zone 32 | 3 | 29 | 159 | 744 | 3,238 | 13,454 |

The total areas in all zones and subzones can be crudely approximated as follows.

| Zone | Area |
|---|---|
| Zone 32 | 261,000 sq. km. |
| Zone 33A | 14,000 sq. km. |
| Zone 33B | 29,200 sq. km. |
| Zone 34 | 76,400 sq. km. |

For all zones, we shall assume that buildings are randomly distributed throughout the zone. Only for Zones 32 and 34 shall we assume that areas covered by earthquakes within the zone do not extend beyond the zone.

For Zones 32 and 34, we can determine the expected frequencies of the occurrence of an earthquake whose area covers a given building. Such an expected frequency equals the expected area covered by a specific intensity and in the zone divided by the total area within the zone. Such frequencies might be regarded as point-frequencies. So, we have for any building the following expected 100-year frequencies at the following given intensities.

| Zone | Intensity | | | | | |
|---|---|---|---|---|---|---|
| | X | IX | VIII | VII | VI | V |
| Zone 32 | 0 | 0 | 0.0006 | 0.0028 | 0.0124 | 0.0515 |
| Zone 34 | 0.0001 | 0.0014 | 0.0083 | 0.0393 | 0.1726 | 0.7212 |

In order to estimate property and human losses for the other zones, it is necessary to derive analogous point-frequencies.

However, two problems arise in regard to the two subzones, Zone 33A and Zone 33B, in pursuing this methodology. First, the subzones are small enough so that one cannot fairly assume that the amount of attenuation into the area roughly equals the amount of attenuation outside the area. Some method must be devised in order to estimate how much ground shaking attenuates outside the subzone, and how much ground shaking enters into the subzone from other zones. Secondly, the attenuation pattern for an assumed 50-kilometer break along the Wasatch fault is not a pattern of concentric circles. Higher intensity earthquakes in Zone 33A, then, are regarded as attenuating more so in the pattern of rectangles having semi-circles at the two ends.

For such a 50-kilometer break, it is assumed that the rectangles are formed by lines parallel to the break, and the semicircles have their centers at the ends of the break. As with the previous method, it is assumed that the distance covered from one intensity to the next is determined by equation (14) and by the assumption that the midpoint between two distances so determined is where the one intensity ends and the next lower intensity begins. So, the distances covered in one direction are 5.15 kilometers for the maximum intensity, 15.65 kilometers for the next highest intensity, 29.9 kilometers for the third highest intensity, and so on.

Since, though, the total width of Zone 33A is only 20 kilometers on each side of the fault, only the first two distances yield areas entirely within the zone, and only part of the third distance is within the zone, so that the following attenuated areas are calculated for an epicentral Intensity X.

| X | IX | VIII |
|---|---|---|
| 515 sq. km. | 1,050 sq. km. | 435 sq. km. |

For the semicircles, only the area within the width of Zone 33A is to be included. Given such areas, aspect ratios were determined in order to estimate the number of semicircles expected to lie within the length of Zone 33A. Since once the earthquake occurs along any 50-km. segment, the endpoints could occur at any point along 300 kms. Given a 350-km. fault line and r as the radius of the intensity, it was assumed that there are (300/r) + 1 possible points uniformly distributed, of which all but one point are in the interior of the break.

For the following radii, the following aspect ratios obtain.

If r = 5.15, then the ratio of area in is 0.983.
If r = 15.65, then the ratio of area in is 0.950.
If r = 29.90, then the ratio of area in is 0.909.
If r = 54.20, then the ratio of area in is 0.847.
If r = 98.00, then the ratio of area in is 0.756.
If r = 172.80, then the ratio of area in is 0.635.

The following attenuated areas (sq. km.) lie within the width of the zone.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 83 | 686 | 1,493 | 2,621 | 3,535 | 6,470 |

Multiplied by aspect ratios, one obtains the following areas (sq. km.) both in the width and in the length.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 82 | 652 | 1,357 | 2,220 | 2,672 | 4,108 |

To find the total areas included, one sums the semicircular areas included and the rectangular areas included.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 597 | 1,702 | 1,792 | 2,220 | 2,672 | 4,108 |

Since the above areas are assumed to be affected for 500 years, one divides by five to obtain the following 100-year areas covered.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 119 | 340 | 358 | 444 | 534 | 822 |

For maximum intensities of IX and below, typical concentric patterns were used, except that aspect ratios were again used in order to estimate, given a uniform distribution of intensities, the percent of the attenuated areas that could be expected to lie within the zone. In particular, if $r < w \leq$ , given length $\ell$ (350 km.), and width w (40 km.), then the zone may be divided into $\ell/r$ units by $w/r$ units. There are hence $(\ell/r + 1) \times (w/r + 1)$ uniformly distributed points.

The total attenuation area for all points is thus $(\ell/r + 1)\ (w/r + 1)\pi r^2$.

Of the four points on the corners, three-fourths of their area lies outside the zone, and of the $2(\ell/r - 1 + w/r - 1)$ other boundary points, one-half of their area lies outside the zone. So, the following aspect ratio obtains.

$$1 - \frac{(\ell/r + w/r + 1)}{(\ell/r + 1)\ (w/r + 1)} = 1 - \frac{(370 + r)}{(350 + r)\ (40 + r)}$$

Where $r > w$, it is assumed that the aspect ratio is

$$\frac{2\ (\ell/r)}{2\ (\ell/r + 1)} = \frac{\ell}{(\ell + r)}$$

Therefore, on the assumption that the points occur along the fault, it is determined trigonometrically what percent of the area lies within the zone. So, using both methods, one obtains the following aspect ratios for various radii.

For r = 5.15, the ratio is 0.98.
For r = 15.65, the ratio is 0.98.
For r = 29.90, the ratio is 0.72.
For r = 54.20, the ratio is 0.40.
For r = 96.77, the ratio is 0.21.

Hence, the area covered

for $I_o - I = 0$ is 82 sq, km.,
for $I_o - I - 1$ is 754 sq. km.,
for $I_o - I = 2$ is 2,018 sq. km.,
for $I_o - I = 3$ is 3,692 sq. km., and
for $I_o - I = 4$ is 6,204 sq. km.

So, the area covered at the lower intensity, the total area covered to the lower intensity minus the area covered by the higher intensities, is as follows.

For $I_o$-I = 0, 82 sq. km.
For $I_o$-I = 1, 672 sq. km.
For $I_o$-I = 2, 1,264 sq. km.
For $I_o$-I = 3, 1,674 sq. km.
For $I_o$-I = 4, 2,512 sq. km.

Given the previously derived intensity figures based on a Modified Mercalli Intensity X, we are able to derive the cumulated areas covered in Zone 33A due to all maximum intensities by means of the following table.

| Epicentral Intensity | Intensity X | IX | VIII | VII | VI | V |
|---|---|---|---|---|---|---|
| X (previous calculation) | 119 | 340 | 358 | 444 | 544 | 822 |
| IX = 0.52 | | 42 | 350 | 657 | 870 | 1,306 |
| VIII = 1.8 | | | 147 | 1,210 | 2,275 | 3,012 |
| VII = 5.8 | | | | 474 | 3,900 | 7,332 |
| VI = 19.2 | | | | | 1,569 | 12,910 |
| V = 63.4 | | | | | | 5,180 |
| Cumulative Area Covered In Zone 33A | 119 | 382 | 855 | 2,785 | 9,148 | 30,562 |
| Point-Frequencies (given 14,000 sq. km.) | 0.0085 | 0.0273 | 0.0611 | 0.1990 | 0.6535 | 2.1830 |

The value for Intensity V is lower than that derived for Zone 33 because the value in Zone 33A does not include the attenuation of earthquakes from outside the subzone. In order to adjust the values, we must attenuate expected earthquakes from outside the area. In effect, the expected frequencies in Zone 33B might be approximated by subtracting the expected frequencies in Zone 33A from those in Zone 33, and result in the following <u>initial</u> estimates.

| Intensity IX | VIII | VII | VI | V |
|---|---|---|---|---|
| 0.20 | 0.8 | 7.8 | 16.5 | 63.4 |

Let us suppose that the attenuated areas that move into Zone 33A, for each radius of attenuation, are 6.9%, 21.2%, 27%, and 32.6%, respectively. For very small r's, the ratio [(390 + 2r)r]/[29,200 + 118r] holds.

Then, we add the following point-frequencies to those already in Zone 33A.

| Intensity | | | | |
|---|---|---|---|---|
| IX | VIII | VII | VI | V |
| 0.0001 | 0.0025 | 0.0205 | 0.1563 | 0.7546 |

We then obtain the following estimated point-frequencies in Zone 33A.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 0.0085 | 0.0274 | 0.0636 | 0.2195 | 0.8098 | 2.9376 |

In estimating earthquake frequencies for the remainder of Zone 33, namely Zone 33B, though, it is assumed that adjustments had to be made for the higher intensities, since our assumptions for Zone 33A imply higher expected values for Zone 33 as a whole. In addition, aspect ratios were developed, and estimates were made of the areas attenuated into Zone 33B from Zone 33B. Given such assumptions, the following point-frequencies eventually were obtained for Zone 33B.

| Intensity | | | | | |
|---|---|---|---|---|---|
| X | IX | VIII | VII | VI | V |
| 0.0002 | 0.0009 | 0.0111 | 0.0647 | 0.3764 | 1.5735 |

In summary, we have obtained the following point-frequencies for the various zones and subzones.

| Zone | Intensity | | | | | |
|---|---|---|---|---|---|---|
| | X | IX | VIII | VII | VI | V |
| Zone 32 | 0 | 0 | 0.0006 | 0.0028 | 0.0124 | 0.0515 |
| Zone 33A | 0.0085 | 0.0274 | 0.0636 | 0.2195 | 0.8098 | 2.9376 |
| Zone 33B | 0.0002 | 0.0009 | 0.0111 | 0.0647 | 0.3764 | 1.5735 |
| Zone 34 | 0.0001 | 0.0014 | 0.0083 | 0.0393 | 0.1726 | 0.7212 |

## PART D: METHOD FOR DERIVING ESTIMATES OF STRUCTURAL LOSSES

In this subsection, we use the seismic frequencies developed in the previous subsection in conjunction with each of two classification schemes for buildings in order to make long-term estimates of losses to various sorts of structures in given zones or subzones. Two estimates are furnished, based upon slightly different assumptions regarding vulnerability of construction classes.

In a paper referred to earlier, Algermissen and Steinbrugge have developed a figure in which earthquake losses at various intensities are estimated for different types of construction based upon observed damage from past earthquakes (Cf. [7], p. 11).

Algermissen and Steinbrugge employ a system of classification as shown in Appendix B. Using their figure, and their taxonomy, one can derive one set of estimates of average percent loss due to ground shaking to buildings in a given class and given a specific intensity.

So, for example, buildings in Class 5E (the most vulnerable class) suffer a 35% average loss at Intensity IX, a 25% loss at Intensity VIII, and so on.

Such estimates of percent losses at given intensities, when used in conjunction with expected frequencies of given intensities for a particular building, can be used to derive expected damage losses.

For a building in Zone 33A, for instance, if the average expected loss from an earthquake of Intensity X is 50%, and if 0.0085 such earthquakes are expected in a 100-year period, then one expects 0.43% losses per 100 years due to intensities of X. If one further adds the percent loss due to each intensity, one finds the cumulative expected loss. The expected loss to a given structure due to ground shaking is the sum of all losses due to expected earthquakes of different intensities. Table C-1 illustrates how the Algermissen and Steinbrugge estimates are combined with our table of expected frequencies in order to derive expected 100-year percent losses for various classes of structures in Zone 33A.

In general, for the relevant zones and subzones, one can use the same method in order to derive the 100-year loss factors based on Algermissen and Steinbrugge estimates, as shown in Table C-2.

From such loss factors, one can estimate, given the replacement costs of a building and its location, the 100-year expected dollar losses, and so the annual average expected dollar losses. Such estimates are the dollar estimates for this study.

For expected structural failures, we use a different classification scheme and a different set of estimates by building class that can be used in conjunction with seismic frequencies by zone or subzone. This classification scheme is borrowed and adapted from a study of estimated earthquake damage in the Wasatch Front region prepared for the U.S. Geological Survey.

In particular, for the USGS study of earthquake losses in the Salt Lake City area, a system of classification was developed, and a corresponding set of structural loss estimates at given intensities was established. The classification scheme, as adapted, is given in the main body of the report. Using the same method as was followed to develop Table C-2, 100-year factors for structural failures, estimated based on this second classification scheme, are given in Table C-3.

From such percentages of non-functional structures, one can establish how many structures can be expected to suffer at least a 50% structural loss over 100 years.

In the Algermissen and Steinbrugge report, the percent loss is defined as "the average percentage of the total actual cash value required to fully repair, in kind, any building of a particular class by a particular degree of Modified Mercalli Intensity Scale. Only losses associated with ground shaking are estimated." ([7], p. 1.). The USGS estimates, in contrast, are percentages of buildings rendered non-functional due to earthquake damage. Fifty percent structural damage is assumed to render a building non-functional. The estimates in Table C-3, then, more accurately are thought of as the expected long-term decimal fractions of buildings by class and zone that are rendered non-functional.

Given estimates of annual damage losses derivable from Table C-3, one can further estimate the losses to a given structure until its life cycle runs out, which losses are equal to:

$$(16) \quad d_a \sum_{j=0}^{z} (1+i)^j = d_a \left[\frac{(1+i)^z - 1)}{i}\right]$$

Tables C-2 and C-3 therefore enable one to compare the percent losses and the long-term losses of different classes of structures in Utah. For instance, in Zone 33A, a building that is in Class 5E has an expected 100-year loss of 9.40% (here, the loss is a percent of the replacement cost).

Thus, the expected annual loss is 0.094% of the replacement cost of the structure. In contrast, a structure of Class 5B in Zone 33A has an expected loss of only 1.44% over 100 years. So, if in Zone 33A, a building in Class 5E were either retrofitted or replaced by a building so as to qualify as Class 5B, then the expected damage loss would be 7.96% less for the retrofitted or replaced structure.

## PART E: METHOD FOR DERIVING ESTIMATES OF LIFE AND CASUALTY LOSSES

The equations employed in Part B presuppose not only that damage losses can be estimated but also that estimates can be made for life and casualty losses.

In this section, we shall first clarify how estimates can be made concerning expected life and casualty losses. Afterwards, we shall clarify some of the historical and economic limitations of the estimates.

In the USGS report on earthquake losses in the Salt Lake City area, it is assumed that one can estimate percents of occupants expected to die or to suffer hospitalized injury from earthquakes of a given intensity. Such basic estimates are modified according to the type of the building that is considered. Table C-4 summarizes the basic estimates for various classes of buildings.

These estimates must be modified by coefficients according to the following types of structures.

| Type | Description | Coefficient |
|---|---|---|
| A | Fully retrofitted building | 0.25 |
| B | Fully retrofitted hospital | 0.40 |
| C | 1-story built after 1962 (for UBC Zone 2) | 0.75 |
| D | 1-story built before 1962 | 1.00 |
| E | 2-story or more built after 1962 (for UBC Zone 2) | 1.25 |
| F | 2-story or more built before 1962 | 1.50 |
| G | Within zone of deformation | 2.00 |

The estimate of 0.25 for fully retrofitted buildings was added to original USGS estimates on the basis of the contrast between expected structural losses for Class 5B structures as opposed to those of other classes. The estimate of 0.40 for fully retrofitted hospitals was based on the assumption that full retrofitting of hospitals would produce only slightly better than a Class 5C structure.

Given such percent estimates in Table C-4, and the estimated seismic frequencies developed in Part D, one can, for each zone, derive the percent of deaths and casualties by type of occupant as shown in Table C-5. The estimates must be modified by the coefficients given above for any particular structure.

Using estimates in Table C-5, one can derive mortality and morbidity estimates for earthquake situations. For instance, if a building has 10,000 sq. ft. and a mean occupancy rate of 1 person per 500 sq. ft., and if the facility is a two-story structure built after 1962, then one obtains the following 100-year estimates.

> 10,000 sq. ft. x 1 person/500 sq. ft. x 1.25 x 0.1229% deaths = 0.03 deaths, and 10,000 sq. ft. x 1 person/500 sq. ft. x 1.25 x 1.968% serious injuries = 0.49 serious injuries.

The estimates made in C-5 are based on a sketchy historical record of deaths and injuries caused by earthquakes. We know, for instance, that on some occasions a total building loss is compatible with few casualties to occupants in the building (Cf. [2], p. 90). So, the data take into account only average expected deaths and casualties.

The number of lives lost in the United States as a result of earthquakes has been low in comparison to the number of lives lost in other countries. As of 1975, the estimated number of lives lost in the United States due to earthquakes had been 1,624 ([13], p. 188). The United States experience, in contrast to the experience in other countries, is here assumed to be chiefly a function of comparatively better building practices and materials (Cf. [2], p. 73).

Estimates of benefits in reduced life loss and injury rates, that might result from retrofitting of existing buildings to achieve improved earthquake resistance, can be made in a manner similar to that described in the preceeding paragraphs. Such estimates may be made for retrofit of the entire classes of facilities, or for retrofit of selected classes and in selected seismic zones. In any case, new assumptions must be made as to the degree of improvement that might be achieved in building performance--that is, full retrofit will result in greater reductions in mortality and casualty rates than will selective retrofit. Since, numerous combinations are possible for such analyses, it is enough to observe in this report that the best benefit-cost relationships obtain when buildings in Zone U-4 are upgraded.

Various other ways could be used to estimate deaths and serious casualties. In the USGS study on Salt Lake City, the assumption is made that there are four hospitalized injuries per life lost (Cf. [2], p. 305). According to one survey made of ten earthquakes, one death is expected per $2 million property damage (1970 dollars) ([13], p. 197). Since 1970 dollars must be multiplied by about 1.61 in order to derive 1978 dollars (for January), then one lost life is expected for about $3.2 million damage.

Since the annual estimate of property losses is $35,000 if all police stations are left as they are, then the estimate of deaths in this method of analysis would be 0.01 per year. For retrofitted structures, the corresponding figure would be almost zero. Hence, there would be 0.01 preventable deaths per year if such retrofitting were done. Such results may be compared to that result of the actual method used in this report which was 0.03 preventable deaths per year.

The way to determine the economic impact of such estimates is less certain. For hospitalized casualties, one can determine the cost of various hospitalized injuries. Here, one can use the average cost of hospitalization, or one can use other data, such as those for the San Fernando earthquake, in order to estimate percents of types of injuries and then use data on costs per type of injury (Cf. [11], p. 262).

The issue of the economic value of life is more controversial, as has been stated previously. One available method for determining the economic value of life, introduced into Utah civil courts by Boyd Fjeldsted, senior research economist at the University of Utah, and presented and developed by Dorothy P. Rice, Director of the National Center for Health Statistics, is to take the economic value of life as the estimated present value of future earnings (Cf. [14], p. 3; [15]; [16]).

For reasons already stated, no detailed economic formulas were developed in this report to determine exactly the economic value of either injuries or lives lost.

## PART F: REVIEWERS COMMENTS AND METHODOLOGY REFINEMENTS

Two objections regarding the methodology presented in this appendix have been raised by reviewers. First, according to S.T. Algermissen, the modeling of a major earthquake along the Wasatch fault should be modified. In particular, as a result of the principle of the conservation of energy, one should expect that the same areas attenuate to a given intensity, whether one assumes the attenuation pattern is a series of concentric circles or a fifty-kilometer break with more or less oval-shaped attenuation patterns. That is, if one expects an area of 686 sq. km. to be affected at Intensity IX for an attenuation pattern consisting of a series of concentric circles with Intensity X as the epicentral pattern, then one should expect an equal area of 686 sq. km. at Intensity IX for any other attenuation pattern developed for an epicentral intensity of X.

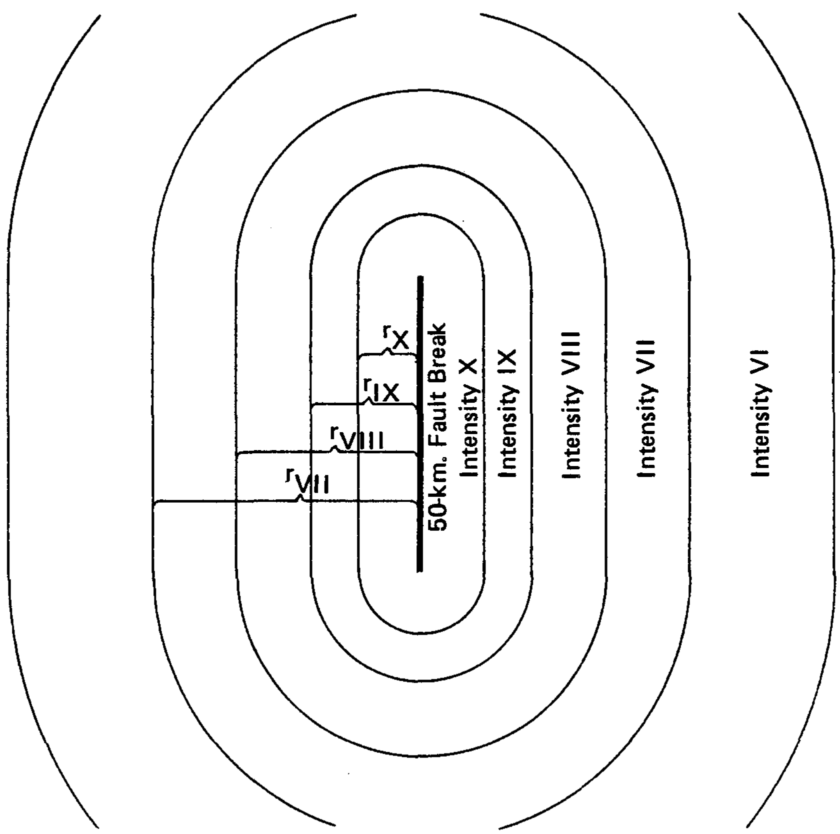
Second, as observed by W.W. Hays, USGS, soil conditions and associated amplification effects were not used as parameter in the methodology. Seismic waves are amplified in unconsolidated soils, and higher intensities therefore are expected. Hence, earthquake loss estimates for macrozones having a high percentage of such soils should reflect such possible increases.

In this sub-section, earlier results for Zone 33A are modified in order to meet the two objections. Since the bulk of losses is expected to occur in Zone 33A, the additional task of correcting for soil conditions in other zones was not undertaken.

Considering first the modeling for attenuation, and in accordance with earlier assumptions made about attenuation, and to correct earlier estimates made for a major earthquake postulated along the Wasatch fault, the areas covered by an earthquake with an epicentral intensity of X are revised as follows.

| | |
|---|---|
| At Intensity X: | 83 sq. km. |
| At Intensity IX: | 686 sq. km. |
| At Intensity VIII: | 2,034 sq. km. |
| At Intensity VII: | 6,424 sq. km. |
| At Intensity VI: | 20,310 sq. km. |
| At Intensity V: | 64,230 sq. km. |

Earlier, it was assumed that a 50-kilometer break would occur somewhere along the Wasatch fault every 450 or so years. The attenuation pattern for such a break appears as follows.




The area covered at Intensity X should equal 83 sq. km., and so on. $r_X$ is defined as the length of the perpendicular to the break measured from the break to one of the boundaries of Intensity X. In general, $r_j$ stands for the length of the perpendicular measured from the break to the boundary of some intensity j. Given the expected areas at each intensity, one can compute values of $r_j$ for $X \leq j \leq V$ if one know that the sum of all areas for Intensity X to Intensity j equals $\pi r j^2 + 100 r_j$.

So, for instance, for Intensity X, one uses the following equation.

$$83 \text{ sq. km.} = r_X^2 + 100r_X$$

For Intensity IX, one uses the following equation.

$$83 \text{ sq. km.} = 686 \text{ sq. km.} = r_{IX}^2 + 100r_{IX}$$

One thus derives the following radii.

$r_X$ = .79 km.
$r_{IX}$ = 5.67 km.
$r_{VIII}$ = 17.93 km.
$r_{VII}$ = 40.58 km.
$r_{VI}$ = 82.36 km.
$r_V$ = 157.62 km.

Since Zone 33A is only 40 km. wide, the following areas in Zone 33A are ascribable at given intensities to the rectangular portion of the break.

| | |
|---|---|
| At Intensity X: | 79 sq. km. |
| At Intensity IX: | 488 sq. km. |
| At Intensity VIII: | 1,147 sq. km. |
| At Intensity VI: | 207 sq. km. |

At each end of the break, a semicircle is formed, with $r_j$ as the radius out to a given intensity. The aspect ratio for determining how much of $r_j$ lies inside the length of the zone is 300 / (300 + $r_j$).

The determination of how much lies within the width of the zone, for $r_j \geq$ 20 km., can be made trigonometrically. Accordingly, the following areas were estimated to lie within the semicircles and in Zone 33A at the specified intensities.

| | |
|---|---|
| At Intensity X: | 2 sq. km. |
| At Intensity IX | 97 sq. km. |
| At Intensity VIII: | 854 sq. km. |
| At Intensity VII: | 2,224 sq. km. |
| At Intensity VI: | 4,441 sq. km. |
| At Intensity V: | 4,805 sq. km. |

Thus, the following total areas in Zone 33A are ascribable to a major earthquake along the fault.

| | |
|---|---|
| At Intensity X: | 81 sq. km. |
| At Intensity IX: | 585 sq. km. |
| At Intensity VIII: | 2,001 sq. km. |
| At Intensity VII: | 2,431 sq. km. |
| At Intensity VI: | 4,441 sq. km. |
| At Intensity V: | 4,805 sq. km. |

Since 0.22 such earthquakes are expected every 100 years, the areas expected to be affected by the various intensities on a 100-year basis are as follows.

| | |
|---|---|
| At Intensity X: | 18 sq. km. |
| At Intensity IX: | 128 sq. km. |
| At Intensity VIII: | 440 sq. km. |
| At Intensity VII: | 535 sq. km. |
| At Intensity VI: | 977 sq. km. |
| At Intensity V: | 1,057 sq. km. |

Adding such estimates to the previous estimates made for all other earthquakes in Zone 33A, one derives the following 100-year estimates.

| | |
|---|---|
| At Intensity X: | 18 sq. km. |
| At Intensity IX: | 171 sq. km. |
| At Intensity VIII: | 937 sq. km. |
| At Intensity VII: | 2,874 sq. km. |
| At Intensity VI: | 9,591 sq. km. |
| At Intensity V: | 30,797 sq. km. |

So, the above estimates are adjustments that result from correcting earlier estimates of attenuated areas due to a major earthquake.

Consideration of soil conditions is a more complicated problem. On page 77 in a report titled Estimation of Earthquake Losses to Buildings (Except Single Family Dwellings), S. T. Algermissen, K.V. Steinbrugge, and H.L. Lagorio use the following intensity increments for different surficial materials.

| | |
|---|---|
| Alluvium: | +1 |
| Tertiary marine sediments: | 0 |
| Pre-tertiary marine and nonmarine sediments: | 0 |
| Franciscan formation: | -1 |
| Igneous rocks: | +1 |

That is, if all of Zone 33A were alluvium, then all previous estimates for intensities would have been increased one intensity higher. I.e., if all of Zone 33A were alluvium, then 937 sq. km. would be affected at Intensity IX.

No map of geologic surficial materials directly bearing upon attenuation presently exists for Zone 33A. With the aid of Fitzhugh Davis at the Utah Geological and Mineral Survey, the following rough translations were made for the Utah State Geological Map.

| | |
|---|---|
| Q (Quaternary) | = +1 |
| T, J, D, E, pEmf | = 0 |
| P, K, M, PE, Tv, Tr, Tilp, Tqm | = 1 |

A mapping of Zone 33A produced the following area estimates.

| | | |
|---|---|---|
| 47% | = | +1 |
| 27% | = | 0 |
| 24% | = | -1 |

In order to adjust the earlier results and take into account geological surficial materials, and using a suggestion made by S.T. Algermissen, one increases 47% of all expected intensities by +1 and one decreases 24% of all expected intensities by -1. Thus, the following areas at expected intensities result.

| | |
|---|---|
| At Intensity X: | 94 sq. km. |
| At Intensity IX: | 494 sq. km. |
| At Intensity VIII: | 1,663 sq. km. |
| At Intensity VII: | 5,566 sq. km. |
| At Intensity VI: | 17,946 sq. km. |

Given that the area of Zone 33A is 14,000 sq. km., the following point-frequencies for 100 years result.

| | |
|---|---|
| At Intensity X: | 0.0067 sq. km. |
| At Intensity IX: | 0.0353 sq. km. |
| At Intensity VIII: | 0.1188 sq. km. |
| At Intensity VII: | 0.3976 sq. km. |
| At Intensity VI: | 1.2819 sq. km. |

Used in conjunction with data on structural types, the following 100-year estimates of structural loss result for different classes of buildings.

| Construction Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5E | 4D | 4E | 4B | 5D | 3B,3D 4C,5C | 3C,4A 5B | 3A | 2B | 2A |
| 0.1545 | 0.1257 | 0.1105 | 0.1042 | 0.0967 | 0.0761 | 0.0227 | 0.0180 | 0.0129 | 0.0177 |

For expected deaths for the general public, the following 100-year estimated rate is obtained from the modified results.

0.1703%

The above value may be used in place of the value 0.1229% for Zone 33A in Table C-5.

For expected injuries for the general public, the following 100-year estimate is obtained.

3.204%

This value may be used in place of the value 1.968% for Zone 33A in Table C-5.

Earlier estimates of structural losses, then, are increased between 55% and 69% for various classes of structures when the suggestions of reviewers are incorporated into the methodology. Mortality estimates are increased 39%, and injury estimates are increased 63%.

It is noteworthy that even with these increases in loss estimates, the benefit-cost results and consequent conclusions reached earlier are not changed. While higher mortality and injury rates tend to make more favorable the cases for replacement and full retrofit programs, they still cannot be justified in economic terms alone. However, the corresponding case for selective correction of seismic hazards in existing facilities, already concluded to be feasible in economic terms, is further enhanced.

## PART G: INTERPRETATION OF RESULTS

While the preceding subsections provide a complete development and discussion of the methodology for seismic risk analysis as applied to Utah's existing buildings, the details and bulk may cause the reader some difficulty in interpreting results and drawing his or her own conclusions regarding the degree of risk that may be present. In this subsection, those results immediately pertinent to the goal of obtaining conclusions about seismic risk are identified, and comments on interpretation of analytical data are furnished.

As a point of beginning this discussion, it may be helpful to state succinctly the objectives of the risk analysis.

These are:

(a) To identify regions or zones of varying degrees of seismic hazard in Utah.

(b) To identify the degree of seismic risk exposure of classes of buildings (classified in terms of their vulnerability) to the varying degrees of seismic risk.

(c) To estimate expected property losses to existing facilities throughout the State according to their vulnerabilities to seismic exposure.

(d) To estimate expected life loss and casualty rates for occupants of buildings throughout the State as a result of building vulnerability to seismic exposure.

(e) To estimate possible reductions in property, life, and casualty losses which could result from alternative mitigation programs.

(f) To identify the most cost-effective program for seismic hazards reduction from among alternatives, commensurate with extent of exposure, if any such program seems justified.

Regions of various levels of seismic risk are indicated in Figure 6. Clearly, the zone of highest risk coincides with the Intermountain Seismic Belt which also is indicated in the figure. Within Zones U-3 and U-4 one finds the likelihood of most frequent and most severe seismicity.

The analysis pointedly recognizes that earthquakes of magnitude above approximately 4.5 Richter magnitude can cause damage to buildings, and that the expected damage, on the average, will increase with increasing earthquake magnitudes. Also, the degree of expected damage is greatly influenced by the type of construction of the buildings. Accordingly, the analysis considers, first, the area distribution of expected earthquakes, including frequency and strength, and, second, the vulnerabilities of various classes of building construction given the distribution of exposure. Distribution of earthquake frequency and strength is made in accordance with the zones shown in Figure 6. Skipping over several tables in Part C which explain the development of data, the last table in that subsection summarizes the point-frequencies of various earthquake intensities for those zones of importance in the State, namely Zones 32, 33A, 33B, and 34 which correspond, respectively, to Zones U-1, U-2, U-3, and U-4 shown in Figure 6.

From this table, it is evident that earthquake frequences, in order of severity, are greatest in Zone U-4, and become successively smaller for Zones U-3, U-2, and U-1, in that order. Moreover, it can be seen that point-frequency values in Zone 33A (U-4) are on the order of two or more times the corresponding values in Zone 33B (U-3) for each earthquake intensity above the threshold damage intensity of V for buildings.

Part D discusses expected building losses based upon the frequencies just discussed. Tables C-2 and C-3 summarize such expected losses for the various classes of building construction and for the various seismic zones. Data are given as a percentage of damage to each building class. Table C-2 data are for property losses, from which dollar losses, in turn, may be estimated. Table C-3 data are for estimates of structural failures.

Since the majority of Utah buildings are of Class 5 (Algermissen and Steinbrugge Classification system) construction (mixed construction with masonry bearing and non-bearing walls), and since Class 5 construction is seen to exhibit the highest seismic vulnerability, the values from Class 5 columns alone provide a pretty good picture of earthquake risk in existing facilities.

Note, however, that for Zone 33A (U-4), the jump from Class 5E to Class 5D (Table C-2) is an improvement of approximately a factor of 2 in reduced seismic vulnerability, i.e., from 0.0940 to 0.0589, and from Class 5E to 5B is an improvement of a factor of over 6, i.e., from 0.0940 to 0.0144. In other words, one could reduce the seismic vulnerability of unreinforced masonry buildings over 6 times if appropriate modifications were made. Such assessments of the data form the basis of conclusions reached in this report.

Life loss and casualty estimates are derived somewhat differently in order to utilize available data gathered by others regarding correlations between construction types and mortality and morbidity rates. The methodology is described in Part E. It is evident that, in relative terms, Zone U-4 is the most severe, and that selective retrofit of some buildings can be justified. However, because of the large number of facilities which, by their construction characteristics, are classed as among the most hazardous, more rigorous analysis of individual buildings of such classes is needed than was provided in this study, in order that costs for such retrofit be kept minimal. Such detailed review of facilities having high seismic hazards indicators is a principal recommendation of this report.

Possible reductions in property, life, and casualty losses are most readily evaluated from assumptions and effects resulting from upgrading of buildings into construction classes that offer improved performance in resisting seismic forces, or resulting from replacement by buildings of improved construction class. Whichever alternative may be chosen, it should be noted that life and casualty losses cannot be entirely eliminated--at least in a statistical sense. Such losses only can be reduced, since there are no earthquake-proof buildings, only earthquake-resistant ones.

Such upgrading of existing building construction is not so easy, however, because most of the problems are associated with seismic resistance of unreinforced-masonry walls, a condition which is costly to upgrade. Still, there are improvements that can be made to such masonry construction. Bracing walls can be added, shear walls can be added along with strengthened floor and roof diaphragms, and unnecessary unsupported masonry can be removed. Since the proper retrofit action for each building will be unique, such detail is beyond the scope of this study.

Table C-1

EXPECTED 100-YEAR LOSSES TO BUILDINGS IN ZONE 33A
BY CLASS OF CONSTRUCTION EXPRESSED AS A PERCENT OF THE CLASS

(Based on Algermissen and Steinbrugge Loss Estimates)

PERCENT LOSS AT A GIVEN INTENSITY

| | Construction Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Intensity | 5E | 4D | 4E | 4B | 5D | 3B,3D 4C,5C | 3C,4A 5B | 3A | 2B | 2A |
| X | 50% | 42% | 37% | 33% | 30% | 23% | 18% | 15% | 12% | 8% |
| IX | 35% | 30% | 27.5% | 25% | 22.5% | 17.5% | 13% | 11% | 8% | 7% |
| VIII | 25% | 22% | 19% | 18% | 16% | 12.5% | 7.5% | 6% | 4.5% | 4% |
| VII | 14.5% | 12.5% | 11% | 10% | 9% | 7% | 2% | 1.5% | 1% | 2.5% |
| VI | 4% | 3% | 2.5% | 2.5% | 2.5% | 2% | 0 | 0 | 0 | 0 |

FREQUENCY CONTRIBUTION OF EACH INTENSITY IN SUBZONE 33A

| | | Construction Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Intensity | Frequency | 5E | 4D | 4E | 4B | 5D | 3B,3D 4C,5C | 3C,4A 5B | 3A | 2B | 2A |
| X | 0.0085 | 0.0043 | 0.0036 | 0.0031 | 0.0028 | 0.0026 | 0.0019 | 0.0016 | 0.0013 | 0.0010 | 0.0006 |
| IX | 0.0274 | 0.0096 | 0.0082 | 0.0075 | 0.0069 | 0.0062 | 0.0048 | 0.0036 | 0.0030 | 0.0022 | 0.0019 |
| VIII | 0.0636 | 0.0159 | 0.0140 | 0.0121 | 0.0115 | 0.0102 | 0.0080 | 0.0048 | 0.0038 | 0.0029 | 0.0025 |
| VII | 0.2195 | 0.0318 | 0.0274 | 0.0242 | 0.0219 | 0.0197 | 0.0154 | 0.0044 | 0.0033 | 0.0022 | 0.0055 |
| VI | 0.9098 | 0.0324 | 0.0243 | 0.0202 | 0.0202 | 0.0202 | 0.0162 | 0 | 0 | 0 | 0 |

CONTRIBUTIONS OF ALL FREQUENCIES COMBINED -- ZONE 33A

| Construction Class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5E | 4D | 4E | 4B | 5D | 3B,3D 4C,5C | 3C,4A 5B | 3A | 2B | 2A |
| 9.40% | 7.75% | 6.71% | 6.33% | 5.89% | 4.63% | 1.44% | 1.14% | 0.83% | 1.05% |

Table C-2

EXPECTED 100-YEAR LOSS TO UTAH BUILDINGS
BY ZONE AND BY BUILDING CLASS

(Based on Algermissen and Steinbrugge Estimates)

| Zone | Building Class | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 5E | 4D | 4E | 4B | 5D | 3B,3D 4C,5C | 3C,4A 5B | 3A | 2B | 2A |
| Zone 32 | 0.0011 | 0.0009 | 0.0007 | 0.0007 | 0.0007 | 0.0005 | 0.0001 | 0 | 0 | 0 |
| Zone 33A | 0.0940 | 0.0775 | 0.0671 | 0.0633 | 0.0589 | 0.0463 | 0.0144 | 0.0114 | 0.0083 | 0.0105 |
| Zone 33B | 0.0278 | 0.0222 | 0.0189 | 0.0182 | 0.0173 | 0.0136 | 0.0022 | 0.0018 | 0.0012 | 0.0021 |
| Zone 34 | 0.0153 | 0.0123 | 0.0106 | 0.0101 | 0.0094 | 0.0075 | 0.0022 | 0.0013 | 0.0009 | 0.0014 |

Table C-3

EXPECTED 100-YEAR LOSS FACTORS FOR UTAH BUILDINGS
BY ZONE AND BY BUILDING CLASS

(Based on Adapted USGS Classification)

| Zone | Building Class | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 7 | 6 | 5 | 4 | 3 | 2 | 1b | 1a |
| Zone 32 | 0.0034 | 0.0026 | 0.0020 | 0.0010 | 0.0006 | 0.0003 | 0.0001 | 0.0001 |
| Zone 33A | 0.2894 | 0.2244 | 0.1728 | 0.1113 | 0.0624 | 0.0347 | 0.0193 | 0.0110 |
| Zone 33B | 0.0917 | 0.0711 | 0.0555 | 0.0324 | 0.0166 | 0.0072 | 0.0041 | 0.0023 |
| Zone 34 | 0.0492 | 0.0379 | 0.0294 | 0.0178 | 0.0095 | 0.0046 | 0.0027 | 0.0015 |

Table C-4

DEATHS AND INJURIES AS A PERCENT OF BUILDING OCCUPANTS BY TYPE OF OCCUPANT AND BY DEGREES OF MODIFIED MERCALLI INTENSITY

| Intensity | Deaths | Injuries |
|---|---|---|
| VII | 0 | 4% |
| VIII | 0.67% | 8% |
| IX | 2% | 15% |
| X | 3% | 20% |

Table C-5

MORTALITY AND SEVERE CASUALTY RATES BY SEISMIC ZONE AND BY TYPE OF OCCUPANT AS A PERCENT OF BUILDING OCCUPANTS

| Zone | Deaths | Injuries |
|---|---|---|
| Zone 32 | 0.0004% | 0.0160% |
| Zone 33A | 0.1229% | 1.968 % |
| Zone 33B | 0.0098% | 0.3626% |
| Zone 34 | 0.0077% | 0.2466% |