SEISMIC SAFETY ADVISORY COUNCIL

STATE OF UTAH

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SEISMIC RISK ASSESSMENT OF UTAH PRIMARY AND SECONDARY SCHOOLS AND RECOMMENDATIONS FOR RISK REDUCTION

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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 primary and secondary school buildings in Utah and provides recommendations for abatement or mitigation of the 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 pheonmena 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 classes of school buildings in the State. No attempt is made, either in methodology or in conclusions, to address site-specific buildings, and the report is not intended for use in that way. The purpose in the approach taken is to develop general program directions for mitigation of seismic hazards in school buildings as a class rather than to identify the specific problems of any one building. From this approach, the Seismic Safety Advisory Council has been able to identify pervasive seismic risk conditions among school buildings and to recommend actions leading to remedies on a statewide or, possibly, on a district-wide basis. In that sense, the recommendations are policy-oriented.

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

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SECTION 1

SUMMARY OF FINDINGS

Principal findings resulting from the seismic risk assessment of existing Utah primary and secondary schools reported herein are presented first, without elaboration or extensive discussion. More detail is provided in Section 3. A full description of the study methodology and considerably more detail are provided in Section 4. Recommendations for dealing with principal findings regarding earthquake hazards are provided in Section 2 which is organized so as to allow their separation from the report without their 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 existing Utah schools.

It seems useful to emphasize that this study addresses the seismic risk only for existing schools in Utah. The principal findings and recommendations which follow are limited accordingly. Seismic hazards mitigation for new school construction involves conditions which are entirely different from existing facilities and, consequently, remedies which also are different. This topic will be covered in another report dealing only with new school construction.

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.

- Public schools in Utah house approximately 315,000 pupils in approximately 580 facilities, and in over 700 separate buildings (1977 data).

- Distribution of schools and pupils in the State corresponds with the distribution of population, with the greatest concentration of both in the central counties along the Wasatch Front. More than 80% of the population and schools are located in a narrow band approximately 40 miles wide extending south about 150 miles from the northern border.

- Age of school buildings ranges from the new to some that approach 100 years. More than 140 buildings are 50 or more years old. This amounts to over 20% of Utah schools.
- New schools are being added at a rate of less than 2% each year. The extent of major additions to existing schools is not known from the data available when this study was made.
- School building construction in Utah is mostly one-story with masonry exterior walls, bearing and non-bearing, and light roof framing of wood or steel joists. However, there are numerous two- and three-story school buildings with construction systems generally similar to the one-story buildings. A relatively large number of the multistory buildings are 50 or more years old, and many of this class are secondary schools.
- Construction types and methods have changed during past decades, but no significant regional variations within the State are evident. Older schools (50 years or more) are, with rare exception, unreinforced-masonry bearing-wall construction built before construction standards were common. Schools built between 1930 and 1950 also generally are of unreinforced-masonry bearing-wall construction and often more than one story. In such cases, the construction typically is a bit more solid than for one-story construction, but the seismic resistance nonetheless is poor typically. Schools built during the 1950's and 1960's and typically governed by building codes of that era, are predominantly one-story, unreinforced-masonry bearing-wall construction. As recently as the 1960's, little attention was being given to seismic-induced lateral forces in Utah construction, and school buildings were no exception. Seismic safety and, therefore, seismic design standards, received wider acceptance in Utah during the 1970's, but, even so, there was no policy or procedure generally in force which allows one to say with certainty that these particular school buildings meet the seismic standards of their era. In general, it is safe to conclude that only a few of Utah's existing school buildings have deliberately designed seismic lateral-force resistance. The fact that schools in recent decades are sounder with respect to seismic resistance than are older schools stems mostly from ever improving

design, construction, and inspection practices resulting from improving construction standards. Such improvements are reflected in the earthquake loss estimates contained in this report.

- 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 not only have occurred in historic times in the State, but Utah can expect to experience more such events in the future.

- Earthquake damage to buildings is determined primarily by three factors: (1) earthquake strentgh, (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 damage. Earthquakes in the 6+ Richter magnitude range can cause severe damage and create severe hazards to life safety, although building collapse is rare. 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.

- Earthquake hazards to school populations in Utah's seismic conditions are expected to be largely associated with injuries caused by falling debris--toppled walls of unreinforced masonry, falling ceiling fixtures, overturned furniture, toppled shelving which is loaded, and broken window glass. However, since larger earthquakes are possible, the possibility must not be overlooked that older buildings of unreinforced masonry construction might collapse.

- Prediction of earthquake damage is highly uncertain at this time with the present state-of-the-art. Predicting when and where the next earthquake will occur and how strong it will be is not yet possible. Neither is such prediction capability foreseen in the near future. Predicting building failures for given seismic intensities, while more advanced in theory than is earthquake prediction, also is inadequate to indicate hazardous conditions with certainty. However, the science of earthquake safety planning has advanced sufficiently so that there are known indicators of hazards. These indicators include site conditions, construction types, and particular building features. Correction of such observed conditions is the best means for mitigation of earthquake hazards in existing buildings today.

- Cost-effective mitigation of seismic hazards in Utah schools requires that inventories of risk indicators be carefully prepared for buildings suspected to have such problems. While some buildings have obvious deficiencies, it is more common that such deficiencies can be identified only by qualified personnel and only by field inspection coupled with some analytical work. Inventories of this type are costly, but they are not so costly as broad-based rebuilding programs. Thus, this report endorses a seismic hazards reduction program for existing schools based upon carefully prepared inventories of possible seismic hazards and selective remedies for identified high-hazard conditions.

- By benefit-cost methods of analysis, it is demonstrated herein that major replacement or retrofitting of entire classes of school buildings is not cost-effective for Utah's seismic environment. However, this finding should not be construed to mean that Utah schools are seismically safe in all cases. They are not. The recommendations of this Council, therefore, aim at better identification of specific hazardous conditions in existing school buildings and selective correction of such deficiencies as may be found. For such a program to be carried out successfully through administrative procedures, as proposed, rather than by means of statutory mandates, will require the utmost cooperation of State agencies and local school districts. Such a program, as proposed, assuredly will reduce future earthquake losses both to life and property.

SECTION 2

RECOMMENDATIONS FOR SEISMIC HAZARDS REDUCTION IN EXISTING UTAH SCHOOLS

The following recommendations result from a benefit-cost study of the expected impact of earthquakes upon existing primary and secondary public schools in Utah. The study provides information on the extent and the nature of earthquake hazards in existing schools and also guidance as to feasible remedies for identified problems. In making these recommendations, earthquakes are considered as potentially continuing conditions to which individual schools may be exposed during their lifetimes. Life safety and long-term reductions in potential property losses are the principal factors considered.

These recommendations are set forth as part of a balanced program for earthquake hazards reduction in Utah. Program balance is based upon the degree and extent of hazard and the cost of remedies. The study findings lead to the conclusion that existing problems of earthquake safety, while present, are not so critical and pervasive that a major State program is needed that would involve refitting or replacing all or nearly all schools. Yet, since problems of earthquake safety do exist in some schools, such problems should be further identified, evaluated, and corrected in an orderly, economic manner. Because the problems are widespread throughout Utah, leadership for mitigation programs should occur at the State government level.

Benefit-cost analyses indicate that the most cost-effective means to reduce life and safety risks due to earthquakes is during the initial siting, design, and construction phases of all buildings. Remedying safety problems in an existing structure can entail major alterations that would have been far less costly if done when the building was first built. Moreover, the level of earthquake risk in many areas of Utah can be shown to justify in benefit-cost terms that the added costs to achieve seismic safety at the time of construction are justifiable. Ensuring that new school construction complies with seismic standards adopted by the State Building Board is strongly encouraged so that the State does not continue to add to its inventory of unsafe school buildings. Existing State statutes governing schoolhouse construction procedures, involving both the State Department of Education and State Building Board, provide the means to ensure compliance.

The recommendations which follow indicate appropriate hazards reduction programs for existing schools, taking into account risk level, feasibility, economics, and time schedules.

1. It is recommended that the State Board of Education, with technical assistance from the State Building Board, establish by administrative procedure definitive seismic safety standards for school construction which shall apply to all new and existing school buildings within the Board's jurisdiction, that the Board of Education establish a Statewide program to be followed by local school districts for expeditiously correcting seismic safety deficiencies as may be discovered through Recommendation 2, that the Board of Education encourage local school districts to evaluate the seismic vulnerabilities of all other existing schools in terms of the established seismic safety standards and prepare long-term plans for correcting discovered deficiencies, and that the Board of Education monitor and report the progress by local school districts to meet this recommendation.

   The essence of this recommendation is to establish earthquake safety as an important consideration to be addressed in Utah's schools. The recommendation suggests mandatory actions only for conditions of suspected high seismic vulnerability, which are believed to be widespread but not pervasive among existing school buildings, and it suggests long-term remedial attention to seismic safety for all other existing schools in which deficiencies may exist but are neither apparent nor believed to be of great immediate risk.

   The recommendation acknowledges the oversight role of the Board of Education for school safety in the State, but also acknowledges the need for technical expertise in construction matters which the State Building Board can offer. Both boards, as well as local school districts, have important roles in satisfying this recommendation. While the technical situations can be assessed by, say, the State Building Board and the program leadership provided by the State Board of Education, the remedies that may be needed must be carried out, under present State statutes, by the individual school districts. The State Board of Education can assist by using its existing authority to guide and monitor the local school districts as they fulfill their responsibilities to provide safe schools.

2. <u>It is recommended that the State Building Board undertake a detailed review of earthquake hazards in two categories of existing school buildings found in seismically active regions: (1) those buildings which are of unreinforced masonry construction, and (2) those four structures identified in the study report as being of stone masonry construction. For those buildings exhibiting weaknesses to lateral forces of magnitude that could result from earthquakes in their locations or those having other seismic hazards, the State Building Board should recommend remedies for expeditious retrofit or replacement to the State Board of Education which shall oversee their implementation.</u>

Stone masonry and unreinforced masonry are two classes of construction which past earthquakes have shown to be specially vulnerable to damage.

There are about 140 schools in the State having unreinforced masonry structures and being at least 50 years old. About 90 such schools are relatively close (within 20 kilometers) to the Wasatch fault, and so are in the most seismically active zone. As a class, buildings of such construction merit individual review of their resistance to seismic forces.

Another four schools have been identified as being of stone-masonry construction and as lying in seismically active zones. Individual analysis of the seismic vulnerability of these buildings may provide justification for their replacement.

Although benefit-cost findings do not justify on a statistical basis a State-mandated program for either replacing or retrofitting all structures of these two categories, detailed investigations may well prove that some of the above-mentioned schools should either be replaced or retrofitted for seismic reasons. Site inspections also may provide information on seismic problems that cannot be uncovered on a statistical basis. The presence of specially hazardous parapets or cornices, or specially vulnerable gymnasiums or auditoriums, are among the conditions which only a building inspection can reveal. Attention should be paid particularly to possible inexpensive remedies for correcting life safety hazards that no doubt exist in some of the abovementioned schools.

3. It is recommended that the State establish an on-going program to review and assess alternative remedies for seismically vulnerable masonry construction with the intent of applying those effective but less costly methods for retrofitting that may be developed through future research.

Most schools in Utah are of masonry construction that is known to be the most seismically vulnerable general class of construction. Unfortunately, current techniques for strengthening in-place masonry walls and partitions are now relatively costly and discourage implementation unless life and safety risk levels are especially high. In addition, the strength of existing masonry construction is difficult to assess, since mortar quality and buried reinforcement, if any exists, cannot be determined readily either by site inspection in the field or from plans.

Because of such general problems with masonry construction, considerable research is presently underway to find solutions. Close monitoring of such research, in the event that suitable remedies are discovered, seems to the Council to be more prudent than for the State to embark upon an extensive, costly program for immediate correction of existing marginal defects. Such close monitoring could lead to a cost-effective means to reduce significantly earthquake hazards for this type of construction. On the one hand, the State must not disregard the fact that there is some degree of earthquake risk in many of its existing school buildings. Ongoing geological research indicates that the degree of seismic risk may be higher than the limited historical record indicates. On the other hand, Utah citizens cannot be called upon to commit considerable sums of money to correct seismically hazardous conditions where the risks posed to life and safety are in many schools marginal.

The recommended monitoring of research involving seismically vulnerable masonry construction should be included as a part of a continuing State earthquake safety program of a designated State agency after the Seismic Safety Advisory Council is discontinued in 1981.

SECTION 3

DISCUSSION OF FINDINGS RESULTING FROM A STUDY OF SEISMIC SAFETY IN EXISTING UTAH SCHOOLS

SCOPE

This study is among several undertaken to determine the merits of replacing or altering buildings in order to make them safer in the event of earthquakes. Degree of seismic risk and economic feasibility are the principal factors addressed.

In this study, existing Utah public primary and secondary schools are examined. Data on existing schools are from secondary sources, that is, without direct and costly inspections of individual buildings in regard to their vulnerability to earthquakes.

In order to make a broad survey of the seismic safety of school buildings, information has been drawn from several disciplines and from numerous sources. Reference documents are indicated at the end of this report. The comparative seismicity of various regions of Utah has been estimated. Utah schools have been identified, and their locations and construction systems recorded. Given data on locations, construction systems, and seismicity, techniques were developed to estimate property losses and also life and casualty losses that could result from the seismicity. Valuation data also were obtained so that estimated money losses caused by earthquake events could be made.

There are many ways to reduce earthquake hazards associated with existing school buildings. For instance, teachers and pupils can be informed as to what to do when an earthquake occurs. Appropriate actions at the time of an earthquake may reduce life and casualty losses but will not alter property losses. For another instance, inspectors and others directly concerned with school buildings can be trained to identify existing seismic hazards, such as unsupported parapets, cornices, unsecured overhead lights, or unfastened bookshelves, and these hazards can be eliminated following orderly, systematic procedures. For still another instance, major structural deficiencies for earthquake resistance can be identified through more exhaustive analysis, and required modifications to correct deficiencies can be undertaken independently or along with other modifications that frequently are made in school buildings. Still another way is to replace unsafe buildings with those more seismically resistant. The last three ways named can reduce life losses and injuries as well as property damage. The merits of any or all of these possible methods of risk reduction cannot be assessed without consideration of economics. In the end, trade-offs between mitigation costs and acceptable risk must be made. Such trade-offs are the basis of recommendations made in this report for risk reduction for existing schools in the State of Utah.

Since this study draws from many sources of information, it contains many of the elements for, but does not directly cover, the economic feasibility of making new buildings seismically sound, at some added cost, at the time of construction. In addition, it considers only benefits and costs relating to seismic safety. The possibility is not considered that seismic safety benefits could be one of several classes of benefits to be realized when a building is modified. An economic study considering seismic safety benefits as one of several sorts of benefits would require addition of the costs of the non-seismic safety benefits to the costs of seismic safety benefits.

This study concentrates upon general aggregate building and life and safety losses due to earthquake-induced ground motions, from which general benefit-cost conclusions regarding State policy are derived or suggested. Such a methodology has its basis in statistical extrapolations. A full examination of the methodology and assumptions is contained in Section 4 of this report.

THE GENERAL FINDINGS

Three broad alternatives were selected for evaluation in this study.

(1) The existing structure is fully replaced by one that is earthquake resistant.

(2) The structure is fully retrofitted to be seismically stronger.

(3) The structure is left as it is.

In all cases, the schools were treated as classes of buildings rather than on an individual basis.

From an ecomonic analysis of these alternatives, one can derive general conclusions about what major actions or programs may be needed so that school buildings will be seismically safer. The various forms of evidence developed in this analysis help to specify the risks expected from earthquakes. This study does not concern itself either with construction activities that are less costly, such as instances of selective remodeling, or with various programs that might be undertaken to prepare teachers and pupils for an earthquake. Analysis of selective remodeling options requires separate detailed analysis of each school building, which is outside the stated purpose of this study. Also, as previously noted, preparedness information on what to do in the event of an earthquake provides no verifiable data regarding reductions in life losses or injuries and no reductions in property losses.

Of the 581 primary and secondary public schools in Utah (1977 data), only 36 schools were not considered in this study. All omitted schools were built after 1974. That date is when the basic construction data on existing schools were gathered and after higher standards for seismic design had come into effect. None of the omitted schools can be expected to require replacement or retrofitting to meet current seismic standards.

In spite of the limitations of this study that are mentioned earlier and which are discussed in greater detail in Section 4, the comparative economic merits of the three alternatives are clear. The estimated present value of capital outlays and expected seismic losses for either replacing or fully retrofitting a seismically unsafe school building exceed the estimated costs of leaving the building as it is. That is, on the aggregate level, no economic case can be made to justify either replacing or retrofitting existing school buildings in order to make them seismically safe. Considerations of life safety must be added to the economic arguments if any justification is to be found for seismic hazards reduction.

On the aggregate level, even the least safe Utah school buildings do not pose sufficient seismic safety hazards to justify, in economic terms, large-scale replacements or retrofitting operations. Those in the worst class may warrant inspection or replacement for other reasons, but they are too few in number to justify any further broad benefit-cost analysis of school buildings in order to evaluate the merits of large-scale reconstruction programs to overcome seismic safety deficiencies.

It has been concluded that a Statewide or district-wide replacement or retrofit of school buildings is unnecessary. At the same time, it has been concluded that some seismic safety problems are present which warrant individual attention and correction.

Even though seismically sounder school structures would substantially reduce property losses and minimize expected life and casualty losses, the costs of making structures much sounder would, on the aggregate level, greatly exceed the estimated benefits of such large-scale construction activities. It must be remembered that, if one decides to leave buildings as they are, one is increasing the risks that there will be deaths and casualties that would have been preventable. Still, the costs of preventing deaths and injuries are extremely high if large-scale seismic replacement and retrofitting operations are undertaken. The cost of preventing death and injury is much less if seismic requirements are met in the initial construction phases.

As a result of the conclusions drawn in this study, it may turn out, in retrospect, that an earthquake causes losses to several particular structures which exceed losses that would have occurred had the structures been fully retrofitted or replaced. This is one limitation of probabilistic type studies. Geological and geophysical studies have not advanced to the point where one can be fairly well assured which structures are going to suffer earthquake damage within a short geologic time-frame. So, it cannot be predicted which if any structures should be replaced. However, it is expected that direct examination of selected school buildings and more detailed seismic predictions would lead to the same conclusion that some do need large-scale construction modifications for seismic resistance.

For the State as a whole, such results are illustrated by the following estimates. The first is expected dollar losses due to earthquake-induced ground motions; the second is expected nonfunctionality in percent caused by building damage. Clarification of these estimates is found both in the discussion to follow and in Section 4 on methodology and assumptions applied in this study. The primary use of estimates of structural failures (a building is held to be nonfunctional if there is a 50-percent structural loss) is to determine how many schools are expected to be usable or to require extensive repair, or even replacement, following earthquakes of various magnitudes.

Estimated cost of replacing the 545 schools surveyed (1978 dollars):

$1,179,539,000

Estimated annual average structural loss to surveyed State schools if all are left as they are:

Dollar estimate (1978 dollars): $706,000

Nonfunctionality estimate: 0.12%

Estimated annual average structural loss to surveyed State schools if all are replaced or fully retrofitted to meet current seismic safety standards:

Dollar estimate (1978 dollars): $140,000

Nonfunctionality estimate: .02%

Estimated annual mortality rate to all pupils while in surveyed schools if all are left as they are:

0.58

Corresponding annual hospitalized injury rate in surveyed schools:

9.43

Speculated annual mortality rate to all pupils while in surveyed schools if all are replaced or fully retrofitted to meet current seismic safety standards:

0.14

Corresponding annual hospitalized injury rate while pupils are in school:

2.34

In life and casualty terms, an extensive seismic replacement or retrofit program for seismic safety of existing school buildings would be expected to prevent about 44 deaths and about 700 injuries in a century. Such estimates certainly indicate that seismic risk is present. Further analysis leads to a conclusion that steps can be taken to reduce this risk without undertaking a costly system-wide replacement or retrofit program.

In economic terms, where one is forced to set a dollar value on life, for every $1.00 spent on replacement, about 1¢ of benefit would ensue. If retrofitting were to cost only one-fifth of replacement, for every $1.00 spent on retrofitting, less than 5¢ of benefit would ensue. If one imagines the worst sort of structure in the most seismically active zone, one still finds less than 13¢ of benefit for $1.00 spent on retrofitting.

In other terms, one would need to estimate the value of life at over $270 million in order to justify, in cost terms, a large-scale statewide building replacement program to reduce (not eliminate) earthquake risk. That is, programs that involve expenditures of less than $270 million for each life saved are economically superior to a statewide rebuilding program. Even for the very worst class of schools, the value of preventing one death would need to be set at about $12 million if retrofitting could be achieved at one-fifth the cost of replacement.

Since there are no doubt less costly ways to prolong the lives of children, the option of replacing or retrofitting all school buildings does not seem to be economically feasible. Yet, based on recent geological evidence and on the fact that most schools lie in the most seismically active zones, the seismic problems cannot be ignored. If less costly means of correcting the problems are available, then such means should be seriously considered.

Even though benefit-cost techniques do not here justify any large-scale rebuilding program to make schools seismically safer, several other noteworthy results of this study are described in subsequent paragraphs which indicate the merits of a modest upgrading effort.

SEISMICITY IN UTAH

Since expected seismic activity in Utah is considerable, especially in those densely populated areas where most schools exist, the failure of a benefit-cost analysis to justify extensive replacement or retrofitting operations is not due entirely to the level of expected seismicity in the State.

A few areas of the United States have higher expected earthquake rates than does Utah. Nonetheless, Utah is one of the most seismically active states. A much more important factor in the failure to justify extensive rebuilding programs is that building vulnerability is generally only marginally hazardous, whereas the dollar investment in school buildings is very large. In Utah, and, in the United States generally, building materials and practices are superior to those in some countries where many lives have been lost during what would in Utah be regarded as moderately damaging earthquakes. (For one comparison, see [1].) Thus, a comparison of risk with cost to reduce the risk shows a very unfavorable relationship for Utah's seismic environment.

In a report by S.T. Algermissen and David M. Perkins, the United States is divided into 71 seismic areas based on expected seismicity in each area ([2], see especially pp. 17, 18). Large areas of the United States are not included in any seismic zone. That is, such areas are not believed to have hazardous earthquakes. Utah has four seismically active zones and one non-active zone, as delineated in the Algermissen and Perkins report. Three specific zones are applicable to Utah schools, namely, Zones 32, 33, and 34 (See Figure 1). One can compare the Algermissen and Perkins zonation map published in 1976 with an earlier 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, and Zones 32 and 43 are least active. Part of the State along the east side lies in a zone where little seismic activity is expected (See Figure 3).

Zone 33, which extends through Utah's most densely populated areas, ranks seventh among the 71 continental United States zones 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 seismicity levels lie predominantly in California, Nevada, and Montana, although expected maximum magnitudes are equal or greater in the St. Louis area and in a portion of South Carolina.

Part of the basis for predicting future earthquakes and their intensities comes from the historical record. The historical record of seismicity for Utah, even though relatively short in geologic time reference, indicates considerable seismic activity in portions of the State (See Figure 3). In a study of records 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 ([4], pp. 703-718). From 1853 to 1975, an estimated 17 Utah

[1]For a partial explanation of the Modified Mercalli Intensity Scale see Appendix A. See also [5], pp. 202-205.

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. [7], pp. 9-20).

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 yet to be published, a revised seismic zone map of Utah has been used in this study in which Zone 33 in Figure 1 has been subdivided into two subzones, 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 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 Zones	Modified Zone Designations
Zone 43	Zone U-1
Zone 32	Zone U-1
Zone 34	Zone U-2
Zone 33B	Zone U-3
Zone 33A	Zone U-4

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

Figure 7, which indicates the distribution of Utah schools by city, shows that most of the cities where schools exist lie in the most severe seismic zones. Moreover, the cities in which the most schools exist, lie in the most seismically active zone, Zone U-4. Figure 8 gives a better indication of this distribution in terms of number counts of the schools by county and by zone.

Study findings indicate that future seismic safety studies should concentrate upon Zones U-4, U-3, and U-2 (even though, say, a large earthquake once occurred in Ibapah, which is in Zone U-1 (Cf. [4], p. 706).

EARTHQUAKE LOSSES

As the aggregate loss estimates presented previously indicate, considerable property damage to all sorts of buildings can be expected as a result of future seismic activity. Losses to schools likely will be included. But, as already stated, expected structural losses do not and cannot justify expenditures for large-scale retrofitting or replacement of schools on the basis of cost alone.

In Section 4 on methodology and assumptions, it is explained how damage estimates are derived. In that section, it is explained both that the relevant losses considered do not include losses to equipment and also why such building losses cannot, in principle, be adequate grounds for replacing structures. If there are reasons for replacing school buildings, they include life and safety factors, energy savings, and factors related to improved educational facilities. Similar conclusions can be drawn for large-scale retrofitting of the whole class of school buildings, although it is possible, at least in principle, for retrofitting to be less costly than the expected damage to structures left as they are.

Thus, whether a school building exists in California or Utah, the justification for replacing such a building cannot be based upon property values alone. As one sees from the damage and loss estimates already given, the results of this study are consistent with such a general conclusion.

Since the estimated replacement costs for Utah's school buildings exceed $1.7 billion, the mean cost of replacement equals about $2.25 million. On a fifty-year basis, the estimated present value of losses in schools due to earthquakes is $7 million, and the mean cost of such damages has a present value of about $13,000.

If it were economically feasible to replace all existing structures, on the basis of structural losses alone, the present value of estimated structural losses due to seismicity would approximate, or exceed, the replacement costs of buildings. Such is obviously not the case.

Similarly, $13,000 is at present not nearly enough money to retrofit fully most schools that need improved seismic resistance.

LIFE SAFETY

Data on life and casualty estimates do not suggest that the number of expected deaths and casualties can even approximate, in economic terms, the difference between building replacement or retrofitting costs and damage losses.

Although there are numerous good objections to setting dollar values on life or the prevention of death, such must be done in order to evaluate the merits of most alternatives for loss prevention. If some economic consideration is not given to such human factors as the value of life, then no benefit-cost analysis can ever justify replacement of school buildings. If, that is, one ignores the issue of the value of life, then one tacitly assumes, for economic purposes, that the value of life is zero. If, in contrast, one places the value of life as being infinite, then one justifies equally every program that is expected to prolong life, no matter how slight the program's contribution to the prolongation of life and no matter how economically ruinous the program may be.

The position here taken is that, for economic purposes, some value of life must be set so that the cost-effectiveness of various programs aimed to prolong life can be compared. In addition, it is here recognized that economic considerations alone should not be determinative of the value of programs to prolong life, even though economic considerations can play a role in the assessment of such programs.

Data for life and casualty estimates due to earthquakes in Utah are lacking owing to the limited number of severe events in the historical record. Two deaths have occurred in Utah that are earthquake-related, both caused by the 1934 Kosmo (Hansel Valley) earthquake of magnitude 6.1 (Cf. [14], p. 37). The estimate in this study that there would be roughly 58 pupils who would die in schools in a century, given the present enrollments, school structures, and distribution of schools, is to a large extent a result of assumptions of earthquake activity extrapolated from the historical record and geological expectations.

As a beginning point of discussion, if one were to assume that the historical record were to repeat itself, with epicenters and magnitudes where they lay, then, owing to increases in population density, more than the previous two deaths would be expected. A more important factor is that geological evidence indicates that epicenters for future earthquakes are more likely to be found in more densely populated areas than has previously been the case. The number of expected deaths and injuries therefore will increase in the future, given the same construction characteristics for Utah buildings, even if future seismicity is the very same as in the past.

Still, the estimate in this study is far less than the USGS estimate of 630 public school deaths if a severe earthquake were to occur in Salt Lake Valley near the Wasatch fault and while school is in session ([7], p. 305). That study assumes a worst-case earthquake. As explained in the section on methodology and assumptions, it is assumed in this study that there is some likelihood of a major earthquake along the Wasatch fault in the next several hundred years, but the exact location cannot be known. Also, the likelihood that such an earthquake will occur in the area where it will cause the greatest life loss, in Salt Lake City near the Wasatch fault, is not very great. Thus, the USGS estimates are derived from a worst-case situation, whereas the estimates of this study are derived from statistical probabilities of expected earthquakes. The USGS estimates thus provide an upper bound for earthquake losses based upon building construction at the time of that study, whereas the estimates in this study give an average loss that would be expected if one were able to accumulate similar loss data caused by earthquakes occurring over many hundreds of years. The lower boundary of losses in this type of analysis is that none will occur. That is to say, it also is possible, although most unlikely, that no severe earthquakes will occur in Utah in the future.

The comments made above illustrate the difficulty of estimating earthquake losses when our knowledge today of seismic recurrence is so limited. Planning for a worst-case earthquake, from the point of view of preventing life and property losses, sounds very correct in the abstract, but when one examines the cost and social disruption to do so, less extreme alternatives become more attractive. At the other extreme, to fail to consider that damaging earthquakes can occur is to disregard all available physical and scientific evidence. Thus, we have chosen to base our analysis on expected average seismic conditions and to recommend mitigation measures commensurate with such average conditions. In doing so, reasonable loss estimates result, and it is believed that substantial loss reductions for average seismic conditions can be accomplished at societal and economic costs that can be afforded. Yet, we simultaneously acknowledge that the recommended measures will not eliminate losses either due to a worst-case earthquake, which is possible, or even due to strong earthquakes given certain unfavorable conditions.

For earthquake loss reduction purposes, one must regard the average loss estimates here given as long-term estimates. However, for disaster planning it should be assumed that a very damaging earthquake may occur, so that the State and its communities are able to deal effectively with earthquakes that are possible.

BUILDING DAMAGE

A primary reason why benefits from replacement or retrofitting do not exceed the costs for such changes is that moderately-sized earthquakes are not expected to cause severe damage to existing school buildings even of the worst class in Utah. Still, many school buildings in Utah are over fifty years old, and many of those are near the Wasatch fault. Proximity to a fault is not in itself a complete indicator of building losses. Ground shaking, which affects a much larger area than ground rupture, is the major cause of building damage and life loss or injury. Still, a fault is an indicator of seismic activity which must be acknowledged. So, many structures in the Wasatch fault zone are more vulnerable to earthquake damage than are others at some distance from the zone. In addition, a few stone or adobe structures, not in Zone U-4 but in seismically active areas, appear to merit more detailed evaluation.

For the purposes of this study, two building classification schemes were used for estimating earthquake losses. Both classification schemes recognize that different construction types have different expected seismic-resistance characteristics.

The first classification scheme comes from a report by S.T. Algermissen and K.V. Steinbrugge, and contains five main classes ([9], p. 3).

(1) Wood-frame and frame-stucco buildings.

(2) All-metal buildings.

(3) Steel-frame buildings.

(4) Reinforced-concrete buildings.

(5) Those with mixed construction, or with masonry bearing and non-bearing walls.

A complete description of these building classes is furnished in Appendix B.

In Table 1 Utah school buildings have been classified in accordance with the scheme suggested by Steinbrugge. Data are tabulated by both construction class and seismic risk zone.

Estimated present values (1978 dollars) of these buildings are furnished in Table 2 in the aggregate for each construction class.

In Utah, only five school structures fit the wood-frame or frame-stucco classification, only ten structures are steel-frame, and only eight are reinforced-concrete structures. The rest are in the fifth class.

Structures in Zones U-4, U-3, or U-2 are believed to be most vulnerable to earthquake damage, though on a statistical basis one could expect occasional damage to structures in Zones U-1 and U-0. Stone or adobe buildings, in the fifth class, particularly those that are very old, typically have very poor resistance to earthquake forces. The few stone or adobe structures that might be more completely examined for their earthquake resistance are listed in Table 3.

Many existing school buildings, though, are very old, and age implies not only a weaker structure but also building practices less concerned with seismic safety.

According to the USGS report on the Wasatch Front, Salt Lake City first adopted building construction regulations in 1933. Hence, the most vulnerable schools in Salt Lake City are those built prior to 1933 and having unreinforced-masonry bearing walls laid with sand-lime mortar and wood floor and roof construction ([7], p. 296). For the Wasatch Front, the USGS report makes further distinctions in terms of construction dates:

1. Structures built before 1961 are designed only for gravity loads and wind forces.

2. Structures built from 1961 to 1970 are designed for earthquake forces based upon a UBC Zone 2[1] classification.

3. Structures built after 1970 are designed for earthquake forces based upon a UBC Zone 3 classification ([7], p. 91).

Even though an examination of the history of the adoption of the Uniform Building Code and compliance with its seismic provisions in Utah has not yet confirmed that the USGS distinctions are completely valid, age remains a factor in assessing vulnerability.

Of the 581 schools in Utah, approximately 140 have structures that are fifty or more years old. The replacement cost for all such older structures is approximately $258 million, or about one-fifth of the replacement costs for all school structures.

In accordance with the Algermissen and Steinbrugge report, such older schools were placed in the worst class of structures. But even for a structure in the worst class and in the worst zone, Zone U-4, the present value of expected earthquake-caused structural losses is only 0.94 percent of the replacement costs. The maximum difference between the present values of the alternatives of leaving buildings as they are and making them seismically sound is only 0.80 percent of the replacement costs.[2]

The second building classification scheme, adapted from the methodology used in the USGS report, gives estimates of nonfunctionality. The building classes range from 1 through 7, with those in Class 7 being the most susceptible to damage.

Roughly speaking, the seven classes are as follows.

(1) Small wood or metal buildings, or buildings with special damage-control features; one or two stories.

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

[2]In the San Francisco Bay area, one of the worst seismic regions of the nation, long-term annual losses for various building classes range from 0.1 to 1.6 percent ([9], p. 1).

(2) Spacious wood or metal buildings, or spacious buildings with special damage-control features; one or two stories.

(3) Tall steel or reinforced-concrete buildings with special damage-control features, or one- and two-story spacious buildings designed for UBC Zone 3.

(4) Tall steel or masonry buildings designed for UBC Zone 3, or one- and two-story spacious buildings designed for UBC Zone 2.

(5) Spacious buildings constructed before 1961, and tall buildings designed for UBC Zone 2.

(6) Tall buildings constructed before 1961, or small structures with unreinforced-masonry bearing walls.

(7) Tall structures with unreinforced-masonry bearing walls, or others with apparent structural defects.

On the basis of secondary sources, and as a percent of estimated replacement costs, about 18% of Utah schools were placed in Class 6, 39% in Class 5, 19% in Class 4, and 13% in Class 3 of this classification scheme.

For the worst class of buildings, Class 7, in the worst zone, Zone U-4, 100-year structural failures are estimated at 29% of the class.

In addition to estimates of structural losses or structural failures for the various classes, as derived from the two classification schemes, some school buildings are relatively close to faults. Buildings that are very old, of masonry construction, and very close to the Wasatch fault deserve detailed inspections. A report by the Utah Geological and Mineral Survey gives approximate distances from faults for educational institutions (Cf. [11], pp. 243-251).

Direct inspections of such older structures, or adobe or stone buildings, or buildings close to faults, by qualified personnel may indicate in some cases that expected damage estimates, and also life and casualty estimates, are too low.

UNCERTAINTIES

Major earthquake losses are expected to occur infrequently, and not by any means with an equal distribution over the years. So, estimates derived here are not suitable for some purposes, such as for earthquake preparedness programs.

In the USGS study of earthquake losses in the Salt Lake City area, it is explicitly stated that the assumptions are made for extreme circumstances:

> The numerical values associated with each problem area, such as damage to and life loss in hospitals, represent reasonable maximum expected conditions ... . Errors in the estimated intensities may stem from inaccurate estimates of maximum magnitude earthquake for the region or a poor choice of epicentral location, focal depth, and fault trace. It is believed, however, that these items have been estimated conservatively and thus, represent worst case assumptions.
>
> ([7], p. 58)

Assumptions made here in this benefit-cost study, however, have been made in order to estimate long-term effects of earthquakes, which should include, when averaged out, very infrequent worst-case assumptions.

Averages, then, can be very misleading for certain purposes, since there can be almost no seismic damage for many years, and then considerable damage can occur. The modal as well as the median annual damage may well be zero in Utah.

In a computer simulation of San Francisco earthquakes from 1800 to 1967, Don Friedman assumed that the 1960 distribution of dwelling properties remained constant, and then derived damage estimates from earthquakes. According to Friedman's estimates, four major earthquakes in the period accounted for 86% of all simulated damages. The 1906 earthquake alone accounted for 44% of the damage. So, the 1906 earthquake alone contained damage 73 times the average annual loss, and the four earthquakes combined accounted for 142 years of the average annual loss ([12], p. 163).

Recent earthquake experience also can be misleading. When Friedman determined the average annual loss from 1948 through 1967, he found that the San Francisco earthquake caused losses that were 339 times the average annual loss in the most recent twenty-year period ([12], p. 163). Were this study to base its estimates, say, on very recent activity along the Wasatch fault, or even upon the historic record, estimated losses would be different from those indicated above.

In a report made public by Senator Alan Cranston (California), the total property damage due to earthquakes in the United States is estimated to be $1,862 million (1971 dollars). Three earthquakes, the 1906 San Francisco earthquake, the 1964 Alaska earthquake, and the 1971 San Fernando Valley earthquake, produced over 84% of the estimated property losses ([13], p. 187).

In Utah, several earthquakes have been intense enough to cause considerable losses. It is estimated that there have been, at least potentially, 40 damaging earthquakes in Utah in the past 128 years, and that the most damaging earthquake occurred in 1962 in Cache Valley, where property losses have been estimated at $1.7 million. Whereas the Cache Valley earthquake registered 5.7 on the Richter scale, the Hansel Valley earthquake, in Kosmo, Utah, in 1934, caused two deaths as it registered 6.7 on the Richter scale ([14], pp. 37, 38). The extent of loss depends upon the amount of development and population density of the area affected by the earthquake.

So, even though losses due to earthquakes may be estimated reliably for the purposes of a benefit-cost analysis, actual losses at any given time depend upon many factors, and so may far exceed even the present value of expected losses.

Since there is such a discrepancy between the losses that occur on some infrequent occasions and the present value of estimated losses given annual loss estimates, and since large portions of Utah are seismically active, the cost estimates used in this study are not appropriate for all public earthquake safety programs. As stated previously, earthquake preparedness programs probably are more suitably based on what actions would need to be taken if earthquakes of high intensity, or higher than might soon be expected, were to occur.

SECTION 4

METHODS AND TECHNICAL RESULTS

PART A: SUMMARY OF METHODS AND RESULTS

The chief function of a benefit-cost analysis is to provide materials relevant to the determination of which of several courses of action is most economic. In this study, three alternatives for existing school 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 earthquake resistance.

Numerous other alternatives have been omitted from detailed evaluation, such as implementing educational 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 schools 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 vulnerability of specific schools 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 secondary factors, such as liquefaction or rockslides.

Property damages, though, form only a part of a benefit-cost analysis of replacing or retrofitting school 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 also 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 is 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 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. Finally, in Part H, some of the significant sources of data, not mentioned in the bibliography, are identified.

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, L_b for the second 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 buildings prices are going to change, we shall assume that they are going to change at the same rate as all prices. In assuming that buildings 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. ([8] contains such data on Utah schools). School buildings, as such, have no market value. The only determinants of the present value of school buildings are the life-spans of the buildings, their present age, their replacement costs, and their present capacity to serve a given population of students until the life-span of the building is over.[1] Even though some data exist to the contrary, we shall assume, in the main, that buildings are suited for present educational 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 seismic upgrading are not considered part of the costs either of retrofitting or of losses due to earthquakes.

One possible assumption is that each school building has a 50-year life-span, or that $z = 50 - y$. Since, though, so many school buildings in Utah are older than 50 years, such an assumption was not found to be satisfactory for all schools, and longer life-spans were assumed in some cases.

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

We shall assume also that the cost of money, as a function of the discount rate, is social cost, and so is not influenced by different ways of financing. So, even if the State can borrow at a 6% rate, the discount

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[1] The expression "present capacity to serve a population of students" can include a variety of matters, many of which are tangential or only distantly related to this study, as the subsequent part of the above paragraph indicates. Replacing a building can improve the educational 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 seismic 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 seismic benefits, since such added benefits presumably would entail added costs.

rate, the rate of borrowing, is nonetheless higher, since the source of funds to the State 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 percentage of funds is provided by the national government,
- -- the cost is paid off immediately, or
- -- funds are borrowed for twenty years at a rate of 12% 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.

It is here assumed that the bulk of any relocation costs will be such social costs as educational losses, including delays, rather than property costs. When a school suffers considerable damage, students may be doubled up at other schools, or bused to vacant schools (if there are any), but the cost of renovating other sorts of buildings, leasing them, and stocking them, is an alternative so costly in many cases that other remedies likely would be sought first. In addition, there also are relocation costs from replacing or retrofitting a school now.[1]

So, in spite of the fact that there may be infrequent high relocation costs such as when leasing of space is required, we shall assume that the main property losses due to relocation are costs of busing.

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.

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[1]According to Arlan Winterton, at the Salt Lake City Board of Education, when East High School suffered considerable fire damage in May, 1974, classes were held outdoors. According to Jean Bond at the Salt Lake City Board of Education, other such cases, as the extreme fire at Lowell Elementary in 1962, caused students to be relocated at other schools.

If an 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 school 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) $[(d_a - d_b) + (L_a - L_b)] \sum_{j=o}^{z-1} (1+i)^{j}$ = 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) $\sum_{j=o}^{z-1} (1+i)^{j} = \frac{[(1+i)^{z}-1]}{i}$,

it follows that

(5) $[(d_a - d_b) + (L_a - L_b)]\left(\frac{(1+i)^{z}-1}{i}\right)$ = damage and casualty loss of selecting (a) rather than (b).

Thus, it is economic to replace the building, rather than to leave it as 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 algebraically 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

$$(10)\quad [(d_a - d_c) + (L_a - L_c)]\left(\frac{(1+i)^z - 1}{i}\right) = \text{damage and casualty losses for leaving the building as it is rather than retrofitting it.}$$

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

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

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 is

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

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 rates can be very controversial matters, the general benefit-cost results of this study would not be changed substantially if higher or somewhat lower discount rates were chosen (Cf. [15], 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 school.

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

In the Algermissen and Perkins study referred to earlier (Cf. [2]), 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 ([2], pp. 17, 18). So, 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), then we can use the above information, in conjunction with equation (13), 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, N, for earthquakes of a given intensity if we employ the following equations.

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

Given the assumption that the occurrence of an earthquake having a given intensity is equiprobable for each year during a 100-year period, then 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 Buchnam 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. [7], pp. 9-20).

In Zone 33A, 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. [7], p. 39) one finds the following equation

$$I_o - I = n \operatorname{Log}_{10} [(\Delta^2 + h^2)^{1/2}/h], \tag{15}$$

wherein Δ = the epicentral distance (km.) from I_o to I,

h = depth of focus (km.),

I_o = maximum intensity at the epicenter,

I = intensity at Δ 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 were 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, was 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 Δ 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 Δ's. That is, if $I_o - I = 1$, and $\Delta =$ 10 kilometers, then the maximum intensity, I_o, extends for a distance of 5 kilometers. So, too, if for $I_o - I_2$, $\Delta = 21$ kms., then the second highest intensity, $I_o - 1$, 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 Δ, given various differences in intensity.

$I_o - I$	Δ (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 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.[1] 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.

[1]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.

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	Intensity					
		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.

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 zones 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. Second, 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 semicircles 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. If 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 $\frac{300}{r} + 1$ 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, then 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 $r < w \leq \ell$, given length ℓ (350 km.), and width w (40 km.), then the zone may be divided into ℓ/r units by w/r units. There are hence $(\ell/r + 1)$ $(w/r + 1)$ uniformly distributed points.

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

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

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

$$\frac{2\left(\frac{\ell}{r}\right)}{2\left(\frac{\ell}{r} + 1\right)} = \frac{\ell}{\ell + r} .$$

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.

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 initial 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 $\frac{(390 + 2r)r}{29{,}200 + 118r}$ 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

in order to 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. 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 sub-section, we use the seismic frequencies developed in the previous sub-section 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. [9], 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, and the class most typical of Utah schools) 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 4 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 5.

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 is, as adapted, given in Section 2. Using the same method as was followed to develop Table 5, 100-year factors for structural failures, estimated based on this second classification scheme, are given in Table 6.

From such percentages of nonfunctional 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." ([9], 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 6, 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 5, one can further estimate the losses to a given structure until its life cycle runs out, which losses are equal to:

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

Tables 5 and 6 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 building that is considered. Table 7 summarizes the basic estimates.

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

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

The estimate of 0.25 for fully retrofitted structures 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.

Given such percent estimates in Table 7, and the estimated seismic frequencies developed in Part D, one can, for each zone, derive the percent deaths and casualties by type of person as shown in Table 8. The estimates must be modified by the coefficients given above for any particular structure.

Using estimates in Table 8, one can derive mortality and mobidity estimates. For instance, if there are 600 pupils enrolled in a 2-story school built after 1962, if the occupancy rate for such pupils is 18% over the year, and if the structure is located in Zone 33A, then one has the following 100-year estimates:

600 pupils x 18% x 1.25 x 0.1229% deaths = 0.17 deaths, and
600 pupils x 18% x 1.25 x 1.968% serious injuries = 2.66 serious injuries.

The estimates made in Table 8 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. [7], p. 90). So, the data take into account only average expected deaths and casualties.

The number of lives lost in the Unites 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 Unites 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.[7], p. 73).

Estimates of deaths and injuries for all existing schools in the State can be approximated from data in Table 8, given pupil enrollments in the schools. Table 9 furnishes such pupil occupancies for the surveyed schools in the aggregate according to seismic zone in which the buildings are located and type of building as described in the table on the previous page. Applying appropriate coefficients as previously shown to data in Table 8, using the pupil occupancy data in Table 9, and assuming an average annual occupancy time in the schools at 18%, we obtain in Table 10 100-year estimates of deaths and injuries.

Two observations are made with respect to Table 10. First, the estimated 100-year totals of deaths and injuries to school occupants due to seismicity are likely to occur in only a few earthquakes, or even just one earthquake. Hence, although one death every two years may appear small, a large number of deaths in any one earthquake most likely would cause a public outcry concerning school safety. Such public response should be anticipated, and certainly adds justification to application of preventative measures before the earthquakes strike.

The second observation is that nearly all of the risk is found in Zone U-4, the most populous as well as seismically most active zone in the State. From the data, one readily can conclude that earthquake mitigation measures applied to buildings in Zone U-4, and to a lesser degree in Zone U-3, will be the most effective from a benefit standpoint.

Estimates of benefits in reduced life loss and injury rates, that might result from retrofitting of existing schools to achieve improved earthquake resistance, can be made in a manner similar to that described in the preceding paragraphs. Such estimates may be made for retrofit of the entire classes of schools, 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 for schools that there are four hospitalized injuries per life lost (Cf. [7], 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 due to earthquakes is $706,000 if all schools are left as they are, then the estimate of deaths in this method of analysis would be 0.22 per year. For retrofitted structures, the corresponding figure would be 0.04. Hence, there would be 0.18 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 suggests 0.44 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 costs of various hospitalization, or one can use other data, such 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. [19], 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. [16], p. 3; [17], [18]).

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. Estimates of lives lost and casualties as determined from Table 8 are here taken as being adequate for conclusions to be drawn in this study.

PART F: REVIEWERS COMMENTS AND METHODOLOGY REFINEMENTS

Two objections regarding the methodology presented in this section 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 conversation of energy, one should expect that the same areas will be attenuated 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 X.

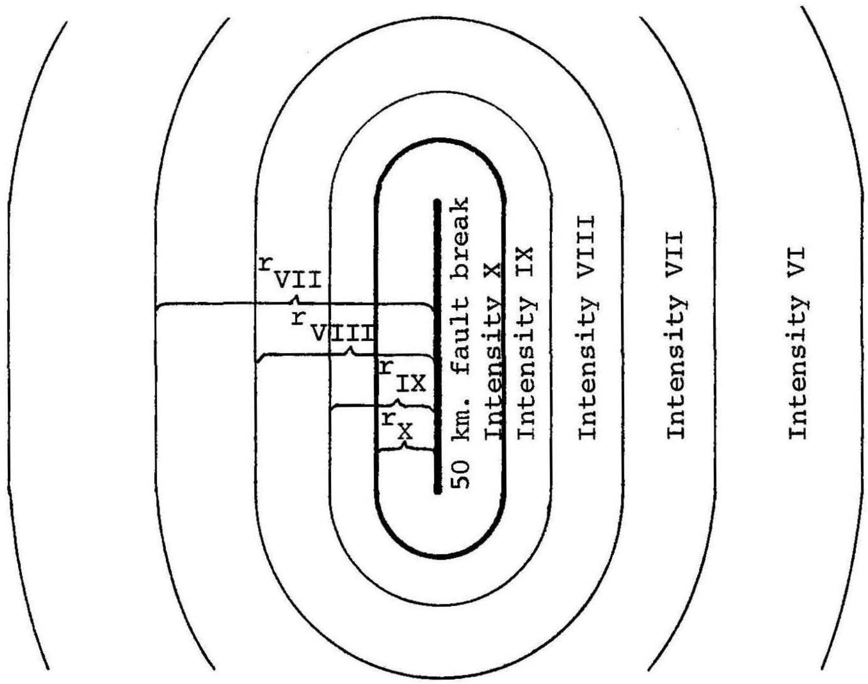
Second, as observed by W.W. Hays, USGS, soil conditions and their associated amplification effects were not used as a parameter in the methodology. Seismic waves are amplified in unconsolidated soils, and higher intensities therefore are expected. Hence, earthquake loss estimates for macrozones having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

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

For Intensity IX, one uses the following equation.

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

One thus derives the following radii.

r_X = 0.79 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 VII:	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 $\frac{300}{300+r_j}$.

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:	129 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 to be increased one intensity higher. That is, 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
29%	= 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
At Intensity IX:	0.0353
At Intensity VIII:	0.1188
At Intensity VII:	0.3976
At Intensity VI:	1.2819

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 estimate for Zone 33A is obtained from the modified results.

0.1703%

The above value may be used as a replacement in Table 8 of 0.122% for Zone 33A.

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

3.204%

This value may be used as a replacement in Table 8 of 1.968 % for Zone 33A.

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.

It is noteworthy that even with these increases in loss estimates, the revised 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 schools, 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 school 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 succintly 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 school buildings throughout the State according to their vulnerabilities to seismic exposure.

(d) To estimate expected life loss and casualty rates for occupants of school 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 their frequency and strength, and, second, the vulnerabilities of various classes of school 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 frequencies, 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 5 and 6 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 5 data are for property losses, from which dollar losses, in turn, may be estimated. Table 6 data are for estimates of structural failures.

Since the vast majority of Utah schools are of Class 5 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 present school buildings.

Note, however, that for Zone 33A (U-4), the jump from Class 5E to Class 5D 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. In Table 10 it is evident that, in relative terms, Zone U-4 is the most severe, and that selective retrofit of some school buildings can be justified. However, because of the large number of schools 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 school buildings 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 of 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 statisitcal sense. Such losses only can be reduced, since there are no earthquake-proof buildings, only earthquake-resistant ones.

If, for example, one were to retrofit all Class 5E buildings (Table 1) in Zone 33A (U-4) so as to upgrade them to classify as Class 5D, and given that 45% of the surveyed existing Utah schools in this zone classify as type 5E, with a corresponding upgraded classification to the next higher, level, then one finds nearly a 50% reduction in mortality and morbidity rates.

Such upgrading of existing 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.

PART H: SOURCES OF DATA

In addition to references listed in the bibliography, of special mention is that data on Utah secondary schools which comes chiefly from a 1974 survey made by Jim Soderburg at the Utah State Building Board and updated by Scott Bean at the Utah State Board of Education. Data exist, for almost every school building, on the following matters:

Building number, number of separate structures, name of school, primary use of structure (classrooms, shop, etc.), number of stories, construction date(s), present value, enrollment 1977-78, maximum occupancy, net square footage, replacement cost, type of footing/foundation, type of structural frame, type of exterior wall system, type of floor system structure, type of floor system floor, type of roof system structure, type of roof system deck, type of flooring, type of nonbearing interior walls, and type of ceiling system.

Given such data, it is possible to use the method so far described, if the information on building types is translated into the building classifications borrowed from the Algermissen and Steinbrugge report [9].

With the help of Ronald Ivey, Building Supervisor, Salt Lake County Department of Building Inspection and Permits, and of Vincent Bush, engineer with the International Conference of Building Officials, Whittier, California, we were able to obtain all copies of the Uniform Building Code back to 1927.

From Al Gailey and Kent Thomas at the Salt Lake City School Board, we were able to determine how valuations were made for Salt Lake City schools.

A further source of information has been Einar Johnson, at the Utah State Building Board, who has pictures of each school building. This data source was helpful in identifying hazards not evident in our general descriptive data.

Special acknowledgement is given to Richard Hughes of the H.C. Hughes Company, Salt Lake City, not only for his significant contributions to the USGS publication on earthquake losses in Salt Lake City [7], but also for data and methodology procedures on death and injury and building loss estimates which are from unpublished and working papers in files. As well, Mr. Hughes furnished much other information and assistance during the course of this study.

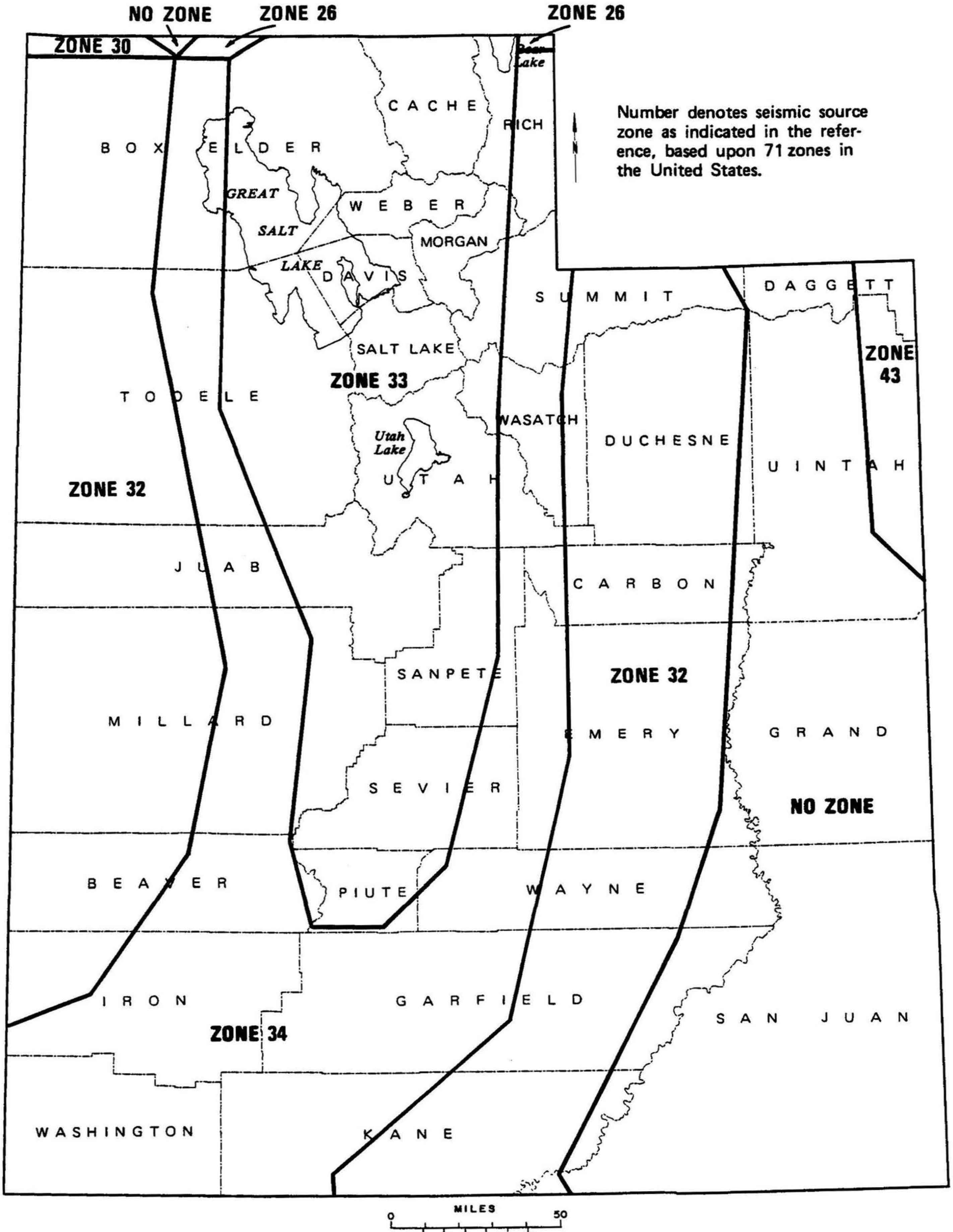


Figure 1
SEISMIC SOURCE AREAS IN UTAH
(Reference: S.T. Algermissen, and D.M. Perkins, USGS Open File Report 76-416)

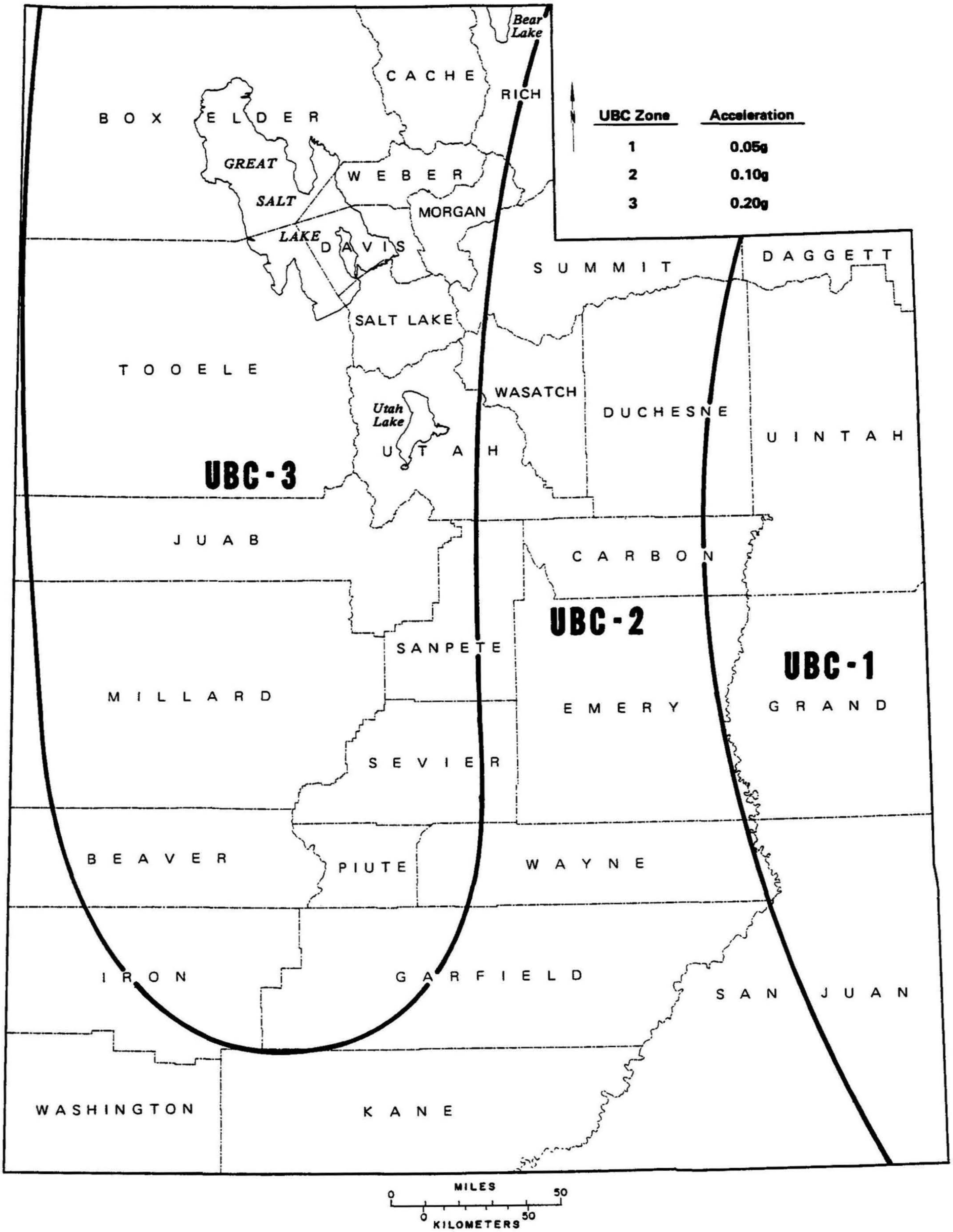


Figure 2
SEISMIC ZONES—1976 UNIFORM BUILDING CODE
STATE OF UTAH

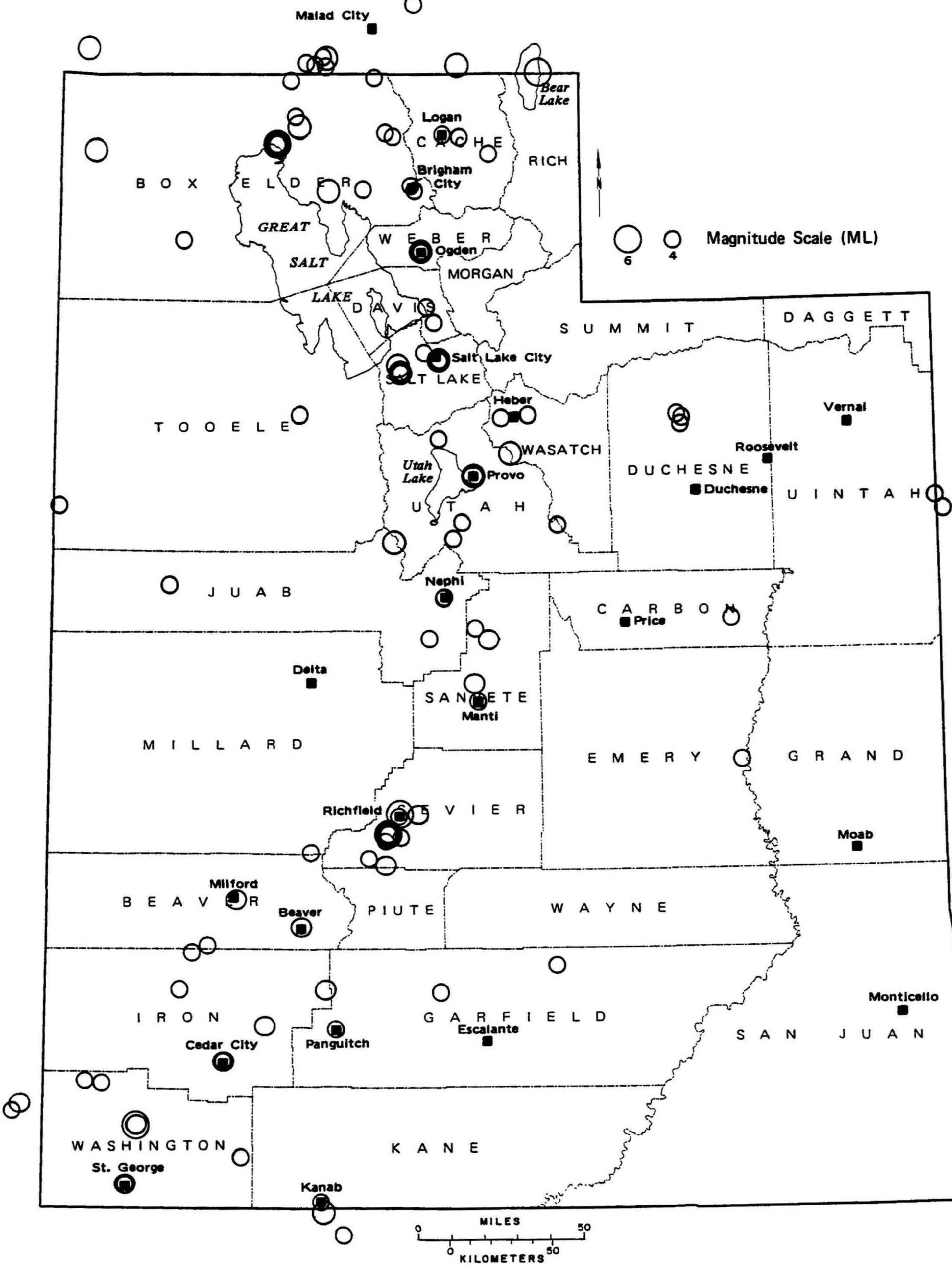


Figure 3

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)

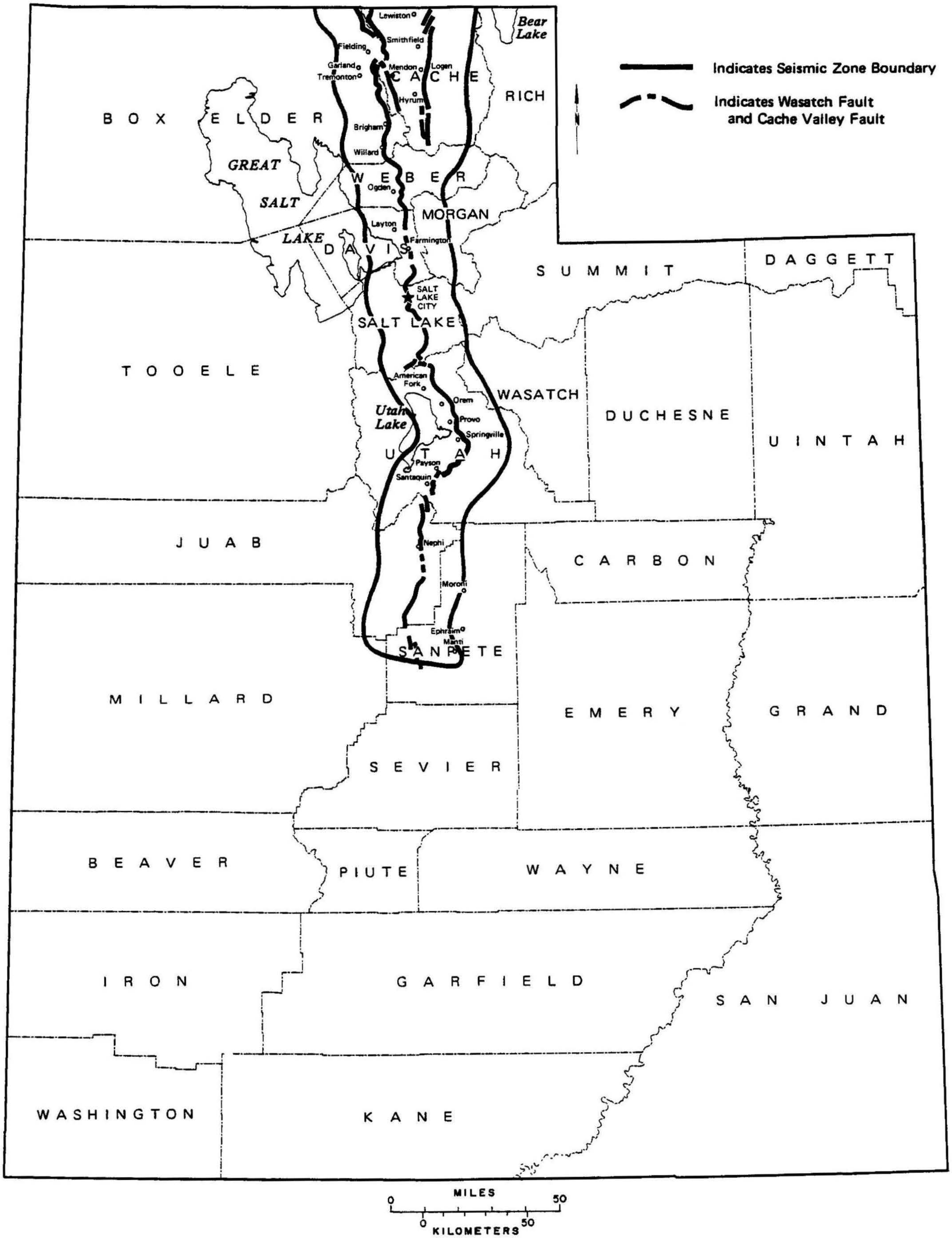


Figure 4
WASATCH FRONT SEISMIC ZONE, WASATCH AND CACHE VALLEY FAULTS
STATE OF UTAH

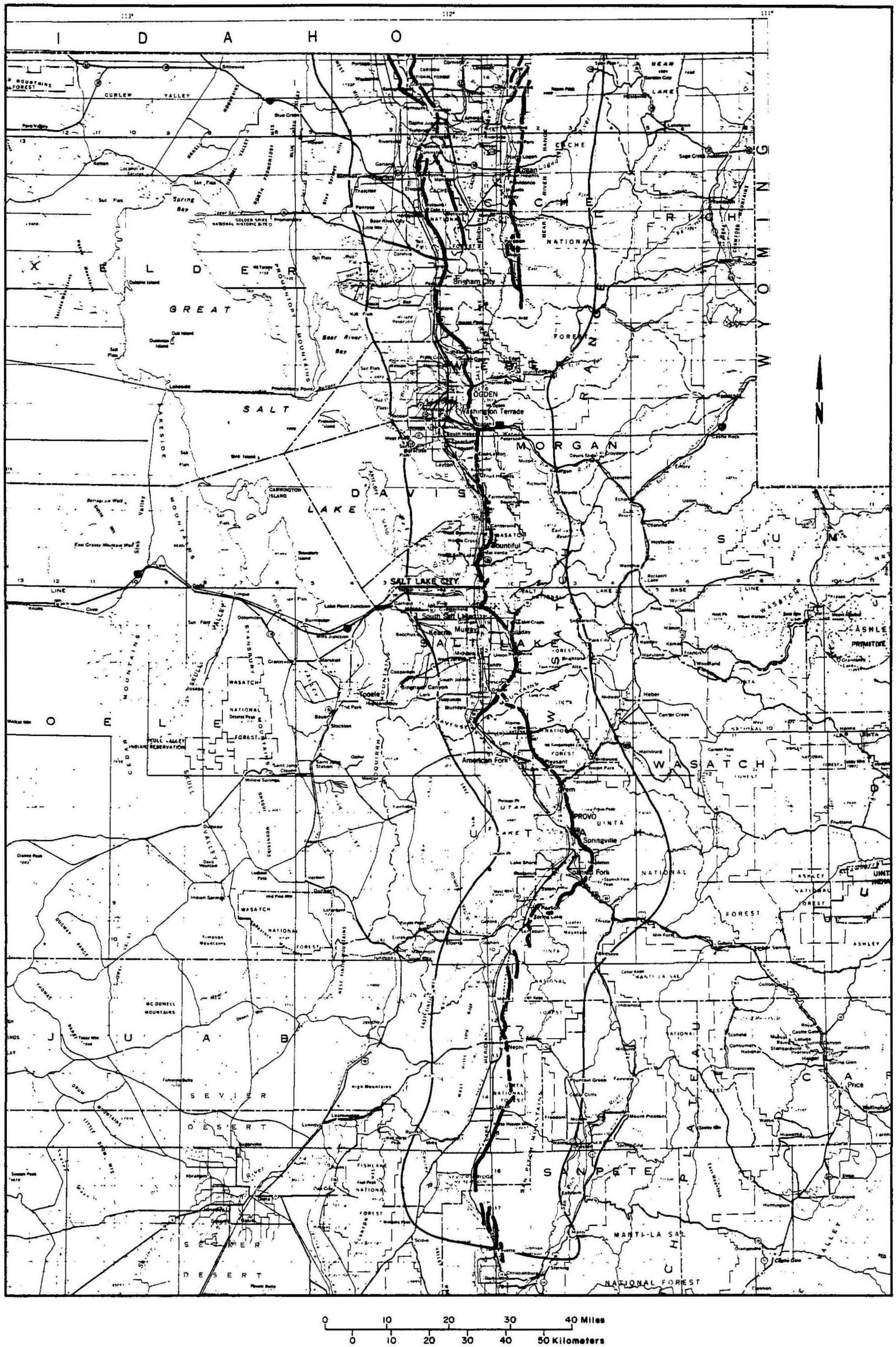


Figure 5

WASATCH FRONT SEISMIC ZONE

STATE OF UTAH

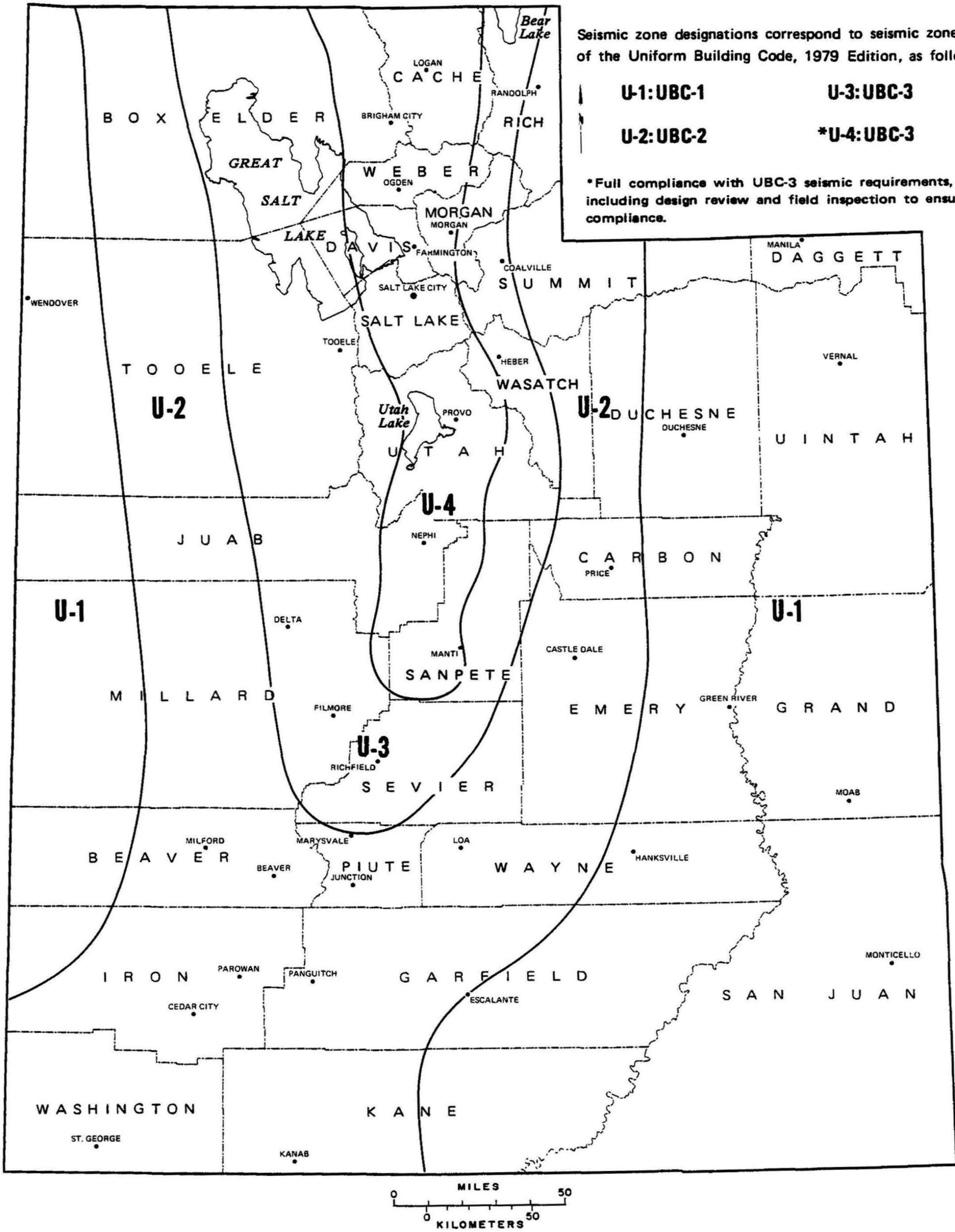


Figure 6
SEISMIC ZONES
January 1980
(Recommended by the Utah Seismic Safety Advisory Council)

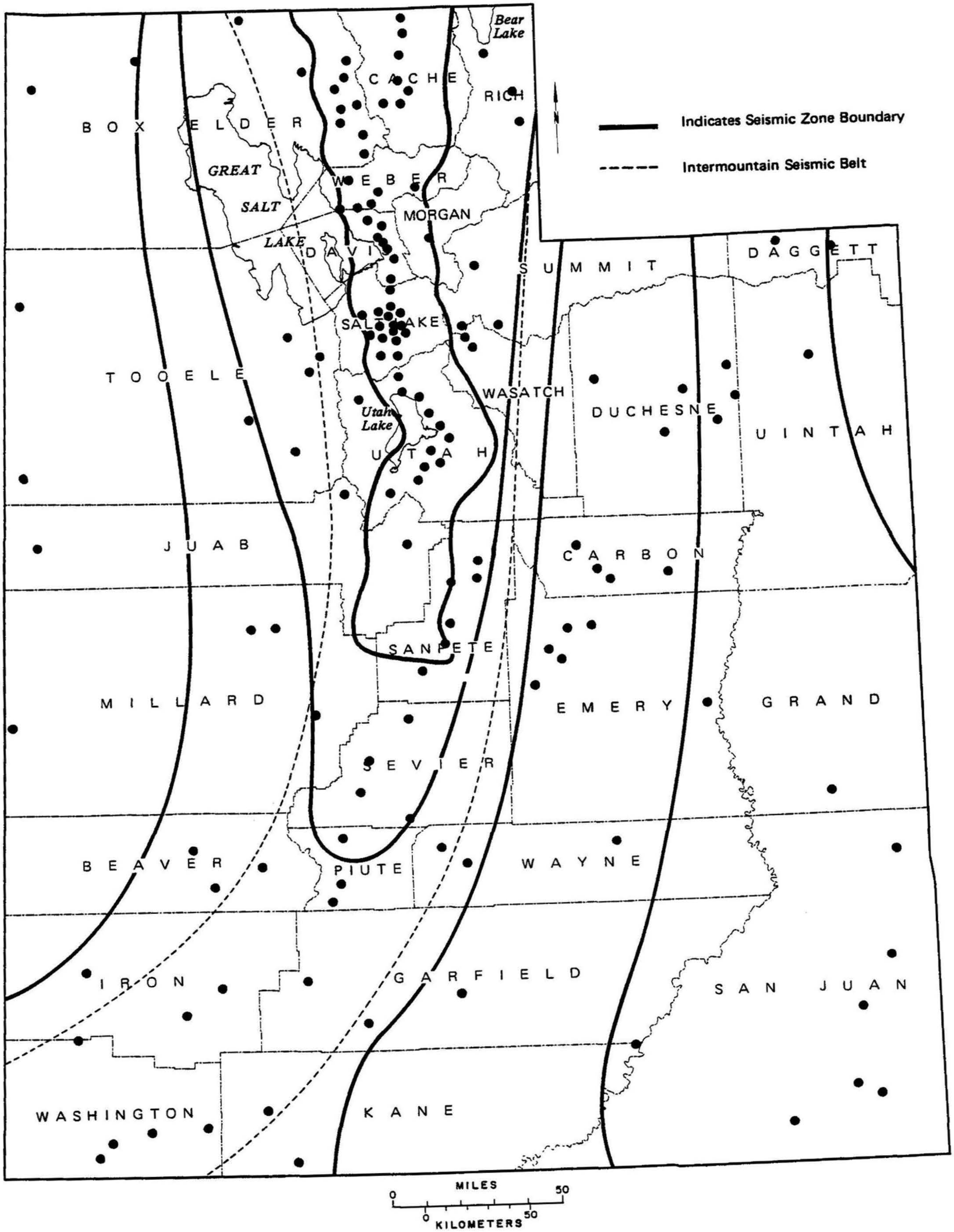


Figure 7
LOCATION OF SCHOOLS BY CITY
STATE OF UTAH

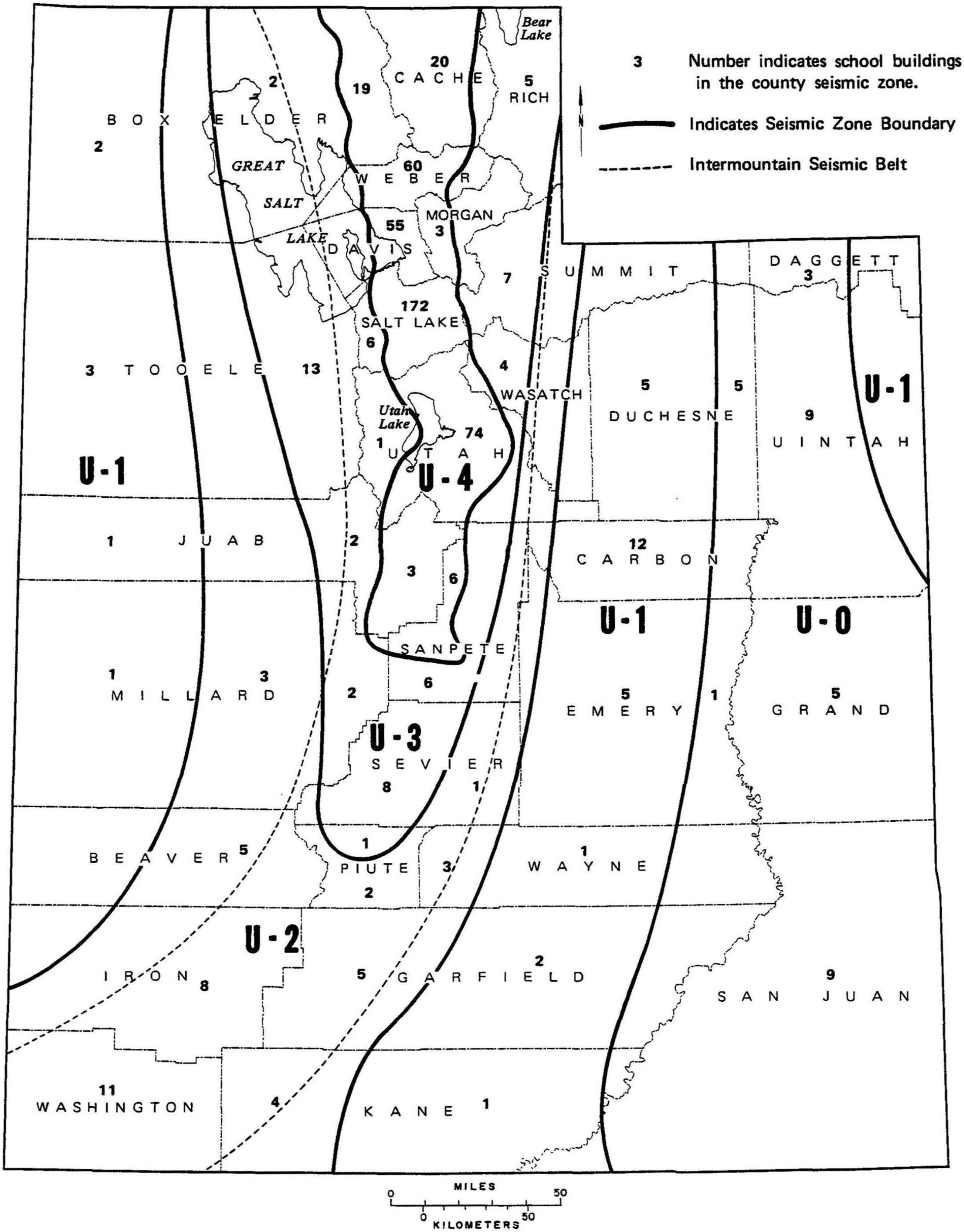


Figure 8
DISTRIBUTION OF SCHOOLS BY SEISMIC ZONE AND BY COUNTY
STATE OF UTAH

Table 1

CLASSIFICATION OF EXISTING UTAH SCHOOLS
IN TERMS OF CONSTRUCTION VULNERABILITY TO EARTHQUAKES[1]

	Building Classification											
Zone	5E	4D	4E	4B	5D	3B,3D 4C,5C	3C,4A 5B	3A	2B	2A	1[2]	Totals
Zone U-O	18	0	0	0	7	7	0	0	0	0	0	32
Zone U-1	17	0	0	0	7	5	0	0	0	0	0	29
Zone U-2	23	2	1	0	8	7	0	0	0	0	0	41
Zone U-3	28	0	0	0	12	7	0	0	0	0	0	47
Zone U-4	247	12	0	0	95	41	1	0	0	0	0	396
Totals	333	14	1	0	129	67	1	0	0	0	0	545

[1]Classification is made for analytical purposes in terms of seismic vulnerability and may not accurately depict the actual construction of each building. To the extent possible from available data, schools are classified in terms of their largest area in a given category. Hence, a school categorized as Class E may have a Class 5D section, for example. In contrast, school valuation figures are summarized by distinguishing the separate sections and their classes of construction.

[2]Owing to lack of information on expected damage losses to wood-frame buildings, given different seismic intensities, 5 such buildings have been classified here as Class 3B.

Table 2

ESTIMATED VALUATION OF UTAH SCHOOLS (1978 $)
BY CONSTRUCTION CLASS AND SEISMIC ZONE

($ In Thousands)

Zone	Building Classification 5E	4D	4E	4B	5D	3B,3D 4C,5D	3C,4A 5B	TOTALS
Zone U-0[1]	--	--	--	--	--	--	--	$ --
Zone U-1	$ 18,566	0	0	0	$ 11,618	$ 3,485	0	$ 33,669
Zone U-2	$ 26,249	$ 989	0	0	$ 17,139	$ 11,889	0	$ 56,266
Zone U-3	$ 60,462	0	0	0	$ 20,426	$ 18,246	0	$ 99,134
Zone U-4	$534,913	$29,982	$483	0	$254,748	$120,086	$1,134	$941,546
Total Valuation--All Classes								$1,130,615

[1]Buildings in Zone U-0 are not classified for seismic vulnerability; since damaging earthquakes are not predicted for the zone.

Table 3

POSSIBLE HIGH-RISK STONE OR ADOBE SCHOOL BUILDINGS
IN SEISMIC ZONES U-2 AND U-3

Building Number	School Name, Location, and School District	Construction Dates	Seismic Zone	Replacement Cost (1-78)	Other Building Characteristics
26-116	Koosharem School Koosharem, Utah Sevier School District	1901-1966	U-2	$ 528,000	Masonry block and stucco structural frame, block bearing exterior wall, wood floor structure and floor system, wood roof structure and deck.
30-704	Dugway High School Dugway, Utah Tooele School District	1951-1972	U-3	$1,659,000	Masonry and stucco structural frame, wood frame/siding bearing walls, concrete floor, steel roof structure, and wood roof deck.
34-112	Loa School Loa, Utah Wayne School District	1908-1966	U-2	$ 471,000	Stone exterior wall, concrete floor, wood roof structure and deck.
34-704L	Wayne High School Bicknell, Utah Wayne School District	1924-1957	U-2	$1,016,000	Stone exterior wall, wood floor, wood roof structure and deck.

Sources: Unpublished survey data from Jim Soderburg, Utah State Building Board; [3]; [8]; [10].

Table 4

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

Intensity	Construction Class 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

Contribution of Each Intensity in Zone 33A

Intensity	Frequency	Construction Class 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	0.8098	0.0324	0.0243	0.0202	0.0202	0.0202	0.0262	0	0	0	0

For All Frequencies Combined--Zone 33A

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 5

EXPECTED 100-YEAR LOSS FACTORS FOR 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 6

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

(Based on Adopted USGS Classifications)

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 7

DEATHS AND INJURIES AS A PERCENT OF SCHOOL OCCUPANTS BY DEGREES OF MODIFIED MERCALLI INTENSITY

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

Table 8

MORTALITY AND SEVERE CASUALTY RATES BY SEISMIC ZONE AS A PERCENT OF SCHOOL OCCUPANTS

Zone	Deaths	Injuries
Zone 32	0.0004%	0.0160%
Zone 33A	0.1229%	1.9680%
Zone 33B	0.0098%	0.3626%
Zone 34	0.0077%	0.2466%

Table 9

PUPIL OCCUPANCIES IN SURVEYED UTAH SCHOOLS
BY SEISMIC ZONE AND TYPE OF BUILDING

(Based upon Table of Coefficients)

Zone	Building Type					Totals
	B	C	D	E	F	
U-O	-	-	-	-	-	11,404
U-1	2,131	5,414	578	785	0	8,908
U-2	4,718	8,760	0	0	0	13,478
U-3	6,444	14,647	0	1,119	0	22,210
U-4	84,855	134,355	9,334	21,290	8,464	258,298
Totals	98,148	163,176	9,912	23,194	8,464 +11,404 =	314,288

Table 10

ESTIMATED 100-YEAR DEATHS AND INJURIES TO SCHOOL POPULATIONS IN UTAH AS A RESULT OF EARTHQUAKES

DEATHS

Zone	Building Type					Totals
	B	C	D	E	F	
U-0	0	0	0	0	0	0
U-1	0.0012	0.0039	0.0001	0.0001	0	0.0053
U-2	0.0490	0.1214	0	0	0	0.1704
U-3	0.0853	0.2584	0	0.0296	0	0.3733
U-4	14.0781	29.7220	2.5811	7.0647	3.7448	57.1907
Totals	14.2136	30.1057	2.5812	7.0944	3.7448	57.7397

INJURIES

Zone	Building Type					Totals
	B	C	D	E	F	
U-0	0	0	0	0	0	0
U-1	0.0460	0.1559	0.0208	0.0339	0	0.2566
U-2	1.5707	3.8884	0	0	0	5.4591
U-3	3.1544	9.5598	0	9.1294	0	21.8436
U-4	225.4428	475.9392	41.3310	113.1265	59.9657	915.8052
Totals	230.2139	489.5433	41.3518	122.2898	59.9657	943.3645

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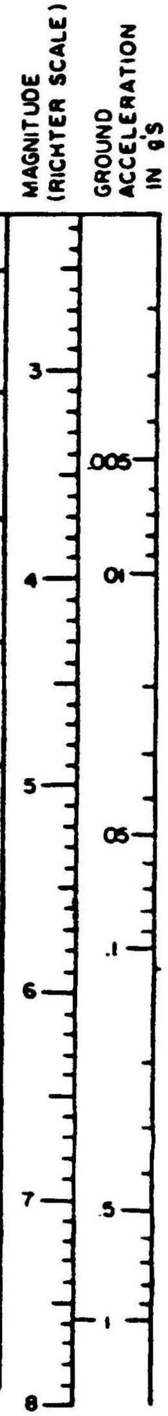
MODIFIED MERCALLI INTENSITY SCALE APPROXIMATE RELATIONSHIP WITH MAGNITUDE AND GROUND ACCELERATION

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.



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

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.