5-1979

Development of a Liquefaction Opportunity Map for Cache Valley, Utah

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DEVELOPMENT OF A LIQUEFACTION OPPORTUNITY MAP FOR CACHE VALLEY, UTAH

by

Richard J. Greenwood

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Engineering

UTAH STATE UNIVERSITY

Logan, Utah

1979

ACKNOWLEDGMENTS

Appreciation is extended to all those who have provided assistance, expecially to Dr. Loren R. Anderson, the writer's major professor. Dr. Anderson provided a great deal of guidance and encouragement during all phases of this study and during the writer's graduate and undergraduate programs, and generously donated many hours of his time.

Appreciation is also expressed to the other members of the committee, Dr. Fred W. Kiefer, and Dr. Winfred O. Carter.

Thanks is also given to Randy Hill who obtained many of the needed maps from the U.S. Geologic Survey, and to faculty members and fellow students who provided support.

A very special thanks is extended to the writer's parents for their financial support and unending encouragement.

Richard John Greenwood

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ABSTRACT

Development of a Liquefaction Opportunity

Map for Cache Valley, Utah

by

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Utah State University, 1979

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A liquefaction opportunity map was developed for Cache Valley, Utah. The study was the initial phase to determine the potential for liquefaction in Cache Valley.

The method used in this study to develop the liquefaction opportunity map was based on a procedure developed by Youd and Perkins (1977).

This opportunity map is proposed to be combined with a map delineating liquefaction susceptible soils to produce a liquefaction potential map. The liquefaction susceptibility map is being developed in a companion study.

The liquefaction potential map will assist in the evaluation of earthquake response in general and microzonation in particular. The liquefaction potential map may also be used by contractors, consultants, governmental organizations, etc., for preliminary planning and decision making to determine the suitability of a given site.

(74 pages)

CHAPTER 1

INTRODUCTION

Nature of Problem

"Ground failures generated by liquefaction have been a major cause of damage during past earthquakes and pose considerable potential for damage and injury during future tremblers," (Youd and Perkins, 1977).

Within Cache Valley there are two major active faults, the East Cache Fault and the West Cache Fault. In addition, the Wasatch Fault is within 10 miles of the valley; the Hansel Valley Faults are located within 25 miles of the valley; and a seismic area exists in the southern portion of Idaho approximately 20 to 30 miles north of the Idaho-Utah border. These seismic sources are capable of generating large magnitude earthquakes (Cluff, Glass, and Brogen, 1974). These earthquakes would be capable of causing considerable damage due to ground failure generated by liquefaction, ground shaking, landsliding, and settlement.

Since a major portion of the residential, commercial, and educational facilities exist along or near the faults within and near Cache Valley, there is a high potential for loss of life and financial investment from a major earthquake. Therefore, there is a need to determine the potential hazard of an earthquake. Hazards from liquefaction should be considered as one of the elements for mitigating possible earthquake damage.

In order for liquefaction to occur there must be a sufficient level of ground shaking as well as soil types capable of liquefying. This study was conducted to evaluate liquefaction opportunity (the likelihood of an earthquake of sufficient intensity to produce liquefaction induced ground failure in susceptible materials).

During the course of this study, location of earthquake epicenters, documented evidence of surface fault rupture, and magnitude vs. intensity relationships were used to evaluate the seismicity of the Cache Valley area. The seismicity was described using curves of frequency of occurrence vs. magnitude for each of the seismic sources within the range of influence of Cache Valley. The seismicity relationships were coupled with a liquefaction opportunity criteria suggested by Youd and Perkins (1977) relating liquefaction to earthquake magnitude and distance from the earthquake source to sites under consideration. By evaluating opportunity at a number of sites within the study area a map of contours of various levels of opportunity was developed. This opportunity map is proposed to be combined with a map delineating liquefaction susceptible soils to produce a liquefaction potential map. The liquefaction susceptibility map is being developed in a companion study.

The liquefaction potential map will assist in the evaluation of earthquake response in general and microzonation in particular. The liquefaction potential map may also be used by contractors, consultants, governmental organizations, etc., for preliminary planning and decision making to determine the suitability of a given site.

Seismic Hazards

General

Damage due to earthquakes depends on many variables: earthquake magnitude, epicentral location, depth of focus, duration of shaking, intensity of shaking, near-surface soils and geologic conditions, structural type, quality of construction, and design. By properly understanding these mechanisms and through appropriate planning, zoning, design and construction in hazardous areas damage due to earthquakes can be mitigated (Green, 1977). The five major causes of damage from earthquakes include:

- strong ground shaking
- surface fault rupture
- liquefaction
- miscellaneous ground failure
- seiches

Strong ground shaking

Transmission of earthquake vibrations from the ground to structures has been the major cause of damage during earthquakes. The factors which determine the extent of such damage are: type of soil deposit, earthquake-resistant design, quality of materials and construction, and the intensity and duration of shaking (Cluff, Glass, and Brogen, 1974).

Local soil deposits may greatly affect the ground motion characteristics during earthquakes. Seed (1975) illustrates this condition by the following account.

> During the Caracus Earthquake, which had a Richter Magnitude of 6.4 and a fault zone located 35 miles from the city, intense shaking caused the total collapse of four 10-to-12 story apartment buildings. A correlation of depth of underlying soils to structural damage showed that for 3-to-5 story buildings located on soil depths of 98 to 164 feet, the damage was many times greater than for similar structures located where soil depth was 328 feet or more. For 5-to-9 story structures, the most damage was found where the soil depths ranged from 164 to 230 feet. However, for structures greater than 10 stories, the structural damage was several hundred percent greater where the soil depths underlying the structure exceeded 525 feet than for depths less than 459 feet. (Seed, 1975).

This example illustrates the variety of ways in which the ground motion characteristics can be affected by soil conditions, even for the same earthquake within the same general locality.

The actual response of the structure to ground shaking is mainly dependent on the fundamental period of the site compared with the fundamental building period. The most critical condition being when the fundamental building period matches the fundamental period of the site.

The fundamental period of the site is dependent on a variety of conditions, the intensity of the bedrock motion, sediment thickness, soil firmness, and degree of saturation. The fundamental building period is a function of its weight, material properties, geometry, and structural details. The conditions which have proven to be the most hazardous are taller buildings located on deep, saturated soil deposits, and short rigid structures located on shallow, very dense, or rocky subsurface conditions. The taller buildings and deep deposits having longer fundamental periods, the short structures and shallow deposits having shorter fundamental periods.

Many examples of damage due to strong ground shaking occurred during the San Fernando Valley Earthquake of 1971 (see Lew, Leyendecker, and Dikkers, 1971). The potential for damage in Utah is as great as the potential in Southern California. Green (1977) states that "earthquakes of an equal or greater magnitude than the 1971 San Fernando Valley earthquake can be expected in Utah, and the earthquake resistance of structures in Utah should not be expected to be any greater than those of Southern California."

Surface fault rupture

Surface fault rupture may be in the form of horizontal or vertical displacement or may have both components of displacement. The rupture can vary from a fraction of an inch to many feet. One example of large displacement was along the San Andreas fault which averaged from 8 to 15 feet and extended approximately 200 miles along the fault, during the California earthquake of April 18, 1906. The largest recorded single fault displacement in United States history occurred within the past 300 years. The vertical movement was 20 feet in length and took place near Salt Lake City, Utah, at the mouth of Little Cottonwood Canyon.

Not only does the surface fault rupture show up as one single fracture surface but may occur along a wide zone involving many fractures (fault zone). The actual movement may be distinguished by its type, a steeply dipping fault is known as a high angle fault, and a shallow dipping fault is classed as a low angle fault. A strike-slip fault is characterized by the movement of two points along the strike, and a dip-slip fault is characterized by movement along the dip (Green, 1977). The relative risk in building structures along a fault is dependent on its activity. The activity of the fault is dependent on the historic record of faulting, the occurrence of earthquakes along the fault traces, evidence of recent geologic offsets and slow fault slippage. According to Cluff, Glass, and Brogen (1974) "a fault is considered active if it has displaced recent alluvium or other recently deposited materials whose surface has not been modified to an appreciable extent by erosion."

Active fault zones may be more than a mile wide and contain many fault traces within this wide zone. The Wasatch fault extending from the southern portion of Utah into Idaho contains some zone widths up to 3/4 of a mile. The relative risk in locating structures within these fault zones is not only dependent on whether the structures are placed on a fault trace, but also depends on the type of development, intended use and the type of structure.

Liquefaction

Damages due to ground failure caused by liquefaction can be quite catastrophic. When a loose, saturated, fine sand deposit is subjected to vibratory motion, the sand can loose its shear strength and liquefy. Several very well known catastrophes occurred in recent earthquake activity. Among these are the building foundation failures in Niigata, Japan, 1964; the Turnagain Heights landslide in Anchorage, Alaska, 1964; the Juvenile Hall landslide in Southern California, and the failure of the Lower San Fernando Dam.

Liquefaction of surface and subsurface soils is an important aspect in evaluating the risk potential of a given site and needs considerable evaluation in terms of engineering prevention. A further explanation of liquefaction causes, factors affecting liquefaction potential, and ways of mitigating damage is discussed in a later section.

Miscellaneous ground failures

Other types of ground failures are brought about by earthquakes. These failures include landslides, ground lurching and cracking, differential settlement, tilting, and loss of strength of loose sand and sensitive cohesive soils.

Landslides can create extensive destruction to both natural and man-made features. They can be the result of faulting causing the oversteeping of slopes, or the loss of strength in susceptible soils brought about by the application of stresses induced by an earthquake. Examples of soils that are susceptible to loss of strength are liquefiable soils and sensitive clays (Green, 1977). Landslides are not only restricted to occurring at the time of earthquake disturbance but can occur days later due to blockage of groundwater channels and decreased stability because of change in seepage conditions.

Large undulating surface waves located near a zone of energy release may cause cracking and the development of compression ridges in concrete, stiff construction materials, or relatively stiff soils.

Settlement is also a significant problem that may arise from earthquake activity. It can be in the form of subsidence of the land surface which compacts the subsurface soil, or from the removal of fine sand by the upward movement of ground water. These excessive settlements can cause damage and large stresses to structures.

Seiches

A standing wave generated by an earthquake in an enclosed body of water is called a seiche. This standing wave usually occurs in a lake or reservoir often reaching a height of 30 feet. Seiches can cause a great deal of property damage and many lives may be lost when it results in the overtopping of dams.

Characteristics of Cache Valley

Cache Valley, Utah is located in the northern extremity of the state, and contains the major portion of Cache County's population. The location of Cache Valley within the border of the county can be seen in Figure 1. Figure 1 also shows the boundaries of Cache Valley, Utah.

Cache County has the 5th largest population and the 23rd largest size out of the 29 counties within Utah. Cache County has a population of 42,300 with approximately one half (24,000) living in Logan (1970 census, as presented by Green, 1977). A large number of the population live in towns and rural communities, although many live on farms. The major economic activities are agriculture and light industry. Most of the valley is irrigated and farmed. The valley growth, however, is increasing with more and more major structures being planned and constructed. Among those are a new hospital, more schools, and larger and larger industry.

The elevation of the valley floor is approximately 4,500 feet above sea level, and is composed principally of lacustrine sediments deposited in the ancient Lake Bonneville, which once covered the valley floor. The lowest point in the valley is about 4,400 feet, located where the Bear River exits at Junction Hills. The valley is a complex graben, bounded by basin and range faults on both sides (Green, 1977).

Purpose of Study

The purpose of this study was to set up the initial phase to determine the potential for liquefaction during an earthquake in Cache Valley, Utah. To determine the potential for liquefaction, it is necessary first

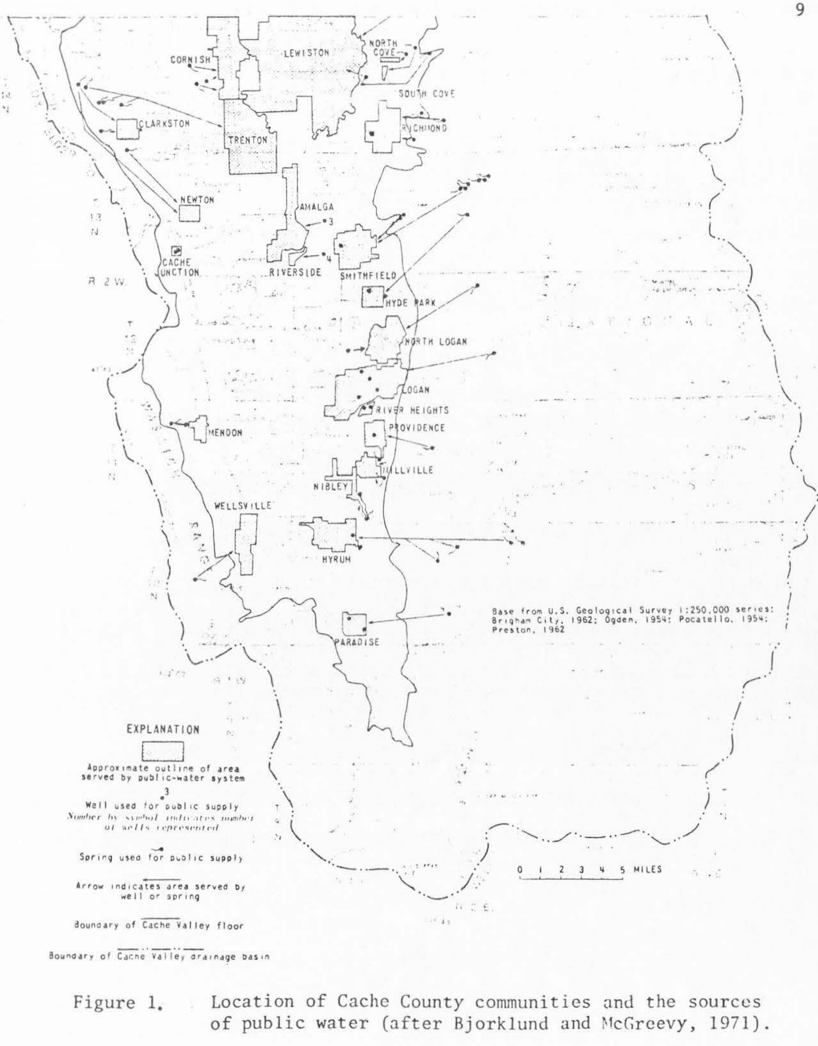

Figure 1. Location of Cache County communities and the sources of public water (after Bjorklund and McGreevy, 1971).

to determine the opportunity for a ground failure of this type to occur. The opportunity for a given area is a function of the rate of occurrence of earthquake ground motion of sufficient intensity to produce ground failure in susceptible materials (Youd and Perkins, 1977). The opportunity of these occurrences is shown in the form of a map with contours indicating the recurrence interval for a level of ground shaking that could produce liquefaction. The opportunity map does not consider whether the soil is capable of liquefaction.

The liquefaction opportunity map will be combined in a companion study, with a liquefaction susceptibility map to produce a liquefaction potential map. The susceptibility map is defined as a map showing the relative ease with which the material under a particular site can be liquefied. The liquefaction potential map shows where liquefiable sediments are most likely to exist and shows how frequently ground motions occur that are strong enough to cause liquefaction. The developed liquefaction potential map will assist, as stated earlier, in evaluation of earthquake microzonation, and can be used by contractors, consultants, government organizations, etc., for preliminary planning and decision making to determine the suitability of a given site.

CHAPTER 2

REVIEW OF LITERATURE

The literature review is divided into two parts; seismicity of Cache Valley, Utah, and liquefaction and the use of seismic risk procedures.

Seismicity of Cache Valley, Utah

Seismic activity of Utah has been documented since 1850. The activity has been concentrated on the southern and northern segments of the Wasatch Front. The only historical ground displacement that has been documented occurred on March 12, 1934, at the north end of the Great Salt Lake. The magnitude of this earthquake was 6.6 and was known as the Hansel Valley earthquake. The earthquake produced 1.5 feet of vertical displacement and an overall subsidence of the alluvial basin. According to Dr. Robert B. Smith, Associate Professor of Geophysics at the University of Utah, "similar disruption could occur along the populated areas of the Wasatch Front from equivalent-sized earthquakes" (Hearing before the Committee on Aeronautical and Space Sciences, United States Senate, Ninety-fourth Congress, April 26, 1975).

Utah is located within the intermountain seismic belt, which extends from Arizona and Southern California, through Utah, Eastern Idaho, and Western Wyoming, and terminates in northeastern Montana. The belt is approximately 800 miles long and extends to a width of 60 miles. The faults in Utah have been characterized by Scholz, et al. (1971) as being major late Cenozoic Crustal extension. The principal belt of seismicity trends north-south and follows the boundary between the Basin and Range province and the Colorado Plateau. The focal mechanisms indicate a predominance of dip-slip movement on north trending faults (Dewey, et al., 1972).

The seismic influence within this region that could effect Cache Valley, Utah, are from five major elements:

- Wasatch Fault
- East Cache Fault
- West Cache Fault
- Hansel Valley Faults
- Bear Lake-Caribou Seismic Area

The approximate locations of the five elements within and near Utah are shown on Figure 2.

Wasatch Fault

The Wasatch Fault is located along the base of the Wasatch Mountain Range. It begins near Gunnison, a small town in the southern central portion of Utah, and stretches to Malad, Idaho, a distance of about 215 miles. The Wasatch Fault is a north-south trending fault and based on fault length the maximum credible earthquake would have a Richter magnitude greater than 8.0 (after Bonilla, 1967 as presented by Seed, Idriss, and Kiefer, 1969). The recorded number of earthquake events along the Wasatch Fault is 80 with 73 events having a magnitude of 3 or greater (U.S. National Oceanic and Atmospheric Administration (NOAA), as presented by Green, 1977; Williams and Tapper, 1953; Cook and Smith, 1967; and Smith, 1974). The Wasatch Fault is considered active on the basis of geomorphic evidence and historic seismicity (Cluff, Glass, and Brogen, 1974).

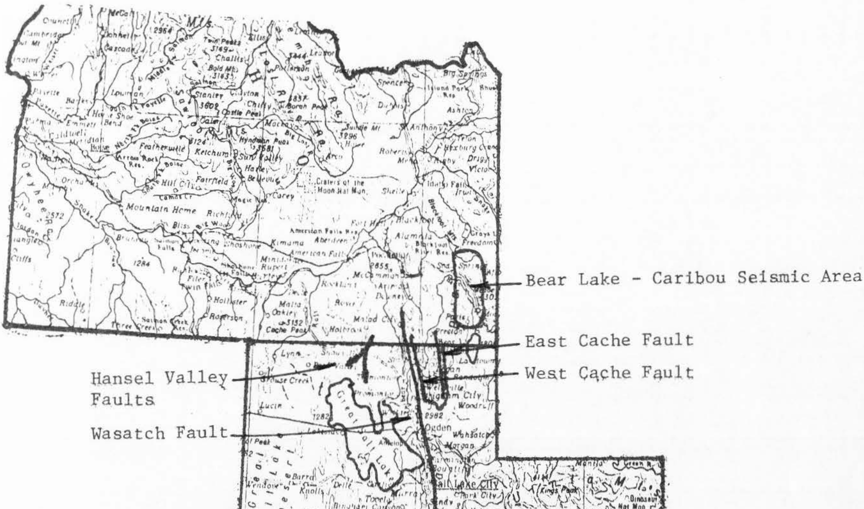

Figure 2. The approximate locations of the fiive seismic sources within and near Cache Valley, Utah.

East Cache Fault

The East Cache Fault extends from about a mile south of Avon, Utah, to Southern Idaho, a distance of approximately 70 miles. It is a north-south trending fault, and based on fault length the maximum credible earthquake magnitude would be 7.7 (from Bonilla, 1967, as presented by Seed, Idriss, and Kiefer, 1969). The recorded number of earthquake events along the East Cahce Fault is 14 with 9 having a magnitude of 3 or greater (U.S. National Oceanic and Atmospheric Administration (NOAA), as presented by Green, 1977; Williams and Tapper, 1953; Cook and Smith, 1967; and Smith, 1974). Cluff, Glass, and Brogen (1974) have also indicated that the East Cache Fault is active on the basis of geomorphic evidence and historic seismicity. The land forms along this and the other faults display features typical of other recently active faults.

West Cache Fault

The West Cache Fault is located along the western extremity of Cache Valley. The length is estimated to be about 55 miles and trends north-northwest. Based on fault length the maximum credible earthquake for this fault would have a magnitude of about 7.5 (after Bonilla, 1967, as presented by Seed, Idriss, and Kiefer, 1969).

Hansel Valley Faults

The Hansel Valley Faults are a collection of faults in a wishbone shape arrangement extending from the northern end of the Great Salt Lake to the northern end of Pocatello Valley, Idaho, a distance of about 36 miles. Based on fault length the maximum credible earthquake magnitude would be 7.5 (from Bonilla, 1967, as presented by Seed, Idriss, and

Kiefer, 1969). The recorded number of earthquake events along the Hansel Valley Faults is 64 with 58 events of magnitude 3 or greater. One of these recorded events was of a magnitude of 6.6 and produced up to 1.5 feet of displacement on vertical faults, and produced a significant amount of liquefaction (Smith, 1974).

Bear Lake-Caribou Seismic Area

There exists an area referred to as the Bear Lake-Caribou Seismic Area by this study, with seismic events ranging from a magnitude less than 3 to a magnitude 5.4. This area extends from the northern portion of Bear Lake, Idaho, through the Caribou National Forest to the northern end of Star Valley, Idaho, a distance of about 60 miles. The total number of recorded events is 58 with 28 events having a magnitude of 3 or greater.

Recent activity of the Wasatch Front

Dr. Smith (1975) has listed the following evidence of the relative activity of the Wasatch Front Region between July, 1962, through September, 1974.

- A well-defined north-south trend of epicenters along the East Cache Fault zone near Logan including a magnitude 5.7 earthquake August 30, 1962.
- Scattered earthquakes along the Wasatch Front north of Brigham City.
- Diffuse activity 10 to 20 miles east of Ogden, but little activity along this segment of the Wasatch Front.

- Marked activity of low magnitude earthquakes north and east of Salt Lake City.
- Scattered activity along the west side of Salt Lake Valley including a magnitude 5.2 earthquake September 5, 1962.
- A north-south zone of activity northeast of Provo including a magnitude 4.5 earthquake October 1, 1972.
- A well-defined zone of north trending activity along the southern Wasatch Front including a magnitude 4.9 earthquake July 7, 1963.

Liquefaction and the Use of Seismic Risk Procedures

The literature on liquefaction and the use of seismic risk procedures have been summarized and discussed in recent conventions held by ASCE. The concepts, terminology and existing "state-of-the-art" on liquefaction was discussed during the annual convention and exposition of ASCE held in Philadelphia, Pennsylvania, September 27 to October 1, 1976 (ASCE, 1976). The use of probabilities in earthquake engineering as it applies to seismic risk procedures were summarized at the fall convention of ASCE held in San Francisco, California, October 17-21, 1977 (ASCE, 1977). The papers presented at these conventions along with the list of references within the papers comprise much of the known and accepted literature on methods of liquefaction analysis.

Liquefaction

Seed (1976) defines liquefaction as,

> A condition where soil undergoes a continued deformation at a constant low residual stress or with no residual resistance, due to the build up and maintainance of high pore water pressures which reduce the effective confining pressure to a very low value.

> Pore pressure build-up leading to true liquefaction of this type may be due either to static or cyclic stress application (Seed, 1976).

More simply liquefaction can be thought of as a total loss of shear strength when a saturated cohesionless soil is subjected to a static or cyclic (vibratory) motion (Castro and Poulos, 1976; Liou, Streeter and Richart, 1976).

Causes of liquefaction. The basic cause of liquefaction is the build up of excess hydrostatic pressure in saturated cohesionless soils during the application of vibratory motions (Seed, 1976; Liou, Streeter and Richart, 1976). When a mass of saturated loose sand is subjected to a disturbance there is a tendency for the volume to decrease. Since the pores are full of water the volume cannot immediately decrease, so the load is transferred to the pore water which increases the pore water pressure and decreases the intergranular stress. During a cyclic disturbance such as an earthquake the sand is repeatedly disturbed, each disturbance causes a transfer of the load from the sand grains to the pore water. The pressure induced in the pore water is known as excess hydrostatic pressure. Continued disturbance of the sand mass will increase the pore pressure until the intergranular stress is reduced to zero. This condition is referred to as "initial liquefaction" (Seed, 1976).

It can be shown that dense sands although they may experience initial liquefaction will ultimately have a greater resistance in withstanding the applied stress than a loose sand (Seed, 1976). The development of liquefaction is not only dependent on the magnitude of the applied stress but also on the number of cycles of the stress (Seed, 1976; Castro and Poulos, 1976).

Factors affecting liquefaction potential. The most important factors which affect the potential for liquefaction are as follows:

- soil type
- relative density
- initial confining pressure
- intensity of ground shaking
- duration of ground shaking

The most susceptible soil type is fine to medium grained sand with a rather uniform grain size. One criteria for whether or not a soil will liquefy is based on the content or percentage of clay size material. If the soil contains more than 15% clay size material (less than 0.002 mm) it is said to have no susceptibility to liquefaction. Relative density is also a very important criteria in determining liquefaction potential. Very loose sand is highly susceptible to liquefaction while dense sand has a very low liquefaction potential. Field cases such as at Niigata, Japan, have shown that initial confining pressure and intensity of ground motion have a significant effect on liquefaction potential (Seed, Lee and Idriss, 1967; Seed, 1976). The higher the confining pressure the higher the stress that is required to initiate liquefaction. The opportunity for a soil to liquefy under a given set of conditions, i.e., soil type, relative density, and initial confining pressure, is related to the magnitude of shear forces induced by the earthquake or more generally the intensity of ground shaking. The higher the intensity the higher the shear forces.

The number of cycles or the duration of strong shaking influences the build-up of excess hydrostatic pore pressure. The longer the duration the greater the likelihood of liquefaction. Seed, Mori, and Chan (1975) indicates that seismic history also has an important influence on liquefaction potential. Disturbed sand specimens of a given density, subjected to cyclic stresses, liquefied sooner than similar undisturbed sand specimens that had a seismic history.

Methods to evaluate liquefaction potential. There are two basic methods of evaluating liquefaction potential:

- A comparison of the earthquake induced cyclic shear stress to the shear stress required to develop liquefaction at representative points within the soil profile.
- Using some in situ soil characteristics as a means of comparing the liquefaction potential of a proposed site to other sites where liquefaction has occurred.

The first method can be characterized by Figure 3, which shows a graph of stress level induced by an earthquake and the level of stress necessary to cause liquefaction for the given earthquake motion. The zone where these two curves overlap is the zone where liquefaction may occur (Seed and Idriss, 1971). Seed (1976) indicates that the major problem with this method is in evaluating the stress required to cause liquefaction. Sample disturbance destroys seismic history and soil structure and therefore makes it difficult to obtain representative laboratory tests.

The second method involves the use of a chart developed by Seed, Mori, and Chan (1975) and is shown in Figure 4. This chart relates the standard penetration test to the ratio of induced shear stress to overburden pressure that would cause liquefaction. By comparing these values for the site under consideration the potential for liquefaction can be

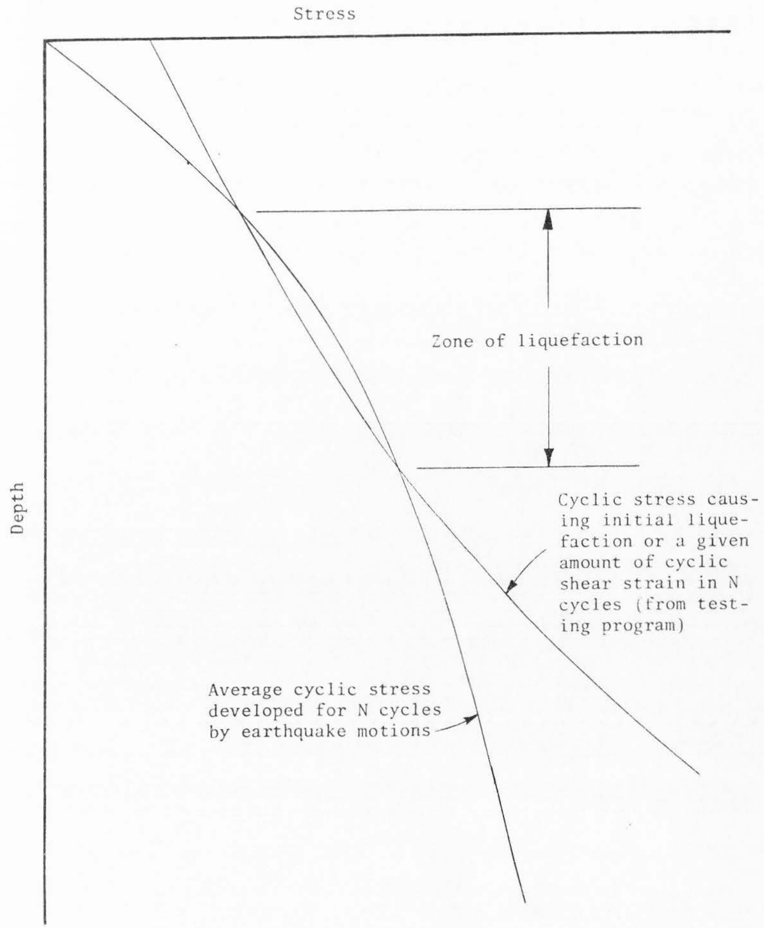

Figure 3. Method of evaluating liquefaction potential (after Seed and Idriss, 1971).

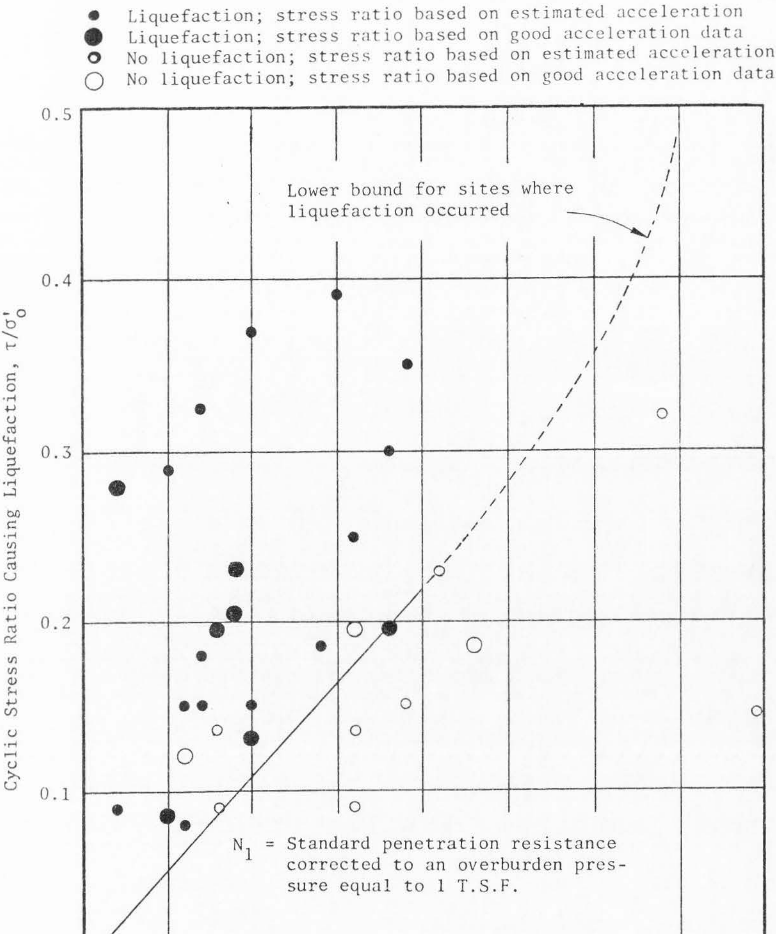

Figure 4. Correlation between stress ratio causing liquefaction in the field and penetration resistance of sand (after Seed, Mori, and Chan, 1975).

found. These two basic methods with some variation are summarized by Seed (1976) and Valera and Donovan (1976).

Seismic risk procedures

A seismic risk procedure requires the use of three separate sets of information. This information includes (1) a knowledge of the geology and tectonics of the study area, (2) the recurrence relationships of earthquakes based on historical seismicity and probability distribution, and (3) earthquake attenuation relationships (Donovan and Bornstein, 1977). Based on this information it is generally accepted that liquefaction potential is a function of:

- level of ground shaking (opportunity)
- nature of the soil deposit (susceptibility)

Yegian and Whitman (1977) presented a method to evaluate liquefaction potential using both opportunity and susceptibility. In this method they describe a procedure to estimate the overall probability of ground failure at a site by liquefaction. Their method first considers the probability of an earthquake occurring and then the probability of the earthquake causing ground failure by liquefaction. They expressed their analysis by the following equation:

$$P_E(F_L) = P(F_L/E) \cdot P(E)$$

where $P_E(F_L)$ is the overall probability of liquefaction of some site during the earthquake E, $P(F_L/E)$ is the probability of liquefaction at the site given that the earthquake E occurs, and P(E) is the probability that the earthquake E occurs.

Youd and Perkins (1977) have also presented a method to evaluate liquefaction potential using both opportunity and susceptibility. Their procedure involves generating a map indicating areas of various levels of liquefaction induced ground failure potentials. This map is generated from two other maps: (1) opportunity for liquefaction and (2) susceptibility to liquefaction. The opportunity map uses contours of return period of earthquake intensity sufficient to cause liquefaction of soils that have the capability to liquefy. The susceptibility map consists of areas showing the susceptibility of soils to liquefy if there is a sufficient level of ground shaking. The potential map then shows the likelihood of an area to liquefy, or the overall susceptibility of a geographic area broken down into various units of potential.

CHAPTER 3

METHODOLOGY

The method used in this study to develop a liquefaction opportunity map is based on a procedure developed by Youd and Perkins (1977). The method considers the geology and tectonics of the study area, the recurrence relationships of earthquakes from historical seismicity, and the probability distribution of the size and location of an event.

Theoretical Basis

Youd and Perkins (1977) examined the factors that influence the opportunity for liquefaction, (1) the stress ratio required to cause liquefaction and (2) the stress induced by an earthquake (dependent on the magnitude of the earthquake, distance from seismic source, and the attenuation properties of the soil). From these factors they showed that a linear relationship should exist between the magnitude of an earthquake required to cause liquefaction induced ground failure and the logarithum of the distance from the site to the seismic source. This relationship can be stated as,

$$M = C_1 + C_2 \log R \qquad (1)$$

where M is the Richter magnitude of the earthquake, C_1 and C_2 depend on properties of the soil, and R is the distance of the site to the seismic source.

After showing the rational behind Equation 1, Youd and Perkins (1977) used the empirical relationship developed by Kuribayashi and Tatsuoka (1975) and Youd (1977) (Figure 5) as a means of relating

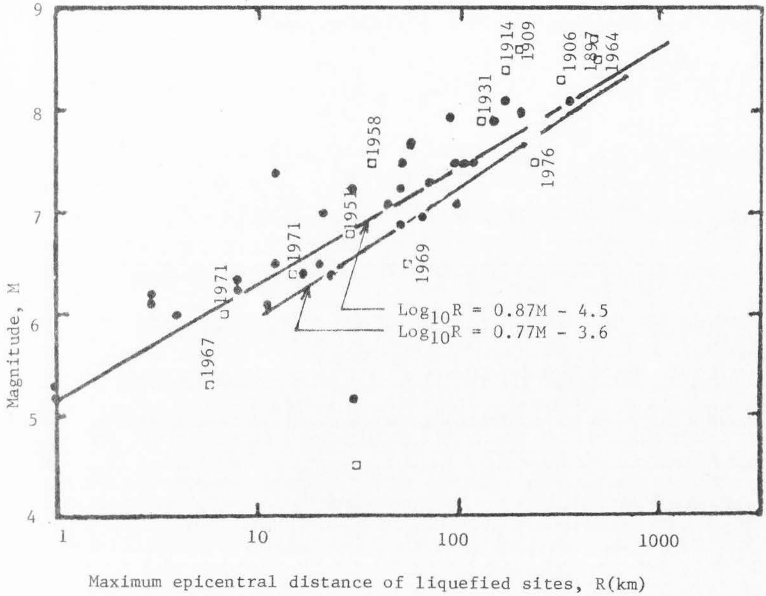

Figure 5. Relationship between the maximum epicentral distance of liquefied sites R and Magnitude M with added non-Japanese data (after Youd, 1977).

magnitude and radius of influence. This relationship was an envelope based on observed data of earthquake magnitude and the maximum distance from earthquake source to points of known liquefaction. Youd and Perkins slightly modified the straight line relationship between magnitude and the log of distance and added a threshold magnitude of 5.0 and a 150 km cut-off distance as shown on Figure 6. This envelope was used as a criteria to establish whether a site could be given the opportunity to liquefy. Once this criteria was established the recurrence of soil failure opportunity was calculated using procedures similar to those used in calculating seismic risk (Algermissen and Perkins, 1972, as presented by Youd and Perkins, 1977).

Establishing Faults, Zones and Seismic Source Areas

The seismic elements within the radius of influence of Cache Valley, Utah, were identified with the aid of previously developed fault maps (Cluff, Glass, and Brogen, 1974) and recorded fault ruptures and earthquake epicenters.

There were five seismic elements identified within the radius of influence for this study. These elements were (1) Wasatch Fault zone, (2) West Cache Fault zone, (3) East Cache Fault zone, (4) Hansel Valley Fault zone, and (5) a seismic source area based on recorded earthquake epicenters identified in this study as the Bear Lake-Caribou seismic source area. As discussed later it was necessary to combine the West Cache Fault zone and the East Cache Fault zone into a seismic source area.

A fault zone is a zone encompassing, insofar as is known, related scarps from past fault ruptures. A seismic source area encloses an area

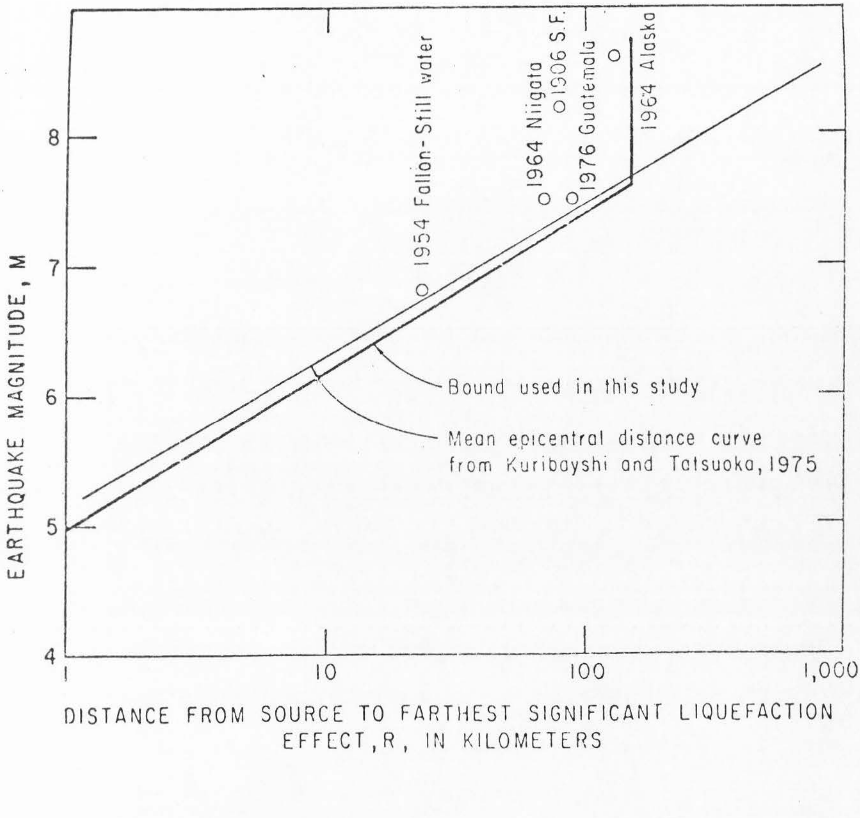

Figure 6. Earthquake magnitude versus maximum distance to significant liquefaction-induced ground failures (after Youd and Perkins, 1977).

of discrete seismicity and, insofar as is known, related tectonic elements (Algermissen and Perkins, 1972).

Recorded earthquake epicenters were then associated with one of the fault zones or the source area and the logarithum of the number of events were plotted against earthquake magnitude for each seismic element. The magnitude ranges that were plotted varied from a magnitude 3 to a magnitude 8. The ranges were 3.0 to 3.75 and then increased by increments of 0.5 up to 8.0. For some of the earlier recorded earthquakes only Modified Mercelli intensities were available. For these earthquakes the intensity was converted to Richter Magnitude by a relationship developed by Cook and Smith (1967) and presented by Algermissen and Perkins (1972). This relationship can be expressed as,

$$M = 0.60\ (Io + 2.167) \qquad (2)$$

where M = Richter Magnitude and Io = Modified Mercelli intensity (Table 1).

Table 1. Conversion of Modified Mercelli intensities to Richter Magnitude.

Modified Mercelli	Richter Magnitude
III	3.10
IV	3.70
V	4.30
VI	4.90
VII	5.50
VIII	6.10
IX	6.70
X	7.30
XI	7.90

Accumulating Frequency of Occurrence

Once the frequency of occurrence for the number of years of record was established for each seismic element, the values were divided by the number of years of record to determine the annual frequency. The frequency of occurrence of sufficient ground shaking to cause liquefaction at grid points within the study area was then determined for the source areas and the fault sources. This was done for the source areas by dividing the source area into a grid of small squares and evenly proportioning the seismicity (annual frequency) of the area to each square. The distance was then calculated between a felt point (a point with the study area) and the center of the source square (point of energy release). For each magnitude range it was then determined whether the distance corresponding to the center of the magnitude range, taken from Figure 6 was greater or less than the distance from the source square to the felt point. If it was greater, the felt point was within the distance at which liquefaction can occur, and the felt point was credited with the annual frequency associated with that magnitude range. This process was repeated for every magnitude range and each felt and source point. The annual frequency was accumulated for each cycle of the entire process.

Source Area Example Problem

Given the source area and the site area of Figure 7 and the magnitude range of 5.75 to 6.25, determine the opportunity for liquefaction of the felt point A.

The first step is to determine the expected annual frequency of earthquake occurrence for the given magnitude range for square #1 of the source

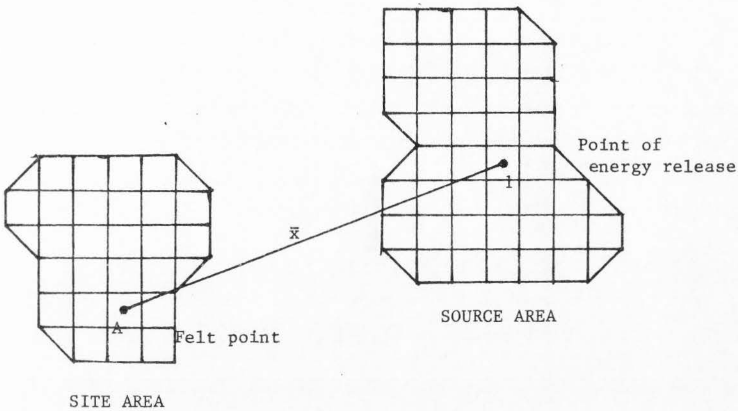

Figure 7. Seismic source area example problem.

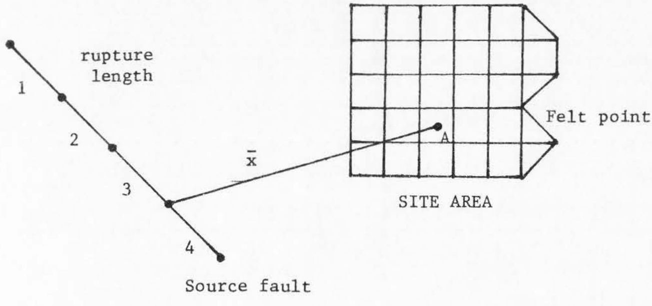

Figure 8. Seismic source fault example problem.

area. This is done from a plot of recorded number of events vs. Richter magnitude for that source area (similar to Figure 12) and determining the number of events that occurred within the magnitude range. Using the center point of the magnitude range i.e., 6, the recorded number of events is found to be 1.2. The annual frequency of square #1 is then determined by:

$$AF = N/(n \cdot s)$$

where AF is the annual frequency of source square #1, N is the number of events for the magnitude range, n is the number of years of available record (98 for this example), and s is the total number of grid squares within the source area.

$$AF = 1.2/\{(98)(43.5)\} = 2.81 \times 10^{-4}$$

The distance, $\bar{x}$, from point A (center of felt point a) to each source square is then compared with the distance found from Figure 6. From point A to point #1 the distance $\bar{x}$ is measured to be 4 miles. The distance, D, from the source to farthest significant liquefaction for a magnitude 6.0 is determined from Figure 6 as D = 4.54 miles. The distance, $\bar{x}$, is less than D, therefore the felt point lies with the distance at which soil failure by liquefaction can occur for the magnitude range. The felt point is credited with the annual frequency of grid point #1 i.e., 2.81 $\times 10^{-4}$.

The opportunity of felt point A is determined by using this procedure for each square within the source area and cumulating the annual frequencies each time the distance between the source square and the felt point is within the liquefiable range.

The opportunity for the other grid squares within the study area is determined in the same manner.

The source faults were handled in a similar manner. The seismicity (for each magnitude range) of the fault was apportioned to each increment along the fault trace. The increment length being determined from a magnitude-fault rupture length relation presented by Bonilla (1967). The opportunity at a given felt point was determined using the closest distance from the felt point to the fault length at its current placement along the fault trace. This procedure was repeated first for all other placements of the rupture length for that magnitude range, and then for each magnitude range, and each source fault.

Fault Source Example Problem

Given the fault source and site area of Figure 8 and the magnitude range 5.25 to 5.75, determine the opportunity for liquefaction of the felt point A due to the fault source.

The annual frequency of occurrence of the source fault is determined in a similar manner to that of the source area. The annual frequency is found by finding the number of events from a graph of number of earthquake events vs. Richter magnitude (similar to Figure 9) and then dividing by the years of earthquake record used to obtain the graph. For each magnitude there is a corresponding length of fault rupture (Bonilla, 1967). For a magnitude 5.5 earthquake corresponding length of fault rupture is 2.34 miles. The rupture length is then incremented along the source fault (as shown above). The annual frequency of the source fault is evenly proportioned to each rupture length by dividing the annual frequency of the source fault by the number of rupture lengths.

$$AF = \frac{N}{n(\ell)}$$

where AF is the annual frequency of a rupture length, N is the number of events for the magnitude range, n is the number of years of available record and ℓ is the total number of rupture lengths.

$$AF = (2.0/98.0)/4. = 1.02 \times 10^{-2} \text{ events/year}$$

The closest distance from each rupture length to the felt point is measured and compared with the distance found from Figure 6. For this example $\bar{x}$ is measured to be 1.5 miles and D from Figure 6 is 1.7. The distance $\bar{x}$ is less than D, therefore the felt point is credited with the annual frequency 1.02×10^{-2} events/year.

The opportunity of the felt point A is determined by using this procedure for each rupture length and magnitude range for the source fault and accumulating the annual frequencies each time the closest distance from the rupture length to the felt point is within the liquefiable range. The opportunity for the other grid squares within the site area is determined in the same manner.

The accumulated opportunities at each felt point due to the source area and the source faults produced a cumulative annual frequency of opportunity of liquefaction induced ground failure. The recurrence interval for each point was then determined as the reciprocal of the annual frequency. A map of ground failure opportunity was then plotted as contours of equal recurrence intervals.

CHAPTER 4

RESULTS

Seismicity

The purpose of this study was to develop a map of liquefaction opportunity for Cache Valley, Utah. The opportunity map was based on the seismicity of the study area which was determined by evaluating the records of earthquake epicenters (U.S. National Oceanic and Atmospheric Administration (NOAA), as presented by Green, 1977; Williams and Tapper, 1953; Cook and Smith, 1967; and Smith, 1974) within a 186 mile radius of Logan, Utah. The earthquake epicenters (as shown in Appendix A) were located by latitude and longitude coordinates. Each event was then associated with one of the identified sources. The sources that were identified in this study were (1) the Wasatch Fault; (2) the Hansel Valley Faults; (3) the Bear Lake-Caribou Source Area and (4) the West Cache and East Cache Faults combined together to form a source area. The locations of each source with respect to Cache Valley are shown in Figure 2.

Once the epicenters were assigned to a specific source the earthquakes were divided into ranges of magnitude and the number of earthquakes within each range was tablulated as shown on Tables 2 and 3. This data was then plotted on semi-log paper for each source as shown on Figures 9 through 12. These plots were used to determine the annual frequency of occurrence (seismicity) for each source by dividing the number of occurrences by the number of years of record.

Table 2. Number of earthquake events within each magnitude range and for each seismic source.

Magnitude Range	Number of Earthquake Events				
	Wasatch Fault	Hansel Valley Fault	Bear Lake-Caribou Source Area	West Cahce Fault	East Cache Fault
3.0 -3.75	22	28	10	0	1
3.75-4.25	18	17	9	0	0
4.25-4.75	15	9	7	2	4
4.75-5.25	13	1	2	0	2
5.25-5.75	4	0	0	1	2
5.75-6.25	0	2	0	1	0
6.25-6.75	1	1	0	0	0

Table 3. Combined earthquake events for the West Cache Fault and the East Cache Fault.

Magnitude Range	Number of Earthquake Events in Each Magnitude Range
3.0 -3.75	1
3.75-4.25	0
4.25-2.75	6
4.75-5.25	2
5.25-5.75	3
5.75-6.25	1
6.25-6.75	0

Liquefaction Opportunity Map

Youd and Perkins' (1977) method was used to determine annual frequencies of ground shaking sufficient to cause liquefaction for a series of grid points within the study area. The reciprocals of the annual frequencies, return periods, were then determined at the grid points and contours of equal return period were developed. The resulting map of return period contours constitutes the liquefaction opportunity map and it is shown on Figure 13.

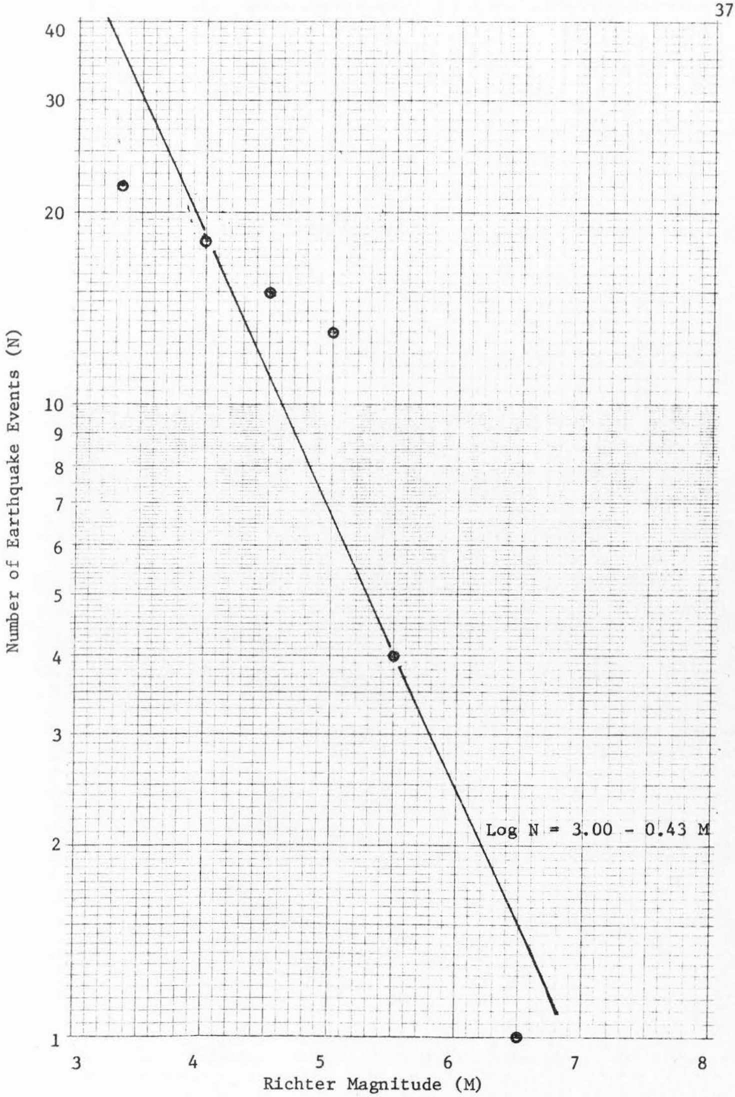

Figure 9. Number of earthquake events vs. Richter Magnitude for the Wasatch Fault.

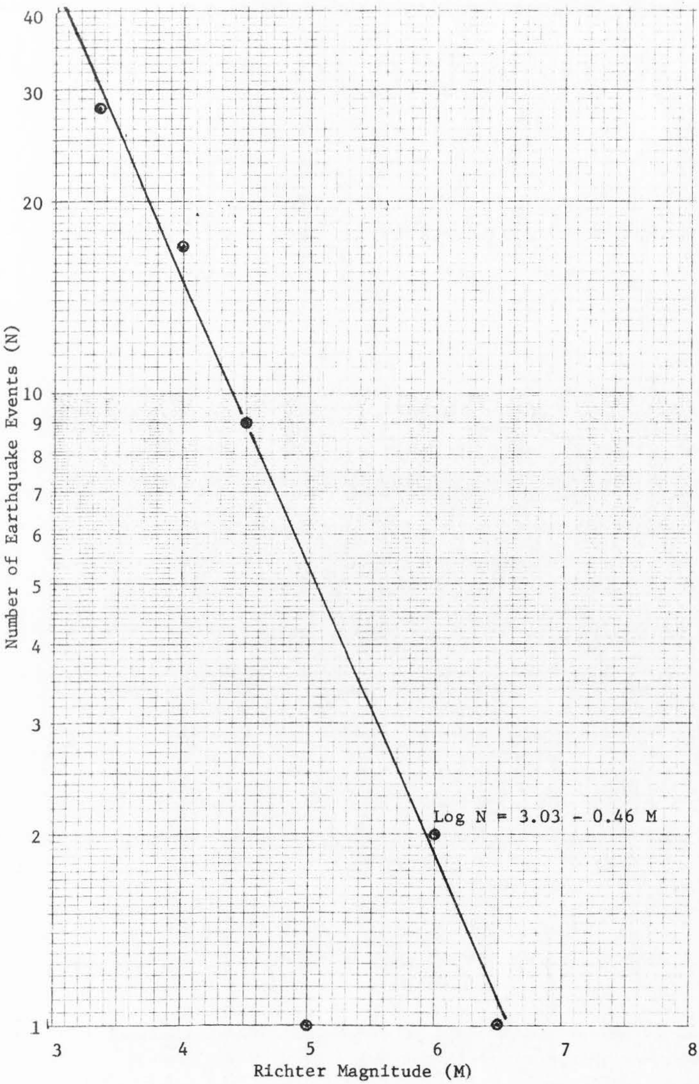

Figure 10. Number of earthquake events vs. Richter Magnitude for the Hansel Valley Faults.

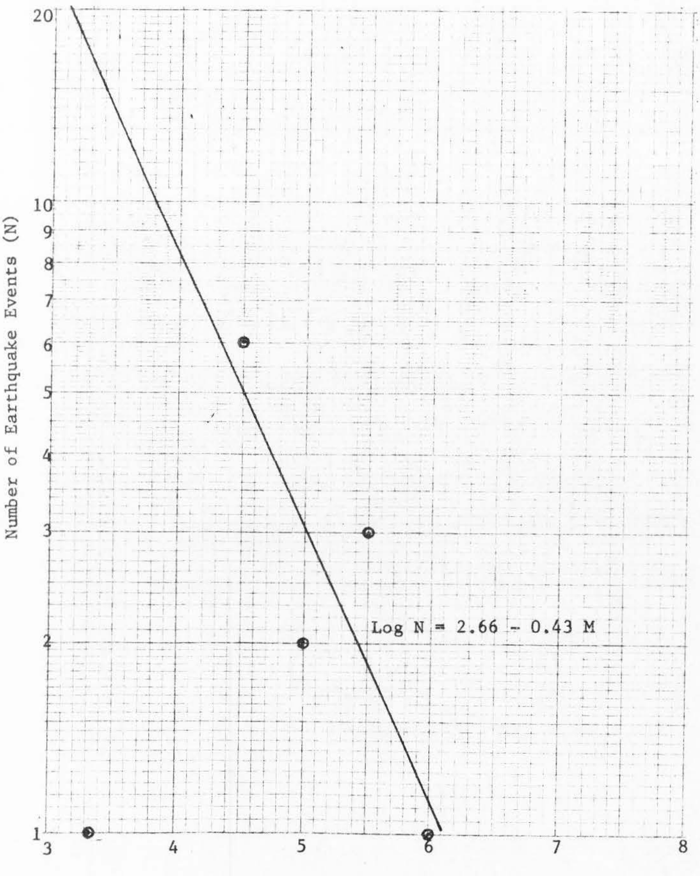

Figure 11. Number of earthquake events vs. Richter Magnitude for the Cache Valley Source Area.

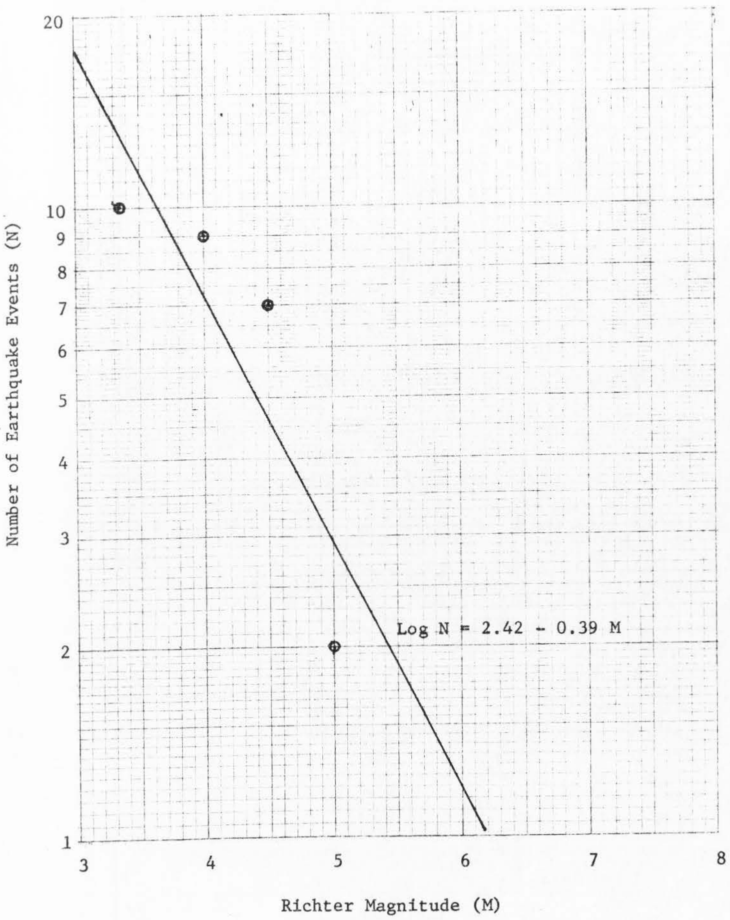

Figure 12. Number of earthquake events vs. Richter Magnitude for the Bear Lake-Caribou Source Area.

Figure 13. Liquefaction opportunity map for Cache Valley, Utah.

CHAPTER 5

DISCUSSION OF RESULTS

Earthquake Epicenter Data

Although some 230 recorded earthquake events were within 186 miles of Cache Valley, only 172 had an associated magnitude. These 172 events had magnitudes ranging from 3 to 6.6. The remaining events were probably of low magnitude and only date, time, and location data were given. The epicenter for each event was located by latitude and longitude coordinates. Prior to 1961 the locations were accurate to the nearest 1/4 to 1/2 degree and after 1961 to the nearest 1/10 degree. Each earthquake event was associated with one of the following seismic sources.

- Wasatch Fault
- Hansel Valley Faults
- Cache Valley Source Area
- Bear Lake-Caribou Source Area

Because of the geographic closeness of the seismic source zones it was sometimes difficult to identify an epicenter with a specific seismic source on the basis of where the epicenter plotted relative to the various faults. This made it necessary to make judgments to determine whether a particular event should be associated with one source or another. Although an incorrect decision would decrease the seismicity of one source it would increase the seismicity of the other and contribute to liquefaction opportunity. Every event was included in the overall analysis.

The Wasatch Fault was a well defined zone of earthquake activity. The fault scarps and fault ruptures were located by Cluff, Glass, and

Brogen (1974) with the aid of low-sun-angle aerial photography and in some cases verification by field study. The earthquake epicenters were generally easy to identify with the fault zone. The Wasatch Fault zone extended from Gunnison, Utah to Malad City, Idaho.

The Hansel Valley faults consist of two fault traces in a 'Y' shaped arrangement. The earthquake epicenters were generally easy to identify with the fault traces. The branches of the 'Y' faults were treated as the same source and the seismicity was apportioned equally to every segment of the fault traces.

Although the fault scarps and fault zones were well defined (Cluff, Glass, and Brogen, 1974) within Cache Valley, the epicentral data was sparce and some events were located midway between the two zones. The two faults were therefore, combined to form a source area enclosing the related events. This could introduce some error but it was unavoidable due to the sparce data and the error should be small.

The earthquake events that were located in the southern portion of Idaho from Bear Lake through the Caribou National Forest were associated with a seismic source area. The seismic source area was defined by the area enclosing the plotted events. Due to the distance from this area to Cache Valley there would be very little difference in the final results between associating these events with a fault source or a source area.

Seismicity

Once the epicenters were associated with a given source they were grouped together by magnitude ranges. Seismicity is commonly represented by Seismologists by means of a magnitude versus frequency of occurrence formula,

$$\log_{10} N = a - bM \tag{3}$$

where N is the number of earthquakes within a magnitude range of average magnitude M and the constants a and b are for a given zone. The seismicity of each source was determined by plotting on semi-log paper, the number of events within each magnitude range against the corresponding Richter Magnitude.

Annual frequencies as determined from earthquake events were apportioned evenly along each fault trace and to each grid square within a source area. There were areas of each source that showed some evidence of higher earthquake activity than others, but this was ignored for this study.

Magnitude Intensity Relationships

Seismic histories were obtained from Williams and Tapper (1953), Cook and Smith (1967), Smith (1974), and U.S. Geological Survey (1976). This data went back to about 1850 giving a historical data base of 126 years. Both the Modified Mercelli Intensity scale and the Richter Magnitude scale were used to indicate the size of the earthquakes.

The Modified Mercelli Intensity scale is based of observations and damages at a particular site and is related to the severity of ground shaking. These values depend on reports of observers and are therefore, subjective. For the older earthquake events the data provides only Modified Mercelli Intensities. A description of the Modified Mercelli Intensity scale is presented in Appendix B.

Richter Magnitude was introduced by Gutenberg and Richter (1954) and revised by Richter (1958). It was not until 1963 that earthquake data for the Utah area was recorded in terms of Richter magnitude. The Magnitude scale was brought about by the advent of instrumentation which greatly improved the accuracy of both the location and the measured amount of energy release. Richter Magnitude is based on actual energy release as measured by a standard seismograph. The relationship between earthquake magnitude and energy released during the earthquake can be stated as,

$$\log_{10} E = 11.5 + 1.5 M \qquad (4)$$

Although the Richter scale is more quantitative and exact, the Mercelli scale is still frequently used in engineering seismology because it accounts for site related characteristics. A comparison of Modified Mercelli Intensities and Richter Magnitudes (Cook and Smith, 1967) can be represented by,

$$M = 0.6 (Io + 2.167) \qquad (5)$$

where M = Richter Magnitude, and I_o = Modified Mercelli Intensity. This relationship was used to convert the Modified Mercelli Intensities of the early earthquakes to Richter magnitudes. Although this relationship may produce some error it provides a comparison of the two methods and allowed a basis for establishing the area seismicity.

Liquefaction Opportunity Map

The liquefaction opportunity map (Figure 13) showed longer return periods located in the southern portion of Cache Valley with a decreasing trend northward and a range of shorter return periods along the western edge of the valley. These return periods varied from 30 to 90 years. The Bear Lake-Caribou Source Area and the Hansel Valley Faults influenced the decreasing trend northward and the Wasatch Fault and to a lesser extent the Hansel Valley Faults caused the range of shorter return periods along the western edge of the valley.

Summary

A liquefaction opportunity map was developed for Cache Valley, Utah and is shown on Figure 13. This study was the initial phase to determine the potential for liquefaction in Cache Valley. The results indicate that the return period for a sufficient level of ground shaking to cause liquefaction varies from 30 to 90 years.

The method used in this study to develop the liquefaction opportunity map was based on a procedure developed by Youd and Perkins (1977). The method considered the geology and tectonics of the study area, the recurrence relationships of earthquakes from historical seismicity, and the probability distribution of the size and location of an event.

The seismicity in the form of annual frequencies of earthquake occurrences was determined from records of earthquake epicenters within a 186 mile radius of Logan, Utah. The annual frequencies were then accumulated to produce accumulated annual frequencies of liquefaction opportunity for a series of grid points within the study area. The reciprocals of the annual frequencies, return periods, were then determined at the grid points and contours of equal return period were developed. The resulting map of return period contours constituted the liquefaction opportunity map.

This opportunity map is proposed to be combined with a map delineating liquefaction susceptible soils to produce a liquefaction potential map. The liquefaction susceptibility map is being developed in a companion study.

The liquefaction potential map will assist in the evaluation of earthquake response in general and microzonation in particular. The liquefaction potential map may also be used by contractors, consultants, governmental organizations, etc., for preliminary planning and decision making to determine the suitability of a given site.

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APPENDICES

Appendix A

The data in this appendix includes a list of 274 earthquakes which occurred within a 186 mile radius of Logan, Utah.

This data was made available by the U.S. National Oceanic and Atmospheric Administration (NOAA) as presented by Green (1977), Williams and Tapper (1953), Cook and Smith (1967) and Smith (1974).

Key to earthquake data

Source: Source of data is listed as follows:

AEC - U.S. Atomic Energy Commission

BCI - Bureau Central International de Seismologie, Strasbourg, France

CGS - Coast and Geodetic Survey

EQH - *Earthquake History of the United States*

ERL - Environmental Research Laboratories

G-R - Gutenborg-Richter

GS - U.S. Geological Survey, Denver, Colorado

NOS - National Ocean Survey

PAS - Pasadena, California

SLC - Salt Lake City, Utah

USE - *United States Earthquakes*

Year, Month, Day: Date

LAT(N), LONG(W): Geographical latitude and longitude

Equivalent Magnitude: Modified Mercelli Intensities converted to Richter Magnitude

Seismic Source: Seismic source to which earthquake event is associated with and they are:

WS - Wasatch Fault
BL-C - Bear Lake-Caribou Source Area
C - Cache Valley Source Area
HV - Hansel Valley Faults

Table 4. Earthquake epicentral data.

Source	Year	Month	Day	Location		Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
				LAT (N)	LONG (W)				
EQH	1853	12	01	39.70	111.80	-	V	4.3	WS
EQH	1880	07	12	42.00	112.30	-	VI	4.9	WS
EQH	1880	09	17	40.80	112.00	-	V	4.3	WS
EQH	1884	11	09	41.50	111.20	-	VI	4.9	C
EQH	1894	07	18	41.20	112.00	-	VII	5.5	WS
EQH	1899	12	13	41.00	112.00	-	V	4.3	WS
EQH	1900	08	01	39.80	112.20	5.5	VII	5.5	WS
EQH	1906	05	24	41.20	112.00	-	V	4.3	WS
EQH	1906	10	19	42.50	111.40	-	V	4.3	BL-C
EQH	1910	05	22	40.80	111.90	-	VII	5.5	WS
EQH	1913	04	12	42.00	112.00	-	V	4.3	C
EQH	1914	05	13	42.00	112.00	-	VIII	5.5	C
EQH	1915	07	15	40.30	111.70	-	VI	4.9	WS
EQH	1915	07	30	41.80	112.20	-	V	4.3	WS
EQH	1915	08	11	40.50	112.70	4.3	V	4.3	HV
EQH	1916	02	05	40.00	111.70	4.3	-	-	WS
EQH	1917	12	12	43.00	111.30	-	V	4.3	BL-C
EQH	1920	09	18	41.50	112.00	-	VI	4.9	WS
EQH	1920	09	19	41.50	112.00	-	VI	4.9	WS
EQH	1920	11	20	41.50	112.00	-	VI	4.9	WS
EQH	1924	11	25	42.50	111.50	-	V	4.3	BL-C
USE	1928	06	02	39.80	111.00	-	-	-	WS
USE	1929	10	01	42.20	111.20	-	-	-	C
USE	1930	06	12	42.60	111.90	-	VI	4.9	BL-C
G-R	1934	03	12	41.50	112.50	6.6	VIII	6.1	HV
G-R	1934	03	12	41.75	112.50	6.0	VIII	6.1	HV
G-R	1934	04	14	41.50	112.50	5.25	-	-	HV
G-R	1934	05	06	41.75	113.50	6.6	VIII	6.1	HV

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	Location LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
CGS	1942	04	18	41.50	112.30	4.3	V	4.3	WS
CGS	1943	02	22	41.00	111.50	4.9	VI	4.9	WS
USE	1950	01	02	41.50	112.00	-	IV	3.7	WS
CGS	1950	02	25	40.00	112.00	-	-	-	WS
CGS	1950	05	08	40.00	111.70	4.3	V	4.3	WS
CGS	1950	09	28	40.40	111.80	4.3	V	4.3	WS
CGS	1953	05	24	40.50	111.50	4.3	V	4.3	WS
CGS	1957	11	03	42.50	111.50	-	-	-	BL-C
USE	1957	11	05	42.50	111.00	-	-	-	HV
USE	1958	02	13	40.50	111.50	4.9	-	-	WS
USE	1958	02	13	40.50	111.50	-	-	-	WS
USE	1958	12	01	40.50	112.50	4.3	V	4.3	WS
CGS	1958	12	01	40.50	112.50	-	-	-	WS
BCI	1958	12	02	40.50	112.50	4.3	-	-	WS
CGS	1960	04	24	43.00	111.50	-	-	-	BL-C
CGS	1960	07	09	41.50	112.00	-	-	-	WS
CGS	1960	07	23	42.50	111.50	-	-	-	BL-C
CGS	1960	07	23	42.50	111.50	-	-	-	BL-C
CGS	1960	07	23	42.50	111.50	-	-	-	BL-C
CGS	1960	07	25	42.50	111.50	-	-	-	BL-C
CGS	1960	07	25	42.50	111.50	-	-	-	BL-C
CGS	1960	08	07	42.40	111.50	-	VI	4.9	BL-C
CGS	1960	08	07	42.50	111.40	-	-	-	BL-C
CGS	1960	08	10	42.50	111.50	-	V	4.3	BL-C
CGS	1960	08	20	42.50	111.70	-	-	-	BL-C
CGS	1960	08	20	42.60	111.70	-	-	-	BL-C
CGS	1960	08	20	42.30	111.30	-	V	4.3	BL-C
CGS	1960	08	20	42.50	111.60	-	-	-	BL-C

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
CGS	1960	08	20	42.60	111.40	-	-	-	BL-C
CGS	1960	08	20	42.40	111.50	-	-	-	BL-C
CGS	1960	08	20	42.50	111.60	-	-	-	BL-C
CGS	1960	08	21	42.40	111.60	-	-	-	BL-C
CGS	1960	08	26	42.40	111.20	-	-	-	BL-C
CGS	1960	09	12	39.10	111.70	-	-	-	WS
CGS	1961	04	16	39.30	111.50	-	-	-	WS
CGS	1961	05	25	42.20	111.90	-	-	-	C
CGS	1961	10	15	39.20	111.40	-	-	-	WS
CGS	1961	10	16	39.20	111.50	-	-	-	WS
CGS	1961	10	17	39.20	111.50	-	-	-	WS
CGS	1961	10	17	40.00	112.50	-	-	-	-
CGS	1962	08	21	39.30	111.00	-	-	-	-
CGS	1962	08	30	41.80	111.80	5.7	VII	5.5	C
PAS	1962	09	05	40.70	112.00	5.1	VI	4.9	WS
CGS	1962	09	09	41.60	111.80	-	-	-	C
CGS	1962	09	14	41.80	111.50	-	-	-	C
CGS	1963	03	05	42.60	111.30	-	III	3.1	BL-C
CGS	1963	04	04	42.30	111.20	-	-	-	BL-C
CGS	1963	07	07	39.60	111.90	4.9	VI	4.9	WS
CGS	1963	07	09	39.90	111.90	-	-	-	WS
CGS	1963	07	09	40.00	111.20	-	-	-	-
CGS	1963	07	10	39.90	111.40	-	-	-	-
CGS	1963	08	14	41.50	112.20	3.7	IV	3.7	WS
CGS	1963	08	16	39.70	112.10	3.4	IV	3.7	WS
CGS	1963	08	16	41.50	112.20	3.6	-	-	WS
CGS	1963	08	17	41.40	112.20	3.5	-	-	WS
CGS	1963	08	24	40.80	112.00	3.9	-	-	WS
CGS	1963	08	28	40.90	111.90	3.4	-	-	WS

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
CGS	1963	09	11	40.70	112.10	-	-	-	WS
CGS	1963	10	31	43.00	111.30	3.0	-	-	BL-C
CGS	1964	02	06	42.00	112.30	-	-	-	WS
CGS	1964	02	06	42.10	112.40	-	-	-	HV
CGS	1964	02	07	42.10	112.40	-	-	-	HV
CGS	1964	03	02	39.60	111.90	3.9	-	-	WS
CGS	1964	06	27	41.00	113.40	-	-	-	-
CGS	1964	07	01	42.60	111.80	-	-	-	BL-C
CGS	1964	08	12	39.40	112.00	3.9	-	-	WS
CGS	1964	05	22	41.90	112.10	-	-	-	C
CGS	1964	08	24	39.10	112.20	-	-	-	WS
CGS	1964	09	06	39.20	111.50	-	-	-	-
CGS	1964	10	18	41.90	111.80	4.3	-	-	C
CGS	1965	03	09	39.90	111.30	3.50	-	-	-
CGS	1965	03	27	42.60	111.50	-	-	-	BL-C
CGS	1965	04	02	42.60	111.50	-	-	-	BL-C
CGS	1965	04	02	42.50	111.50	4.5	-	-	BL-C
CGS	1965	04	02	42.50	111.50	-	-	-	BL-C
CGS	1965	04	27	41.30	112.80	-	-	-	-
CGS	1965	05	11	41.00	111.50	4.1	-	-	WS
CGS	1965	05	24	42.80	111.40	-	-	-	BL-C
CGS	1965	06	17	39.70	111.30	-	-	-	-
CGS	1965	07	05	39.30	111.50	-	-	-	-
CGS	1965	08	17	41.70	112.70	-	-	-	-
CGS	1965	08	23	42.5	111.30	3.6	-	-	BL-C
CGS	1965	11	04	39.50	111.10	-	-	-	-
CGS	1965	11	28	42.60	111.30	-	-	-	BL-C
CGS	1966	02	11	42.10	111.40	3.5	-	-	BL-C
CGS	1966	02	12	42.30	111.20	3.2	-	-	BL-C

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
CGS	1966	03	17	41.70	111.50	4.7	V	4.3	C
CGS	1966	04	23	39.20	111.40	-	-	-	WS
CGS	1966	04	24	39.20	111.40	-	-	-	WS
CGS	1966	06	19	42.70	111.40	-	-	-	BL-C
CGS	1966	10	20	39.60	111.10	-	-	-	-
CGS	1966	11	12	41.90	112.80	-	-	-	HV
CGS	1966	11	14	41.70	112.70	-	-	-	HV
CGS	1967	01	05	41.85	112.56	-	-	-	HV
CGS	1967	01	22	39.64	111.93	-	-	-	WS
CGS	1967	02	26	41.61	111.77	-	-	-	C
CGS	1967	03	05	41.33	111.67	3.5	IV	3.7	WS
CGS	1967	03	10	40.78	111.90	-	IV	3.7	WS
CGS	1967	04	03	39.49	111.12	-	-	-	-
CGS	1967	04	08	42.87	111.31	4.2	-	-	BL-C
CGS	1967	06	26	43.00	111.00	4.0	-	-	BL-C
CGS	1967	08	24	42.90	111.30	-	-	-	BL-C
CGS	1967	09	02	41.10	111.60	-	-	-	WS
CGS	1967	09	11	43.00	111.00	3.5	-	-	BL-C
CGS	1967	09	11	43.00	111.20	-	-	-	BL-C
USE	1967	09	24	40.70	112.10	-	V	4.3	WS
CGS	1967	09	24	40.70	112.10	3.7	-	-	WS
CGS	1967	10	31	42.50	111.50	-	-	-	BL-C
CGS	1967	11	04	39.20	111.70	-	-	-	WS
USE	1967	12	07	41.30	111.70	4.3	-	-	WS
CGS	1967	12	09	41.60	111.80	-	-	-	C
CGS	1968	01	16	42.80	111.60	3.9	-	-	BL-C
CGS	1968	01	16	39.30	112.10	4.10	-	-	WS
CGS	1968	01	16	39.30	112.10	3.90	-	-	WS
CGS	1968	01	16	39.30	112.10	-	-	-	WS

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
CGS	1968	01	16	39.20	111.90	-	-	-	WS
CGS	1968	01	16	39.20	112.00	4.0	-	-	WS
CGS	1968	01	17	39.30	112.20	-	-	-	WS
CGS	1968	01	19	39.30	112.10	-	-	-	WS
CGS	1968	02	15	42.80	111.70	-	-	-	BL-C
CGS	1968	02	26	39.60	111.00	-	-	-	-
CGS	1968	03	07	41.90	112.70	-	-	-	HV
CGS	1968	05	11	42.35	111.34	-	-	-	BL-C
CGS	1968	08	02	39.52	111.04	-	-	-	-
USE	1968	08	04	39.10	111.40	-	-	-	-
CGS	1968	09	10	42.68	111.90	-	-	-	BL-C
CGS	1969	02	01	42.01	111.65	-	-	-	C
CGS	1969	06	30	42.69	111.169	3.7	-	-	BL-C
CGS	1969	09	19	42.987	111.43	4.5	-	-	BL-C
CGS	1969	09	19	43.01	111.266	4.3	-	-	BL-C
CGS	1969	09	19	42.964	111.493	3.9	-	-	BL-C
CGS	1969	09	23	42.923	111.474	3.9	-	-	BL-C
CGS	1969	09	25	42.871	111.698	3.9	-	-	BL-C
NOS	1970	10	17	42.697	111.115	4.3	-	-	BL-C
NOS	1970	10	25	39.152	111.385	-	-	-	-
NOS	1970	10	27	39.103	111.355	-	-	-	-
NOS	1971	04	22	39.424	111.978	3.4	-	-	WS
ERL	1971	07	16	42.215	111.392	3.6	-	-	BL-C
ERL	1972	03	06	41.873	111.616	4.6	-	-	C
ERL	1972	10	01	40.581	111.302	-	-	-	-
ERL	1972	10	16	40.415	111.039	-	-	-	-
ERL	1972	11	24	42.505	111.158	4.4	IV	3.7	BL-C
ERL	1973	04	13	42.09	112.643	-	-	-	HV
ERL	1973	04	14	42.051	112.525	4.4	IV	3.7	HV

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
GS	1973	07	16	39.149	111.508	-	-	-	-
GS	1973	10	27	42.770	111.109	-	-	-	BL-C
GS	1973	11	20	42.042	112.692	-	-	-	HV
GS	1975	03	27	42.07	112.545	4.4	-	-	HV
GS	1975	03	28	42.061	112.548	6.1	VIII	6.1	HV
GS	1975	03	28	42.051	112.481	4.3	-	-	HV
GS	1975	03	28	42.03	112.534	4.1	-	-	HV
GS	1975	03	29	42.08	112.453	4.3	-	-	HV
GS	1975	03	29	42.016	112.521	4.7	-	-	HV
GS	1975	03	30	42.02	112.578	4.3	-	-	HV
GS	1975	03	30	42.028	112.62	4.0	-	-	HV
GS	1975	03	30	42.023	112.605	4.3	-	-	HV
GS	1975	03	30	42.097	112.644	3.9	-	-	HV
GS	1975	03	30	42.039	112.537	4.0	-	-	HV
GS	1975	03	30	42.014	112.594	4.0	-	-	HV
GS	1975	03	30	42.011	112.605	4.0	-	-	HV
GS	1975	03	31	42.063	112.500	3.5	-	-	HV
GS	1975	03	31	42.008	112.497	4.4	-	-	HV
GS	1975	03	31	41.981	112.411	4.5	-	-	HV
GS	1975	04	02	42.094	112.444	4.7	-	-	HV
GS	1975	04	04	42.008	112.477	-	-	-	HV
GS	1975	04	06	42.022	112.493	3.2	-	-	HV
GS	1975	04	07	42.041	112.492	3.1	-	-	HV
GS	1975	04	07	42.147	112.585	3.1	-	-	HV
GS	1975	04	07	42.039	112.498	4.4	-	-	HV
GS	1975	04	08	41.880	112.374	4.0	-	-	HV
GS	1975	04	10	42.012	112.554	3.2	-	-	HV
GS	1975	06	30	42.112	112.466	3.0	II	2.5	HV
GS	1975	08	16	42.124	112.448	3.6	-	-	HV

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
GS	1975	09	12	42.072	112.571	-	III	3.1	HV
GS	1975	09	12	42.086	112.489	-	-	-	HV
GS	1975	09	14	41.871	112.426	-	III	3.1	HV
GS	1975	09	22	42.075	112.453	3.6	IV	3.7	HV
GS	1975	10	13	42.000	112.556	-	-	-	HV
GS	1975	11	09	41.992	112.517	-	-	-	HV
GS	1975	11	17	41.955	112.533	3.0	-	-	HV
GS	1975	12	20	42.001	112.528	-	-	-	HV
GS	1976	02	11	41.270	111.843	-	III	3.1	WS
GS	1976	02	14	42.719	111.272	3.4	-	-	BL-C
GS	1976	02	21	41.989	112.553	3.3	-	-	HV
GS	1976	02	23	42.010	112.523	-	-	-	HV
GS	1976	02	27	41.240	111.275	-	-	-	-
GS	1976	03	07	42.059	112.571	-	-	-	HV
GS	1976	03	22	42.050	112.642	-	-	-	HV
GS	1976	06	14	42.118	112.480	3.6	-	-	HV
GS	1976	06	15	41.886	112.442	3.1	-	-	HV
GS	1958	11	28	39.6	111.80	4.3	V	4.3	WS
GS	1963	08	16	39.538	111.923	3.5	-	-	WS
GS	1963	07	07	39.54	111.88	4.4	-	-	WS
GS	1963	07	09	39.63	111.812	3.3	-	-	WS
GS	1963	08	16	39.538	111.923	3.5	-	-	WS
GS	1964	03	02	39.549	111.836	3.0	-	-	WS
GS	1971	04	03	39.41	111.890	3.2	-	-	WS
GS	1880	09	16	40.80	111.90	3.7	-	-	WS
GS	1915	07	15	40.40	111.70	4.9	VI	4.9	WS
GS	1916	02	04	40.00	111.80	4.3	V	4.3	WS
GS	1935	07	09	40.70	111.80	4.3	V	4.3	WS
GS	1894	07	18	41.20	111.90	4.3	-	-	WS

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
GS	1899	12	13	41.10	111.90	3.7	-	-	WS
GS	1909	10	05	41.70	112.30	6.7	-	-	WS
GS	1909	11	16	41.70	112.20	4.3	V	4.3	WS
GS	1920	11	20	41.50	112.00	4.3	V	4.3	WS
GS	1914	04	08	41.20	111.60	4.3	V	4.3	WS
GS	1914	05	13	41.30	112.00	4.9	VI	4.9	WS
GS	1946	05	06	41.70	112.20	4.3	V	4.3	WS
GS	1963	08	14	41.586	112.128	3.3	-	-	WS
GS	1963	08	16	41.723	112.133	3.0	-	-	WS
GS	1880	07	11	42.00	112.20	4.30	V	4.3	WS
GS	1967	12	07	41.292	111.773	3.7	-	-	WS
GS	1938	06	30	40.70	112.10	4.3	V	4.3	WS
GS	1947	03	28	40.60	111.80	4.3	V	4.3	WS
GS	1962	09	05	40.765	112.131	5.2	-	-	WS
GS	1949	03	07	40.80	111.90	4.9	VI	4.9	WS
GS	1963	07	10	40.00	111.30	4.2	V	4.3	WS
GS	1967	09	24	40.704	112.906	3.00	-	-	WS
GS	1962	07	09	40.299	111.815	3.2	-	-	WS
GS	1962	09	05	40.70	112.00	5.1	VI	4.9	WS
GS	1913	04	12	42.30	112.00	4.3	V	4.3	C
GS	1923	06	07	41.70	111.80	4.3	V	4.3	C
GS	1962	08	30	42.04	111.799	5.7	-	-	C
GS	1964	10	18	41.765	111.778	3.9	-	-	C
GS	1966	03	17	41.637	111.573	4.3	-	-	C
GS	1972	03	06	41.867	111.815	3.2	-	-	C
GS	1965	04	02	42.50	111.40	4.5	-	-	BL-C
GS	1934	03	12	41.700	112.80	4.9	VI	4.9	HV
GS	1975	03	28	42.022	112.509	3.10	-	-	HV
GS	1975	03	29	42.06	112.569	3.10	-	-	HV

Table 4. Continued.

Source	Year	Month	Day	Location LAT (N)	LONG (W)	Richter Magnitude	Modified Mercelli Int.	Equivalent Magnitude	Seismic Source
GS	1975	03	29	42.009	112.558	3.1	-	-	HV
GS	1975	03	28	41.981	112.456	3.00	-	-	HV
GS	1975	03	28	41.99	112.493	3.00	-	-	HV
GS	1975	03	30	42.028	112.595	3.10	-	-	HV
GS	1975	03	31	42.040	112.531	3.6	-	-	HV
GS	1975	04	02	42.09	112.442	3.2	-	-	HV
GS	1975	04	05	42.04	112.503	3.10	-	-	HV
GS	1975	04	06	42.026	112.488	3.2	-	-	HV
GS	1975	04	07	42.053	112.491	3.10	-	-	HV
GS	1975	04	07	42.157	112.585	3.10	-	-	HV
GS	1975	04	07	42.049	112.493	3.00	-	-	HV
GS	1975	04	10	42.018	112.554	3.2	-	-	HV
GS	1976	06	15	41.890	112.422	3.10	-	-	HV

Appendix B

Table 5. Modified Mercalli intensity scale of 1930. (Abridged and rewritten.) (After Lew, Leyendecker, and Dikkers, 1971.)

Intensity	Description
I.	Not felt.
II.	Felt by persons at rest, on upper floors, or favorably placed.
III.	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. May not be recognized as an earthquake.
IV.	Hanging objects swing. Vibration like passing of heavy trucks or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. Wooden walls and frames creak.
V.	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move.
VI.	Felt by all. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.
VII.	Difficult to stand. Noticed by drivers of automobiles. Hanging objects quiver. Furnature broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slices and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

Table 5. Continued.

Intensity	Description
VIII.	Steering of automobiles affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX.	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated area sand and mud ejected, earthquake fountains, sand craters.
X.	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI.	Rails bent greatly. Underground pipelines completely out of service.
XII.	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

	Quality of Masonry (Brick or Other)
Masonry A	Good workmanship, mortar, and design; reinforced especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.
Masonry B	Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Table 5. Continued.

	Quality of Masonry (Brick or Other)
Masonry C	Ordinary workmanship and mortar; no extreme weaknesses like failing to tie at corners, but neither reinforced nor designed against horizontal forces.
Masonry D	Weak materials, such as adobe; poor mortar, low standards of workmanship; weak horizontally.