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A Liquefaction Potential Map for Cache Valley, Utah

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A LIQUEFACTION POTENTIAL MAP

FOR CACHE VALLEY, UTAH

by

Randall Jones Hill

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Randall J. Hill

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ABSTRACT

A Liquefaction Potential Map

for Cache Valley, Utah

by

Randall J. Hill, Master of Science

Utah State University, 1979

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Department: Civil and Environmental Engineering

The identification of liquefaction susceptible soil deposits in Cache Valley, Utah and the relative potential that these deposits have for liquefaction were the two main purposes of this study. A liquefaction susceptibility map was developed to outline areas where liquefaction might occur during an earthquake. The susceptibility map was combined with a liquefaction opportunity map to produce a liquefaction potential map for Cache Valley, Utah. The opportunity map for Cache Valley was developed in a companion study, Greenwood (1978).

The development of the susceptibility map and the opportunity map and combining them to form a liquefaction potential map for Cache Valley was based on a procedure developed by Youd and Perkins (1977).

The liquefaction potential map is a general location map and will be a useful tool for preliminary planning by governmental agencies, planners, developers, and contractors. The use of the liquefaction potential map by these various groups will aid them in avoiding possible problem areas for project locations. It will also be a guide for further analysis of specific sites where liquefaction is probable.

(106 pages)

CHAPTER 1

INTRODUCTION

Statement of Problem

General

In the past, ground failures caused by earthquakes have been a serious problem that has had little understanding. However, because of the extensive loss of life and tremendous amounts of damage that earthquakes and resulting ground failures have caused in the last 50 to 60 years, many investigators have been studying these natural phenomena. It has only been within the last 10-15 years that ground failures caused by the mechanism of liquefaction has been understood in any detail. There are still, unfortunately, many questions to be answered before the information now available will be of benefit in eliminating the damages caused by liquefaction induced-ground failures.

The basic concepts of liquefaction were first presented by Casagrande (1936) in his studies on slope stability. Casagrande's work dealt mainly with volume change and/or pore pressure build-up during the application of a static shearing stress. In recent years cyclic stresses like those created by earthquakes have been found to cause similar volume change and pore pressure phenomena. This study deals with liquefaction-induced ground failures created by the cyclic stresses that an earthquake generates in a soil mass.

Definition of liquefaction

The term liquefaction has been used and defined differently by different investigators over the years. There has also been some controversy over how the term should be used to describe different phenomena. The term liquefaction, as it is used in this study, will refer to the changing of a soil from a solid state to a liquefied state due to the build-up of excess hydrostatic pore pressures. In connection with this change of state, deformations causing ground failure must occur. The build-up of excess pore pressure results from cyclic shear stresses that are induced by earthquake ground shaking. Seed (1976) describes the build-up of excess pore pressure as the trade-off between a tendency for a volume decrease, due to cyclic loading, and a rebound of the soil structure, due to the load being transferred from the soil structure to the pore water. The difference between soil structure rebound and the tendency for the volume of the soil mass to compact results in the excess pore pressure (Seed, 1976).

Case histories

All the interest over the past 10-15 years in liquefaction-induced ground failures stems from a few significant earthquakes. The earthquake in Niigata, Japan in June, 1964 (M=7.3) produced some interesting damages and resulted in a number of Japanese engineers performing many investigations into the causes of these failures (Seed and Idriss, 1967). There were many instances of damages to highways, utilities, port facilities, and buildings. The most significant damages relating to liquefaction are shown on Figures 1, 2, and 3. In Figure 1, the apartment buildings have tilted because of the development of liquefaction in the foundation soils. Figure 2 shows a sewage treatment tank that floated to the surface because the buoyant forces lifting the tank were not resisted by the soil, which had liquefied. Figure 3 shows the development of a flowing spring in a developed area of the city. This resulted from the development of liquefaction and a release of the excess pore pressures to the surface. Seed and Idriss (1967) indicate that much of the damage was the result of the soils having liquefied. The damages could possibly have been prevented if more had been known about liquefaction and how to prevent it.

Another example of extensive damage created by liquefaction occurred during the Alaska Earthquake of March 1964. A large magnitude earthquake (M=8.5) struck South Central Alaska disrupting many highways and utilities and severely damaging many structures. Ross, Seed and Migliaccio (1969) reviewed a number of highway bridge failures and indicated that liquefaction of the support soils during and shortly after the earthquake caused the failures. Also, an entire subdivision in the city of Anchorage slid into the sea (Figure 4) because the foundation soils liquefied and caused a slope failure (Seed and Wilson, 1967). Millions of dollars of damage from this earthquake resulted from liquefaction-induced ground failures.

In 1971 an earthquake (M=6.6) struck the San Fernando Valley of California causing millions of dollars of damage (Youd, 1971). A large amount of this damage was attributed to liquefaction. The near

Figure 1. Tilting of apartment buildings in Niigata, Japan, 1964 (after Seed and Idriss, 1967).

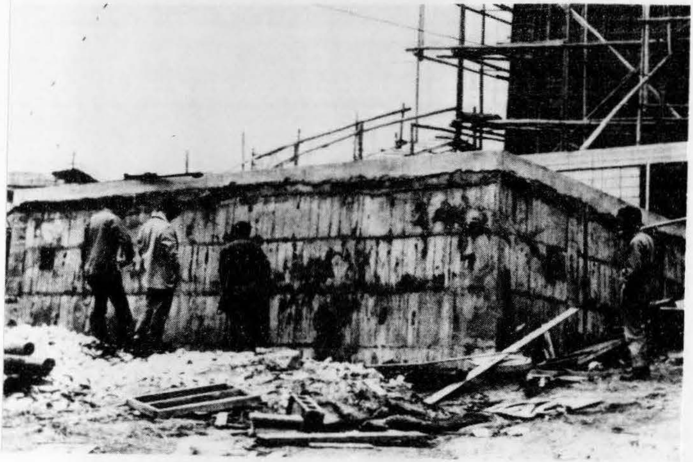

Figure 2. Sewage treatment tank floated to ground surface (after Seed and Idriss, 1967).

Figure 3. Springs developing during earthquake in Niigata, Japan, 1964 (after Seed and Idriss, 1967).

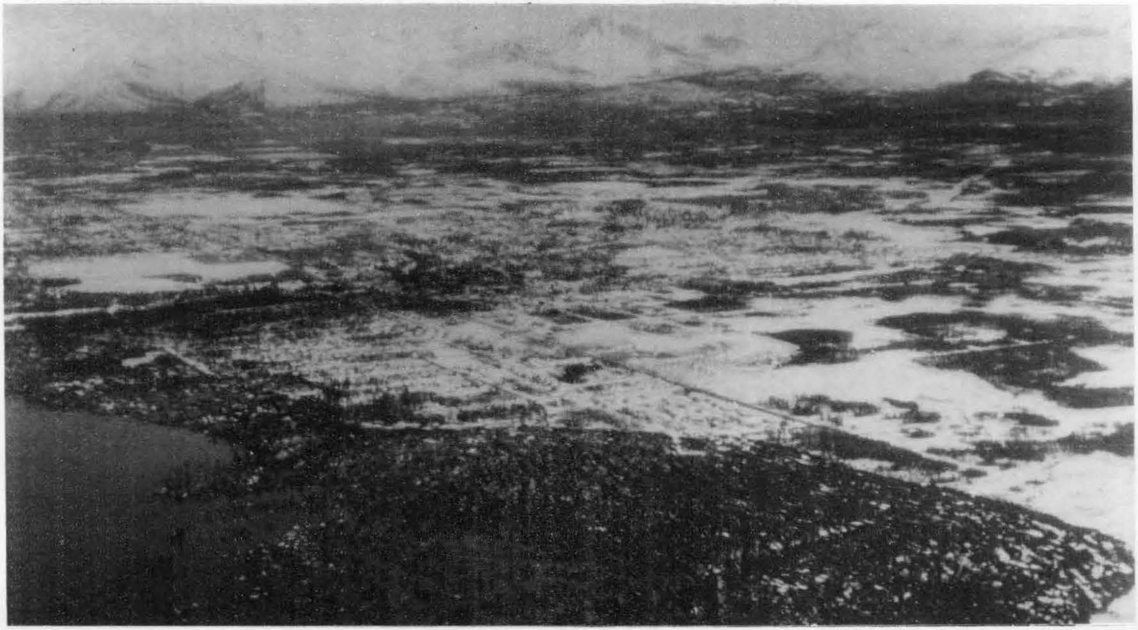

Figure 4. Aerial view of Turnagain Heights Landslide in Alaska, 1964 (after Seed and Wilson, 1967).

catastrophic failure of the Lower San Fernando Dam (Seed, et al. 1975) has been attributed to liquefaction of the embankment soil, (Figure 5). The dam was located above a large population center and if it had failed many additional lives would have been lost. A juvenile hall structure suffered extensive damage due to ground cracking and ground spreading as a result of liquefaction of the support soils. No loss of life was suffered, but damage to the structure was extensive (Lew, Levendecker, and Dikkers, 1971). Another site that was affected by liquefaction was the Joseph Jensen Filtration Plant (Dixon and Burke, 1973). Slope failure, ground surface cracking, and building settlements created many problems at this site that were very expensive to repair.

There have also been reports of ground failures and ground disturbances from earlier earthquakes that have now been linked with liquefaction. Ambraseys and Sarma (1969) discuss numerous incidents of sand boils, mud flows, ground ruptures, flowing springs, and building subsidence being caused by liquefaction. These accounts are from earthquakes from as far back as 1897. Youd and Hoose (1976) describe various ground failures that occurred during the 1906 San Francisco Earthquake that have now been attributed to liquefaction of the soils. Estimates of 85% of the damage to San Francisco in 1906 was caused by the fire that followed the earthquake. However, much of the fire damage could have been prevented if several arterial main water lines into the city had not been severed by a liquefaction-induced ground failure.

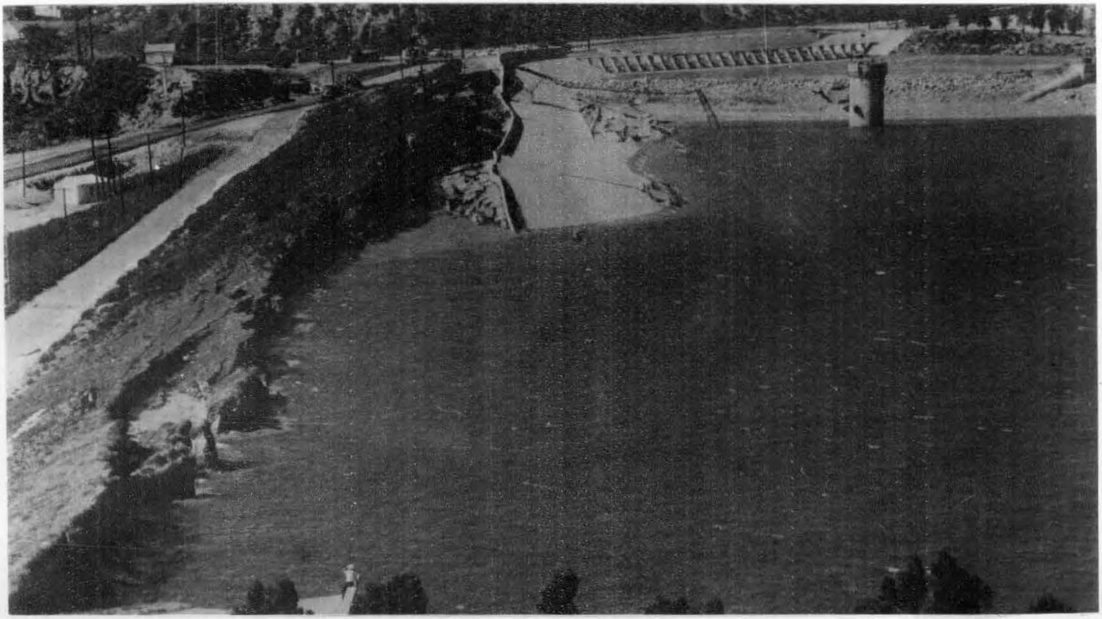

Figure 5. Collapsed crest of the Lower San Fernando Dam (after Lew, Leyendecker, and Dikkers, 1971).

Technological advances

As pointed out by the previous examples, liquefaction-induced ground failures have been directly or indirectly responsible for many serious problems associated with earthquakes. As a result, wide interest in the problem of liquefaction has developed over the past few years. Within that time new technology and new theories have been developed to understand and analyze the mechanism of this seismic hazard.

Laboratory testing procedures such as the cyclic simple shear test, the cyclic triaxial test, and the shaking table test have greatly helped in the formulation of theories. Data from these tests have enabled investigators to determine the causes of liquefaction, the factors affecting the mechanism, and procedures of analysis and design for the liquefaction problem.

Another important source in understanding the problem has been the field work at various sites where liquefaction has occurred. A large data base has been established on insitu characteristics of soil profiles. Most of this data comes from the case histories mentioned above. A new data source that may be very important in the future is the information from Chinese records on earthquakes. These records are estimated to extend farther back than any other recorded histories on earthquakes. Together with the present records that are now available on earthquakes, a very substantial collection of information is available for analysis and comparison.

Although new theories have been developed from laboratory results and compared to observed field conditions with good correlation, more answers and information are needed. A universally accepted method of analysis has not yet been developed. Several analysis methods are available, but they do not consider the whole problem. Any information that could be used to find a well accepted approach to the problem would be a very important contribution in controlling the possibility of liquefaction-induced ground failures.

Purpose of Study

The purpose of this study was to develop a useful guide for evaluating the possibility of liquefaction-induced ground failures in Cache Valley, Utah. A liquefaction potential map of Cache Valley, Utah was the final result. The potential map will be useful as a preliminary guide in identifying areas of possible liquefaction. The map will only locate general areas of possible liquefaction. Then, depending on the project, a more detailed site-specific analysis should be performed for any site where liquefaction is considered possible. It should be emphasized that the map is only a preliminary guide and not a final site design tool.

Cache Valley lies in a seismically active area. It has been placed in a Zone 3 classification by the 1976 Uniform Building Code's seismic zone classification map, as shown on Figure 6. This zone classification indicates a large amount of seismic activity in and around the Cache Valley area.

There have been reports of ground disturbances caused by liquefaction during past earthquakes in Cache Valley. During the August 30, 1962

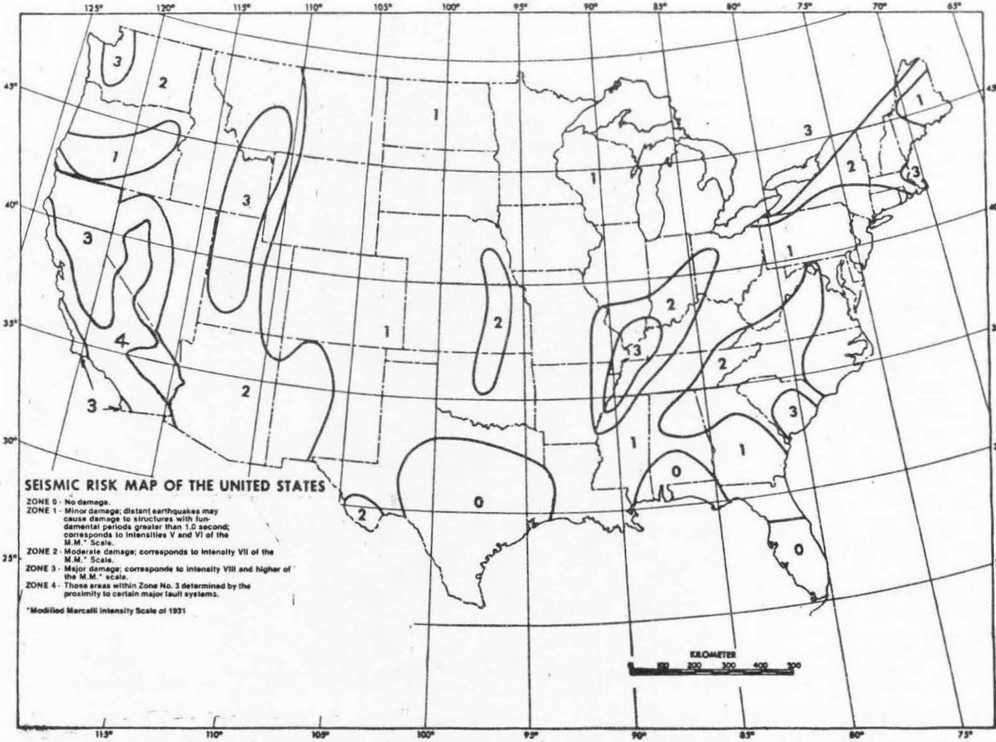

Figure 6. Seismic zone map of the United States (after Uniform Building Code, 1976).

earthquake, ground surface cracking and extrusion of sand and water from the cracks were found in the north end of the valley near the community of Trenton. Sand boils were also noticed in this area. The earthquake was of sufficient magnitude and close enough to the site to induce liquefaction. This occurrence agrees quite well with a magnitude-distance relationship that was utilized to prepare the liquefaction potential map. A more detailed discussion of the occurrences of liquefaction in Cache Valley is presented in the appendix.

Because of the seismicity of the area and the fact that some soils in Cache Valley are highly susceptible to liquefaction, it is very important to have at least a general idea as to where liquefaction might occur. Sudden and possibly catastrophic failures of structures, dams, and soil embankments could possibly be prevented if liquefaction-susceptible areas are outlined. Given the possibility that various sites could liquefy, more specific design procedures could be implemented to correct any problems that exist at a site, or a problem site may be avoided completely.

Cache Valley has experienced a large population and economic growth in the past few years. It also seems reasonable that this trend will continue for a number of years to come. City and county planners will be making many decisions about the growth and development within the valley. Therefore, all types of information concerning the valley will need to be considered in making wise choices of where to place industries, subdivisions, utilities and businesses. A liquefaction potential map would aid the planners and developers in their site selections and the level of analysis and design that a specific site might need. The liquefaction potential map could be a useful planning tool for various groups.

Study Area

Location

Cache Valley is a long narrow valley that lies partly in Northern Utah and partly in Southeast Idaho. However, the study area only encompassed Cache Valley, Utah. Figure 7 shows the study area. The study area is small, approximately 365 square miles. The size of the area was limited to enable more detail to be included in the mapping.

Population

The population of the Utah section of the valley was approximately 42,300 in 1970. This is undoubtedly a low figure for the present time. There has been a significant amount of development in the past few years with a substantial increase in population. It is now estimated that Cache Valley, Utah has a population of well over 50,000.

Industry

Agriculture and dairy farming are the main industries within the valley. However, there are a number of small businesses and industries that are directly linked to these two primary markets. These businesses and industries provide a number of jobs to the valley. There are also a few non-agriculture industries scattered throughout the valley that employ a substantial number of people. Utah State University is located in Logan and is also a primary source of employment for people in the

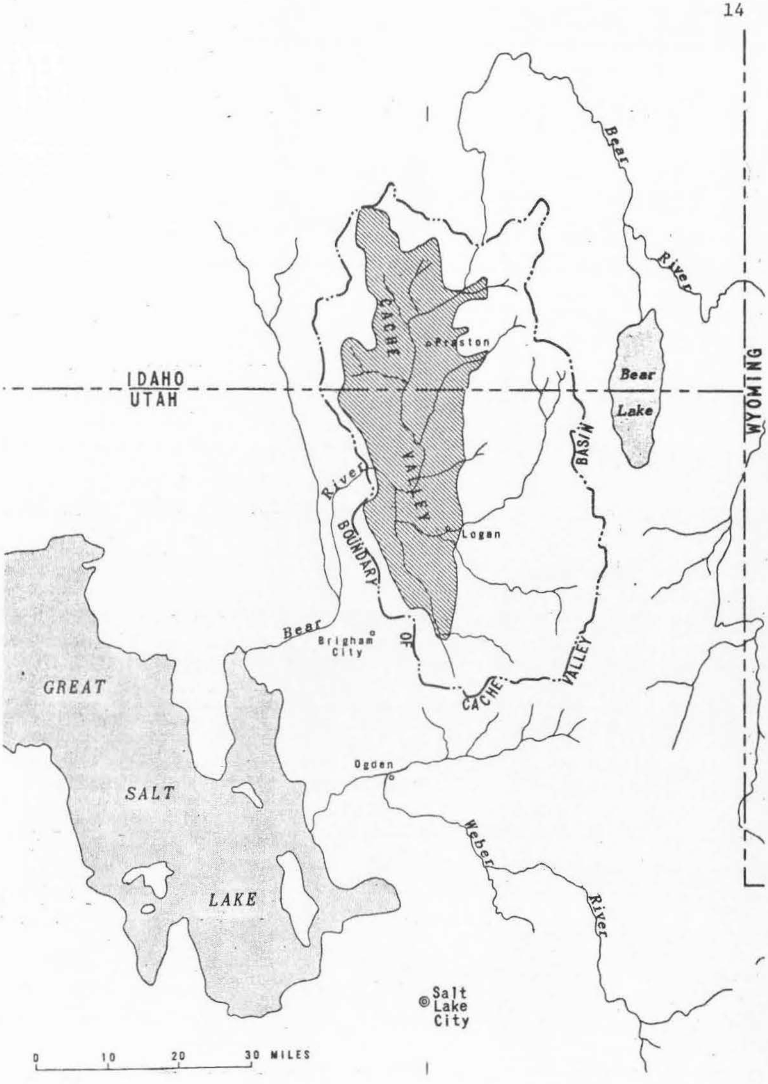

Figure 7. Study area location map.

valley. A large number of people that live within the valley commute to employment outside of the valley. As in the past, the probable future population growth will come from small industry work forces and commuting workers that will settle in the valley.

Methodology

Rather than making site-specific studies, the problem of ground failures caused by liquefaction has been approached in this study from a more general method of analysis covering a large area. This method of identifying liquefaction susceptible areas on a large scale was first proposed by Youd and Perkins (1977). Their procedure combines two base maps into one map that describes the liquefaction potential of a given area.

First, a geologic map showing the soil deposits in the study area is used. Consideration is given to the different types of soils, the method of deposition, and the age of the deposits. Each of these are contributing factors in whether or not a soil mass will liquefy. The depth to the water table is another factor that is considered. These factors are used to develop a liquefaction susceptibility map that outlines the soil deposits in the study area that are susceptible to liquefaction. There are other geotechnical factors that affect soil susceptibility to liquefaction that are not considered in this procedure. The factors mentioned above and those that are not considered are discussed in more detail in Chapters 2 and 3.

Youd and Perkins (1977) then use a second map that is based on the seismicity of the study area. They use an empirical relationship between earthquake magnitude and distance to the farthest occurrence of liquefaction in conjunction with probability concepts to develop a liquefaction opportunity map. The liquefaction susceptibility map is then combined with the liquefaction opportunity map to indicate liquefaction potential.

In this study each soil deposit on the valley floor was identified using a map prepared by Williams (1962). Each soil deposit was then examined in detail and assigned a specific liquefaction susceptibility classification. Specific data on groundwater depths were also considered in assigning the liquefaction susceptibility classification.

A companion study by Greenwood (1978) developed the liquefaction opportunity map for Cache Valley, Utah. Greenwood's study is discussed in more detail in Chapter 4 of this report.

The end result of this study is a liquefaction potential map for Cache Valley, Utah. As mentioned previously, it is only a preliminary guide and not a detailed site-specific analysis of possible ground failures caused by liquefaction.

CHAPTER 2

REVIEW OF LITERATURE

General

Liquefaction-induced ground failures caused by seismic activity are a relatively new problem. Casagrande's work in the 1930's introduced the term liquefaction as it related to slowly applied loads. The concern over cyclic loads causing liquefaction only began in the early sixties. Since that time numerous investigators have supplied answers to many questions as to what liquefaction is, what causes it, what factors influence its development, and how to alleviate or design for the problem. There has been much literature presented in the last 10 to 15 years that covers laboratory studies, case histories, and methods of analysis of the liquefaction problem. It is not the purpose of this chapter to go over all the details of these studies or even to provide a complete list of what has been accomplished. This chapter describes liquefaction and presents methods of analysis that are now being utilized, as well as several new methods of analysis that have recently been developed. This chapter provides a basis for the approach utilized in this study of liquefaction.

Definition of Liquefaction

Because of the many independent studies that have been performed on liquefaction, there have been some slight differences in definition of terms. There are two basic components to most definitions of liquefaction, a strength loss criteria and a flow deformation criteria. Youd (1975) indicates that the combining of these two distinct phenomena into one definition results in the controversy over the definition of liquefaction.

Some of the definitions that Youd (1975) used to illustrate his point are listed below.

> "The sudden decrease of shearing resistance of a quick sand from its normal value to almost zero without the aid of seepage pressure." (Terzaghi and Peck, 1948).

> "The sudden large decrease of shearing resistance of a cohesionless soil, caused by a collapse of the structure by shock or strain, and associated with a sudden but temporary increase of the pore fluid pressure [is liquefaction]. It involves a temporary transformation of the material into a fluid mass." (ASCE, 1958), (American Geological Institute, 1972).

> "The phenomenon of the loss of strength of saturated granular soils during earthquakes is generally referred to as liquefaction. The process of liquefaction transforms an element of soil from a state of saturated granular solid to a state of viscous fluid." (Ghaboussi and Wilson, 1973).

> "A phenomenon in which a cohesionless soil loses strength during an earthquake and acquires a degree of mobility sufficient to permit movements from several feet to several thousand feet." (Seed and Idriss, 1971).

> "Complete liquefaction - when a soil exhibits no resistance (or negligible resistance) to deformation over a wide strain range, say a double amplitude of 20 percent."

> "Partial liquefaction - when a soil first exhibits any degree of partial liquefaction during cyclic loading."

> "Initial liquefaction - when a soil first exhibits any degree of partial liquefaction during cyclic loading." (Lee and Seed, 1967).

"The conventional use of the term [liquefaction] as it will be used throughout this thesis, refers to the phenomenon which takes place in a mass of soil during flow slides. Liquefaction or flow failure of a sand is caused by a substantial reduction of its shear strength." (Castro, 1969).

The first five definitions refer to liquefaction as the loss of shear strength of the soil mass. The last definition by Castro refers to flow failures or deformations as liquefaction that results from the soil losing its shear strength.

The actual controversy results in how much deformation constitutes liquefaction. Seed and Idriss (1971) and Lee and Seed (1967) seem to indicate that any flow deformation of the soil mass constitutes a liquefaction condition. However, Castro (1969) and Casagrande (1976) feel that the term liquefaction should refer to a condition of unlimited flow and that cyclic mobility should refer to the condition where the deformation is arrested by a pore pressure reduction. The pore pressure reduction results from soil dilatancy.

It would seem that the differences are only slight and that the basic phenomena is the same in both cases. In fact, in his state-of-the-art address, Seed (1976) notes these similarities and proposes the terms "initial liquefaction with limited strain potential" or "cyclic liquefaction" [cyclic mobility] to refer to the condition where limited strains, caused by liquefaction, are exhibited in a soil mass. This suggestion would seem to eliminate the controversy and help all concerned to understand the basic mechanism.

Youd (1975) also answers the controversy with the following definition:

> "Liquefaction is defined as the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore water pressures. Solidification is defined as the opposite process, that is, the transformation of a granular material from a liquefied state into a solid state. Once liquefied, a granular material is free to flow, until solidification occurs. If solidification occurs after a finite flow deformation, the condition is termed limited flow. If flow continues unbated under constant total stress, the condition is termed unlimited flow."

In his definition, Youd accounts for both liquefaction and initial liquefaction with limited strain potential in a manner similar to Seed (1976).

Definition for this study

The definition of liquefaction that is used in this study is: the transformation of a soil mass from a solid state to a liquefied state. The resulting deformations have to be of sufficient magnitude to cause failure at the ground surface. The transformation from a solid to liquefied state is the result of an increase in the pore water pressures caused by the cyclic loading of an earthquake.

Mechanism of Liquefaction

The basic cause of liquefaction is fairly well understood and accepted. When an earthquake occurs it creates shock waves in the bedrock that radiate away from the source in all directions. At a particular site when the bedrock is excited by these shock waves the soil profile above the rock is set into motion. Shear waves propagate up through the soil profile from the bedrock to the surface as shown on Figure 8. The shear waves cause cyclic shearing stresses to develop within the soil mass which leads to the problem of liquefaction.

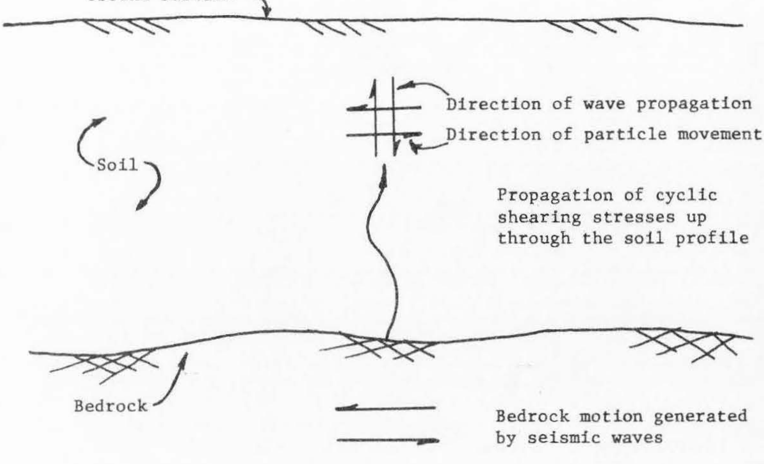

Figure 8. Sketch illustrating propagation of cyclic shearing stress through the soil profile.

If a saturated granular soil mass is subjected to these shear waves, under undrained conditions, a build-up of excess hydrostatic pore pressure develops. Seed (1976) indicates that this build-up of pore pressure results from two interacting mechanisms. As the cohesionless soil mass is subjected to cyclic loading there is a tendency for the structure of the soil to change and to decrease in volume. As the soil is trying to compact, the load is transferred to the pore fluid which results in a build-up in pore pressures under undrained conditions.

The other mechanism that is associated with the build-up of pore pressures is the soil structure rebound. As the load is transferred to the pore fluid the structure exhibits an elastic rebound due to the load release. The structure will rebound enough to maintain a constant volume within the soil system. The combination of the volume decrease, due to cyclic loading, and the soil rebound, due to load release, determines the amount of excess pressure that is generated.

Figure 9 shows a diagram that Seed (1976) used to illustrate this point. Point A on the void ratio vs log of pressure compression curve is the existing effective pressure on the soil element. As the soil element is subjected to a cyclic shearing stress the soil tends to compact to point B. Associated with the cyclic loading and soil compacting is the transfer of load to the pore fluid. As the load is released from the soil structure the soil will tend to rebound along a rebound curve to point C. Under a drained condition the cyclic loading would cause an effect of moving from point A to point B with a net volume decrease. Under undrained conditions, where no volume change can take place, the

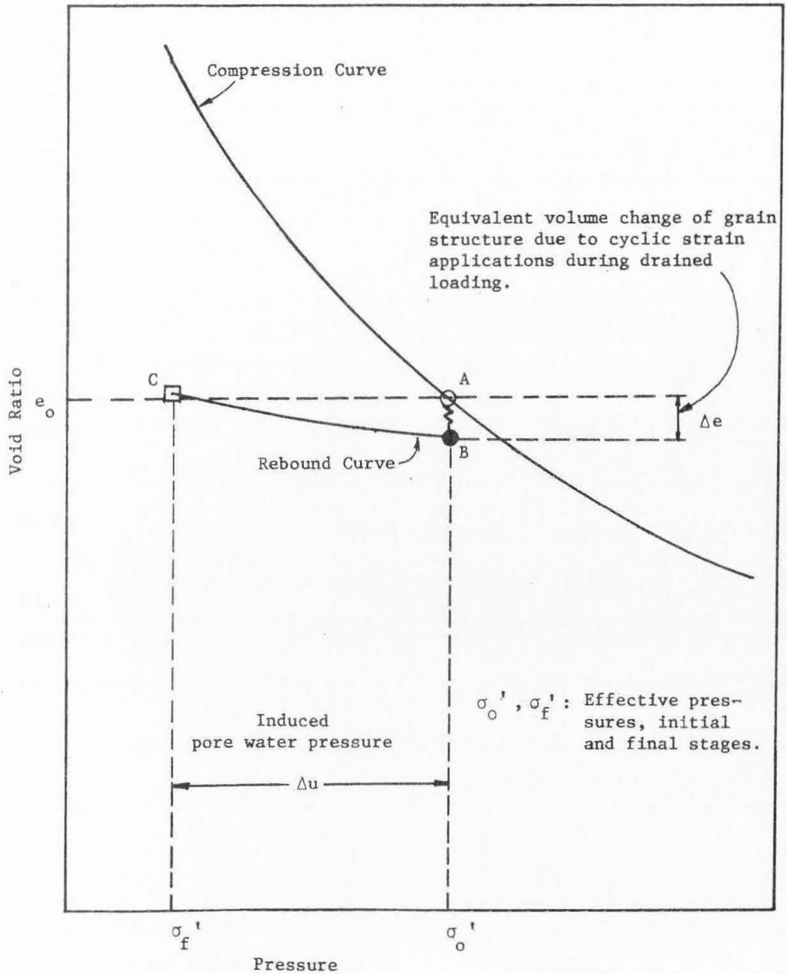

Figure 9. Schematic illustration of mechanism of pore pressure generation during cyclic loading (after Seed, 1976).

net effect is moving from point A to point C with a build-up of pore pressure. The net change in pore pressure is determined from the initial and final effective stresses on the soil element.

If the build-up of pore pressure reaches the value of the initial effective confining pressure then the soil will fail or liquefy. At this point all resistance to deformations have been overcome and the soil will deform under the applied loads. The amount of deformation will depend on the density-state of the soil mass. If the soil is in a loose condition then the deformations could be unlimited. However, if the soil is in a medium to dense state then the soil will begin to dilate. When dilation occurs the pore pressures are reduced and continued deformation is arrested.

This is not the only description of the liquefaction mechanism, but it includes the basic ideas on pore pressure build-up, loss of strength, and flow deformation. These are the main items listed in the definitions of liquefaction mentioned previously.

Factors Affecting Liquefaction

General

When determining the liquefaction potential of a soil profile there are usually two problems that are considered. The first problem is what magnitude of shearing stresses will be induced in the soil profile as a result of an earthquake. The magnitude of induced shearing stresses is a function of the seismic parameters used in the analysis. The second problem is determining the magnitude of cyclic shearing stresses that is required to cause liquefaction in the soil profile. The magnitude of required shearing stresses is dependent on soil properties. The effect that different parameters have on the induced shearing stresses and the required shearing stresses are discussed in more detail below.

Induced shearing stresses-seismic parameters

General. The fact that a seismic event can cause liquefaction was pointed out earlier and examples were cited to illustrate the problem. The main factors from an earthquake that are generally considered in determining induced shearing stresses are listed below.

- Intensity of ground shaking
- Duration of ground shaking
- Magnitude-distance relationship (intensity related)

Not all studies agree on the same seismic parameters to be used in a liquefaction analysis. But some form or combination of the parameters listed above are contained in almost every method of analysis.

The most common combination of seismic parameters is intensity and duration of ground shaking. These two factors are listed in analysis procedures and case studies by many investigators as the principal seismic parameters (Seed and Idriss, 1971), (Kishida, 1970), (Lee, 1971), (Seed, 1976), (Ferritto, 1977), (Christian and Swiger, 1975). The last parameter, the magnitude-distance relationship, has been used in place of intensity and duration by other investigators. Kuribayashi and Tatsuoka (1975), Yegian and Whitman (1977), and Youd and Perkins (1977) all list this parameter as the basic seismic factor that influences the liquefaction analysis. Greenwood (1978), in a study patterned after the work of Youd and Perkins, also utilized this parameter in his analysis. Greenwood's results have been combined into this study. The importance of each of these parameters is discussed below.

Intensity of ground shaking. The intensity of ground shaking or ground surface acceleration governs the magnitude of the shearing stresses that are applied to the soil elements (Seed and Idriss, 1971). The higher the acceleration of the soil profile the higher the shearing stresses that will be induced. Liquefaction will occur faster from a high intensity of ground acceleration than from a low intensity of ground acceleration. In fact, a certain threshold acceleration is required to even cause liquefaction.

Ground surface accelerations have been related to magnitude of energy release and distance to causitive source by Housner (1964). This type of relationship uses empirical data to relate the intensity of ground shaking to the amount of energy released. However, Housner (1964) also indicates that the best method to arrive at the intensity of ground acceleration is to measure it with instruments near a seismic source, not from magnitude-distance relationships.

Because there are only a few recorded acceleration histories, some studies have used the magnitude of earthquakes and distances to causitive sources as their parameters instead of the estimated ground acceleration values. There are more data on earthquake magnitudes than on earthquake accelerations and so the larger data base on earthquake magnitudes would provide a better solution for development of empirical relationships.

Duration of ground shaking. The duration of intense ground shaking has a significant effect on the possibility of liquefaction. It takes time for the pore pressures to build up large enough to overcome the confining pressure and reduce the soils's resistance to deformation. If the duration of strong shaking is not long enough then liquefaction cannot develop and cause ground failure. This has been pointed out by Seed and Wilson (1967) in their analysis of the Turnagain Heights Landslide in the 1964 Alaskan Earthquake. Reports indicated that the slide started approximately 90 seconds after the earthquake began. Therefore, if the earthquake had only lasted 45 seconds the slide probably would not have occurred (Seed and Wilson, 1967).

The duration of ground shaking is usually characterized by the equivalent number of significant stress cycles (Seed and Idriss, 1971), (Lee and Chan, 1972). An earthquake produces erratic stress cycles of varying frequencies and magnitudes. These cycles are hard to use in an analysis procedure because of their non-uniform nature. As a result, a procedure was developed where the effects of the significant earthquake cycles were simulated by a certain number of uniform stress cycles (equivalent number of significant stress cycles). Each uniform stress cycle requires a certain amount of time to oscillate and so the duration of strong ground shaking is determined by the number of uniform cycles that are applied to the soil. The equivalent number of significant stress cycles is used extensively in laboratory work to simulate earthquake conditions.

Magnitude-distance relationship. The magnitude of the earthquake and the distance from a particular site to the causitive source of the earthquake seem to be obvious factors that influence the potential of liquefaction. Seismic waves are attenuated the farther they travel, so that at some distance from the source they have little affect on the bedrock or soil profile. The distance that the seismic waves travel is dependent on the amount of energy released (magnitude) during the earthquake.

Magnitude-distance relationships have been used by different studies as mentioned before and are usually based on empirical data. The magnitude-distance relationship used by Greenwood (1978) to develop his opportunity map was proposed by Youd and Perkins (1977) and is a lower bound envelope for magnitude versus the distance to sites where liquefaction has occurred.

Required shearing stresses-geotechnical parameters

General. The potential of liquefaction not only depends on the seismic activity of a region, but also on the conditions within a soil deposit. Many soil deposits will not liquefy regardless of the magnitude and duration of the cyclic shearing stresses that are applied to the soil. The main factors that are considered to influence a soil deposit's resistance to liquefaction are listed below.

- Soil type
- Density state
- Initial confining pressures
- Soil structure (method of deposition)

- Age of deposit
- Depth to groundwater
- Seismic history

Some of the above governing factors such as soil type, density, initial confining pressure, and depth to groundwater are fairly well understood. Their affect on the liquefaction mechanism can be recognized and quantified. The other factors have been recognized as having some affect on the liquefaction mechanism, but they are not fully understood. Each of these factors are discussed in more detail below.

Soil type. Soil type has been established as one of the main contributing factors to liquefaction. Many studies and investigations have pointed to the grain size distribution curves of the soils involved as a major factor in evaluating liquefaction potential. Fine uniformly-graded sands are cited as the most susceptible to liquefaction. However, there is a range from large silt particles to medium coarse sands that could be classified as very susceptible to liquefaction. This range of particle sizes seems to allow the build-up of excess pore pressures more readily than any other grain size distribution.

Coarse grain sands and gravelly deposits have experienced some cases of liquefaction, but in general have a higher resistance to liquefaction than the finer sands (Wong, Seed, and Chan, 1975) (Ross, Seed, and Migliaccio, 1969). The reason given for this is the rapid dissipation of excess pore pressures. Gravelly deposits allow the excess pore pressures to dissipate so rapidly that they do build up to the effective confining pressures and cause failure (Wong, Seed, and Chan, 1975).

Fine grained soils such as clays and plastic silts have not been found to liquefy . This is probably attributed to the cohesion that these soils exhibit.

A new development, even for fine grained sands, is the grain characteristics of the sand. Several studies (Annaki, 1975), (Castro and Paulos, 1976) have shown that different types of sands with essentially the same grain size curves, compacted to the same relative density, and compacted with the same compaction methods, differ as to their liquefaction susceptibilities. This phenomenon is not completely understood as to what causes the observed differences, but is probably related to grain shape.

Density state. Relative density has long been recognized as a major factor affecting the liquefaction potential of a deposit. If a deposit is in a relatively loose condition, low relative density, liquefaction can be initiated by lower shearing stresses or shorter durations than if the deposit is at a higher relative density. There have been many studies that have taken this factor into account and have found the same conclusion; deposits at lower relative densities are more susceptible to liquefaction than deposits at higher relative densities. DeAlba, Chan, and Seed (1975) give convincing evidence of this fact.

Another difference between a loose deposit and a dense deposit is the amount of deformation that will occur once the soil has initially lost its strength. A loose deposit could flow or deform an unlimited amount, but a dense deposit will develop additional resistance due to the dilatancy effects mentioned earlier. If the soil dilates then it will undergo only a limited amount of deformation.

Initial confining pressures. The confining pressure that a soil element is under is of significant importance in determining its liquefaction potential. The higher the effective confining pressures the higher the excess pore pressures need to be to overcome the strength of the soil that prevents deformation.

As far as the overburden pressure is concerned, the deeper the deposit is the higher the overburden pressure and the more resistant the soil becomes. However, the past geologic history of a deposit is what affects the lateral earth pressures. If a deposit has been subjected to higher overburden pressures than now exists on the deposit, it has been overconsolidated to some degree. By increasing the overconsolidation ratio (ratio of highest past overburden pressure to present overburden pressure), an increase in lateral earth pressure is also produced. The result of increasing the lateral pressure is the same as increasing the overburden pressure, a more resistant soil deposit against liquefaction. The effects of increasing the value of the lateral earth pressure coefficient, K_o, have been mentioned in many laboratory studies. Seed and Peacock (1971) show that as K_o is increased the resistance to liquefaction is also increased.

The parameter that many laboratory studies base their results on is the cyclic stress ratio. The cyclic stress ratio is the ratio of the shearing stress that is required to cause liquefaction to the effective confining stress on the sample. The cyclic stress ratio is usually plotted versus the number of equivalent uniform stress cycles that is required to cause liquefaction. The shearing stress is proportionate to the confining stress so the cyclic stress ratio provides a convenient dimensionless parameter that includes two factors that influence the liquefaction characteristics of a soil deposit.

Soil structure (method of deposition). Soil structure and the effect that it has on the liquefaction characteristics of a soil is a fairly recent finding. Mulilis, Chan, and Seed (1975) clearly show that the method in which a soil deposit has been laid down makes a difference in its liquefaction characteristics. Their report deals mainly with different methods of preparing laboratory samples, but the conclusions are easily extrapolated to field conditions. This means that a cohesionless deposit probably will have different potentials for liquefaction depending on whether it was deposited by fluvial deposition, direct sedimentation, or by eolian deposition. Each soil structure would be different and would produce different susceptibilities to liquefaction.

The exact nature of what the soil structure does to alter liquefaction potential is not completely understood. It is therefore hard to quantify and to indicate how the soil structure could be considered in an analysis procedure.

Age of deposit. The length of time that a soil deposit has been in place also has an effect on its liquefaction characteristics. The older a soil deposit is the less chance there seems to be that it will liquefy. Holocene (recent) and late Pleistocene deposits are cited as the most likely deposits to liquefy. This conclusion is based on numerous case studies that determined the age of deposits that were known to liquefy during a seismic event (Youd and Hoose, 1977), (Youd and Perkins, 1977). Recent laboratory studies have also shown that the longer a sample is allowed to sit before testing, the more resistant the sample becomes to liquefaction. Lee (1975) indicates that this increase in resistance might be the result of cementation between the contact points of sand grains, or the development of a more stable structure resulting from secondary compression.

Depth to groundwater. The depth to the groundwater plays a major role in liquefaction susceptibility. If a soil deposit is not saturated then it is impossible to develop excess hydrostatic pore pressures. Partially saturated soils do not develop positive excess pore pressures. If excess pore pressures do not develop, then liquefaction of a soil deposit will not occur.

The depth to the water table also affects the confining pressure on the soil elements. The higher the water level in the soil profile, the lower will be the effective confining pressures at any depth below the water level. This indicates that a high water table in a soil deposit not only saturates the deposit, making liquefaction possible, but also reduces the effective pressures on the soil elements below the water level. If the effective confining pressures are reduced on the soil elements then the deposit is more susceptible to liquefaction.

Seismic history. Seismic or strain history, although not completely understood, has a significant effect on the susceptibility of a soil deposit to liquefaction. Seed, Mori, and Chan (1977) state that this change in liquefaction susceptibility could possibly result from a volume change during previous earthquakes that changes the pore pressure build-up mechanism. The effects were first presented by Finn, Bransby, and Pickering (1970), but other studies since then have shown some of the same results (Seed, Mori and Chan, 1977), (Lee and Focht, 1975). The result of prestraining a deposit or sample of soil is to increase the resistance of the soil to liquefaction. A series of seismic events in the field will strengthen a deposit so that if an event of larger magnitude were to occur the deposit would have more resistance to liquefaction. The important point to note is that prior straining or prior seismic events, that do not produce liquefaction, can make the deposit more resistant to further liquefaction. Once the deposit has liquefied, however, then it becomes more susceptible, not more resistant, to liquefaction when future straining occurs. The soil deposit is disturbed upon reaching liquefaction and any strengthening effects from cementation, prior strain history, or grain structure are lost. There have been reports where re-liquefaction has occurred in the field after sufficient ground shaking was induced by a subsequent earthquake (Youd and Hoose, 1976), (Kuribayashi and Tatsuoka, 1975). In these situations the prior seismic history had a deteriorating effect on the soil deposit's resistance to liquefaction.

When all of the factors discussed above are taken into account the liquefaction problem becomes quite complex. At the present state-of-the-art all of these factors cannot be considered in a quantitative manner. More research on how some of the factors actually affect the liquefaction characteristics of a soil deposit will be needed before a complete solution to the problem can be formulated.

Methods of Analysis

General

With all the information now being generated concerning liquefaction some authors have attempted to form a rational method of analysis. These different methods are based on what the various authors feel are the most important parameters to include. They refer to the seismic and geotechnical factors that have been discussed earlier. No one method is clearly better, nor has one method been universally accepted. Some methods might be used more than others, but it is generally because they have been in existence longer.

Simplified method

One of the first practical methods of evaluating liquefaction potential was developed by Seed and Idriss (1971). This method takes the complex mechanism of liquefaction and makes some simplifying assumptions in creating a simple procedure for evaluating the liquefaction potential for a given site. The basic premise is to compare the cyclic stresses that an earthquake will cause in a soil profile to the cyclic stresses that are required to cause liquefaction in that same profile, see Figure 10. The overlap region on the figure is the area of concern.

The stresses that are induced by an earthquake are estimated by a simplified equation of the form,

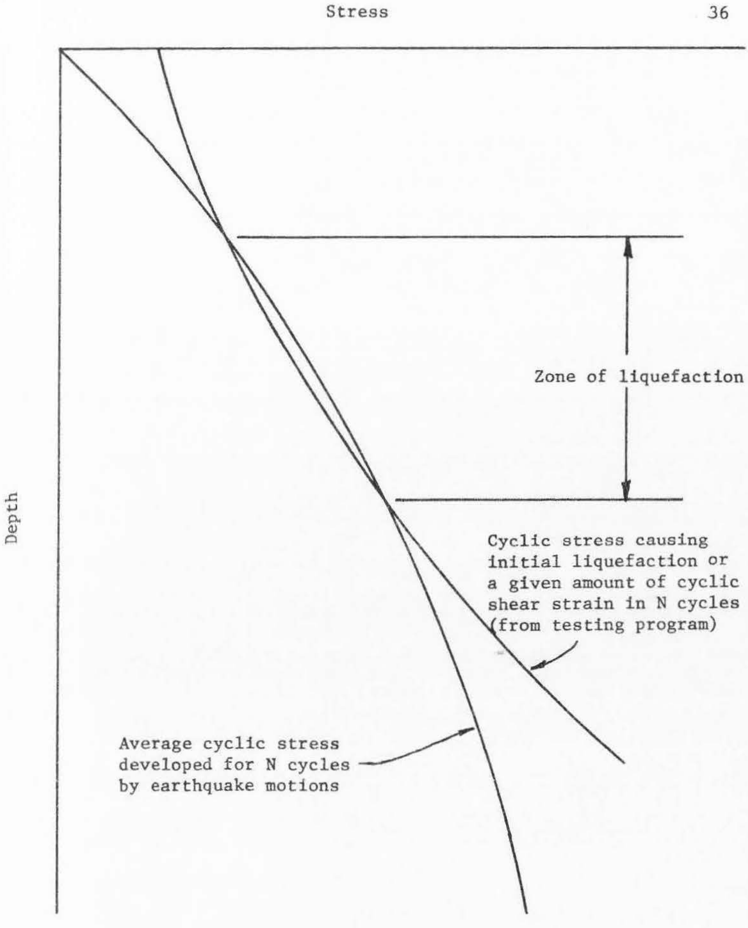

Figure 10. Method of evaluating liquefaction potential (after Seed and Idriss, 1971).

$$\tau_{ave} \cong 0.65 \frac{\gamma h}{g} a_{max} r_d \tag{1}$$

τ_{ave} - the average shearing stress caused by the earthquake

γ - unit weight of soil

h - depth to the soil element

g - acceleration of gravity

a_{max} - maximum ground surface acceleration

r_d - stress reduction coefficient

The average shearing stress is based on the amount of stress that will be realized beneath a rigid column of soil at a depth h. The stress reduction coefficient, r_d, is used because the soil column is not truly rigid. The multiplier is an assumption that the average stress is 65% of the maximum stress induced by the irregular stress history. This figure is based on numerous calculations of equivalent uniform shearing stresses for different stress histories.

The duration of ground shaking is accounted for by adjusting the number of equivalent uniform cycles that are assumed to be applied to the soil profile by the earthquake. The assumed number of cycles depends on the earthquake magnitude.

Shearing stresses that are required to cause liquefaction in the soil profile are usually determined on the basis of laboratory tests. Dynamic triaxial shearing tests are usually run to determine the cyclic stress ratio required to cause liquefaction in a given number of cycles and at a given relative density. The stress ratio also depends on the mean grain size diameter, D_{50}.

If dynamic tests are not performed, then a cyclic stress ratio can be estimated for a given D_{50} value, at a given relative density, and at a given number of uniform stress cycles from dynamic test data run on other samples (Seed and Idriss, 1971). The form of the equation used for estimating stresses required to cause liquefaction is,

$$\left(\frac{\tau}{\sigma_o'}\right)_{\ell D_r} \cong \left(\frac{\sigma_{dc}}{2\sigma_a}\right)_{\ell D_r'} c_r \frac{D_r}{D_r'} \qquad (2)$$

$\left(\frac{\tau}{\sigma_o'}\right)_{\ell D_r}$ - cyclic stress ratio causing liquefaction at a relative density of D_r

$\left(\frac{\sigma_{dc}}{2\sigma_a}\right)_{\ell D_r'}$ - ratio of the deviator stress to the initial ambient pressure that causes liquefaction at a relative density equal to D_r', from dynamic triaxial tests

c_r - correction factor to correct triaxial data to field conditions

$\frac{D_r}{D_r'}$ - relative density ratio, to change data from a relative density of D_r' to a relative density of D_r.

This form of the equation is good for relative densities up to 80%.

If the average shearing stress, τ_{ave}, from Equation 1 is set equal to the shearing stress, τ, from Equation 2, then the maximum acceleration a_{max} can be solved for. Both equations must be for the same number of shearing stress cycles. The value of a_{max} can be plotted versus the value of D_r for that set of data. Different relative densities can be used to arrive at different values of a_{max}. The plot forms a boundary between liquefaction and non-liquefaction conditions. An example of this type of plot is shown in Figure 11.

This type of analysis gives a simple procedure in evaluating liquefaction potential. The same procedure could be followed on a more rigorous basis if no short cuts were taken. The average shearing stresses induced by an earthquake would come from a ground response analysis and the shearing stresses causing liquefaction would be received from actual dynamic tests on samples from the deposit.

Empirical methods

Another method that is becoming widely known is presented in its most recent form by Seed, Mori, and Chan (1977). This method is based on empirical data of sites that have been studied where liquefaction has or has not occurred. The cyclic stress ratio causing liquefaction was plotted versus blow count data from the standard penetration test, corrected to an effective overburden pressure of 1 T.S.F. A lower bound curve was established that separates the liquefaction conditions from the non-liquefaction conditions, see Figure 12.

To use the figure the cyclic stress ratio must be determined. First, the shearing stresses that would be created in a soil profile by an earthquake need to be predicted. This can be accomplished by the use of Equation 1 as given for the simplified procedure for evaluating soil liquefaction potential. Then, the initial effective confining stress used to form the ratio can be determined from boring data taken at the

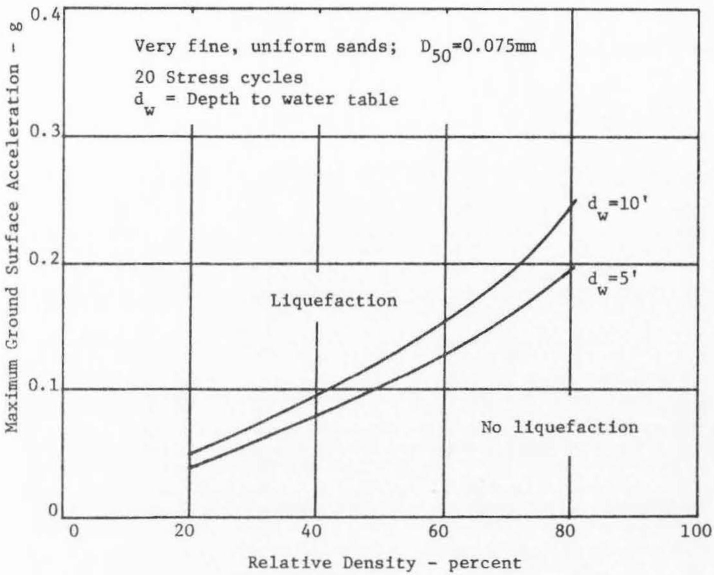

Figure 11. Evaluation of liquefaction potential for very fine sand--20 stress cycles (after Seed and Idriss, 1971).

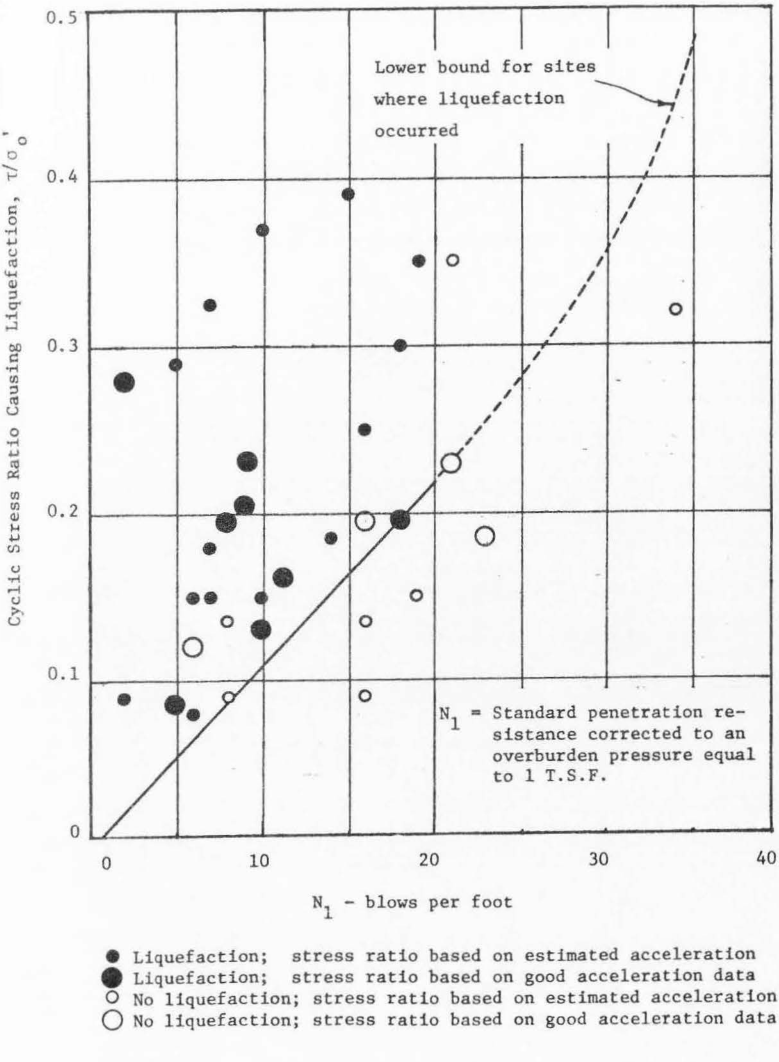

Figure 12. Correlation between stress ratio causing liquefaction in the field and penetration resistance of sand (after Seed, Mori, and Chan, 1977).

site. The ratio of the shearing stress to the initial confining stress is plotted on the chart versus the corrected blow count, also obtained from boring data. If the point is above the boundary line, then liquefaction is a possibility. If the point plots below the line, then liquefaction probably will not develop. If the point plots close to the line, on either side, then a closer look at the data using a different more detailed method of analysis is probably justified. This type of approach could be used to pick out the sites and profile layers that might need more attention.

Whitman (1971) presented a method very similar to the above empirical method. He also used data from earthquakes that have caused liquefaction, as well as from a few that did not. The data that he plotted was the stress ratio versus relative density. He pointed out that the data is not sufficient to define a trend or a boundary line, but with more information on other earthquakes some type of distinction could be made between liquefiable and non-liquefiable deposits.

The main difference between Whitman's chart and Seed, Mori, and Chan's chart is the plotting of relative densities instead of blow count data. The relative densities are arrived at using standard penetration results and relationships from Gibbs and Holtz (1957). However, it is probably more appropriate to plot the standard penetration results rather than the relative densities. The blow count data in some ways accounts for more of the factors that influence a soil's liquefaction potential than does relative density alone. As the factors such as relative density, soil particle cementation, lateral earth pressure, and prior seismic histories affect liquefaction potential they similarly affect blow count data. It is, therefore, postulated that the blow count data gives a better representation of true strength resulting from many influencing factors and not just one (Seed, Mori, and Chan, 1977).

Probabilistic and statistical methods

Some of the most recent approaches to the problem contain concepts of statistics and probability analysis. Christian and Swiger (1975) presented a statistical approach that involves the apparent relative densities and ground accelerations at sites where liquefaction did and did not occur during an earthquake. The basic data was used in a statistical analysis that determined whether the soil would fit into a liquefiable or non-liquefiable category. Confidence levels or proability levels were also included within the analysis to determine how good their procedure was. It was pointed out that their probability levels were not the probability of liquefaction, but the level of confidence in their dividing lines between liquefiable and non-liquefiable sites.

Yegian and Whitman (1977) presented a method of analysis based on a probabilistic model. They developed a parameter in their analysis that is basically the ratio of the induced cyclic shearing stress to the available strength that the soil has. The basic inputs into the parameter are the magnitude of the earthquake and the hypocentral distance from the site to the causitive source. They include the liquefaction parameter in their probability model. The probability model gives the probability that a site will liquefy under any earthquake loading. This is a function of the probability that a site will liquefy given a certain magnitude earthquake and the probability of that magnitude earthquake occurring.

Youd and Perkins (1977) have also developed a procedure that is based on probability concepts. The technique develops a liquefaction potential map that gives the relative possibilities of a site developing liquefaction. The potential map is a combination of two base maps, a susceptibility map and an opportunity map. The susceptibility map outlines the soil deposits within a study area that are most likely to liquefy. The factors that were used to classify the susceptibility of each deposit were the soil type of the deposit, mainly grain size distribution, and the age of the deposit. A general statement concerning water table depth was also considered in their analysis.

A liquefaction opportunity map provided the seismicity of the study area. The seismicity was determined from the seismic history of the study area. Using the seismic data and a magnitude-distance relationship, a contour map showing the return periods of earthquakes large enough to cause liquefaction was developed. The development of the return period contours were based on concepts from probability analysis.

The final potential map was the combinationof the susceptibility and opportunity maps. This type of analysis is a preliminary guide for a given study area. It is not intended to be used as a site-specific analysis that could be included in design calculations. It can, however, help in planning and site location decisions.

Other methods

Two other methods that do not fit into the other categories are presented by Donovan (1971) and Ghaboussi and Dikmen (1978). Donovan (1971) presented a method referred to as a cumulative damage approach. The method makes use of Miner's damage equation and sums up the damage caused to the soil structure by the cyclic loading of an earthquake. This is analagous to the fatigue failure in structures. A factor of safety is determined to indicate liquefaction or no liquefaction at a particular site.

Ghaboussi and Dikmen (1978) presented a procedure that models the soil profile as a two-phase fluid-solid system. The method is based on the equations of motion of a lumped mass system. The solution of the equations of motion include the non-linear properties of the soil and two separate types of damping. Pore pressure distribution is monitored at different depths by the equations of motion to determine when and where liquefaction will occur.

CHAPTER 3

LIQUEFACTION SUSCEPTIBILITY MAP

General

A liquefaction susceptibility map was developed for utilization in determining liquefaction potential. It supplies important information on the conditions of soil deposits in an area and the relative susceptibility that they have for liquefaction. The only factors considered in the development of the liquefaction susceptibility map are the geotechnical related properties of the soil deposits.

Geologic Setting

Location and structure of Cache Valley

Cache Valley is a long narrow basin that lies on the border between Northeast Utah and Southeast Idaho. The valley is approximately 60 miles long and 8-16 miles wide. However, the study area described in this study only includes the Utah portion of the valley. This covers approximately 35 miles from the state border to the southern end of the valley. Approximately 365 square miles are contained in the Utah section. The valley floor is surrounded by mountains on all sides. The Bear River Range is to the east, the South Hills to the south, the Wasatch, Bannock, and Malad Ranges line the west side, and the Portneuf Range bounds the north end in Idaho.

Green (1977) describes Cache Valley and the surrounding mountains as a complex horst and graben structure that is typical of the Basin and Range physiographic province that Cache Valley is located in. The valley floor is bounded by high angle faults on both sides and is the down thrown block between two uplifted blocks. The maximum vertical displacement is approximately 10,000 feet (Bjorklund and McGreevy, 1971). The base of the valley floor is Cenozoic age rock that is covered by hundreds of feet of lacustrine deposits left by an ancient Pleistocene period lake.

Fault systems

Cache Valley lies in a seismically active region that is part of the intermountain seismic belt. Fault systems that are within the valley and close to the valley are the main sources of this seismic activity.

Greenwood (1978) identifies and explains the major seismic sources that could affect the Cache Valley region. He lists four fault systems and one seismic area that could possibly cause an earthquake that would severely shake the Cache Valley area.

The major source that he lists is the Wasatch Fault system. This system is approximately 215 miles long. It has been listed as seismically active by Cluff, Glass, and Brogan (1974).

The next two important seismic systems lie on the east and west boundaries of the valley floor. The East and West Cache fault systems are 70 and 55 miles long, respectively. Both systems are considered to be recently active (Cluff, Glass, and Brogan, 1974).

The Hansel Valley fault system lies to the west of Cache Valley at the north end of the Great Salt Lake. This system extends into Idaho approximately 36 miles.

A seismic area that lies northeast of Cache Valley is also outlined in Greenwood's study. Greenwood refers to this area as the Bear Lake-Caribou seismic area. For the purpose of his study, Greenwood grouped the faults within the area into the category of a seismic source area. It is estimated to cover some 60 miles extending north from the north end of Bear Lake into Idaho. The locations of these seismic sources are shown on Figure 13.

Soil deposition

The soil deposits on the floor of the valley are mainly the sediment deposits from an ancient lake that once covered the entire valley. Lake Bonneville was an Ice Age lake that occupied parts of Utah, Idaho, and Nevada for an unknown period in the Pleistocene Epoch (Williams, 1958). The lake is believed to have risen to three different highwater elevations on three separate occasions. The first rising of the lake was to an elevation of 5100 feet. The lake then receded and possibly even withdrew from Cache Valley all together before rising the second time to the 5135 foot elevation known as the Bonneville level of the lake. At this level an outlet began to be cut in the basin rim in the north end of Cache Valley, at Red Rock Pass. This is where the lake drained until a recession of the lake occurred again. The third rising of the lake reached the base of the Red Rock Pass outlet at the 4770 foot elevation

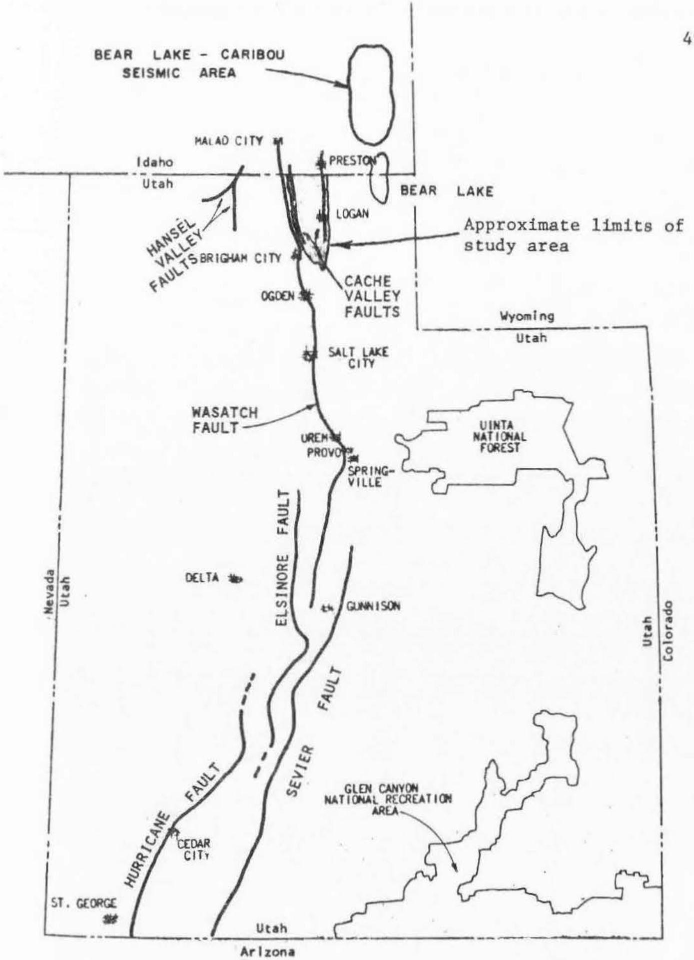

Figure 13. Location of seismic sources (after Cluff, Glass, and Brogan, 1974; Greenwood, 1978).

known as the Provo level (Williams, 1958). The lake has not risen much higher than the present level of the Great Salt Lake, the remnant of Lake Bonneville, for thousands of years.

Soil particle sedimentation when the lake was at the Bonneville and Provo levels was the main source of soil deposits in Cache Valley. The rivers that flowed from the mountains into the lake transported soil particles into the environments of the lake. As these particles were moved back and forth by the lake action they formed the different soil deposits as they settled out of suspension.

The formations from the Bonneville level are only visible on the higher bench areas that surround the valley. They consist mainly of gravels, sands, and silts. There are numerous gravel pockets spread along the sides of the valley floor where the floor of the valley intersects the mountains. These gravel pits that are higher than the Provo level were deposited during the Bonneville level of the lake.

On the valley floor the Bonneville formations are overlaid by the sediments from the Provo level of the lake. Provo formations are the predominant deposits from the Lake Bonneville time period. The Provo deposits are grouped into two members, the gravel and sand members and the silt and clay members. These two groups extend over a large percentage of the valley floor and are still visible in the valley today (Williams, 1962).

A typical cross-section of the valley was presented by Williams (1962) to show the relative depths of the lake formations and is shown on Figure 14. The relative location of the faults are also shown on this cross-section.

Another geologic process that was connected with the lake has also accounted for some of the soil deposits on the valley floor. When Lake Bonneville was at the Provo level the five major rivers and streams that entered the lake formed deltaic deposits at their entrances into the lake. When the lake began to recede these gravel and sand deposits were reworked and cut into by the rivers as the rivers flowed over them towards the receding lake. The result was the formation of thin layers of sand and gravel being spread out over the silt and clay members on the valley floor. The most noticeable formations of this type are the sand and gravel members that cover the entire valley floor in the Lewiston and Cornish areas. The large delta formed during the Provo level by the Bear River was the source of this material that was later washed out over the valley.

The soil deposits have essentially remained the same since the Lake Bonneville time. No major geologic process has altered the formations from the time that the lake occupied the valley.

Soil Types

General

A soil susceptibility map shows the areas with soils that are likely to liquefy given a sufficient level of ground shaking. To liquefy the soil must be in a condition that is prone to liquefaction. One of the prime factors that determines this condition is the soil type in the

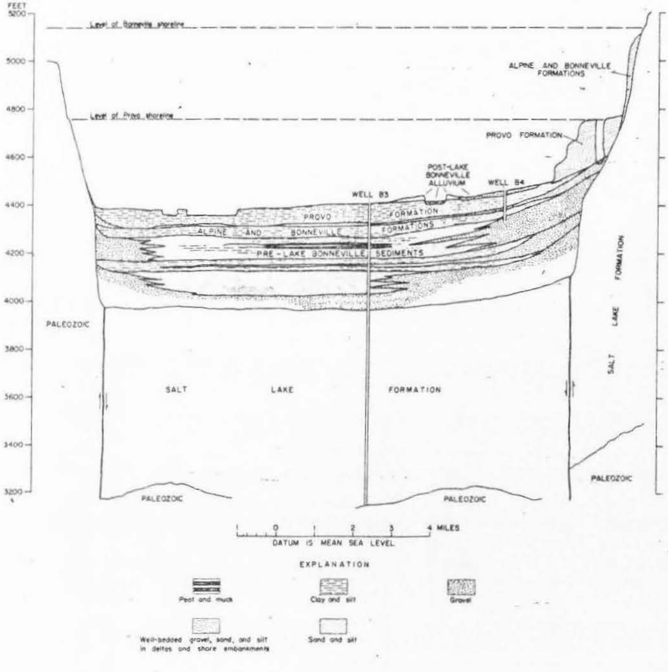

Figure 14. Diagrammatic cross section of Cache Valley from Cache Butte through Amalga and Smithfield (after Williams, 1962).

deposit. The reasons that soil type has an affect on the liquefaction characteristics have been discussed in Chapter 2. It is important to include a knowledge of soil type in a liquefaction analysis. A map showing soil deposits in Cache Valley was prepared by Williams (1962) and was utilized in this study to give the information on soil type that was required for analysis.

Williams' map

Williams (1962) presented a detailed map of the surface soils in Cache Valley showing the different geologic formations from the Tertiary and Quaternary Periods. The map was developed from extensive field work and used a planimetric base map compiled from aerial photographs for location. Figure 15 shows the map that was developed by Williams.

The Tertiary formations are exposed mainly at the higher elevations on the sides of the mountains. They extend up to the tops of the mountains and are found throughout the mountain ranges surrounding the valley.

Quaternary deposits are found everywhere covering the valley floor. Williams has identified many locations of deposits that range in age from Pre-Lake Bonneville time down to post-lake time. The latter being when the river deltas were being spread over the valley floor. The major part of the mapping was performed on the Quaternary deposits and so the most detail is exhibited in these deposits.

Because the age of a deposit affects its liquefaction characteristics, the detailed mapping of the Quaternary units was extremely helpful

Figure 15. Geologic map of Southern Cache Valley, Utah (after Williams, 1962)

Explanation

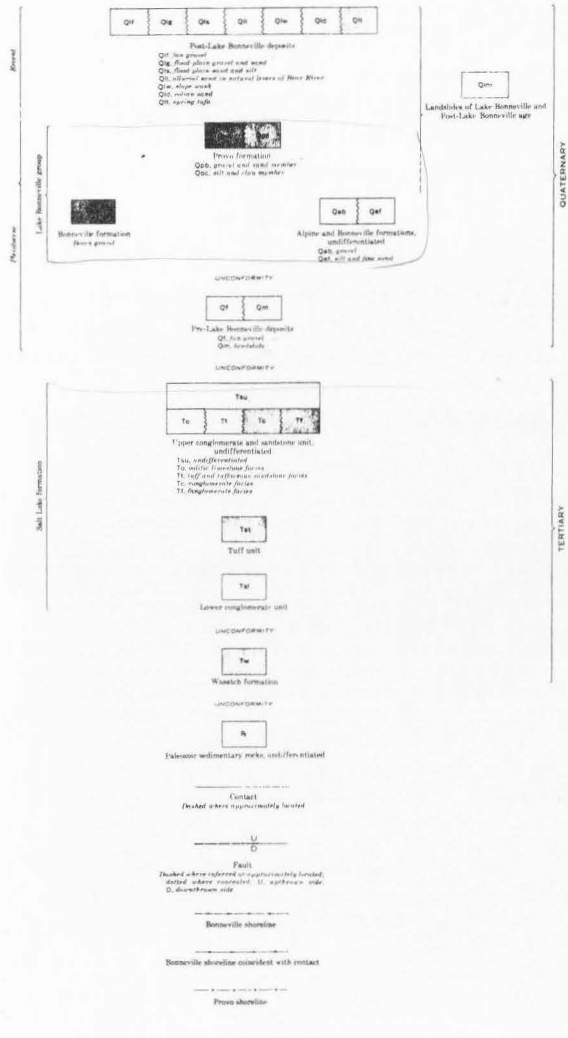

Figure 15. Continued.

in developing the susceptibility map. The fifteen different soil types that Williams identified in the Quaternary Period were classified with respect to liquefaction potential and used to produce the susceptibility map. The specific classification for each soil type is discussed later.

Some of the more important formations as far as liquefaction is concerned are the sand formations created by the spreading of the river deltas. It was indicated that the rivers washed the deltas out over the valley floor as Lake Bonneville receded from the Provo level. Williams (1978) felt that these layers of sands and gravels were relatively thin. He said that they taper from an approximate depth of 20 feet near the river channels to zero depth out at the fringes. The outer edges are where the silts and clays from the lake-bottom sediments are again exposed. These sand formations proved to be the main areas of high liquefaction susceptibility.

SCS maps

Soil maps compiled by the Soil Conservation Service and Forest Service (1974) were used as a check on Williams' (1962) soil map. These maps were compiled in a combined effort from numerous agencies that gathered the information. They provided a large amount of information on the soils in the valley down to a depth of approximately 5 feet. This information covered all fields of interest in soils, from agriculture and engineering properties to chemical analysis of the soil. These maps were used to check the soil type classification by Williams (1962). The soil deposits were assigned a certain liquefaction susceptibility using information from Williams' map, then the most susceptible areas were checked again for soil type using the Soil Conservation Service maps. This helped in assuring that misclassification of soil deposits did not occur.

Geotechnical reports

There were a few geotechnical reports at various sites within the valley that provided some information on soil deposits. Well boring logs were also examined in an effort to gain more information on soil type. These reports and well logs were used as a check on Williams' map in the same way that the Soil Conservation maps were used. However, there were only a few detailed boring logs that were available at sites in the valley to use for this purpose. Well logs were fairly general in their soil description and were few in numbers so their use was of limited value also. The use of boring data to determine soil type is one method that could be very helpful in refining classification of susceptibility to liquefaction. Detailed boring logs in a study area would give more assurance in using surface soil maps for the location of liquefaction susceptible deposits.

Groundwater

The importance of a high groundwater level and its effects on susceptibility to liquefaction have been discussed earlier. Cache Valley has a large amount of subsurface water. There have been a few studies, the most recent one by Bjorklund and McGreevy (1971), that have given a detailed picture of the groundwater resources in the valley.

Recharge of the groundwater levels in the valley are a result of infiltration by precipitation on the valley floor, seepage from the major streams and rivers, seepage from irrigation systems, and subsurface inflow from snowmelt in the mountains. Discharge of the groundwater level comes from springs, wells, seeps, drains, and evapotranspiration. There is very little subsurface outflow of groundwater. The long range level of the groundwater table has changed very little over the past 30 years as indicated by records for that period of time. This of course neglects seasonal changes in the groundwater levels. The amount of groundwater flowing into the valley is in equilibrium with that flowing out (Bjorklund and McGreevy, 1971).

Bjorklund and McGreevy (1971) also indicate that the lacustrine deposits from Lake Bonneville play a major role in the groundwater resources of the valley. There are large water bearing aquifers that are interbedded between the clay and silt layers from the lake. These aquifers are confined over some 200 square miles of the valley by additional lake deposits. The confined aquifers establish an artesian pressure condition. Hydrostatic heads as high as 62 feet have been measured in some parts of the confined aquifers. However, most heads are 40 feet or less (Bjorklund and McGreevy, 1971).

Perched water is also a condition that exists in the valley. This results from the impervious silt and clay layers laid down by Lake Bonneville that do not allow infiltrating water to percolate down to the lower groundwater level. A schematic diagram by Bjorklund and McGreevy (1971) is shown in Figure 16 and indicates how the groundwater

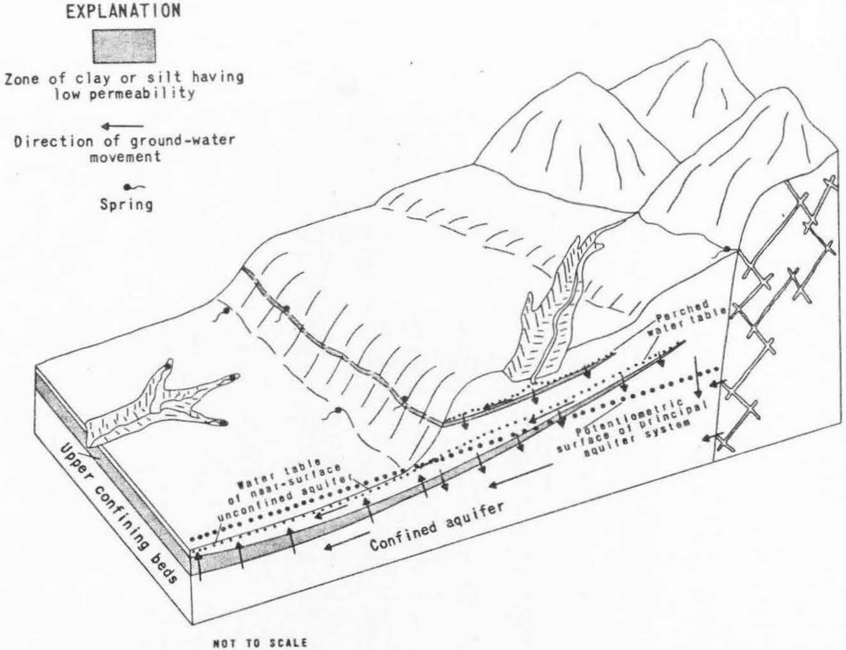

Figure 16. Relation of confined, unconfined, and perched groundwater in Cache Valley (after Bjorklund and McGreevy, 1971).

patterns are altered by the soil deposits to cause the perched water and artesian conditions.

The most useful information on groundwater in Cache Valley, used by this study, is a map developed by Bjorklund and McGreevy (1971). The map shows the depths to groundwater throughout the valley. The information that it contains makes it possible to include the effects that different water levels have on liquefaction susceptibility. The map is shown in Figure 17. The way this map was included in developing the susceptibility map is discussed later.

Susceptibility Classification

General

The development of the liquefaction susceptibility map was based on the factors that influence liquefaction potential. Because of the general nature of the susceptibility map not all of the influencing factors discussed in Chapter 2 were considered. Most of the geotechnical factors require site-specific characteristics to determine their effect on the liquefaction potential. This prevented their use in a general large scale map. However, there were three geotechnical factors that were used that were of such a nature that the soil deposits could be classified as far as relative susceptibility to liquefaction. The three factors were: age of deposit, soil type, and depth to groundwater. Each soil deposit was examined in terms of these three factors and classified as to whether it had a high, moderate, low, or no susceptibility to liquefaction.

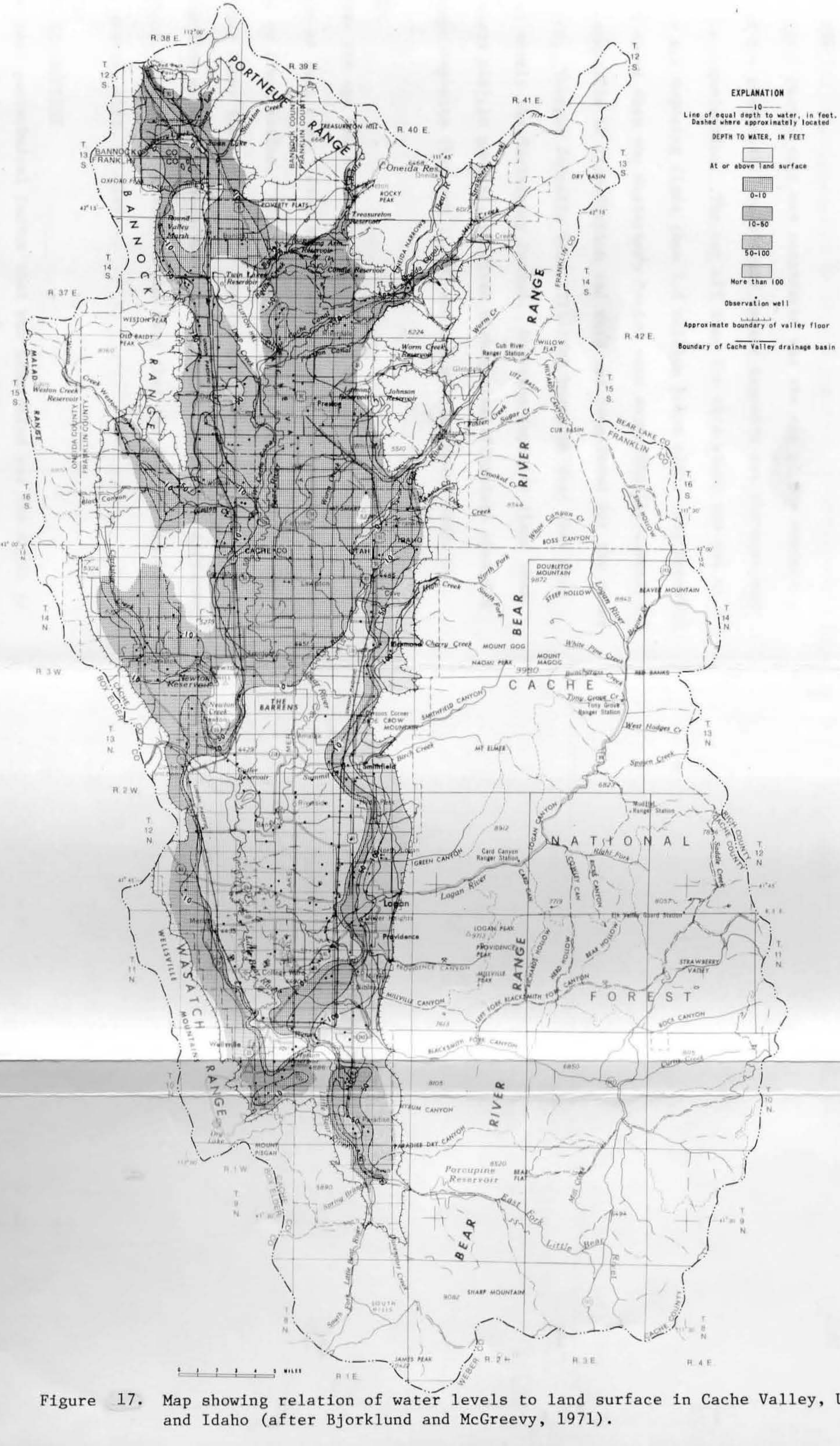

Figure 17. Map showing relation of water levels to land surface in Cache Valley, Utah and Idaho (after Bjorklund and McGreevy, 1971).

Age of deposit

The first factor that was considered was the age of the deposit. As pointed out previously, relatively recent deposits are the most susceptible to liquefaction. The cut off time for this study was set at Quaternary age deposits (less than 1.8 million years old). Any deposits that were older than the Quaternary Period were automatically classified as non-susceptible to liquefaction and were not considered for the other two factors. Younger deposits were classifed based on when they were deposited within the Quaternary Period. Holocene deposits (less than 11,000 years old), in general, received higher classifications than did Pleistocene deposits (between 11,000 and 1.8 million years old).

Soil type

After the age had been considered, each deposit was classifed on the basis of soil type. Fine to medium grained sands are the most susceptible to liquefaction. Williams' map did not distinguish between grain sizes other than in a fairly general way. The sands were not listed as fine or medium sands but just as sands. Therefore, different classifications were given only on the fact that the deposit was either a sand, gravel, silt, or clay.

Depth to groundwater

The last geotechnical factor that was considered was the depth to groundwater. The important influence of the water level was discussed in Chapter 2. The groundwater contour map by Bjorklund and McGreevy

(1971) provided the information to include the depth to groundwater in the deposit classification.

The groundwater contour map enabled three depth ranges to be outlined and used to further adjust deposit classifications. If the depth to the water level was between 0 and 10 feet a higher classification was given to a soil deposit than if the water level was between 10 and 50 feet. The 50 foot level was used as a lower bound. If the water level is too deep then the effective confining pressures become so large that liquefaction is prevented. This was also discussed in Chapter 2.

It should be pointed out that the water depth contours were given only for the 0, 10, 50, and 100 foot depths. Intermediate depths between these primary depths were not given. Youd and Perkins (1977) suggested that a depth of 30 feet might be a lower bound. The 30 foot figure is probably a better estimate than the 50 foot depth used in this study. However, it was decided that the contour map did not have enough detail to interpolate between the 10 and 50 foot levels to establish the 30 foot interval.

Factors not included

It was mentioned that some of the factors that influence liquefaction were not included in the classification process. This was due primarily to the site-specific nature of these factors and to the lack of information on the different properties. Relative density, initial confining pressure, seismic history, and soil structure were the factors listed in Chapter 2 that were not included in this analysis. Relative density and initial confining pressure are site-specific properties calculated from boring log data. There were only a few detailed boring logs at locations across the valley and development of basic trends for these two factors could not be developed from the amount of data available. Seismic history and soil structure are factors that are not completely understood. Because of this lack of understanding and the absence of data, these factors were also excluded from establishing liquefaction susceptibility.

Perched water tables and artesian pressure conditions are two factors, present in Cache Valley, that were also not considered in the analysis. Perched water conditions were excluded because data on specific locations and depths were not available. Information on artesian pressure conditions was available, but no method for inclusion of this data was developed.

Initial susceptibility

A list of the soil deposits from Williams' (1962) map is given below with a brief description of the soils contained in the deposits. A discussion on the classification of liquefaction susceptibility for each soil deposit is also given in this description. These classifications are based only on age of deposit and soil type. Depth to groundwater will be considered later.

Pre-Quaternary deposits. All deposits that were older than Quaternary age were considered to have no susceptibility to liquefaction. The other two geotechnical factors were not even considered for these deposits.

Qf-Pre-Lake Bonneville fan gravel. These deposits were laid down in the early part of the Pleistocene Epoch and were given a low classification based on age. The classification was changed to no susceptibility based on soil type. Gravelly deposits are not very susceptible to liquefaction as was pointed out in Chapter 2.

Qm-Pre-Lake Bonneville landslide. These deposits were deposited in the early Pleistocene Epoch and received a low classification. Williams (1962, 1978) indicated that these slides are masses of sandstone and older rocks that are conglomerate in nature. Based on these descriptions the deposits were reclassified to no susceptibility.

Qbb-Lake Bonneville bench gravel. These deposits were formed during the time that Lake Bonneville was in the valley at the Bonneville level. This places the age of deposit in the late Pleistocene time and so the deposits were given a moderate classification. However, they are gravelly deposits and were reclassified as having no susceptibility, based on soil type.

Qab-Alpine and Bonneville formations: gravel. These deposits are also of late Pleistocene age and received a moderate classification. The soil type is gravel and so the classification was changed to no susceptibility.

Qaf-Alpine and Bonneville formations: silt and fine sand. The age of deposit classification for these deposits was moderate. They were laid down during the late Pleistocene Epoch. The classification remains as moderate based on soil type. There was no distinction between how much sand and how much silt were in the deposits, so the worst conditions were assumed.

Qpb-Provo formation: gravel and sand member. The Provo formations were deposited during the time that Lake Bonneville was at the Provo level. This was during the late Pleistocene time and the age classification for these deposits was moderate. When the soil type was considered the deposits were reclassified as low susceptibility. This was because of the gravel that is contained in the deposits.

Qpc-Provo formation: silt and clay members. The age of the deposits are late Pleistocene so the age classification was a moderate susceptibility. Plastic silts and clays are nonsusceptible to liquefaction as was described in Chapter 2. Reclassification of the deposits, from moderate to no susceptibility, was largely the result of the silt and clay soil types.

Qlm-Lake Bonneville and Post-Lake Bonneville landslides. The landslides were close to the end of the Pleistocene Epoch and beginning of the Holocene Epoch so their age classification was in the moderate category. However, based on soil type they were reclassified as having no susceptibility to liquefaction. Williams (1962, 1978) describes them as gravelly conglomerates that are severely disrupted and broken up. This type of soil is not very likely to produce liquefaction.

Qlf-Post-Lake Bonneville fan gravel. Post-Lake Bonneville places the time of deposit into the Holocene Epoch or more recent geologic time frame. For this reason the age of deposit classification was a high susceptibility. However, classification based on soil type dropped the classification down to no susceptibility.

Qlg-Post-Lake Bonneville flood-plain gravel and sand. The age of deposition was again in the Holocene Epoch and so a high susceptibility classification was given to the deposits. A soil type reclassification dropped the rating to a moderate category. This lowering of classification was because of the gravel found in the deposits. The classification was not dropped to the low rating because the deposits are on the flood-plain and could possibly contain a significant amount of sand.

Qls-Post Lake Bonneville flood-plain sand and silt. The age of deposition was Holocene time and so the age classification was a high susceptibility. Sands with some silt are very susceptible to liquefaction so the classification remained in the high category based on soil type.

Qll-Post-Lake Bonneville alluvial sand in natural levees of Bear River. These deposits were also deposited during the Holocene Epoch and received a high classification based on age. The high rating was unchanged based on soil type because of the high susceptibility of the sands within the deposits.

Qlw-Post-Lake Bonneville slope wash. These deposits were also formed after Lake Bonneville receded and were given a high classification. The soil type classification dropped the rating to a low susceptibility. Based on descriptions by Williams (1978), these deposits are a mixture of sands, silts, clays, and gravels. This type of mixture most likely would not exhibit a liquefaction problem.

Qld-Post-Lake Bonneville eolian sand. These deposits were also laid down after the lake exited the valley and so they received a high rating based on age. The soil type also indicated a high susceptibility based on the sands contained in the deposits. The combined rating is, therefore, left at a high susceptibility.

Qlt-Post-Lake Bonneville spring tufa. The age classification on these deposits was also a high rating because of their Holocene age. The soil type is a limestone rock deposited by warm springs. The classification was, therefore, dropped to a no susceptibility, because the deposits were rock formations.

Final susceptibility

Two of the three geotechnical factors influencing the liquefaction susceptibility of a soil deposit have now been accounted for in the previous descriptions. A summary of how the first two factors affected each soil deposit is listed in the appendix.

The third geotechnical factor, the depth to groundwater, was considered separate from the other two factors. This factor depended on the location of the soil deposit and the groundwater depth contours of the valley.

It can be noted that susceptible deposits on the valley floor were influenced more by the depth to groundwater than those that were higher up on the bench areas. The groundwater is closer to the surface on the floor of the valley than it is at the edges of the valley nearer the mountains. This can be seen very clearly from Figure 17, which shows

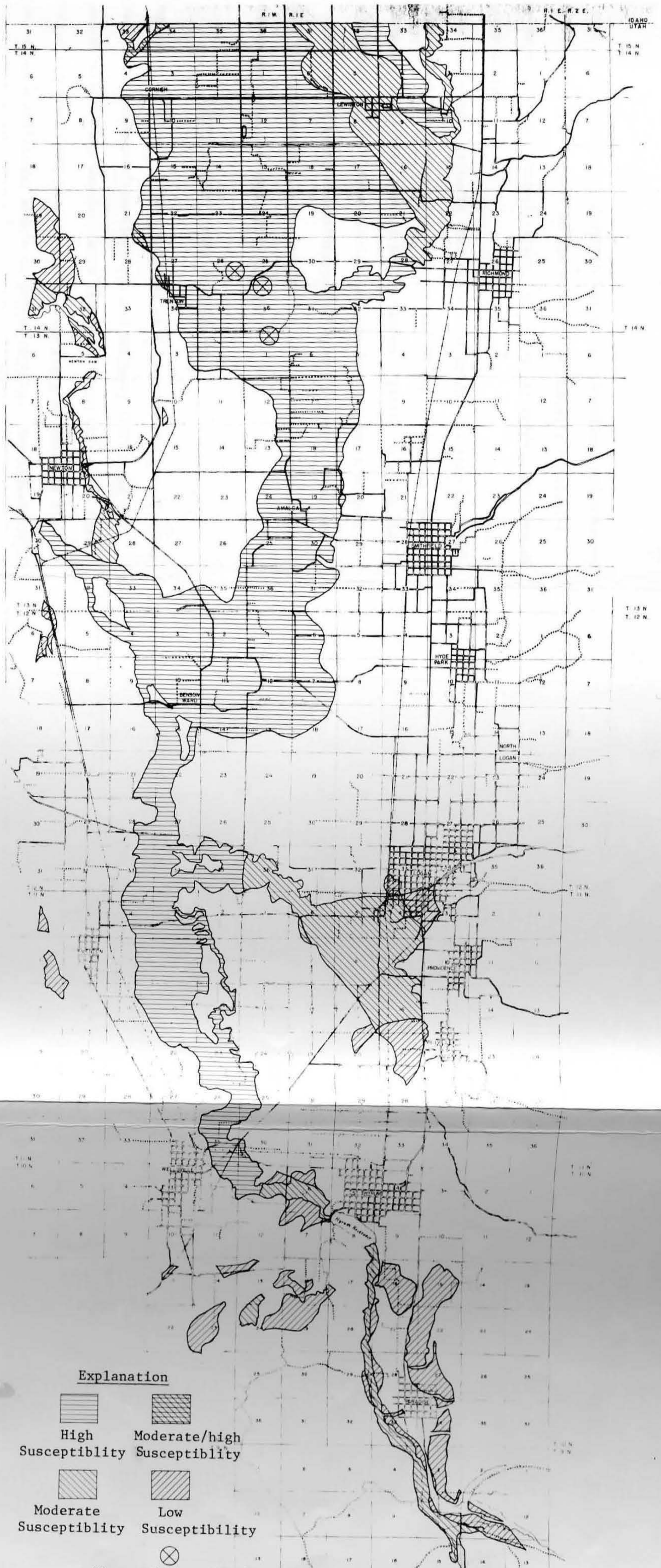

Figure 18. Liquefaction susceptibility map showing the susceptible soil deposits in Cache Valley, Utah.

the contours of groundwater depth in the valley (Bjorklund and McGreevy, 1971). Therefore, a deposit on the valley floor usually received a higher susceptibility classification than a similar deposit that was on the bench areas.

The groundwater criteria that was stated before was then combined with the classification results from the age of deposition and the soil type into a liquefaction susceptibility matrix. Table 1 shows the susceptibility matrix. This matrix indicates how the depth to groundwater affected the final classification of a soil deposit. Youd and Perkins' (1977) susceptibility chart is included in the appendix for comparison with the susceptibility matrix.

Liquefaction Susceptibility Map

By using Williams' (1962) soil map as a base map and transferring the groundwater contours from Bjorklund and McGreevy (1971) map the soil susceptibility map was initially laid out. From that point the susceptibility matrix was used to outline the areas of probable liquefaction, given a sufficient amount of ground shaking. The liquefaction susceptibility map is presented in Figure 18 and shows the areas of relative liquefaction susceptbility.

Table 1. Susceptibility matrix - estimated susceptibility of soil deposits to liquefaction, based on age of deposit, soil type, and depth to groundwater.

Depth to groundwater (feet)	Tertiary	Quaternary														
	Pre-Pleistocene	Pleistocene							Holocene							
		Qf	Qm	Qbb	Qab	Qaf	Qpb	Qpc	Qlm	Qlf	Qlg	Qls	Qll	Qlw	Qld	Qlt
0-10	N	N	N	N	N	M	L	N	N	N	M	H	H	L	H	N
10-50	N	N	N	N	N	L	N	N	N	N	L	M/H	M/H	N	M/H	N
>50	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

H - high susceptibility

M/H - moderate to high susceptibility

M - moderate susceptibility

L - low susceptibility

N - no susceptibility

CHAPTER 4

LIQUEFACTION OPPORTUNITY MAP

General

The second phase in developing the liquefaction potential map was the inclusion of the seismicity of the study area. Seismic data was included by way of a liquefaction opportunity map. The procedure for developing an opportunity map was discussed by Youd and Perkins (1977). The primary information required in generating a ground failure opportunity map is location and frequency of earthquake occurrence and a relationship between earthquake magnitude and the distance from the earthquake source to possible locations of liquefaction-induced ground failures (Youd and Perkins, 1977). The seismic history of the study area, combined with an empirical magnitude-distance relationship, provides the required seismic input for the analysis. By using the seismic data, an opportunity map showing the return periods of earthquakes large enough to induce liquefaction can be produced. The opportunity map is combined with the susceptibility map to give the liquefaction potential map which shows the relative potential for liquefaction in the study area.

Development of Cache Valley Map

Seismicity

In a companion study, Greenwood (1978) developed a liquefaction opportunity map for Cache Valley, Utah. Greenwood used the same criteria suggested by Youd and Perkins (1977) to develop this map. The locations and magnitudes of 172 earthquakes were compiled and associated with identified seismic sources. Greenwood (1978) listed five seismic sources that could generate sufficient levels of ground shaking to induce liquefaction in Cache Valley. The five seismic sources that he considered were (1) Wasatch Fault System; (2) Hansel Valley Fault System; (3) Bear Lake-Caribou Seismic Area; (4) East Cache Fault; and (5) West Cache Fault. However, when he developed the opportunity map he combined the East and West Cache Faults into one seismic area. This was done because of sparce data and because in some cases it was difficult to identify an earthquake epicenter with a specific fault.

After the seismic sources had been identified, the various earthquakes were assigned to one of the sources. Each source had a number of earthquakes of varying magnitudes assigned to it. These earthquakes were further broken down into magnitude ranges for each seismic source. The number of events in each magnitude range was plotted versus the mid-point magnitude of the range on a semi-log plot. From this plot a relationship between magnitude and frequency of occurence was developed for each seismic source. The relationship used for the East Cache and West Cache Fault Source is shown on Figure 19. The annual frequency of occurrence for each magnitude was determined by dividing the number of occurrences, determined from the magnitude-occurrence relationship, by the number of years of record. This annual frequency was equally distributed over the source area or along the source fault.

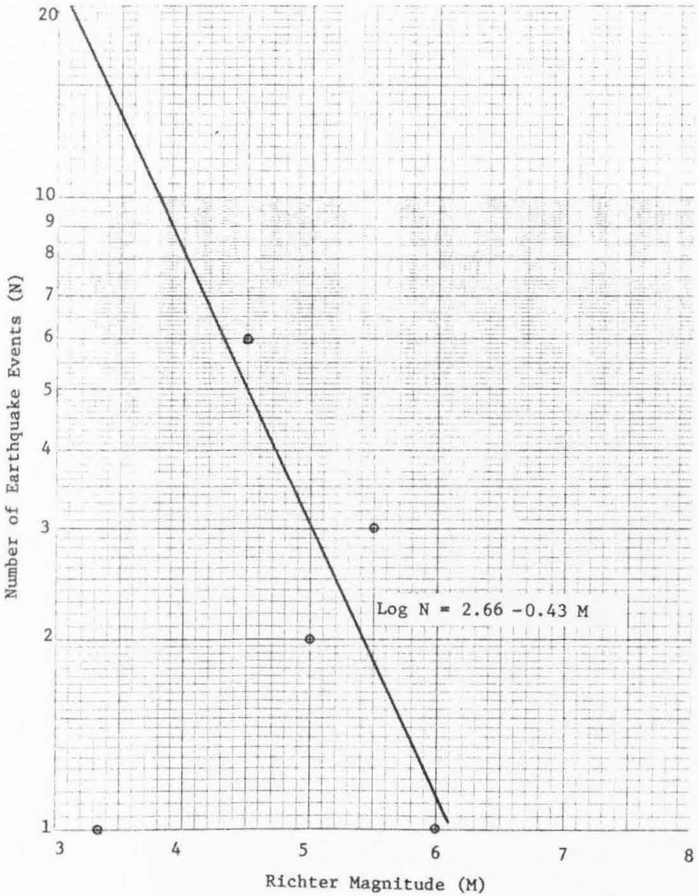

Figure 19. Number of earthquake events versus Richter Magnitude for the Cache Valley Source Area for 126 years (after Greenwood, 1978).

One of the main factors used to determine opportunity was a magnitude-distance relationship. This magnitude-distance relationship was first presented by Kuribayashi and Tatsuoka (1975) and by Youd (1977). The relationship is an envelope based on data of the magnitude of previous earthquakes and the farthest distance to sites where liquefaction was known to occur. The envelope is shown on Figure 20. A modified lower bound envelope that Youd and Perkins (1977) established in their analysis is also shown on Figure 20. The lower bound envelope has a threshold magnitude of 5 and a cut-off distance of 150 km. Youd and Perkins postulated that any site with a given magnitude earthquake and distance to causitive source that plotted to the left and above this lower bound had a possibility of liquefying. Greenwood used this lower bound envelope in establishing the opportunity map for Cache Valley.

Opportunity for liquefaction

The opportunity for liquefaction involved the annual frequency of occurrence for each magnitude range of a seismic source and the magnitude-distance relationship. The annual frequency of occurrence for a given magnitude range was proportioned equally over a seismic area grid or along increments of fault rupture on a fault system. This gave the same seismic activity to all portions of the seismic source. In determining the opportunity for liquefaction at a particular point in the study area, the distance from the study point to a grid point in the source area or the distance to a segment of fault rupture along a fault system was determined. This distance was compared to the magnitude-distance criteria from Figure 20. If the distance from the figure was

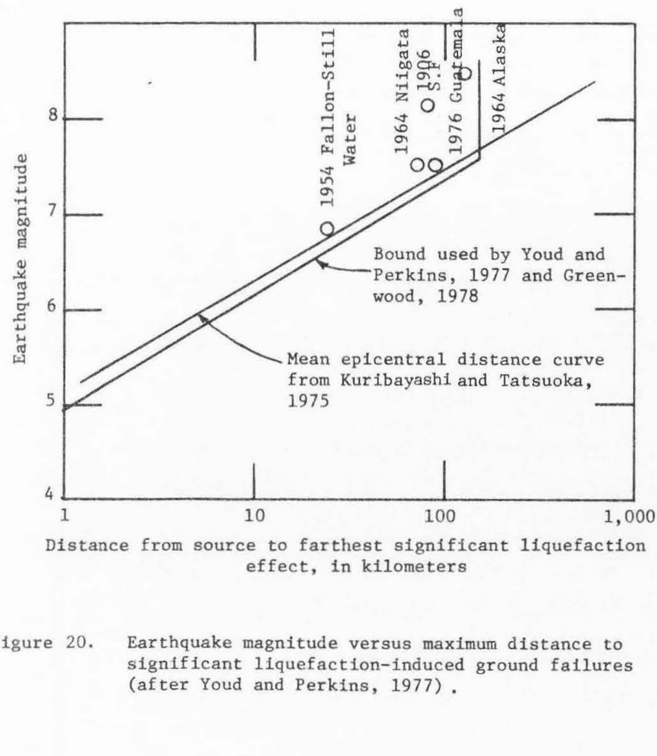

Figure 20. Earthquake magnitude versus maximum distance to significant liquefaction-induced ground failures (after Youd and Perkins, 1977).

greater than the distance between the point in the study area and the point from the seismic source then the site was within the range where liquefaction could occur. The study point was then credited with the opportunity to liquefy by assigning it the annual frequency of occurrence associated with the source grid point or fault rupture increment. This process was repeated for the same study point using each grid point in a source area or each placement of fault rupture along a fault system. This was for a particular magnitude range. All magnitude ranges for each seismic source were considered for each study point. This procedure produced the annual frequency of opportunity for liquefaction for all points in the study area. This method is similar to that used in calculating seismic risk (Algermissen and Perkins, 1972).

Liquefaction Opportunity Map

The opportunity map was developed by accumulating the opportunity for liquefaction at grid points in the Cache Valley area. The reciprocal of the accumulated annual frequencies of occurrence, return period, was evaluated at each point. Return period data was used in forming contours of equal return periods for earthquakes large enough to induce liquefaction. The return period contour map constitutes the liquefaction opportunity map. The opportunity map for Cache Valley, Utah is shown on Figure 21.

Figure 21. Liquefaction opportunity map for Cache Valley, Utah (after Greenwood, 1978).

CHAPTER 5

LIQUEFACTION POTENTIAL MAP

A liquefaction potential map was developed by combining the liquefaction susceptibility map and the liquefaction opportunity map. The potential map outlines areas of relative potential for liquefaction in Cache Valley, Utah. This map is presented in Figure 22. The liquefaction susceptible deposits in Cache Valley are identified by a line pattern that gives the estimated boundaries of these deposits. Different degrees of susceptbility are distinguished by the different line patterns. Where no susceptibility exists the areas are left blank. The opportunity for liquefaction is included by a stipple pattern covering the areas of shorter return periods. Because of the small study area, the return periods did not vary significantly. Greenwood's (1978) opportunity map shows a range from 30 to 90 years of return periods. Therefore, only one division of seismicity was shown on the potential map. The 50 year return contour was plotted and all areas with return periods less than 50 years were given a stipple pattern.

The areas of most concern are those areas where there is an overlap of the highly susceptible line pattern and the stipple pattern. The relative potential decreases as the patterns change.

The largest areas that show a high potential for liquefaction are the flood-plains of the Bear River. These areas have highly susceptible soil deposits and receive more frequent occurrences of ground motion strong enough to induce liquefaction. These deposits underlie most areas

Note: Shading with the stipple pattern indicates the areas where the return period for sufficient ground shaking to cause liquefaction is less than 50 years. The return period for areas without the stipple pattern indicates various degrees of liquefaction susceptibility. The map indicates no potential for liquefaction in areas without a stripped pattern even if the area has a stipple pattern.

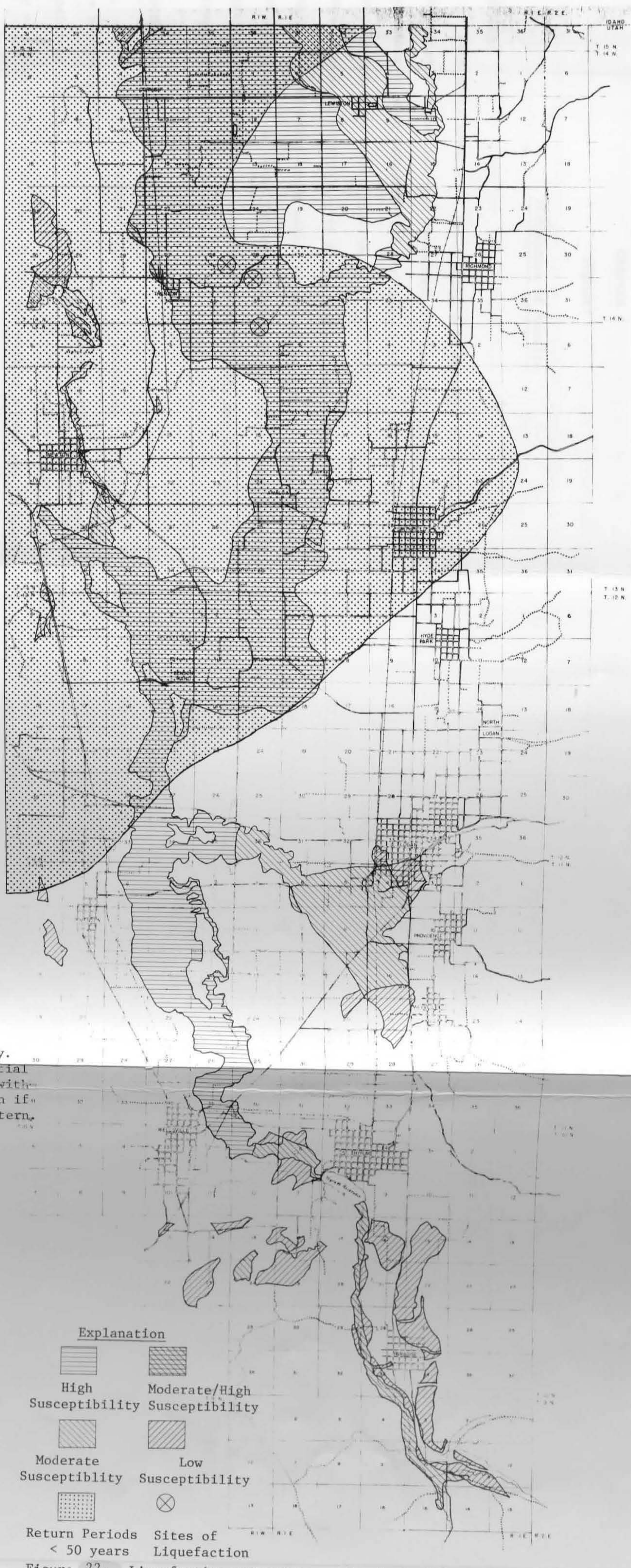

Figure 22. Liquefaction potential map for Cache Valley, Utah.

CHAPTER 6

SUMMARY

Discussion of Results

General

This study identified liquefiable soil deposits in Cache Valley and the relative potential that these deposits have for liquefaction. The locations of soil deposits that are susceptible to liquefaction are shown on a liquefaction susceptibility map. The factors that influence the liquefaction susceptibility of a soil deposit were considered in outlining the susceptible areas within Cache Valley. The relative potential for liquefaction in Cache Valley was obtained by combining the soil susceptibility data with the liquefaction opportunity map developed by Greenwood (1978).

Liquefaction susceptibility map

The liquefaction susceptibility map is presented in Figure 18. The map presents general areas where it is highly probable that soil conditions are right for the development of liquefaction. A geologic map of Cache Valley by Williams (1962) was used as a base map in locating susceptible soil deposits in Cache Valley. Based on checks with Soil Conservation maps, detailed site borings, and well logs, the location of soil types by Williams (1962) was verified as reasonably correct. This gave some confidence in the use of Williams' map as a base map in establishing the susceptible areas. However, it should be realized that there exists within these susceptible areas, places or sites where liquefaction would not occur. The mapping of susceptible regions on a large scale did not allow for the exclusion of specific sites from receiving high classifications when the chance for liquefaction was low or nonexistent. This also applies to specific sites located in an area that received a low classification when the probability for liquefaction at the specific site was quite high. This type of misclassification of susceptibility was unavoidable.

Because of the importance of depth to groundwater on liquefaction potential, the groundwater map by Bjorklund and McGreevy (1971) was an important factor in developing the susceptibility map. It provided information that was used in establishing the susceptibility classification of the various deposits.

Some general statements can be made about the susceptibile areas in Cache Valley. The major portions of susceptible areas lie along the banks and flood-plains of the major rivers that flow through the valley. These areas of cohesionless materials are reworked deposits from the river deltas formed during the time of Lake Bonneville. Williams (1978) indicated that these layers of materials are relatively thin. The largest of these river deltas, that were washed out over the lake bottom sediments, was formed by the Bear River. The materials from this delta cover the areas in the northern end of Cache Valley, Utah. This portion of the valley has the largest area that is susceptible to liquefaction. This is a direct result of the spreading of the Bear River delta. Other sections of the valley have only narrow strips of susceptible areas along the rivers.

Liquefaction opportunity map

Greenwood (1978) showed various levels of liquefaction opportunity on a liquefaction opportunity map by return period contours as shown on Figure 21. He indicated that there are two basic patterns that show up. The first pattern is the increase in return period going from the north end of the valley to the south end. The more frequent seismic activity in the north end was influenced by the Hansel Valley Faults and the Bear Lake-Caribou Seismic Area. The second trend is the fact that there are shorter return periods along the west side of the valley than along the east side of the valley. He states that this results mainly from the influence of the Wasatch Fault and to a lesser extent from the Hansel Valley Faults. The opportunity for liquefaction does not change that much from place to place in the valley. Greenwood's map shows a range from 30 to 90 years for return periods of earthquakes large enough to induce liquefaction. This change in seismicity was so small that only the 50 year return period was used to differentiate liquefaction return period on the liquefaction potential map.

Liquefaction potential map

The liquefaction potential map is shown on Figure 22. The areas that have a greater potential for developing liquefaction are located mainly in the northwest quarter of the valley. The susceptibile areas outlined in Benson, Amalga, Trenton, Cornish, Newton, and parts of Lewiston have more opportunity to liquefy than any other portions of the valley. The division contour from the opportunity map reduced the relative potential for liquefaction of susceptible deposits on the east side of the valley and in the southern end. The potential map shows only relative potentials and does not rule out the possibility of liquefaction developing in susceptible deposits outside of the stipple shaded boundary.

Reports of liquefaction occurrence in Cache Valley were mentioned earlier. During the August 30, 1962 earthquake there were reported cases of ground surface cracking with the extrusion of sand and mud. The development of sand boils were also reported in the same general area. The liquefaction potential map indicates that the areas of these reported incidents are areas of high susceptibility to liquefaction. The location of the specific sites are near the community of Trenton and are identified on the liquefaction potential map shown on Figure 22. A brief summary of personal interviews with the people who reported these occurrences are listed in the appendix. The agreement between these reported cases and the liquefaction potential map adds credibility to the map in locating areas where liquefaction might occur.

It must be pointed out again that the potential map is a general location map. Specific sites that will liquefy will depend on site investigations. Detailed boring data and site-specific analysis of a soil profile will determine the actual potential for liquefaction. However, the potential map will be a useful guide for planning purposes.

Recommendations

The development of a liquefaction potential map provides an insight into a seismic hazard that exists in Cache Valley. It is recommended that the potential map from this study be used in planning and development decisions that are made in connection with the growth of the valley. Various state, county, and local agencies will be making decisions on locations for utilities, businesses, industries, and housing areas as growth occurs. All types of information will be needed in helping these different groups make wise choices on locations for these developments. The liquefaction potential map will be a useful tool in this process. Contractors and developers would also be able to make better site selections for their projects if they had a general idea of what problems might exist within certain areas. A project will require more analysis and design if it is located within an area that has a high potential for liquefaction. The liquefaction potential map will provide a general guide in making these planning and development decisions.

A second recommendation would be the improvement and updating of the susceptibility map as new information is made available. New boring logs would provide valuable information that could be used in refining the susceptibility map. If enough boring data becomes available, then some of the factors that influence liquefaction potential, but were not included in this study, might be included in the liquefaction susceptibility and potential maps. New and additional groundwater information such as the depth and locations of perched water tables would also be important in further refinement of the susceptibility map.

Additional information on the seismicity of the area should also be obtained to improve the liquefaction opportunity map.

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APPENDIX

Table 2 Initial classification of soil deposits

Soil deposit	Classification based on age of deposit	Re-classification based on soil type
Pre-Quaternary	N	N
Qf	L	N
Qm	L	N
Qbb	M	N
Qab	M	N
Qaf	M	M
Qpb	M	L
Qpc	M	N
Qlm	M	N
Qlf	H	N
Qlg	H	M
Qls	H	H
Qll	H	H
Qlw	H	L
Qld	H	H
Qlt	H	N

Table 3 Estimated susceptibility of sedimentary deposits to liquefaction during strong seismic shaking (after Youd and Perkins, 1977).

Type of Deposit	General distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefaction (by age of deposit)			
		<500 Yr.	Holocene	Pleistocene	Pre-Pleistocene
Continental deposits					
River channel	Locally variable	very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	–	Low	Very low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Coastal zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach					
High wave energy	Widespread	Moderate	Low	Very low	Very low
Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
Artificial					
Uncompacted fill	Variable	Very high	–	–	–
Compacted fill	Variable	Low	–	–	–

Interview with Harold Spackman

Trenton, Utah

After the earthquake on August 30, 1962, Mr. Harold Spackman of Trenton, Utah reported some ground disturbances on his farm in Trenton. Mr. Spackman recalled seeing cracks in the ground surface at numerous spots along the river banks of the Bear River. At one location where the cracks had developed, mud and water had been extruded and formed small ridges. The formation of these small ridges left a ripple pattern over an entire grazing field and this pattern still exists today.

Mr. Spackman indicated that Mr. J. Stewart Williams, a geologist from Utah State University, came out to inspect these disturbances and to make a record of his findings. Mr. Williams told Mr. Spackman that the blue-grey mud that was extruded from the cracks was probably from deposits some 90 feet beneath the ground surface. Mr. Spackman felt that this was quite reasonable, based on his experiences from drilling wells in the general area of these disturbances. He stated that when drilling wells in the area they usually run into a grey clay layer at around 90 feet. He also indicated that until they reached the clay layer that there was what he termed a quicksand condition from a few feet below the ground surface, down to the clay.

Mr. Spackman also stated that the entire river bottom area was covered with mud, not only on his property, but also on the fields owned by his neighbors. Informal reports from other people in Trenton also agree on this phenomena.

The areas of these ground disturbances have been identified on the liquefaction potential map on Figure 22. This type of disturbance indicates that liquefaction has occurred in the subsurface layers.

Interview with Walter Wood

Trenton, Utah

After the earthquake on August 30, 1962, Mr. Walter Wood of Trenton, Utah reported the development of some sand boils along the banks of the Bear River. He remembers seeing little mounds of sand developing with water and sand coming up through the tops of the mounds and flowing down over the sides. There were quite a few of these sand boils scattered all along the river bottoms in the one particular area. Mr. Wood also remembers the main shock of the earthquake at approximately 7:00 a.m. and an aftershock at approximately 11:00 a.m. He stated that both times the sand boils extruded sand and water.

Mr. Wood also indicated that the plateaus on his farm are mainly sandy soils and that down in the river bottoms more clayey deposits exist. This agrees with descriptions of the area given by Mr. J. Stewart Williams, a retired geologist from Utah State University.

The location of these sand boils have been plotted on the liquefaction potential map on Figure 22. The development of sand boils is a definite indication that liquefaction has occurred in the subsurface soil layers.