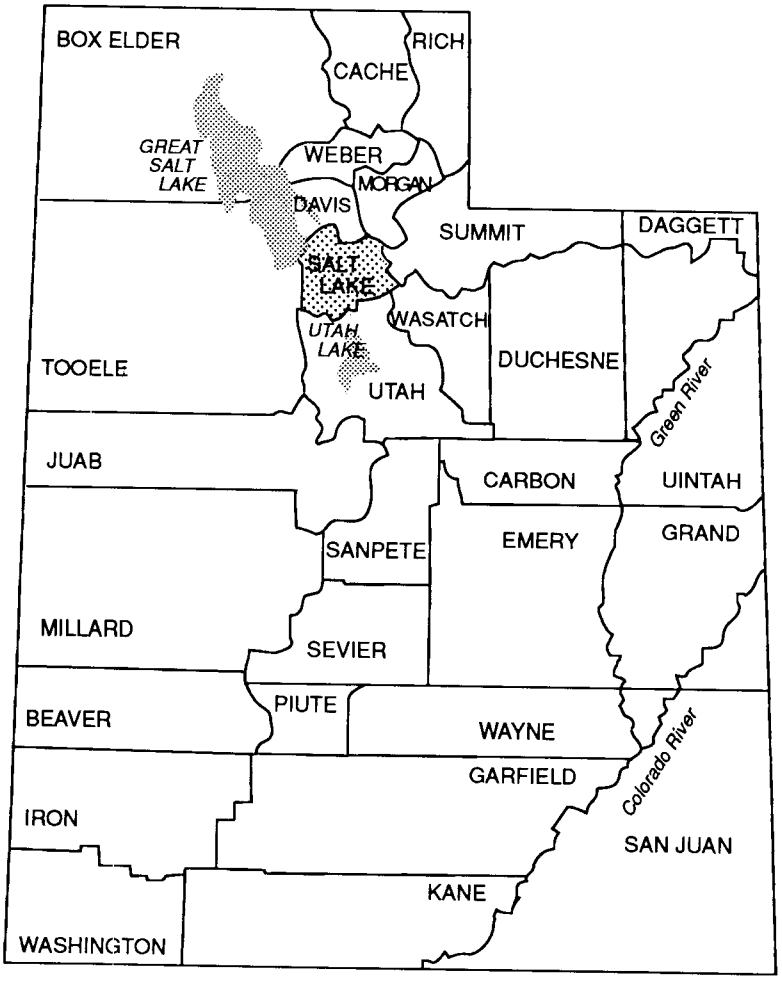
# LIQUEFACTION POTENTIAL MAP FOR SALT LAKE COUNTY, UTAH COMPLETE TECHNICAL REPORT

*by*
*Loren R. Anderson*
*Jeffrey R. Keaton*
*John E. Spitzley*
*Andrew C. Allen*




**CONTRACT REPORT 94-9** **September 1994**
**UTAH GEOLOGICAL SURVEY**
*a division of*
UTAH DEPARTMENT OF NATURAL RESOURCES

# LIQUEFACTION POTENTIAL MAP

for

# SALT LAKE COUNTY, UTAH

by

Loren R. Anderson, Jeffrey R. Keaton
John E. Spitzley and Andrew C. Allen

Sponsored by: U.S. Geological Survey
Contract: 14-08-0001-19910

Department of Civil and Environmental Engineering
Utah State University
Logan, Utah
and
Dames & Moore Consulting Engineers
Salt Lake City, Utah

May 1986

ACKNOWLEDGMENTS

This project was sponsored by the U.S. Geological Survey as part of their Earthquake Hazards Reduction Program with Mr. Gordon Greene and Mr. Steve Wegener as the Contracting Officer's Representatives. Dr. T. Leslie Youd of the U.S. Geological Survey and Brigham Young University reviewed the work during the project and made valuable suggestions. The financial support and the technical advice of the Survey is gratefully acknowledged.

TABLE OF CONTENTS


| | Page |
|---|---|
| ACKNOWLEDGEMENTS | ii |
| LIST OF TABLES | v |
| LIST OF FIGURES | vi |
| LIST OF PLATES | vii |
| EXECUTIVE SUMMARY | viii |
| INTRODUCTION | 1 |
| General | 1 |
| Purpose and Scope of Study | 2 |
| Liquefaction-Induced Ground Failure | 4 |
| Regional Seismicity | 5 |
| General Subsurface Conditions | 5 |
| METHODOLOGY | 9 |
| General | 9 |
| Factors Affecting Liquefaction Potential | 9 |
| Evaluation of Liquefaction Potential | 10 |
| Correlations for Difference Magnitude Earthquakes | 16 |
| Use of SPT Correlation Charts with CPT Data | 16 |
| Liquefaction Potential Based on Critical Acceleration | 19 |
| Liquefaction Potential Map | 23 |
| Ground Failure Mode | 24 |
| GEOTECHNICAL CONDITIONS IN SALT LAKE COUNTY, UTAH | 25 |
| Geology Related to Liquefaction | 25 |
| Introduction | 25 |
| Pre-Lake Bonneville Materials | 26 |
| Lake Bonneville Materials | 26 |
| Material Properties | 26 |
| Age and Elevation of Lake Levels | 27 |
| Significance of Lake Environment | 29 |

TABLE OF CONTENTS (Continued)


Post-Lake Bonneville Materials . . . . . 30
Soil Development . . . . . 32

Geotechnical Data . . . . . 33

Available Subsurface Data . . . . . 33
Field Investigation . . . . . 35
Lab Analysis . . . . . 36
Soils and Ground Water Data Map . . . . . 36

Existing Ground Failure . . . . . 37

Introduction . . . . . 37
Lateral Spread Failures . . . . . 37
Other Ground Failures . . . . . 37

Ground Slope Data . . . . . 38

LIQUEFACTION POTENTIAL . . . . . 38

Critical Acceleration as a Liquefaction Potential Indicator . . . . . 38

Liquefaction Potential Map . . . . . 40

CONCLUSIONS AND RECOMMENDATIONS . . . . . 41

LIST OF REFERENCES . . . . . 44

## LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1. | Earthquake magnitudes and their associated number of representative cycles. (After Seed and Idriss, 1982) | 17 |
| 2. | Liquefaction potential related to exceedance probability | 22 |
| 3. | Ground slope and expected failure mode (After Youd, 1978) | 24 |
| 4. | Liquefaction potential related to critical acceleration (From Dames and Moore, 1978) | 40 |

LIST OF FIGURES


| Figure | | Page |
|---|---|---|
| 1. | Map of Utah showing Salt Lake County Study Area . . . | 3 |
| 2. | Epicenter Map of Intermountain Seismic Belt (1850-1974) (After Arabasz, Smith and Richins, 1979) . . . . | 6 |
| 3. | Epicenter of earthquakes in the Wasatch Front area from July through September 1974. (Arabasz, Smith and Richins, 1979, p. 265) . . . | 7 |
| 4. | Known and suspected Quaternary faults in Utah (After Arabasz and others, 1979; Anderson and Miller, 1979) . . . . . | 8 |
| 5. | Method of evaluating liquefaction potential (After Seed and Idriss, 1971) . . . . . | 11 |
| 6. | Observed field behavior of sand correlated to cyclic stress ratio and standard penetration resistance (After Seed, Mori, and Chan, 1977) . . | 13 |
| 7. | Correlation between field liquefaction behavior of silty sands ($D_{50}$>0.15mm) under level ground conditions and standard penetration resistance. (Data after Tokimatsu and Yoshimi, 1981) (From Seed and Idriss, 1982) . . . | 15 |
| 8. | Representative relationship between $\tau/\tau_1$ and the number of cycles to cause liquefaction (After Seed and Idriss, 1982) . . . . . | 17 |
| 9. | Chart for evaluation of liquefaction potential for sands for different magnitude earthquakes (after Seed and Idriss, 1982) . . . . | 18 |
| 10. | Correlation between field liquefaction behavior of sands under level ground conditions and static cone penetration resistance (after Seed and Idriss, 1982) . . . . . | 20 |
| 11. | Penetration resistance conversion relationship for cohesionless sands and silts (After Lowe and Zacchoe, 1975 . . . . . | 34 |
| 12. | Exceedance Probability Curves Dames and Moore, 1978) . . . . . | 39 |

## LIST OF PLATES


| Plate | |
|---|---|
| 1A | Selected Geologic Data (North) |
| 1B | Selected Geologic Data (South) |
| 2A | Soils and Ground Water Data (North) |
| 2B | Soils and Ground Water Data (South) |
| 2C | Soils and Ground Water Data (Metro Area) |
| 3A | Ground Slope and Critical Acceleration (North) |
| 3B | Ground Slope and Critical Acceleration (South) |
| 4A | Liquefaction Potential (North) |
| 4B | Liquefaction Potential (South) |

# EXECUTIVE SUMMARY

As part of the U.S. Geological Survey's Earthquake Hazard Reduction program a "Liquefaction Potential Map" has been prepared for Salt Lake County, Utah. Liquefaction potential was evaluated from existing subsurface data and from a supplementary subsurface investigation performed as one of the tasks in this study. All of the data used in this study are summarized on the base maps presented as Plates 1A and 1B and 2A, 2B and 2C.

For this regional assessment, liquefaction implies liquefaction-induced ground failure. The liquefaction potential is classified as high, moderate, low and very low depending on the probability that a critical acceleration will be exceeded in 100 years. The critical acceleration for a given location is defined as the lowest value of the maximum ground surface acceleration required to induce liquefaction. The categories of high, moderate, low and very low correspond to probabilities of exceeding the critical acceleration in the ranges of greater than 50 percent, 10 to 50 percent, 5 to 10 percent and less than 5 percent, respectively.

The Liquefaction Potential Map on Plates 4A and 4B shows that for a significant portion of Salt Lake County the probability of exceeding the critical acceleration in 100 years is greater than 50 percent. Hence, liquefaction induced ground failure is a significant seismic hazard. Ground slope information, as well as the subsurface conditions documented on the Soils and Ground Water Data Map, can be used in combination with the Liquefaction Potential Map as a means of assessing the type of

ground failure likely to occur. Three slope zones have been identified from the characteristic failure modes induced by liquefaction during historic earthquakes (Youd, 1981, personal communication).

At slope gradients less than about 0.5 percent, loss of bearing capacity is the type of ground failure most likely to be induced by soil liquefaction. Stratified soil conditions, which existing in Salt Lake County, provide vertical confinement for liquefiable layers and may tend to reduce the probability of bearing capacity failures. Buildings imposing light loads on the subsurface soils may not be affected by loss of bearing capacity during an earthquake. Heavy buildings, on the other hand, might be severely affected. Additionally, during earthquakes, heavy buildings subjected to movement from deformation of the subsurface soils might cause damage to adjacent lightly-loaded structures.

Buried tanks, even those full of water or gasoline, could "float" to the surface if the soils surrounding them were to liquefy. For this to happen, however, the tanks would have to be buried in very thick deposits of sand. The stratified nature of the soils in Salt Lake County generally tends to reduce the likelihood of this type of failure.

Slope gradients ranging from about 0.5 percent to about 5.0 percent tend to fail by lateral spread processes as a result of soil liquefaction. Evidence exists in Salt Lake County for large lateral spread landslides (see Plates 1A and 1B). Consequently, it appears that these kinds of failures have occurred in response to earthquakes within the past few thousand years.

Lateral spread landslides present the greatest concern because of the potential consequences. A small amount of movement can do a great deal of damage. Lifelines (buried utilities) are particularly vulnerable.

A large amount of Salt Lake County falls within the slope range characterized by lateral spread landslides induced by soil liquefaction.

Slopes steeper than about 5 percent tend to fail as flow slides if the mass of soil comprising the slope liquefies. In Salt Lake County, the stratified nature of the geologic materials suggests that flow-type failures are likely to be relatively rare. Instead, translational landslides or lateral spreads are likely to result from liquefaction on slopes steeper than about 5 percent.

It should be emphasized that perched ground water is equal to true ground water with respect to soil liquefaction. Saturated granular material is the chief concern; the source of the saturation is immaterial.

The results of our research on the liquefaction potential of Salt Lake County leads us to conclude that lateral spread landsliding is the type of ground failure most likely to accompany soil liquefaction. The probability of extensive damage due to this type of ground failure is high. All types of structures could be damaged by liquefaction-induced ground failure; lifelines are especially susceptible to damage.

Anderson and Keaton (1986) present a decision matrix that suggests mitigation measures for liquefaction induced ground failure hazards. The matrix considers the rating of the liquefaction zone and the proposed land use of the area.

# INTRODUCTION

## General

The effects of earthquakes can cause loss of life and costly property damage; therefore, in areas of high seismic activity, earthquake hazard reduction must be an important consideration for intelligent land use planning. Damage during earthquakes can result from surface faulting, ground shaking, ground failure, generation of large waves (tsunamies and seiches) in bodies of water, and regional subsidence or downwarping (Nichols and Buchanan-Banks, 1974). Although all of these causes of damage need to be considered in reducing earthquake hazards, this report deals only with liquefaction-induced ground failure.

Ground failure associated with earthquake-induced soil liquefaction has caused major damage during past earthquakes (Seed, 1979; Youd and Hoose, 1977). The seismic history of the Wasatch front area in north-central Utah clearly indicates that ground motion of sufficient intensity and duration to induce liquefaction of susceptible soils is very likely to occur in the relatively near future.

Deposits of loose fine sand, highly susceptible to liquefaction, exist along the Wasatch front (McGregor and others, 1974; Anderson and others, 1982). Areas of shallow ground water are also widespread (Hely and others, 1971, Fig. 80). In addition, evidence of liquefaction was observed following the 1934 Hansel Valley earthquake in Box Elder County, Utah (Coffman and von Hake, 1973, p. 71) and again following the Cache Valley earthquake of 1962 (Hill, 1979).

The seismic history, subsurface soil and ground water conditions, and evidence of liquefaction in Utah indicate that liquefaction is a

significant hazard which must be assessed as an important element in seismic hazard reduction planning.

## Purpose and Scope of Study

The purpose of this study was to develop a liquefaction potential map for Salt Lake County, Utah. Salt Lake County is located in northern Utah's urban corridor, and it is the major population of the state. The procedure was developed in an earlier study for Davis County, Utah, Anderson and others (1982). Development is rapidly expanding into the previous rural areas to the west of Salt Lake City. The study area includes the Salt Lake Valley which extends from the base of the Wasatch Mountains on the east to the base of the Oquirrh Mountains on the west and it is bound by the Great Salt Lake on the north. The location of Salt Lake County is shown on Figure 1.

The liquefaction potential was evaluated on the basis of subsurface data that was obtained from private engineering consultants, state and local government agencies, and from a supplementary subsurface investigation performed as one of the tasks in this study. The results of the study are summarized on four maps; each map consists of two parts (A and B) separating the county into the north half and south half. The soil and ground water map has an additional part for the Salt Lake City metropolitan area.

The base maps are 50 percent reductions of U.S. Geological Survey 7 1/2-minute topographic quadrangles (a scale of 1:48,000), except for the Salt Lake City metropolitan area which is at a scale of 1:24,000. The maps are presented in later sections of this report and consist of (1) Selected Geologic Data Map, (2) Soils and Ground Water Data Map, (3)

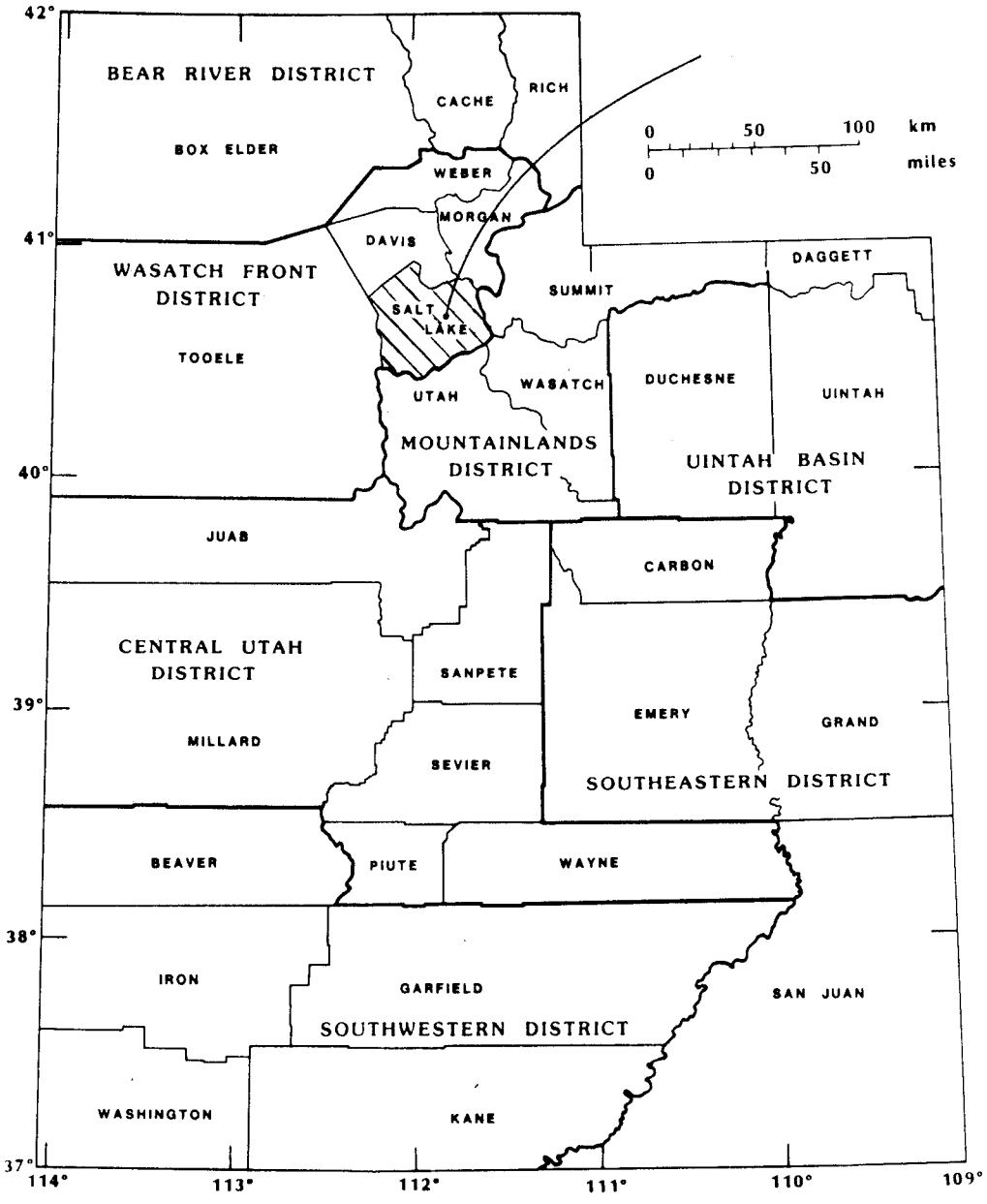



Figure 1. Map of Utah Showing Salt Lake County Study Area.

Ground Slope and Critical Acceleration Map and (4) Liquefaction Potential Map.

Boring logs and laboratory data that were collected and developed during the study are maintained in the files of the Civil Engineering Department at Utah State University.

## Liquefaction-Induced Ground Failure

Loose, saturated fine sand deposits subjected to earthquake shaking can liquefy, losing essentially all shear strength, because pressures are rapidly transferred from the granular structure of the soil to the pore water. If the pore water pressure increases until the intergranular stress is reduced to zero, a condition of "initial liquefaction" is reached (Seed, 1976). For loose sands, this condition is usually accompanied by large deformations and ground failure typically occurs.

Ground failure commonly associated with liquefaction may be manifested in several forms: (1) sand boils, (2) flow landslides, (3) lateral spread landslides, (4) ground oscillation, (5) loss of bearing capacity, (6) buoyant rise of buried structures, (7) ground settlement, and (8) failure of retaining walls (National Research Council, 1985). Youd and others (1975) related flow landslides, lateral spread landslides, and bearing capacity failures to the slope of the ground surface. The most common type of liquefaction-induced ground failure is probably lateral spread landsliding. However, the topographic and geologic conditions of Salt Lake County make all eight types of ground failure possible.

## Regional Seismicity

The state of Utah is bisected by the Intermountain Seismic Belt (Fig. 2). The occurrence of earthquakes in the state is common and has been documented since 1850; a plot of the locations of epicenters from July 1962 to September 1974 (Fig. 3) graphically illustrates that earthquakes in Utah are common.

Many known and suspected Quaternary faults have been mapped in Utah (Fig. 4); the Wasatch fault zone is one of the most prominent. The distribution of fault traces (Fig. 4) has a strong relationship with epicenter locations (Fig. 3). Swan and other (1980) investigated the Wasatch fault zone at two sites in the urban corridor of the Wastach front. They estimated that moderate to large magnitude earthquakes ($M_L$ = 6 1/2 to 7 1/2) on the Wasatch fault zone may occur as frequently as 50 to 430 years.

## General Subsurface Conditions

Virtually all of the urbanized area of Salt Lake County was inundated by Pleistocene Lake Bonneville, of which the Great Salt Lake and Utah Lake are remnants. Consequently, most of the sediments in Salt Lake County are probably late Pleistocene or younger in age.

The lake bed sediments of the region generally consist of deposits of sand, silt and clay. The liquefiable sand and silt deposits vary in thickness from several millimeters to several meters and occur throughout Salt Lake County. Extensive gravel deposits are present along the east side of the study area on the upper Lake Bonneville shore lines and along the west side of the study area.

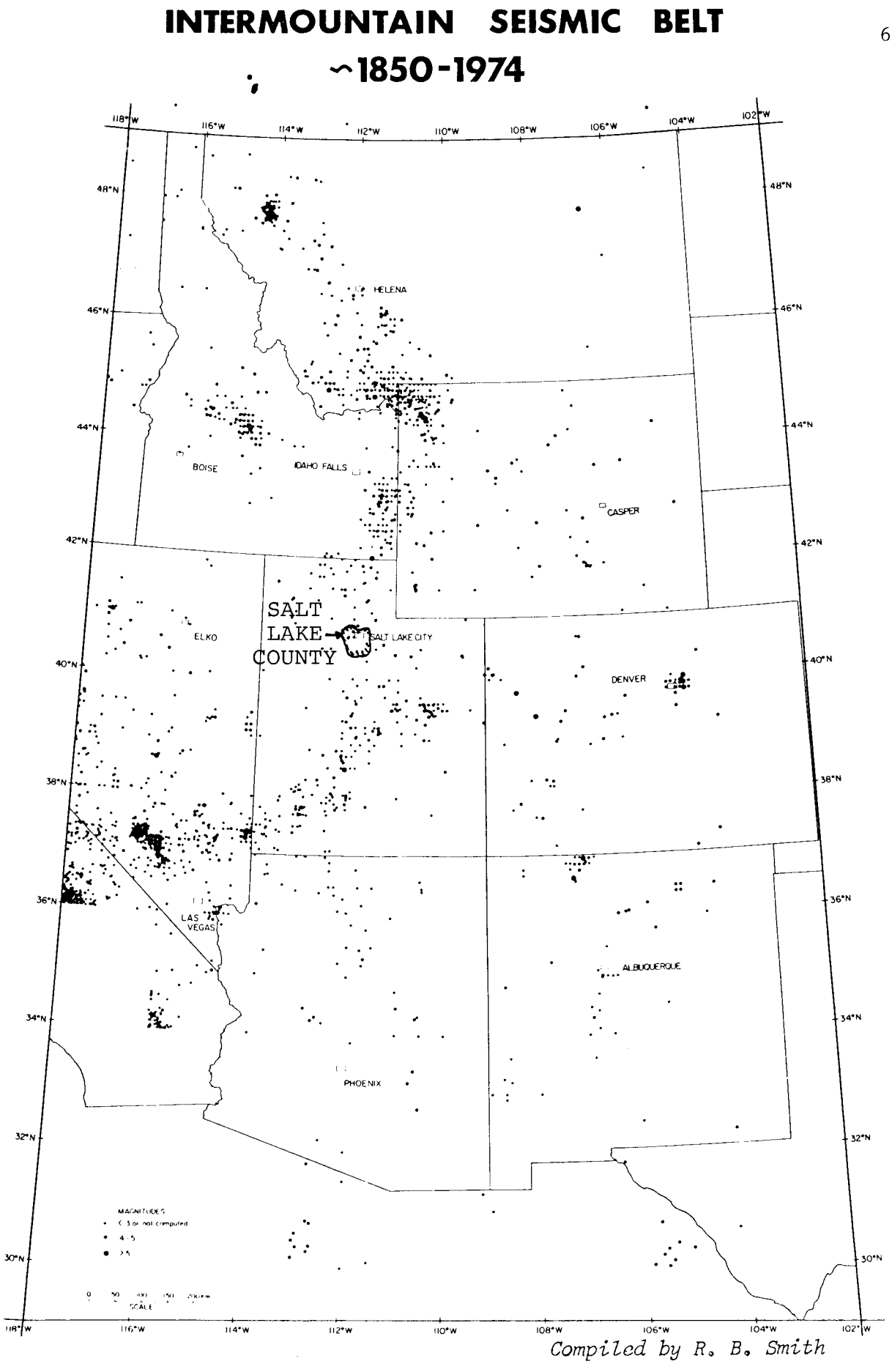



Figure 2. Epicenter Map of Intermountain Seismic Belt (Arabasz and Smith, 1979, p. 3).

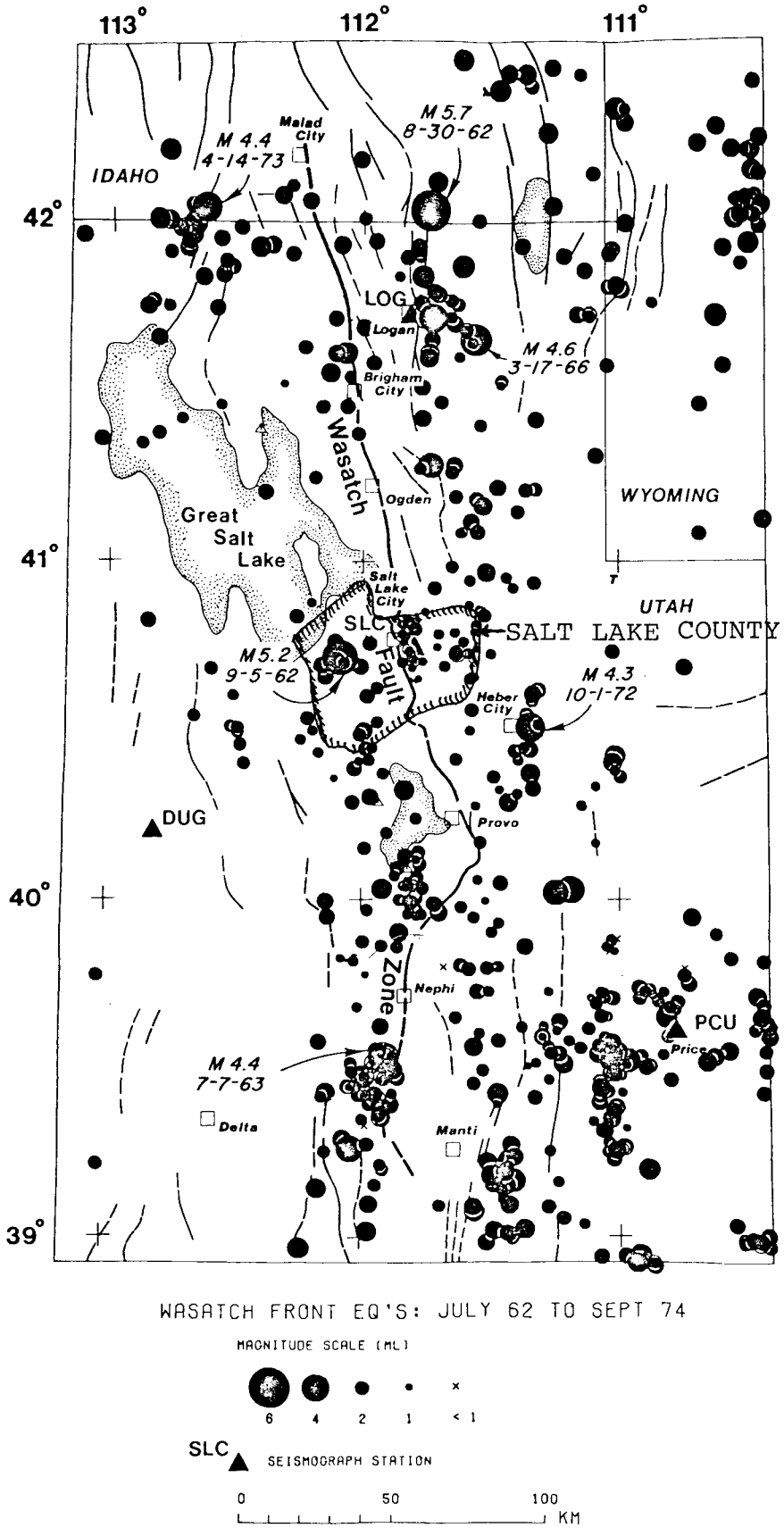



Figure 3. Epicenters of earthquakes in the Wasatch Front area from July 1962 through September 1974. (Arabasz, Smith and Richins, 1979, p. 265).

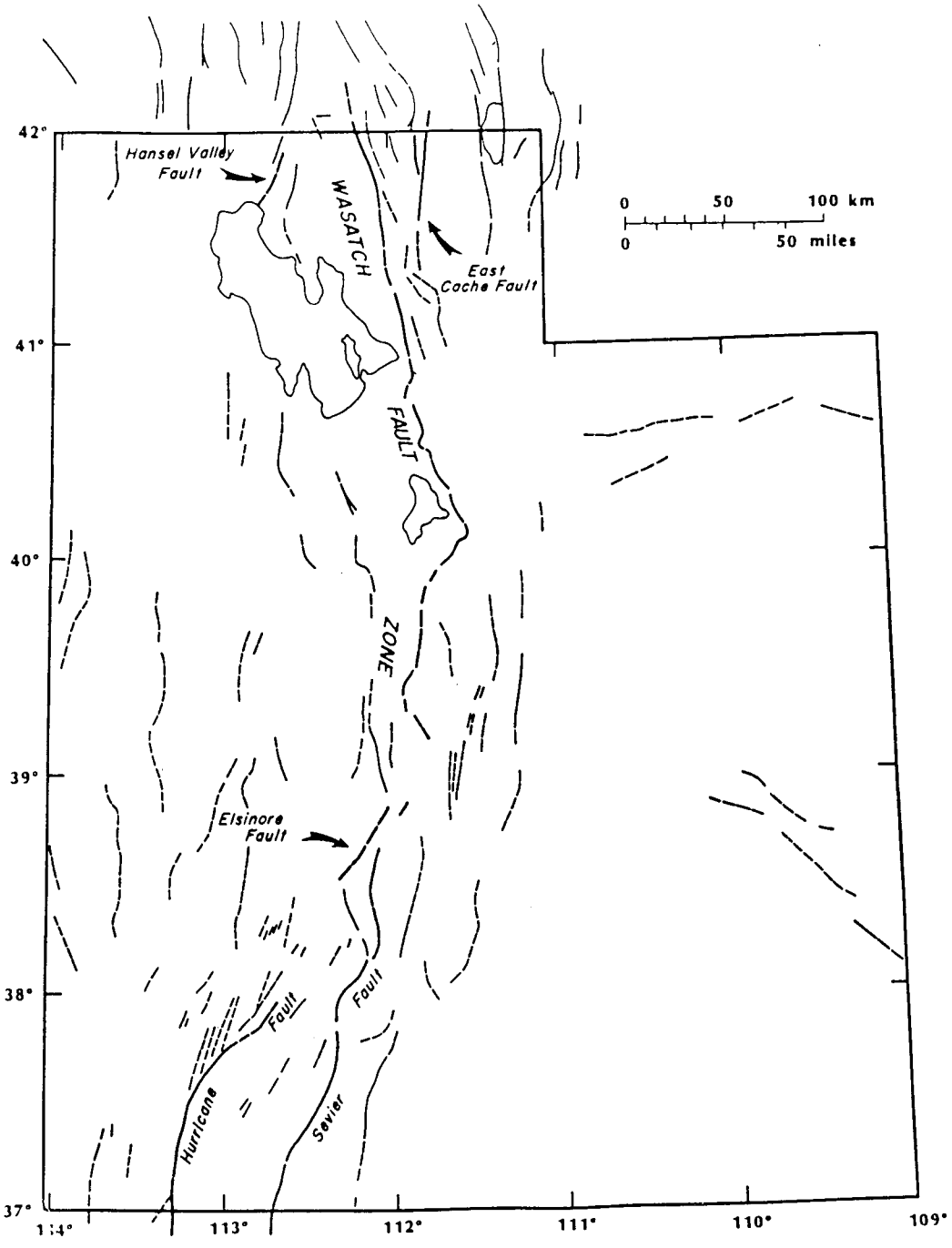



Figure 4. Known and suspected Quaternary faults in Utah (After Arabasz and others, 1979; Anderson and Miller, 1979).

The ground water table in much of the study area is within a few feet of the ground surface and local areas of artesian conditions are present. In the bench areas along the higher shore lines of Lake Bonneville, the water table is generally much deeper but cases of perched ground water are known to exist. Lawn sprinkling and other effects of additional development along the bench areas will probably contribute to the occurrence of perched ground water.

## METHODOLOGY

### General

Subsurface data was collected for selected sites from throughout the Salt Lake County study area. Ground surface accelerations required to induce liquefaction at each site were computed. These acceleration values are referred to as "critical accelerations." The liquefaction potential for each site was then classified as high, moderate, low or very low depending on the probability of the computed "critical" ground surface acceleration being exceeded in 100 years.

### Factors Affecting Liquefaction Potential

The factors affecting liquefaction include soil properties, initial stress conditions, seismic history and the characteristics of the earthquake motion. Aside from saturated conditions, the following factors are considered fundamental: (1) soil type, (2) relative density, (3) initial confining pressure, (4) intensity and duration of ground shaking, (5) soil structure and (6) seismic history.

Deposits of loose fine to medium sand with uniform grain size distributions are generally considered to be the most susceptible to

liquefaction. Soils with more than about 15 percent clay typically have sufficient cohesive strength that liquefaction will not occur. Very loose sands are most susceptible to liquefaction while very dense sands are least susceptible. High confining pressure requires more stress to initiate liquefaction than does low confining pressure. Sands that have been subjected to repeated ground shaking without inducing liquefaction are less susceptible to liquefaction than sands without such a seismic history.

The characteristics of the earthquake motion that affect liquefaction opportunity are the intensity and duration of ground shaking. Consideration of these ground shaking characteristics is important in evaluating liquefaction potential.

## Evaluation of Liquefaction Potential

An evaluation of liquefaction potential at a given site by current state of the art methods involves comparing the predicted cyclic stress ratio ($\tau/\sigma_o'$) that would be induced by a given design earthquake with the cyclic stress ratio required to induce liquefaction. Figure 5 illustrates this comparison. The predicted cyclic stress ratio can be computed using response analysis techniques or by a simplified procedure based on rigid body theory modified to account for the flexibility of the soil profile (Seed, 1976). The simplified theory for computing the cyclic stress ratio induced by an earthquake is given by Eq. 1.

$$\frac{\tau_{av}}{\sigma_o'} \approx 0.65 \frac{a_{max}}{g} \left(\frac{\sigma_o}{\sigma_o'}\right) r_d \qquad (1)$$

where, $a_{max}$ = maximum acceleration at ground surface

$\sigma_o$ = total overburden pressure on sand layer under consideration

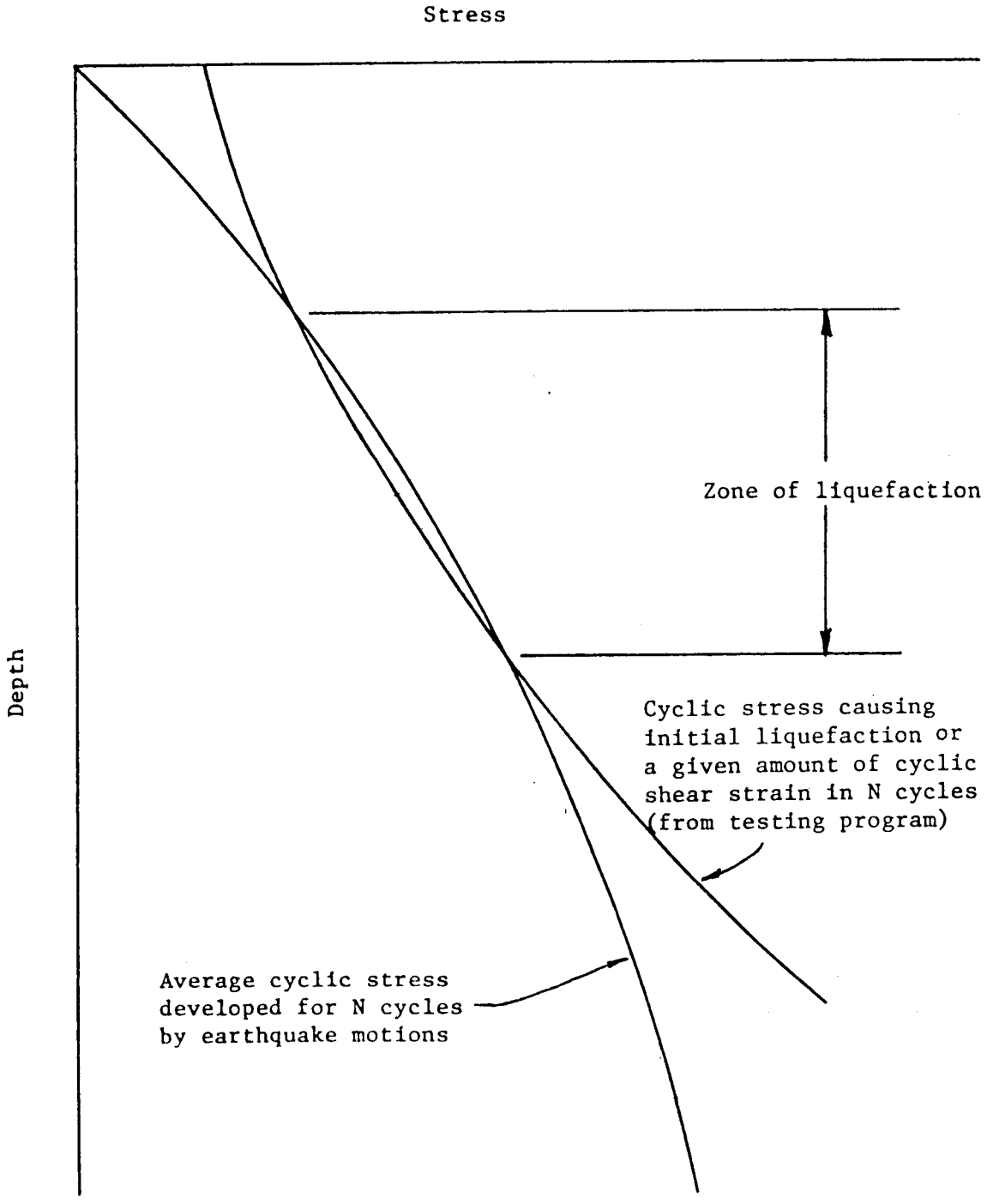



Figure 5. Method of evaluating liquefaction potential (after Seed and Idriss, 1971).

$\sigma_o'$ = initial effective overburden pressure on sand layer under consideration

$r_d$ = a stress reduction factor varying from a value of 1 at the ground surface to a value of 0.9 at a depth of about 30 ft.

The cyclic stress ratio required to cause liquefaction can be evaluated either by laboratory tests on undisturbed samples or by an empirical relationship between some insitu property of the soil and the cyclic stress ratio required to cause liquefaction. Securing undisturbed samples of sand for laboratory testing is a very difficult, if not impossible, task and the use of reconstituted samples would not model the seismic history or structure of the soil deposit. Therefore, the use of laboratory tests to evaluate the cyclic stress required to induce liquefaction in natural deposits is questionable.

Seed, Mori and Chan (1977) have developed an empirical relationship (shown on Fig. 6) between the cyclic stress ratio required to cause liquefaction and the standard penetration resistance of the soil.

Seed (1976) points out that the factors that tend to influence liquefaction susceptibility such as relative density, age of the deposit, seismic history and soil structure also tend to influence the standard penetration resistance in a like manner. Although the penetration test has its shortcomings, if used properly and with judgment, it provides a convenient and rapid method of evaluating the insitu characteristics of sand. The standard penetration test also provides a convenient method to utilize existing data in evaluating liquefaction potential because in the past the most common method to obtain samples of sand has been the standard penetration test.

Silty sands ($D_{50}$ < 0.15mm) have been found to be less liquefiable than clean sands ($D_{50}$ > 0.25mm) for the same penetration resistance,

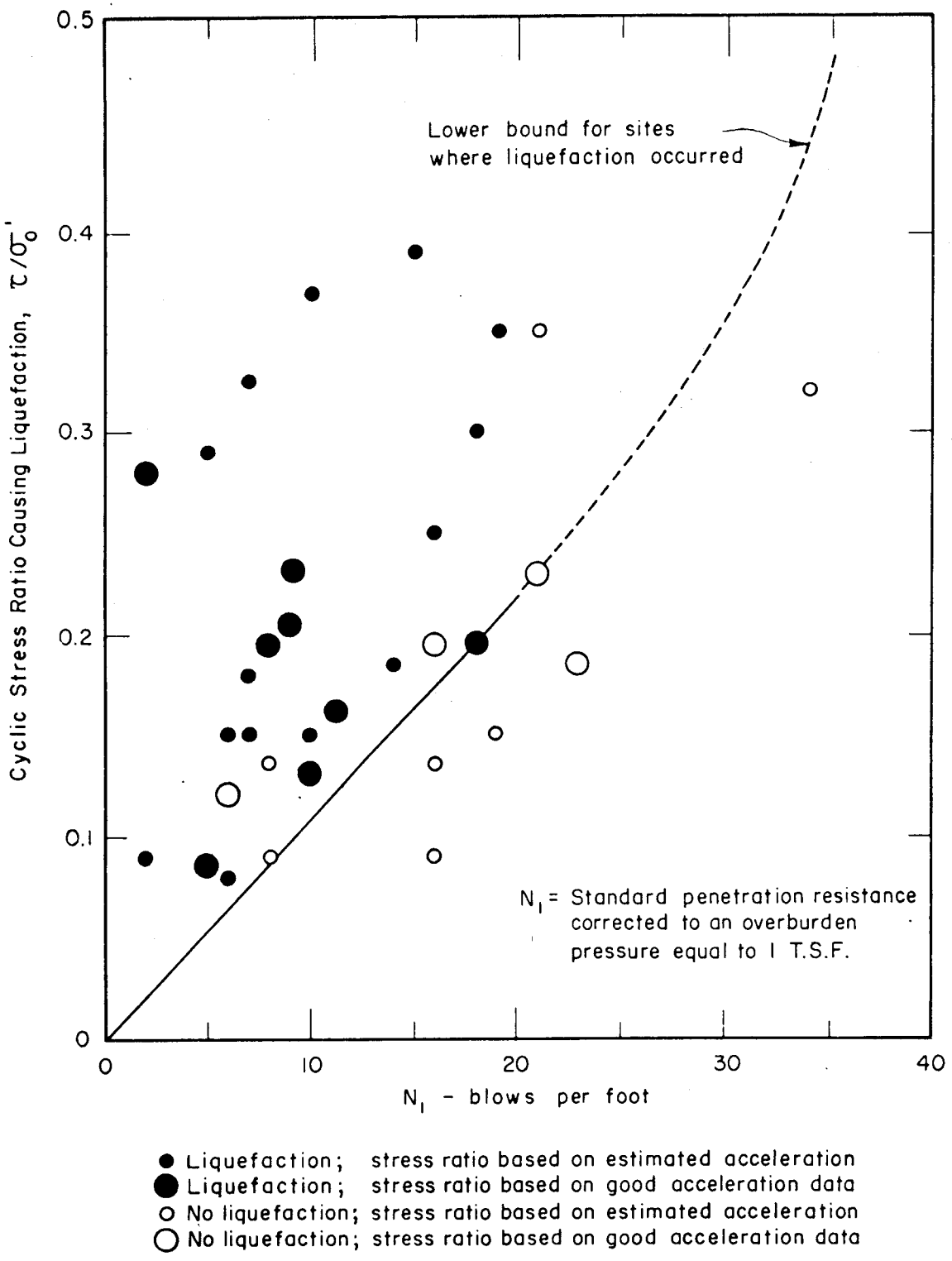



Figure 6. Observed field behavior of sand correlated to cyclic stress ratio and standard penetration resistance (after Seed, Mori and Chan, 1977).

Seed and Idriss (1982). Therefore, correlation between field liquefaction behavior of silty sands and standard penetration resistance has been developed (Tatsuoka and others, 1980) and is shown in Figure 7. The difference in the blow count values between the clean sand and silty sand curves is about 7.5. Therefore, "for silty sand and silts plotting below the A-line and with $D_{50} < 0.15$mm, use N=(N) + 7.5, and then use the standard correlation curves for sands." (Seed and others, 1983, p. 479).

Gibbs and Holtz (1957) correlated standard penetration resistance with relative density and effective overburden pressure. Their work showed that the standard penetration resistance for a constant relative density was a function of the overburden pressure. Therefore, Seed, Mori and Chan (1977) used a standard penetration resistance corrected to an overburden pressure of one ton per square foot in developing the relationship between standard penetration resistance and the cyclic stress ratio required to cause liquefaction given by Fig. 6. A correction factor must also be used with Figure 7. The correction factor used by Seed, Mori and Chan is based on Gibbs and Holtz work and was suggested by Peck, Hansen and Thornburn (1973). The correction factor is applied as follows:

$$N_1 = C_N . N \qquad (2)$$

where,

$$C_N = 1 - 1.25 \log \frac{\sigma_o'}{\sigma_1'}$$

$\sigma_o'$ = effective overburden pressure in tons per square foot where the penetration has a value of N

$\sigma_1'$ = one ton per square foot

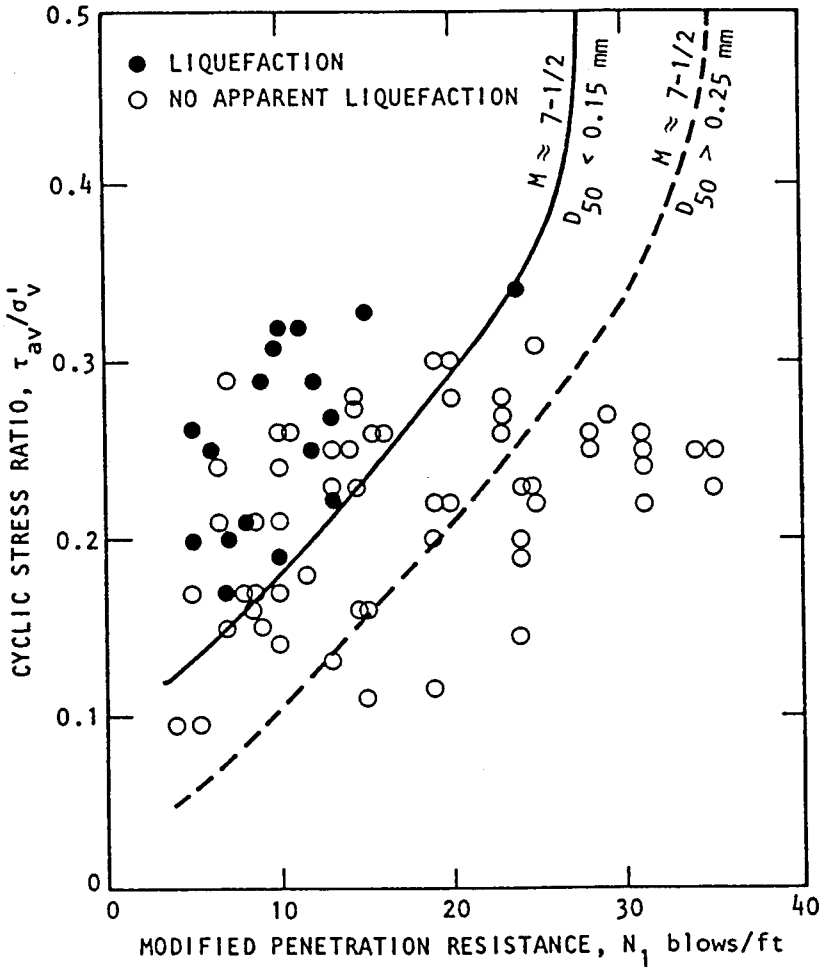



Figure 7. Correlation between field liquefaction behavior of silty sands ($D_{50}$ > 0.15 mm) under level ground conditions and standard penetration resistance (Data after Tokimatsu and Yoshimi, 1981). (From Seed and Idriss, 1982).

## Correlations for Difference Magnitude Earthquakes

Figures 6 and 7 provide a basis for developing correlations between SPT values and liquefaction characteristics of sands and silty sands for magnitude 7.5 earthquakes. These results have been extended to other magnitude events by noting that the main difference between different magnitude earthquakes is the number of cycles of stress which they induce (Table 1).

The relationship between cyclic stress ratio and number of cycles required to cause liquefaction is shown in Figure 8. Therefore, by multiplying the 7.5 magnitude boundary curve in Figure 7 by the scaling factors shown in Figure 8, boundary curves separating sites where liquefaction is likely to occur or unlikely to occur may be determined for different magnitudes (Figure 9).

## Use of SPT Correlation Charts with CPT Data

The main advantages of the cone penetrometer (CPT) are that it provides information rapidly and it provides a continuous record of penetration resistance. The main disadvantage is that the CPT is accompanied by a very limited data base to provide correlation between soil liquefaction characteristics and CPT values (Seed and others, 1983). The test may be used, however, by establishing correlation between the CPT and SPT values at new sites (Douglas and others, 1981), or by using available SPT-CPT correlations from previously conducted studies.

Cyclic stress ratios required to cause liquefaction can be obtained using the CPT values by either converting these values to SPT N values, then normalizing the N values and using the relationship shown in Figure 9, or by normalizing the Q value by use of the equation:

Table 1. Earthquake magnitudes and their associated number of representative cycles (After Seed and Idriss, 1982).

| Earthquake Magnitude, M | No. of representative cycles at $0.65\tau_{max}$ |
|---|---|
| 8½ | 26 |
| 7½ | 15 |
| 6¾ | 10 |
| 6 | 5-6 |
| 5¼ | 2-3 |

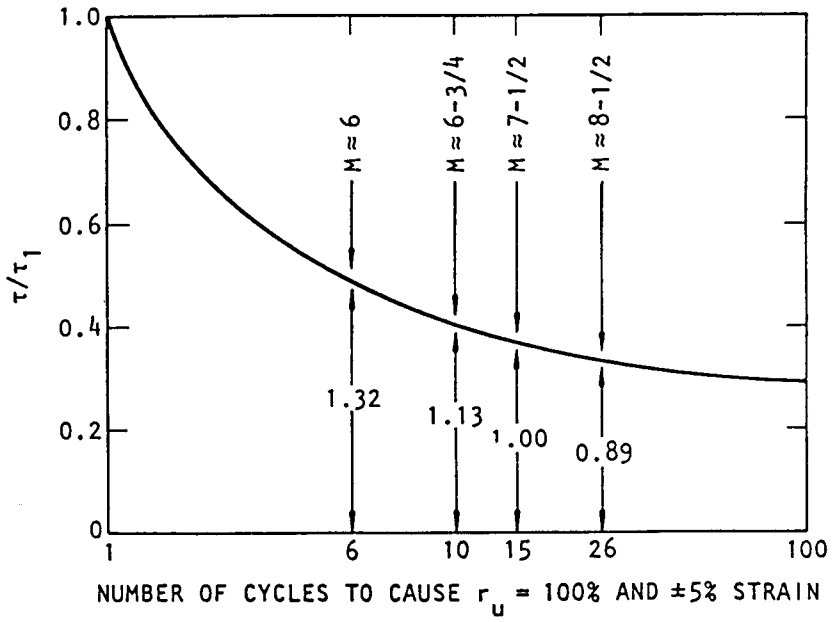



Figure 8. Representative relationship between $\tau/\tau_1$ and the number of cycles required to cause liquefaction (after Seed and Idriss, 1982).

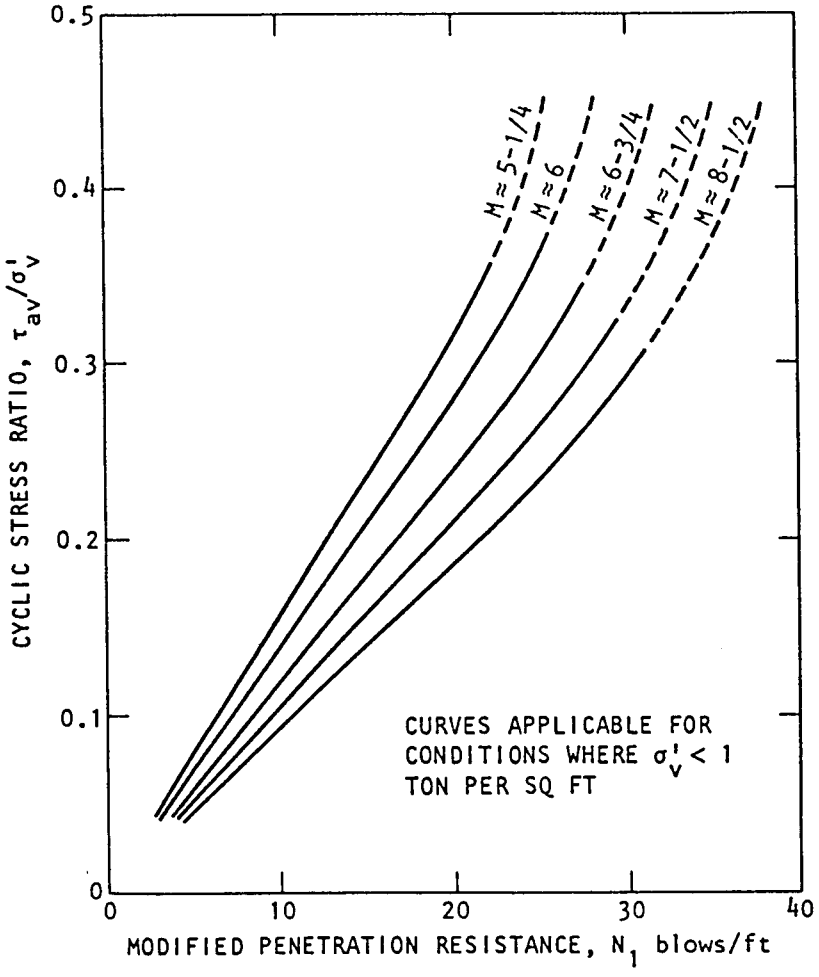



Figure 9. Chart for evaluation of liquefaction potential for sands for different magnitude earthquakes (after Seed and Idriss, 1982).

$$Q_{c1} = Q_c * C \qquad (3)$$

Then with the $Q_{c1}$ values, Figure 10 may be used directly to obtain the critical cyclic stress ratio (Seed and others, 1983).

## Liquefaction Potential Based on Critical Acceleration

Qualitative descriptions of the liquefaction potential in the Salt Lake County study area were assigned on the basis of the probability that the computed values of critical acceleration would be exceeded during a 100 year time period. The critical acceleration for a given location is defined as the lowest value of maximum ground surface acceleration required to induce liquefaction.

The standard penetration test data from soil borings and cone penetrometer data in conjunction with Eq. 1 and Figs. 9 and 10 were used to compute the critical acceleration at numerous locations throughout the study area (Plates 2A and 2B). Equation 1 can be solved for the critical acceleration and stated as:

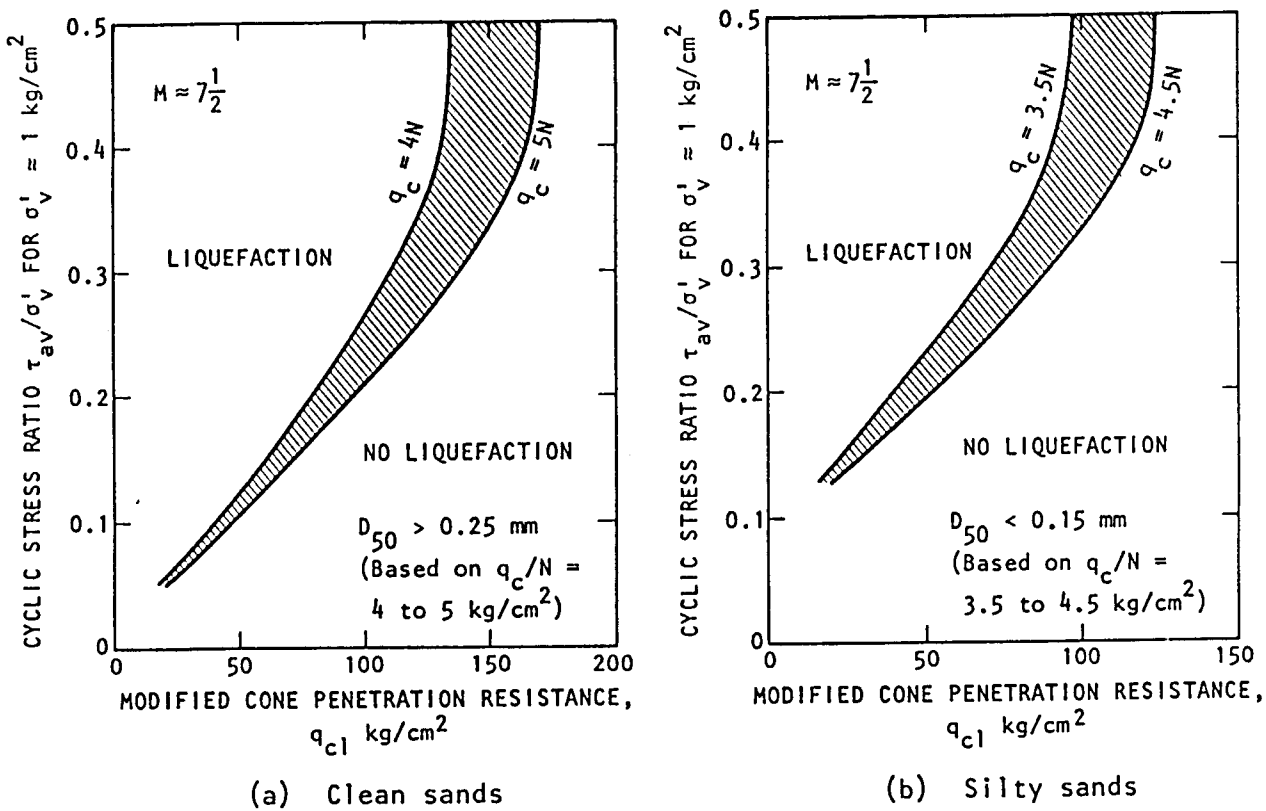
$$(a_{max})_c = \left(\frac{\tau_{av}}{\sigma_o'}\right) \left(\frac{\sigma_o'}{\sigma_o}\right) \left(\frac{1}{0.65\ r_d}\right) \qquad (4)$$

where, $(a_{max})_c$ = critical acceleration (ground surface acceleration required to induce liquefaction at a given site)

$\left(\frac{\tau_{av}}{\sigma_o'}\right)$ = cyclic stress ratio required to cause liquefaction at the given site and obtained from the standard penetration resistance and Figure 6.

$\sigma_o$ = total overburden pressure at the point where the standard penetration resistance is measured.

$\sigma_o'$ = effective overburden pressure at the point where the standard penetration resistance is measured.




(a) Clean sands

(b) Silty sands

Figure 10. Correlation between field liquefaction behavior of sands under level ground conditions and static cone penetration resistance (after Seed and Idriss, 1982).

Note that the cyclic stress ratio, $(\frac{\tau_{av}}{\sigma_o'})$, required to cause liquefaction is computed using Figures 9 and 10 and the standard penetration and cone sounding results from each boring and cone location. The 7 1/2 magnitude curve in Figure 9 was utilized to be consistent with previous studies and in light of suggestions that the characteristic earthquake for the Wasatch fault is in the 7.0 to 7.5 range.

Judgment was required in assigning critical acceleration values. Generally more than one boring log was available for a given site and many standard penetration values were reported for each boring. Therefore, several critical acceleration values were computed for each boring at each site. A value considered to be representative of the critical acceleration was then assigned to the site. In assigning this representative value, consideration was given to consistency within and between borings, to the soil type and to the limitations of the standard penetration test. A single low critical acceleration value at a site was not considered representative if it was not consistent with other critical acceleration values at the site and in the general area. Computer programs aided in the computation of the critical accelerations.

Critical acceleration values were computed for gravelly sand, sand and silty sand, and for sandy silt with generally less than 15 percent clay-size material and a plastic index less than 5. Since the penetration value is the number of blows required to drive a standard sampler one foot, layers being evaluated must be at least one foot thick. For this reason, borings containing sand layers thinner than one foot could not be assigned acceleration values. However, very limited cone penetrometer data did allow computation of critical acceleration values for sand layers less than 1 foot thick.

As stated above, the liquefaction potential was assigned on the basis of the probability that the critical acceleration would be exceeded in 100 years. The probabilities used in assigning liquefaction potential are presented in Table 2.

Table 2. Liquefaction potential related to exceedance probability

| Probability of Exceeding Critical Acceleration in 100 years | Liquefaction Potential |
|---|---|
| > 50% | High |
| 10-50% | Moderate |
| 5-10% | Low |
| < 5% | Very Low |

The probability values delineating liquefaction potential were selected partially on the basis of probability limits frequently used in selecting accelerations for structural design purposes. In structural engineering the concept of dual levels of design accelerations has become widely accepted in recent years. This concept first considers an earthquake with a moderate probability of occurrence during the projected lifetime of a structure; the structure should be designed to remain elastic (completely functional) during the earthquake event. The structure as designed for this first event should then be analyzed to estimate its probable response to a larger event which has a smaller probability of occurrence. The structure would be expected to develop ductility (be damaged) during its response to the second and larger motion but not expected to collapse.

The values usually chosen for these two levels of acceleration are (1) the value which has a 50 percent probability of being exceeded

during the projected life of the structure (the elastic design motion) and (2) a value close to that which has only a 10 percent probability of being exceeded during the life of the structure (the larger acceleration for which the structure may develop ductility). These probability values of 50 percent and 10 percent were set as the limits delineating the high and moderate liquefaction potential categories. A probability value of 5 percent was then arbitrarily selected to separate low and very low liquefaction potential. For planning purposes, a 100-year time period was used.

Other probability limits could have been selected and this would have some effect on the configuration of liquefaction potential categories on the map. However, regardless of the probability values used to define the high, moderate, low and very low classifications, those selected clearly allow a relative assessment of the liquefaction hazard within the study area.

## Liquefaction Potential Map

Computed critical acceleration values for specific sites were plotted on a map of the study area. A two-step procedure was then used to develop the Liquefaction Potential Map. Contours of equal critical acceleration were first drawn on the basis of the critical acceleration values. These contours were used to divide the study area into zones of high, moderate, low and very low liquefaction potential. The contours represented the critical accelerations that had exceedance probabilities of 50, 10 and 5 percent in 100 years.

After the liquefaction potential zones were initially identified from the critical acceleration contours, they were adjusted to reflect

the geology of the area. This adjustment was particularly important because subsurface data and critical acceleration values were available only at selected locations and did not necessarily reflect specific geologic features such as the locations of stream beds and the late Pleistocene Lake Bonneville shore lines.

## Ground Failure Mode

The Liquefaction Potential Map delineates the various liquefaction potential zones. It can be used in conjunction with soil data and ground slope maps to predict the probable type of ground failure. Youd (1978) suggested that the type of ground failure induced by liquefaction is related to the ground surface slope and proposed the relationships between ground slope and failure mode shown in Table 3.

Table 3. Ground slope and expected failure mode (after Youd, 1978)

| Ground Surface Slope | Failure Mode |
|---|---|
| < 0.5% | Bearing capacity |
| 0.5 - 5.0% | Lateral spread |
| > 5.0% | Flow landslide |

The thickness and setting of the sand deposit should also be considered in determining the probable mode of ground failure. For example, a 1 meter-thick loose sand layer at a depth of 10 meters in an otherwise clay soil profile is not likely to cause a flow landslide or a significant bearing capacity failure regardless of the ground surface slope. However, this condition might induce a translational landslide

in steep slopes or magnify ground surface movement due to ground oscillation (lurching) in flat areas.

A Ground Surface Slope Map and a Soil Properties Map were prepared for the study area. These maps can be used in conjunction with the Liquefaction Potential Map to evaluate the potential for various types of ground surface failure.

## GEOTECHNICAL CONDITIONS IN SALT LAKE COUNTY, UTAH

### Geology Related to Liquefaction

#### Introduction

The geology of the urbanized area of Salt Lake County is dominated by erosional and depositional features associated with the several still-stands of pluvial lakes which existed in the Great Salt Lake basin over the past 30,000 or more years. Intermittent displacement along major geologic structures in the Great Basin since early Tertiary time created fault-bounded mountain blocks separated by deep basins (Cook and Berg, 1961, p. 75). The Wasatch fault zone is the dominant structural feature of Salt Lake County.

Geologic materials in Salt Lake County can be characterized into three types: pre-Lake Bonneville materials, Lake Bonneville materials, and post-Lake Bonneville materials. In Salt Lake County, pre-Lake Bonneville materials are not susceptible to liquefaction because they are dense an cemented (indurated). Lake Bonneville materials and post-Lake Bonneville materials exhibit liquefaction potentials ranging from very low to high depending on ground water conditions and proximity to the mountain front. The three types of geologic materials are identified on Plates 1A and 1B, Selected Geologic Data, and are discussed below.

## Pre-Lake Bonneville Materials

These materials constitute the Wasatch Range and the Oquirrh Mountains on the east and west sides of Salt Lake County and underlie lake deposits in the basin. The exposed rocks in Salt Lake County range in age from Precambrian to Quaternary and range in composition from granite to glacial till. Common bedrock types also include limestone, siltstone, shale, sandstone, conglomerate and volcanic rocks (Mansell and Threet, 1960).

The pre-Lake Bonneville materials in the Bonneville basin are significant to liquefaction potential only to the extent that they provided the source of lake sediments. The pre-Lake Bonneville Materials exposed within Salt Lake County are not particularly significant themselves because the currents in the lake distributed widely all but the coarsest sediments. Consequently, a substantial amount of the finer sediment in the lake deposits in Salt Lake County could have been derived from places other than Salt Lake County. However, glaciers in Big and Little Cottonwood Canyons contributed much sediment to the system resulting in significant deltas at the mouths of these two canyons. Currents in the lake tended to drift the materials toward the south along the east side of the basin. The presence of granite rock in the glaciated watersheds is very significant because the mechanical breakdown of these rocks resulted in sand-size pieces of quartz which can be susceptible to liquefaction processes.

## Lake Bonneville Materials

Material Properties. These materials constitute the near-surface sediments in most of the Bonneville basin below an elevation of about 5180 ft. (1580 m). This elevation is significant because it represents

the shore line created by the largest lake in the basin. The elevation of the highest shore line varies considerably from place to place within the basin because of differential isostatic rebound resulting from loading and unloading of the earth's crust with the water impounded by the lake. Tectonic deformations along fault zones also contribute to the variation in elevation of shore lines.

The lake materials are principally silt. Varying amounts of sand, gravel and clay are present with the coarsest fraction being found closest to the mountain front and the finest being found in the central part of the basin.

The lake sediments are commonly thinly bedded. Fine sand layers are commonly present between clayey silt layers. Locally, thick layers of sand are present in the basin. Very coarse sand and gravel are commonly located where lake shore lines were once present.

Age and Elevation of Lake Levels. Four principal lakes occupied the basin in latest Pleistocene time. The basin existed prior to late Pleistocene time and lacustrine sediments undoubtedly accumulated. Evidence for the existence of major lakes in this basin prior to latest Pleistocene time has been obscured by the younger lake deposits. Reinterpretation of evidence used by early workers to substantiate the existence of large lakes in the basin during early late Pleistocene time has recently been done (Scott, 1980; Currey and Oviatt, 1985). The basic conclusion is that the lake at the Bonneville level (elevation 5180 ft. (1580 m) was the largest of the Pleistocene lakes in the basin. Radiocarbon dates on materials collected from the highest beach deposits suggest that Lake Bonneville existed at this level during a

period from about 16,000 to 15,000 years ago (Currey and Oviatt, 1985), with a brief period of lake lowering about 15,500 years ago.

A probable reason that no lakes as large as Bonneville existed prior to about 30,000 years ago is that the Bear River, which formerly flowed to the Snake River, was captured about that time by one of the drainages of the Bonneville basin. With the added volume of water from the Bear River, which drains part of the northern slope of the western Uinta Mountains, inflow greatly exceeded evaporation and the lake rose to its maximum level controlled by topography at Red Rock Pass at the northern end of Cache Valley in Idaho.

The lake appears to have paused at an elevation of about 4480 ft. (1365 m) as the basin was filling. Shore line features at this elevation have been dated at about 21,000 years old (Currey and Oviatt, 1985). The name "Stansbury" was given to shore line features by Gilbert (1890). The lake continued its filling phase to the Bonneville level after a period of approximately 1,000 years.

Approximately 15,000 years ago, Lake Bonneville eroded a channel at Red Rock Pass. The erosion cut quickly through about 365 ft. (110 m) of weakly cemented materials and caused catastrophic flooding of the Snake River Plain (Currey, 1980, p. 74). A new threshold elevation of approximately 4815 ft. (1470 m) was established. The shore features associated with this threshold have been named the Provo shore line. This shore line apparently was occupied from about 15,000 to 14,000 years ago (Currey and Oviatt, 1985, p. 19).

The climate of the basin controlled the lake levels after the Provo shore lines were formed. After 14,000 years ago, evaporation exceeded inflow and the lake dropped about 510 ft. (155 m) to the Gilbert shore

line. This shore line was probably occupied between 11,000 and 10,000 years ago (Currey and Oviatt, 1985). Because of its assigned age, the Gilbert shore line is considered to represent the Pleistocene/Holocene time boundary in the basin.

It appears that a period of desiccation occurred in early Holocene time in the Bonneville basin and only a playa existed in the bottom of what is now the Great Salt Lake. At least twice in the past 3,000 years, the lake has risen to an elevation of 4217 ft. (1285 m) (Currey and others, 1984). The most recent rise to this elevation may have been in about 1700 A.D.

Significance of Lake Environment. The ages of the lake levels are significant for the purpose of comparing the Salt Lake County liquefaction potential analysis to published analyses of other areas. In general, Youd and Perkins (1978, p. 441) considered lacustrine deposits less than 500 years old to have high liquefaction susceptibility. They assigned moderate susceptibility to Holocene lacustrine sediments and Pleistocene lacustrine sediments were considered to have low liquefaction susceptibility.

The results of the current research on liquefaction potential of Salt Lake County and the results previously published for Davis County (Anderson and others, 1986) indicate that sediments deposited in late Pleistocene lakes are highly susceptible to liquefaction. This may result from the restricted ground water lowering that can take place in closed basins. Sea level is the controlling plane for erosion and deposition in coastal areas, such as San Francisco, where much research has been done with respect to liquefaction potential. Lajoie and Helley (1975, p. 50) distinguished younger and older alluvial deposits

on the basis of the sea level stand to which they are graded. Young deposits comprise alluvial fans being formed under existing hydrologic conditions; active streams in young deposits are graded to present sea level. Older alluvial deposits are partly covered by Holocene sediments and were formed by streams which were graded to lower stands of sea level during the late Pleistocene.

The significance of this observation is that late Pleistocene deposits in coastal areas were formed either when sea level was low (e.g., Oxygen Isotype Stage 2 or 6, Shackleton and Opdyke, 1973, p. 45) or deposits formed before the last low stand of sea level were drained and dissected during the last low stand. The 365 ft. (110 m) drop in sea level during Oxygen Isotype Stage 2 (approximately 17,000 years ago) would have a pronounced affect on sedimentation in coastal areas.

The age of the most recent low stand of sea level corresponds fairly well with the high stand of Lake Bonneville. This suggests that the large volume of water constituting glaciers on land masses at this time contributed not only to lower of sea level, but raising Lake Bonneville as well. Therefore, sediments were essentially being dewatered in coastal areas at the same time they were being deposited in Lake Bonneville. Consequently, ages of material relating to liquefaction potential on the basis of research done in coastal areas do not appear appropriate for internally-drained areas such as the Great Sale Lake basin.

Post-Lake Bonneville Materials

These materials have limited distribution in Salt Lake County. Chiefly, they are present along the principal drainage channels entering the Valley from the Wasatch Range and the Oquirrh Mountains and along the Jordan River which bisects the county in a northerly direction.

Relatively isolated alluvial and debris fans are scattered throughout the county.

Five large lateral spread landslides involving lake deposits have been mapped in Davis County by Van Horn (1975a and 1982), and Miller (1980). However, similar evidence of large earthquake induced ground failure in Salt Lake County is lacking. Other landslides in lake deposits have been mapped in Salt Lake County by Van Horn (1972) and evidence for ground failure in lake deposits has been found in the county during the present study. These ground failures are discussed in some detail later in this report on the section pertaining specifically to ground failures.

Post-Lake Bonneville materials have been mapped in Salt Lake County by Van Horn (1966, 1972, 1975, 1979 and 1982) and Miller (1980) and Davis (1983a and b). One of the most dominant processes responsible for deposition of post-Lake Bonneville materials is cloudburst and snowmelt floods (Marsell, 1972). Material deposited by cloudburst is relatively local in nature and typically situated near the mountain front as alluvial fans and debris fans. Large boulders can be carried by the floods which consist of viscous slurries of clay, silt and sand. This process was active in the spring of 1983 due to snowmelt (Anderson and others, 1984)

Most post-lake deposits in Salt Lake County are associated with the channels of the Jordan River, Big and Little Cottonwood Creeks, and other streams draining relatively small areas of the adjacent mountains. Deposits associated with fluctuations of the Great Salt Lake after it fell below the Gilbert shore line also have been considered to be post-

lake to some extent, particularly delta deposits of the Jordan River in the northern part of the county.

Soil Development

In general, aside from local accumulations of alluvial fan, debris fan, and stream deposits, lacustrine materials in Salt Lake County have been continuously exposed as lake levels dropped. The soil survey of the Salt Lake area prepared by Woodward and others (1974) shows no distinctive soil patterns consistent with geologic interpretations.

The distribution of the Jordan silty clay loam provides an example of the lack of correlation between pedogenic soils and geology. This series has been mapped in the north part of the county at an elevation of 4215 ft. (1285 m). The first time these soils were exposed to soil forming processes was in early Holocene time, approximately 10,000 years ago. Yet they have an argillic B horizon (B2t) with strong, medium and course, columnar structure and few moderately thick clay films (Woodward and others, 1974, p. 35-36).

Youd and others (1979, p. 40) used relative development of pedogenic soil profiles to distinguish Holocene and Pleistocene deposits. Pleistocene deposits were generally taken as those possessing argillic B (B2t) horizons which generally requires considerable time for formation. However, in Salt Lake County, younger Holocene soils can also exhibit B2t horizons, so this criteria is not useful in liquefaction susceptibility evaluation.

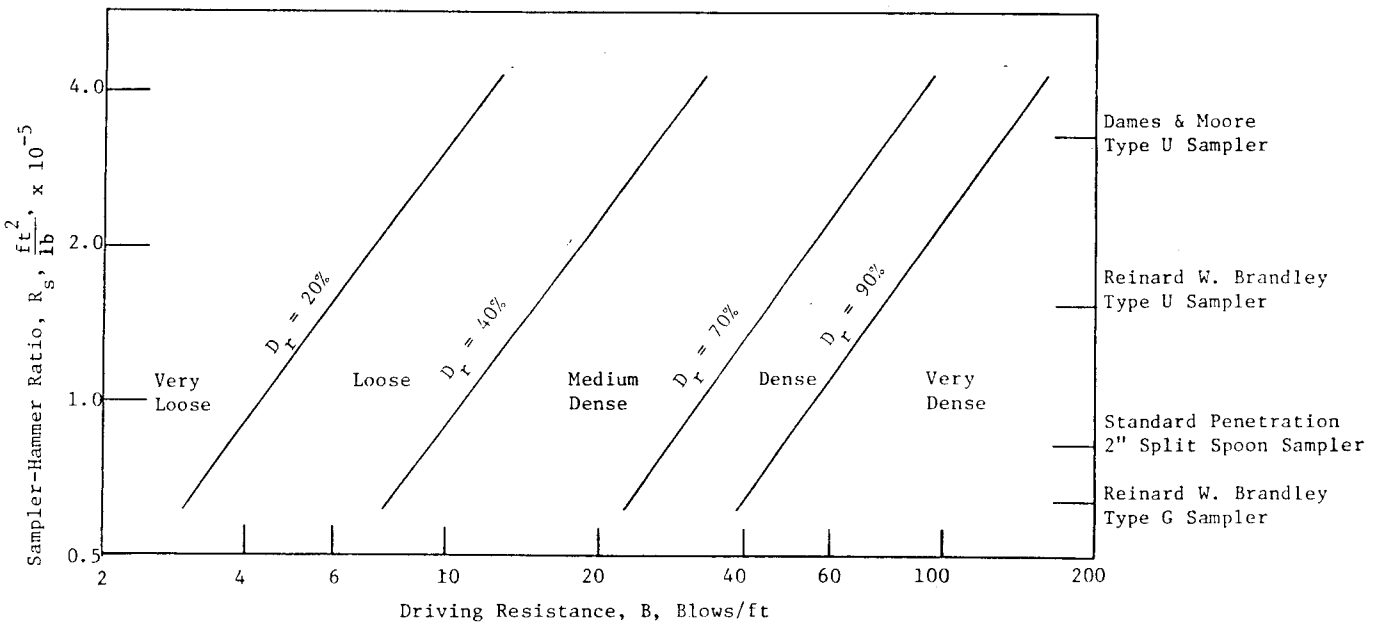
## Geotechnical Data

### Available Subsurface Data

Soils considered to be susceptible to liquefaction are found virtually everywhere within the study area. Consequently, site specific analyses were required to delineate zones of differing liquefaction potential. The necessary soil boring data required to perform a liquefaction analysis included accurate descriptions of the soil profiles, standard penetration resistance data, ground water depth and the grain size characteristics of granular layers. Such information was sought from existing records and supplemented by field and laboratory testing programs.

More than 1,000 soil boring logs were obtained from various consulting firms and government agencies which had performed subsurface investigations within Salt Lake County. Numerous techniques had been used to obtain subsurface information. The standard penetration test was not used by all investigators to measure field densities and to obtain samples. Therefore, it was necessary to convert various (non-standard) penetration values to standard penetration blow count values so that the data could be used with the Seed and Idriss (1982) chart (Fig. 9). The energy conversion technique presented by Lowe and Zaccheo (1975) is shown on Fig. 11 and was used to convert non-standard data.

All existing data was then plotted on the Soils and Ground Water Data Map of the study area shown on Plates 2A, 2B and 2C. The data presented on this map consist of 1) the boring depth, 2) the location of liquefiable deposits, and 3) the depth to ground water.




$$R_s = \frac{D_o^3 - D_i^3}{144\ WH}$$

$D_o$ = Outside Diameter of Sampler, inches

$D_i$ = Inside Diameter of Sampler, inches

W = Weight of Hammer, pounds

H = Height of Drop, inches

$D_r$ = Relative Density, %

Figure 11. Penetration resistance conversion relationship for cohesionless sands and silts (after Lowe and Zacchoe, 1975)

## Field Investigation

Locations for additional subsurface investigations in the study area were selected, based on lack of existing data in those areas. The subsurface investigation consisted of performing borings and cone penetration soundings. Permission was obtained from the landowners where each boring or cone penetration was to be performed.

During a nine day period, 57 electric cone penetration tests (CPT) and during a 10 day period, 20 borings with standard penetration tests (SPT) were performed. The electric cone penetrometer is pushed at a constant rate downward through the soil deposit. The CPT electronically records the resistance at the cone tip and on the cone sleeve. The record was made on a strip chart recorder for both endbearing and sleeve resistance.

The CPT production rate averaged approximately 250 feet per day. When numerous, shallow soundings (less than 20 meters) were made, a large percentage of time was devoted to travel and equipment set up. The production rate also decreased from encountering near surface gravels which stopped penetration. In the northern part of the county where sites were closer together and fewer gravels encountered, the production rate increased to 350 feet per day.

At nine sites where CPT soundings had been conducted, conventional borings were made. The borings took place over a five day period averaging a depth of forty feet. Samples were obtained using a split spoon sampler driven in accordance with requirements of the Standard Penetration Test. Procedural recommendations as given by Seed (1976) were followed. These include the use of drilling mud; two wraps of the

hammer rope around the cathead; a small diameter hole; and the blow count measured over the range of six to eighteen inches of penetration.

The sample depths were based on the results of the CPT soundings. For several sites at which the soundings indicated the presence of thin layered deposits, eighteen inch samples were taken at approximately two and one-half foot intervals. In other instances, the soundings revealed the presence of thick uniform layers throughout the profile. At these sites samples were taken at selected depths.

## Lab Analysis

The laboratory testing program included soil classification according to the Unified Soil Classification System. This system is based on sieve analyses on sandy soils and Atterberg limit determination of silts and clays.

## Soils and Ground Water Data Map

The Soils and Ground Water Data Map shown on Plates 2A, 2B and 2C was prepared to summarize the aerial extent and vertical depth of the liquefiable soil deposits and the ground water conditions in Salt Lake County. The soils and ground water data include:

1. Depths at which liquefiable layers exist
2. Depth to ground water

Ground water contour lines showing zones of various depths to first ground water have been drawn on the map. As shown on Plates 2A through 2D, a letter designation was used to show the range of water table depths.

# Existing Ground Failure

## Introduction

Ground failures involving the lake deposits exist in a few locations in Salt Lake County as shown on the Selected Geologic Data Map, Plates 1A and 1B. The ground failures have been interpreted simply as "landslides" which are not necessarily caused by earthquake shaking. However, earthquake activity could have played a role in the timing of such landslides. Lateral spread landslides have been reported in Davis County (Anderson and others, 1982) and subsurface evidence has been found at several locations Salt Lake County.

## Lateral Spread Failures

Evidence of lateral spread failures has been found at several sites in Salt Lake County. The evidence consists of sand dikes, minor offsets of marker beds, and contorted and folded beds. The areas where these features have been found are located in areas we have identified as having moderate potential for liquefaction. The reason that these locations are not within zones of high liquefaction potential is that current ground water conditions are different now than they must have been at the time of the ground failure.

## Other Ground Failures

A few landslides involving lake deposits have been mapped in Salt Lake County by Van Horn (1972). Earthquake shaking could have played a significant role in initiating the landslides. However, these landslides could be static failures related simply to down-cutting of the streams caused by lowering of lake levels. The down-cutting would tend to create oversteepened slope conditions which promote instability.

## Ground Slope Data

As discussed earlier, the major types of ground failure which result from earthquake-induced liquefaction include flow landslides, lateral spreading landslides, and loss of bearing capacity. Youd (1978) suggests that the type of ground failure induced by liquefaction is related to the ground surface slope. A letter designation was used on Plates 3A and 3B, Ground Slope and Critical Acceleration Map, to show the range of slopes which may be used to predict the type of failure that might occur. The ground slope ranges shown on Plates 3A and 3B were estimated from U.S. Geological Survey topographic quadrangles.

# LIQUEFACTION POTENTIAL

## Critical Acceleration as a Liquefaction Potential Indicator

Critical accelerations computed for specific sites within the study area were assigned liquefaction potential classifications according to the probability that the critical acceleration would be exceeded during the next 100 years. The liquefaction potential and the corresponding exceedance probabilities were discussed earlier and presented in Table 2.

Five seismic risk studies were performed by Dames and Moore in Davis, Salt Lake, and Utah Counties. Figure 12 shows the results of these studies as curves of probability of exceedance vs. ground surface acceleration for a 100 year time period. The average curve shown on Figure 12 was considered to be representative for Salt Lake County and was used to select the critical acceleration boundaries for the various classes of liquefaction potential. Table 4 summarizes exceedance probability data vs. critical acceleration.

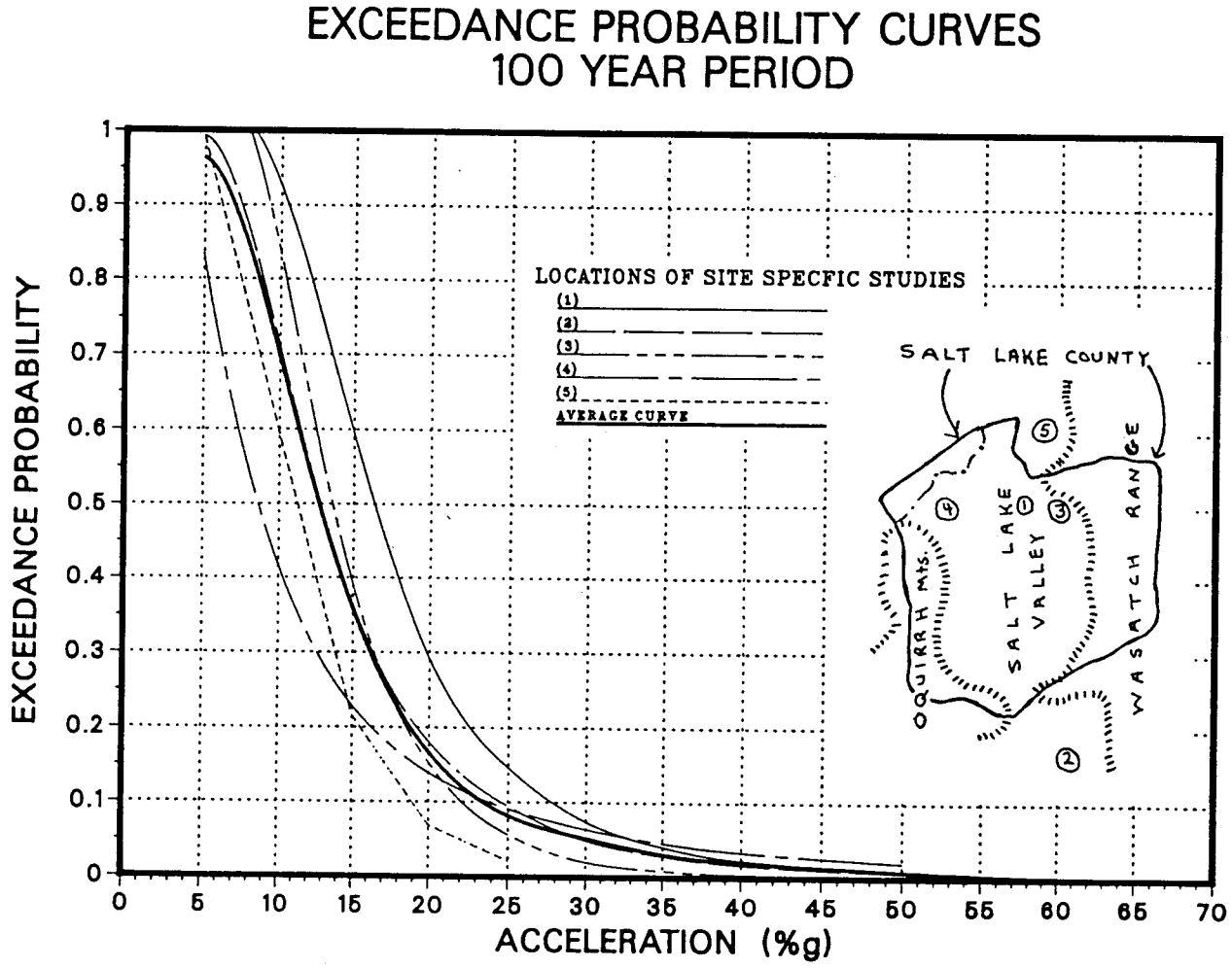



Figure 12. Exceedance Probability Curves (Dames and Moore, 1978).

Table 4. Liquefaction potential related to critical acceleration. (From Dames & Moore, 1978)

| Liquefaction Potential | Critical Acceleration | Approximate 100 year Exceedance Probability |
|---|---|---|
| High | < 0.13 g | > 50% |
| Moderate | 0.13 - 0.23 g | 50 - 10% |
| Low | 0.23 - 0.30 g | 10 - 5% |
| Very Low | > 0.30 g | < 5% |

Symbols were used to illustrate accelerations on the Critical Acceleration Map on Plates 3A and 3B. The symbols are keyed in the explanation on the plates.

The method of evaluating liquefaction potential in this study is based primarily on the results of the standard penetration test which measures the resistance a soil exhibits to driving a standard sampler one foot. Therefore, a critical acceleration value could not be assigned to sand layers less than one foot thick.

## Liquefaction Potential Map

The Liquefaction Potential Map developed for the Salt Lake County study area is shown on Plates 4A and 4B. Liquefaction potential has been classified as high, moderate, low and very low depending on the probability that the critical acceleration will be exceeded in 100 years. As previously discussed, the probable types of ground failure may be predicted by using the Liquefaction Potential Map in conjunction with the Ground Slope Map and the Soils and Ground Water Data Map.

A general summary of the liquefaction potential of Salt Lake County can be made with reference to the ground surface elevations. Generally, the areas most susceptible to liquefaction are below an

elevation of about 4300 ft. The areas with a liquefaction potential classification of very low are located at the higher elevations of the study area as shown on the Liquefaction Potential Map, Plates 4A and 4B.

## CONCLUSIONS AND RECOMMENDATIONS

Ground failure caused by liquefaction is a primary hazard associated with earthquakes. The first step in avoiding this hazard is to recognize where liquefaction might occur. A Liquefaction Potential Map has been compiled for Salt Lake County, Utah showing areas where conditions are favorable for liquefaction to occur.

Fine sand and silty sand are the soil types most conductive to liquefaction and they are found throughout the Salt Lake County study area. Soil type alone, however, does not determine the liquefaction potential of a given site. Several important factors influencing liquefaction potential were considered in this study. The standard penetration test provided a useful means for evaluating the influence of the soil structure, previous seismic history, and age of the deposit as well as the relative density of the soil. An increase in the resistance to liquefaction from any of these factors is reflected by a corresponding increase in the standard penetration resistance.

The standard penetration resistance along with limited cone penetration resistance was used to compute the ground surface acceleration that would be required to induce liquefaction (critical acceleration). The liquefaction potential was then assigned on the basis of the probability that the critical acceleration would be exceeded in 100

years. Local geologic conditions were also considered in refining liquefaction potential boundaries.

The information generated by this study should prove to be valuable for those concerned with future land development. Planners and other concerned parties should realize that areas showing a high liquefaction potential need not be ruled out as possible sites for construction. However, we believe further analyses should be required for these sites including an economic analysis of preventive or protective measures that can be used to reduce the liquefaction potential. Haldar (1980) has developed a decision analysis framework which considers both the technical and economic aspects of limiting or eliminating damage associated with liquefaction. Anderson and Keaton (1986) have presented a decision matrix that relates potential mitigation measures to the liquefaction potential and the proposed land use.

One problem often encountered during this study was how to assess the susceptibility of thin sand layers and lenses. Since the standard penetration test primarily was used as a basis for this study, reliable data could only be obtained for sand strata greater than one foot thick. Damages associated with the liquefaction of thin sand layers and lenses are not uncommon (Seed, 1968) but an accurate means for identifying the relative density of such strata has not been developed. The cone penetrometer provides a direct means for continuously identifying liquefaction susceptibility in a soil profile and was used on a limited basis in this study. The cone penetrometer offers an economical means of providing continuous subsurface profiles, however, the validity of the data is still somewhat questionable because of the relatively small

amount of correlation data between the cone penetrometer and soil liquefaction characteristics (Seed and others, 1983).

It is recommended that the liquefaction potential map be updated continually as more soil boring information becomes available and as new and improved techniques are developed for analyzing liquefaction.

# LIST OF REFERENCES

Algermissen, S.T., and D.M. Perkins. 1972. A technique for seismic zoning: general considerations and parameters: Proc. Int'l Conference on Microzonation, Seattle, Washington, p. 865-878.

Anderson, L.R., J.R. Keaton, K. Aubry, and S.J. Ellis. 1982. Liquefaction Potential Map for Davis County, Utah. Final report to the U.S. Geological Survey by Utah State University. Contract No. 14-08-0001-19127.

Anderson, L.R., J.R. Keaton, T.F. Saarineen, and W.G. Wells, II. 1984. The Utah Landslides, Debris Flows, and Floods of May and June 1983. Committee on Natural Disasters, Commission on Engineering and Technical Systems, National Research Council.

Anderson, L.W. and D.G. Miller. 1979. Quaternary Faulting in Utah: In Proceedings of Conference X, Earthquake Hazards Along the Wasatch and Sierra-Nevada Frontal Fault Zones, National Earthquake Hazards Reduction Program, 29 July - 1 August, 1979. U.S. Geological Survey Openfile report 80-801, p. 194-226.

Arabasz, Walter J., R.B. Smith and W.D. Richins. 1979. Earthquake Studies in Utah, 1850-1978. University of Utah Seismograph Stations, Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah.

Baligh, M.M., V. Vivatrat and C.C. Ladd. 1980. Cone penetration in soil profiling. Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT4, Proc. Paper 15377, April. p. 447-461.

Coffman, J.L. and C.A. von Hake. 1973. Earthquake history of the United States: National Oceanic and Atmospheric Administration, publication 41-1.

Cook, K.L. and J.W. Berg, Jr. 1961. Regional gravity survey along the central and southern Wasatch Front, Utah: U.S. Geological Survey Professional Paper 316-E, p. 75-89, 1 Plate.

Currey, D.R. 1980. Coastal geomorphology of Great Salt Lake and Vicinity: in Gwynn, J.W., ed., Great Salt Lake, a Scientific, Historical and Economic overview: Utah Geological and Mineral Survey, Bulletin 116, p. 69-82.

Currey, D.R., Genevieve Atwood, and D.R. Mabey. 1984. Major levels of Great Salt Lake and Lake Bonneville: Utah Geological and Mineral Survey Map 73.

Currey, D.R. and C.G. Oviatt. 1985. Durations, average rates, and probable causes of Lake Bonneville expansions, still stands, and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago: in Kay, P.A. and Diaz, H.F., eds. Problem of and prospects for predicting Great Salt Lake levels, Conference Proceedings, Center for Public Affairs and Adminstration, University of Utah, p. 9-24.

Dames and Moore. 1978. Final report, Development of criteria seismic risk mapping in Utah, for State of Utah Department of Natural Resources Seismic Safety Advisory Council. Unpublished Consultants Report. July 20. 14 p.

Davis, F.D. 1983a. Geologic Map of the Central Wasatch Front, Utah: Utah Geological and Mineral Survey, Map 54-A.

Davis, F.D. 1983b. Geologic Map of the Southern Wasatch Front, Utah: Utah Geological and Mineral Survey, Map 55-A.

Gibbs, H.J. and W.G. Holtz. 1957. Research on determining the density of sands by spoon penetration testing. Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering. London.

Gilbert, G.K. 1980. Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Haldar, A. 1980. Liquefaction study - a decision analysis framework. Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT12m Proc. paper 15925. December. p. 1297-1312.

Hely, A.G., R.W. Mower, and C.A. Harr. 1971. Water Resources of Salt Lake County, Utah: Utah Department of Natural Resources Technical Publication No. 31, 244 p.

Hill, R.J. 1979. A liquefaction potential map for Cache Valley, Utah. Unpublished M.S. thesis. Utah State University Library, Logan, Utah.

Lajoie, K.R. and E.J. Helley, 1975. Differentiation of sedimentary deposits for purposes of seismic zonation: in Borcherdt, R.D., ed., Studies for seismic zonation of the San Francisco Bay Region, U.S. Geological Survey, Professional Paper 941-A, p. 39-51.

Lowe, John and Philip Zaccheo. 1975. Subsurface explorations and sampling. Chapter 1 of Foundation Engineering Handbook, Hans F. Winterkorn and Hsai-Yang, Eds. Van Nostrand Reinhold Co., New York, New York. p. 1-66.

Marsell, R.E. 1972. Cloudburst and snowmelt floods, in Environmental geology along the Wasatch Front, 1971: Utah Geological Association Publication 1, p. N1-N28.

Marsell, R.E. and R.L. Threet. 1960. Geologic map of Salt Lake County, Utah: Utah Geological and Mineral Survey, R.S.83.

McGregor, E.E., Richard Van Horn, and Ted Arnow. 1974. Map showing the thickness of loosely packed sediments and the depth of bedrock in the Sugar House Quadrangle, Salt Lake County, Utah: U.S. Geological Survey map I-766-M.

Miller, R.D. 1982. Surficial geologic map along part of the Wasatch Front, Salt Lake Valley, Utah: U.S. Geological Survey Map MF-1198.

Nichols, D.R. and J.M. Buchanan-Banks. 1974. Seismic hazards and land-use planning: U.S. Geological Survey Circular 690.

Peck, R.B., W.E. Hanson and T.H. Thornburn. 1974. Foundation engineering, second edition. John Wiley and Sons, Inc., New York. 514 p.

Schmertmann, J.H. 1978. Study of feasibility of using Wissa-type piezometer probe to identify liquefaction potential of saturated fine sands. Technical Report S-78-2, U.S. Army Engineer Waterways Experiment station. February. 73 p.

Scott, W.E. 1980. New interpretations of Lake Bonneville stratigraphy and their significance for studies of earthquake hazard assessment along the Wasatch Front: Proceedings of Conference X, Earthquake Hazards along the Wasatch and Sierra-Nevada Frontal Fault Zones, National Earthquake Hazards Reduction Program, 29 July - 1 August 1979, U.S. Geological Survey Openfile report 80-801, p. 548-576.

Seed, H.B. 1968. Landslides during earthquakes due to soil liquefaction. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM5, Proc. Paper 6110. September. p. 1053-1122.

Seed, H.B. 1975. Earthquake effects on soil foundation systems. Chapter 25 of Foundation Engineering Handbook, Hans F. Winterkorn and Hsai-Yang Fang, Eds. Van Nostrand Reinhold Co., New York, New York. p. 700-732.

Seed, H.B. 1976. Evaluation of soil liquefaction effects on level ground during earthquakes. Preprint 2752, State-Of-The-Art Paper, ASCE Annual Convention and Exposition, Philadelphia, Pennsylvania. September 27 - October 1.

Seed, H.B. 1979. Soil liquefaction and cyclic mobility for level ground during earthquakes. Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, Proc. Paper 14380. February. p. 201-255.

Seed, H.B., K. Mori and C.K. Chan. 1977. Influence of seismic history on liquefaction of sands. Journal of The Geotechnical Engineering Division, ASCE, Vol. 103, No. GT4, Proc. Paper 12841. April. p. 257-270.

Seed, H.B. and W.H. Peacock. 1971. Test procedures for measuring soil liquefaction characteristics. Journal of the Soil Mechanics and Foundations Division, ASCE; Vol. 97, No. SM8, Proc. Paper 8330. August.

Shackleton, N.J. and N.D. Opdyke. 1973. Oxygen isotype and paleomagnetic stratigraphy of Equatorial Pacific core V28-238: oxygen isotype temperatures and ice volumes on a $10^5$-year and $10^6$-year scale: Quaternary Research Vol. 3, p. 39-55.

Van Horn, Richard. 1966. Preliminary geologic map of the southern half of Fort Douglas quadrangle, Salt Lake County, Utah: U.S. Geological Survey Openfile report, 2 pls.

Van Horn, Richard. 1972. Surficial geologic map of the Sugar House quadrangle, Salt Lake County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-776-A, scale 1:24,000.

Van Horn, Richard, J.L. Baer, and E.F. Pashley, Jr. 1972. Landslides along the Wasatch Front, Utah, in Environmental geology of the Wasatch Front, 1971: Utah Geological Association Publication 1, p. J1-J-16.

Van Horn, Richard. 1975a. Largest known landslide of its type in the United States; a failure by lateral spreading in Davis County, Utah: Utah Geology, Vol. 2, No. 1, p. 83-87.

Van Horn, Richard. 1975b. Unevaluated reconnaissance geologic maps of Salt Lake and Davis Counties west of the Wasatch Front, Utah: U.S. Geological Survey Openfile Report 75-616, 29 pls., scale 1:48,000.

Van Horn, Richard. 1979. Surficial geologic map of the Salt Lake City South quadrangle, Salt Lake County, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1173, scale 1:24,000.

Van Horn, Richard. 1982. Surficial geologic map of the Salt Lake City North Quadrangle, Davis and Salt Lake Counties, Utah: U.S. Geological Survey Map I-1404.

Woodward, Lowell, J.L. Harvey, K.M. Donaldson, J.J. Shiozaki, G.W. Leishman, and J.H. Broderick. 1974. Soil survey of Salt Lake area, Utah: U.S. Soil Conservation Service, 132 p., 58 maps, scale 1:20,000.

Youd, T.L. 1978. Major cause of earthquake damage is ground failure. Civil Engineering, ASCE, Volume 48, No. 4, April. p. 47-51.

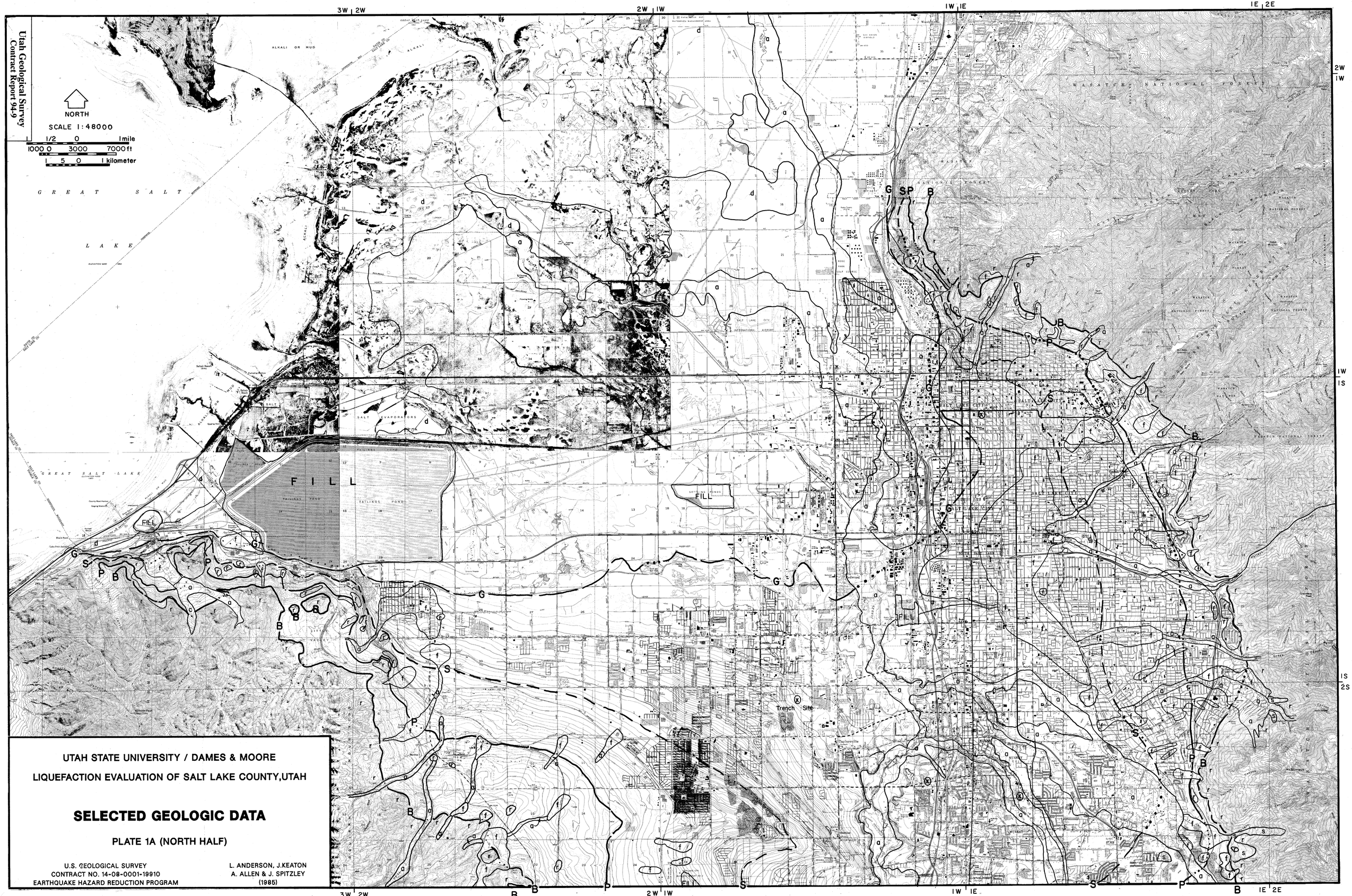
Youd, T.L. 1981. Engineer, U.S. Geological Survey, Menlo Park, California, personal communication.

Youd, T.L. and S.N. Hoose. 1977. Liquefaction susceptibility and geologic setting. Proceedings of the 6th World Conference on Earthquake Engineering, New Delhi, India. January 10-14.

Youd, T.L. and David M. Perkins. 1978. Mapping liquefaction-induced ground failure potential. Journal of the Geotechnical Engineering Division, ASCE. 104(GT4):433-446.

Youd, T.L., D.R. Nichols, E.J. Helley and K.R. Lajoie. 1975. Liquefaction potential: in Borcherdt, R.D., ed., Studies for seismic zonation of the San Francisco Bay Region, U.S. Geological Survey Professional Paper 941-A, p. A68-A74.

Youd, T.L., J.C. Tinsley, O.M. Perkins, E.J. King, and R.F. Preston. 1979. Liquefaction Potential Map on San Fernando Valley, California: in Brabb, E.E., ed., Progress on Seismic Zonation in the San Francisco Bay Region: U.S. Geological Survey Circular 807, p. 37-48.




UTAH STATE UNIVERSITY / DAMES & MOORE

LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

## SELECTED GEOLOGIC DATA

PLATE 1A (NORTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J. KEATON
A. ALLEN & J. SPITZLEY
(1985)

NORTH

SCALE 1:48000

1 1/2 0 1 mile

1000 0 3000 7000 ft

1 .5 0 1 kilometer

## EXPLANATION

Pre-Lake Bonneville Materials
chiefly above elevation 1580m (5180 ft).

- r Undifferentiated pre-lake materials; ranges in age from Precambrian to late Pleistocene, ranges in composition from granitic rock to limestone.

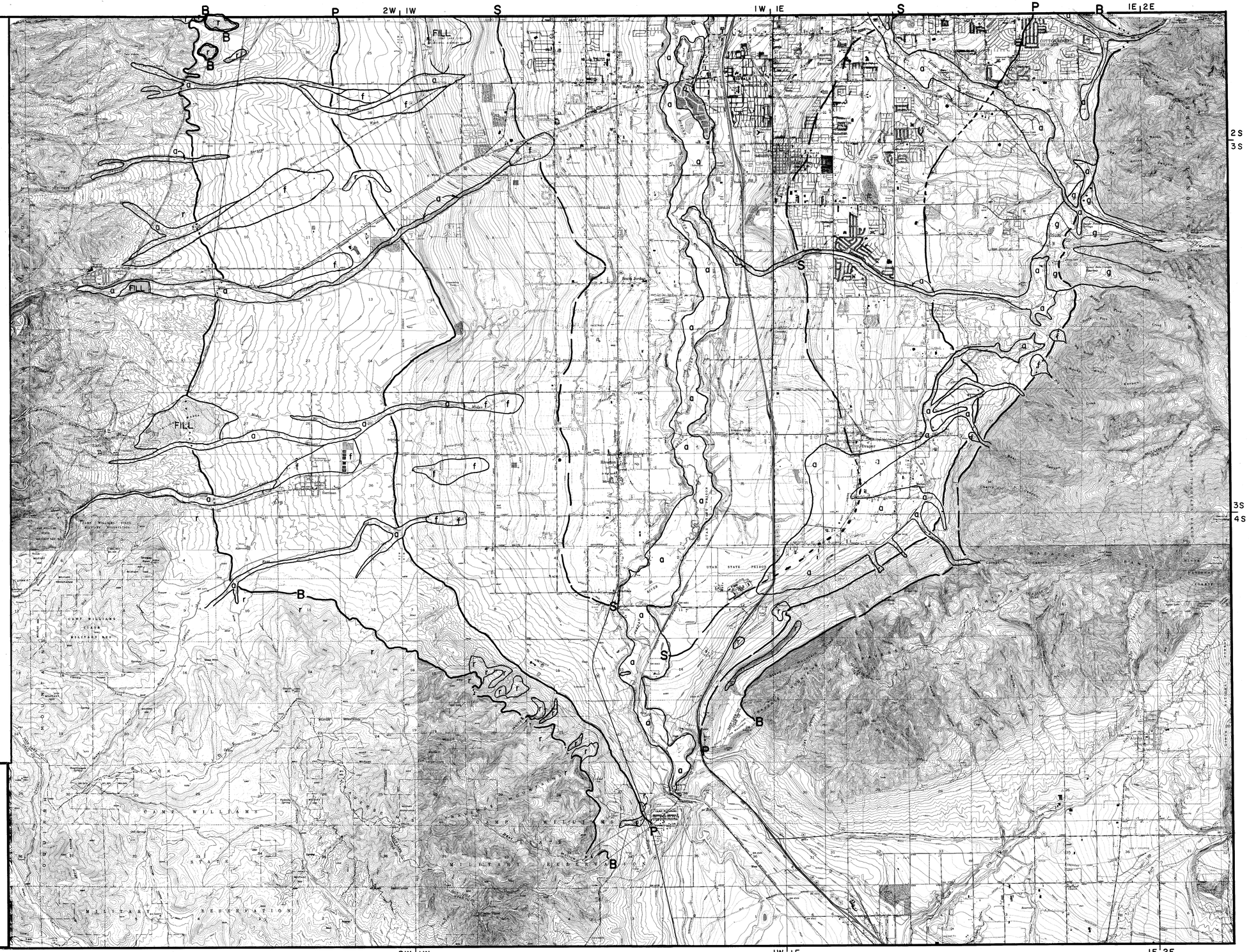
Lake Bonneville Materials
below elevation 1580m (5180 ft); interbedded silty clay and fine sand at lower elevations with coarse sand and gravel along former beach lines. Age distinguished by shoreline features.

- —B— Bonneville Shoreline; elevation ▲1580m (5180 ft), age 16,000 to 14,000 years B.P.
- —P— Provo Shoreline; elevation ▲1470m (4815 ft), age 14,000 to 13,000 years B.P.
- —S— Stansbury Shoreline; elevation ▲1365m (4480 ft), age 23,000 to 20,000 years B.P.
- —G— Gilbert Shoreline; elevation ▲1290m (4240 ft), age 11,000 to 10,000 years B.P.

Post-Lake Bonneville Materials
at varying elevations but chiefly below 1580m (5180 ft).

- a Stream Deposits
- f Alluvial fan and debris fan deposits
- d Delta deposits
- g Glacial deposits
- s Slide deposits

⊗ TRENCH SITE




Utah Geological Survey
Contract Report 94-9

UTAH STATE UNIVERSITY / DAMES & MOORE

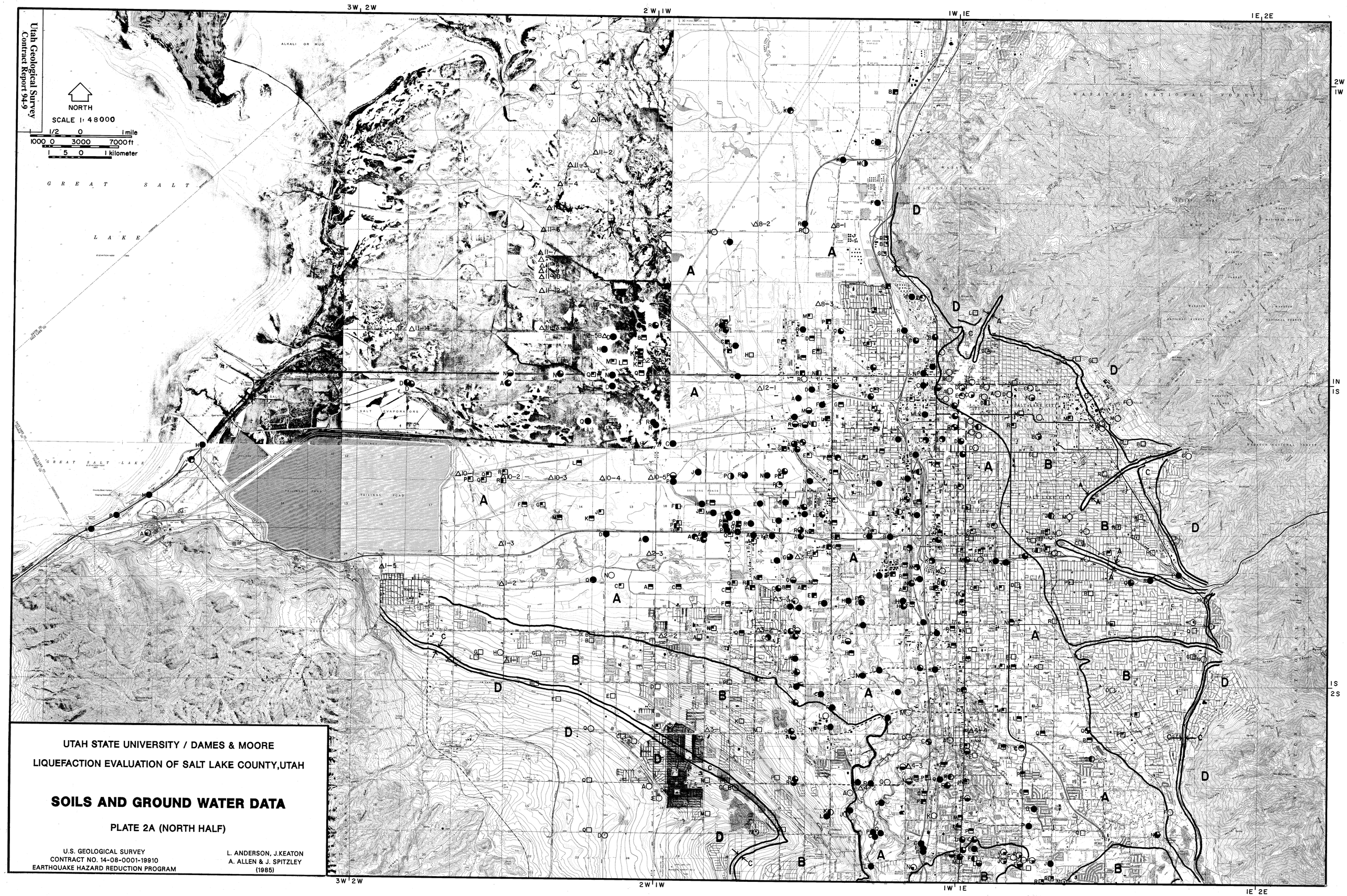
LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# SELECTED GEOLOGIC DATA

PLATE 1B (SOUTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J. KEATON
A. ALLEN & J. SPITZLEY
(1985)




UTAH STATE UNIVERSITY / DAMES & MOORE

LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# SOILS AND GROUND WATER DATA

PLATE 2A (NORTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J.KEATON
A. ALLEN & J. SPITZLEY
(1985)

NORTH

SCALE 1:48000

1 1/2 0 1 mile

1000 0 3000 7000 ft

1 .5 0 1 kilometer

EXPLANATION

Soils Data

I

I = Location of Boring within Section

△ = Cone Penetrometer Test

| | | | |
|---|---|---|---|
| D | C | B | A |
| E | F | G | H |
| M | L | K | J |
| N | P | Q | R |

26

| Symbol | Depth of Boring |
|---|---|
| ○ | > 30.0 feet |
| □ | < 30.0 feet |

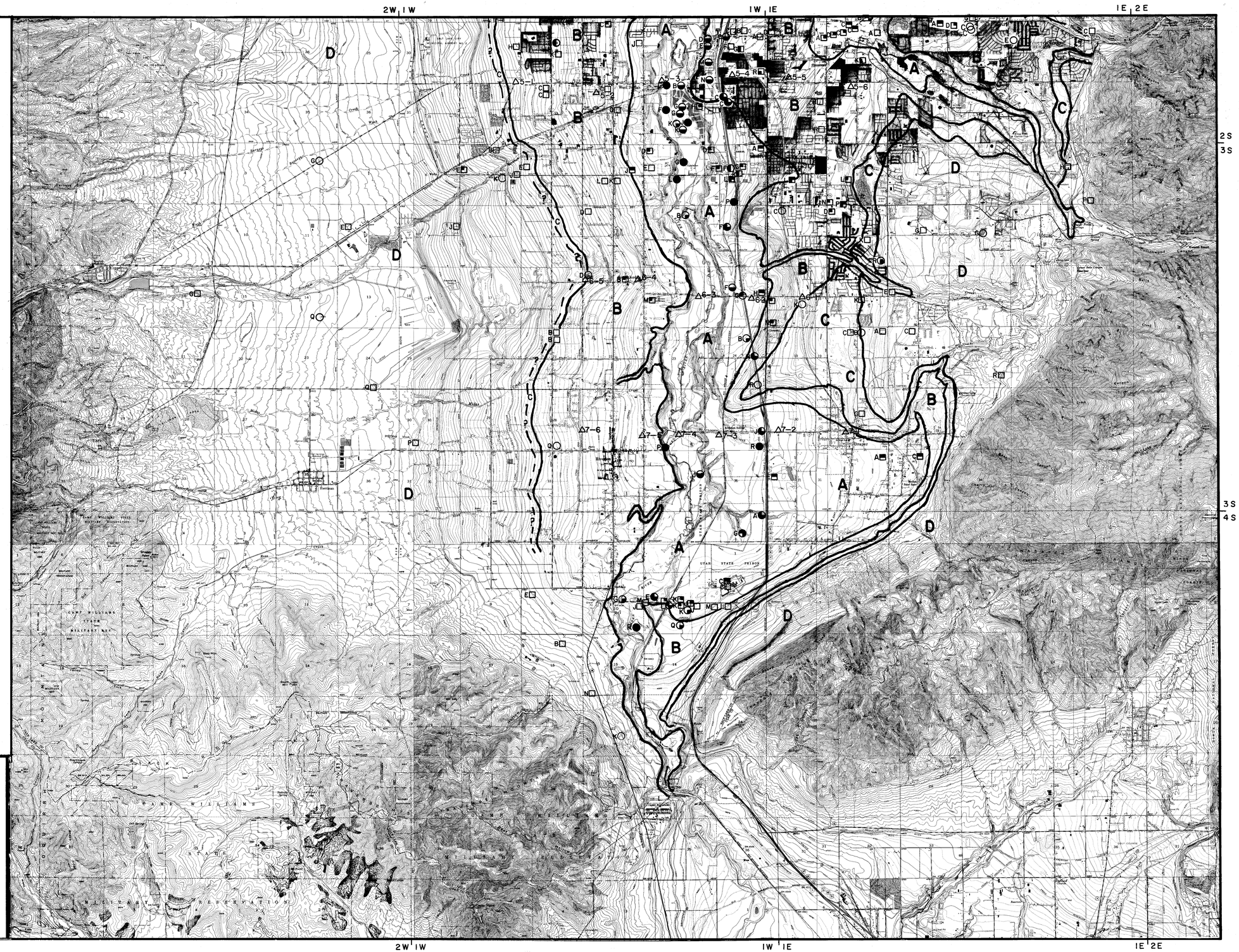
| Symbol | Depth of Liquefiable Deposits |
|---|---|
| ◔, ◪ | 0 - 10.0 feet |
| ◑, ◨ | 10.0 - 20.0 feet |
| ◕, ◩ | 20.0 - 30.0 feet |
| ◕ | > 30.0 feet |

Ground Water Data

Letter Indicates depth to water table

| Letter | Depth to Ground Water |
|---|---|
| A | 0 - 10.0 feet |
| B | 10.0 - 30.0 feet |
| C | 30.0 - 50.0 feet |
| D | > 50.0 feet |

Note: Ground Water and Soil Data found in Appendix




Utah Geological Survey
Contract Report 94-9

UTAH STATE UNIVERSITY / DAMES & MOORE

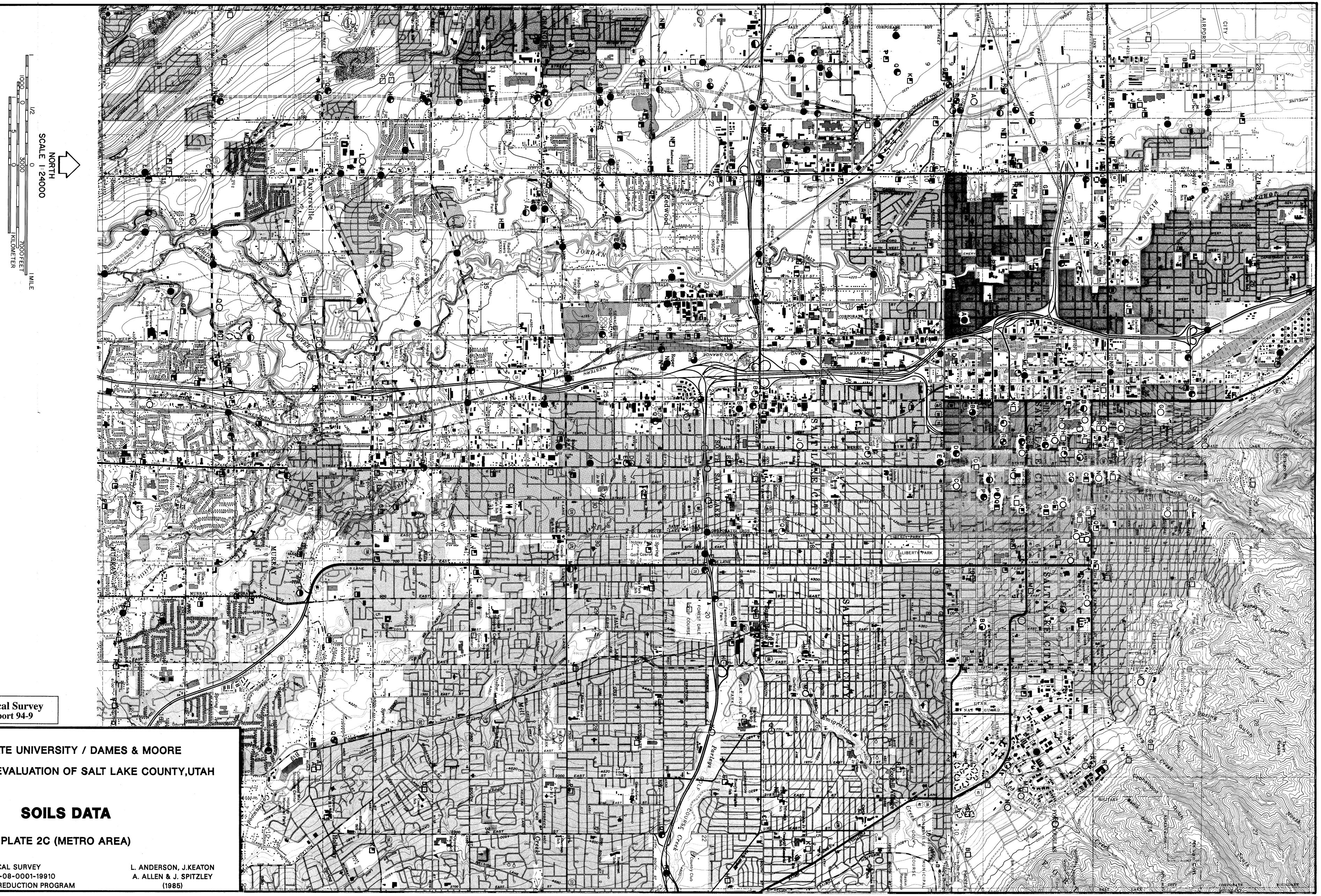
LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# SOILS AND GROUND WATER DATA

PLATE 2B (SOUTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J. KEATON
A. ALLEN & J. SPITZLEY
(1985)




UTAH STATE UNIVERSITY / DAMES & MOORE

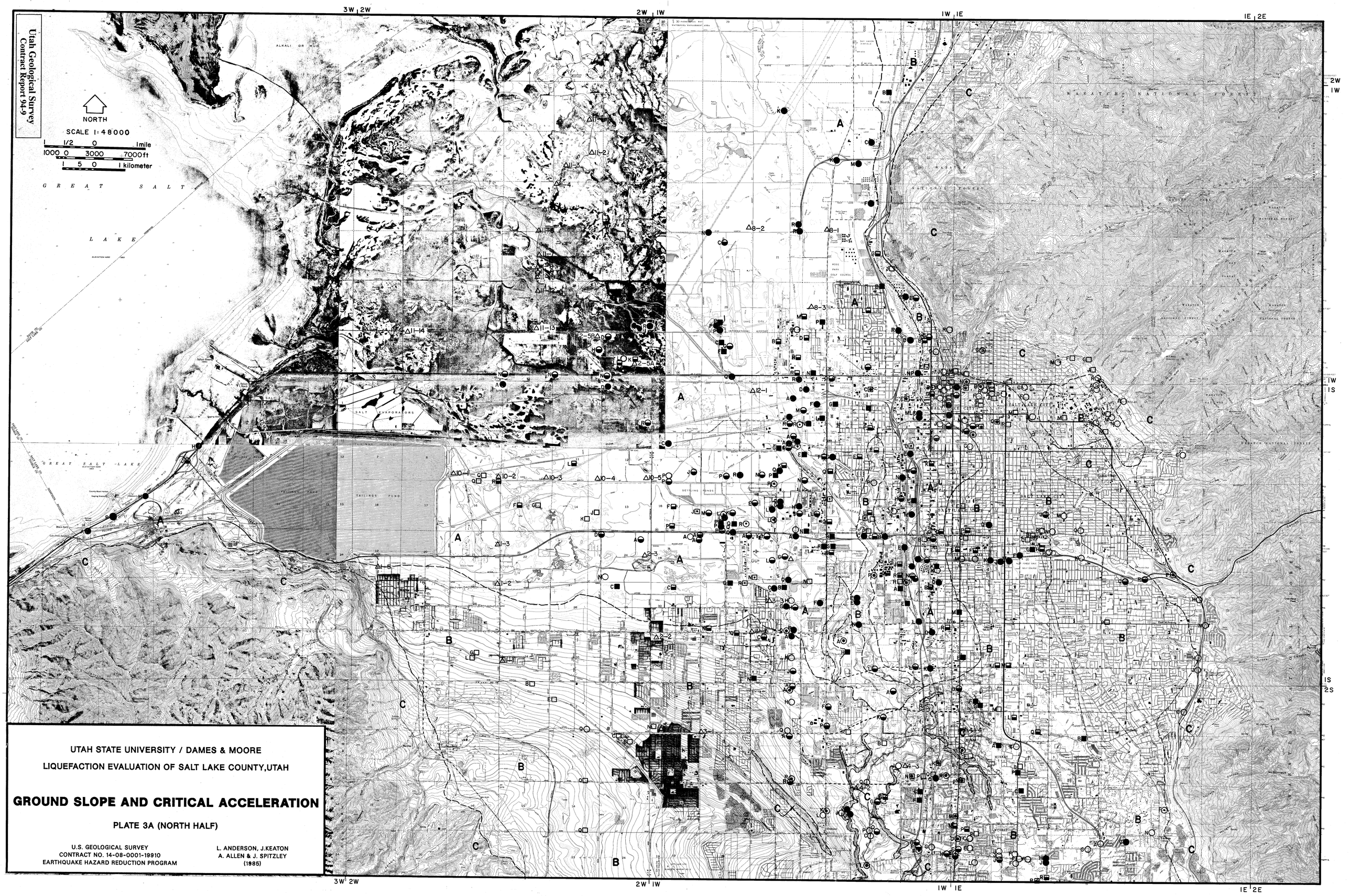
LIQUEFACTION EVALUATION OF SALT LAKE COUNTY,UTAH

# SOILS DATA

PLATE 2C (METRO AREA)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J.KEATON
A. ALLEN & J. SPITZLEY
(1985)




UTAH STATE UNIVERSITY / DAMES & MOORE

LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# GROUND SLOPE AND CRITICAL ACCELERATION

PLATE 3A (NORTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J. KEATON
A. ALLEN & J. SPITZLEY
(1985)

NORTH

SCALE 1:48000

1 1/2 0 1 mile

1000 0 3000 7000 ft

1 .5 0 1 kilometer

EXPLANATION

Critical Acceleration Data

I

I = Location of Boring within Section

| | | | |
|---|---|---|---|
| D | C | B | A |
| E | F | G | H |
| M | L | 26 K | J |
| N | P | Q | R |

Symbol indicates liquefaction susceptibility

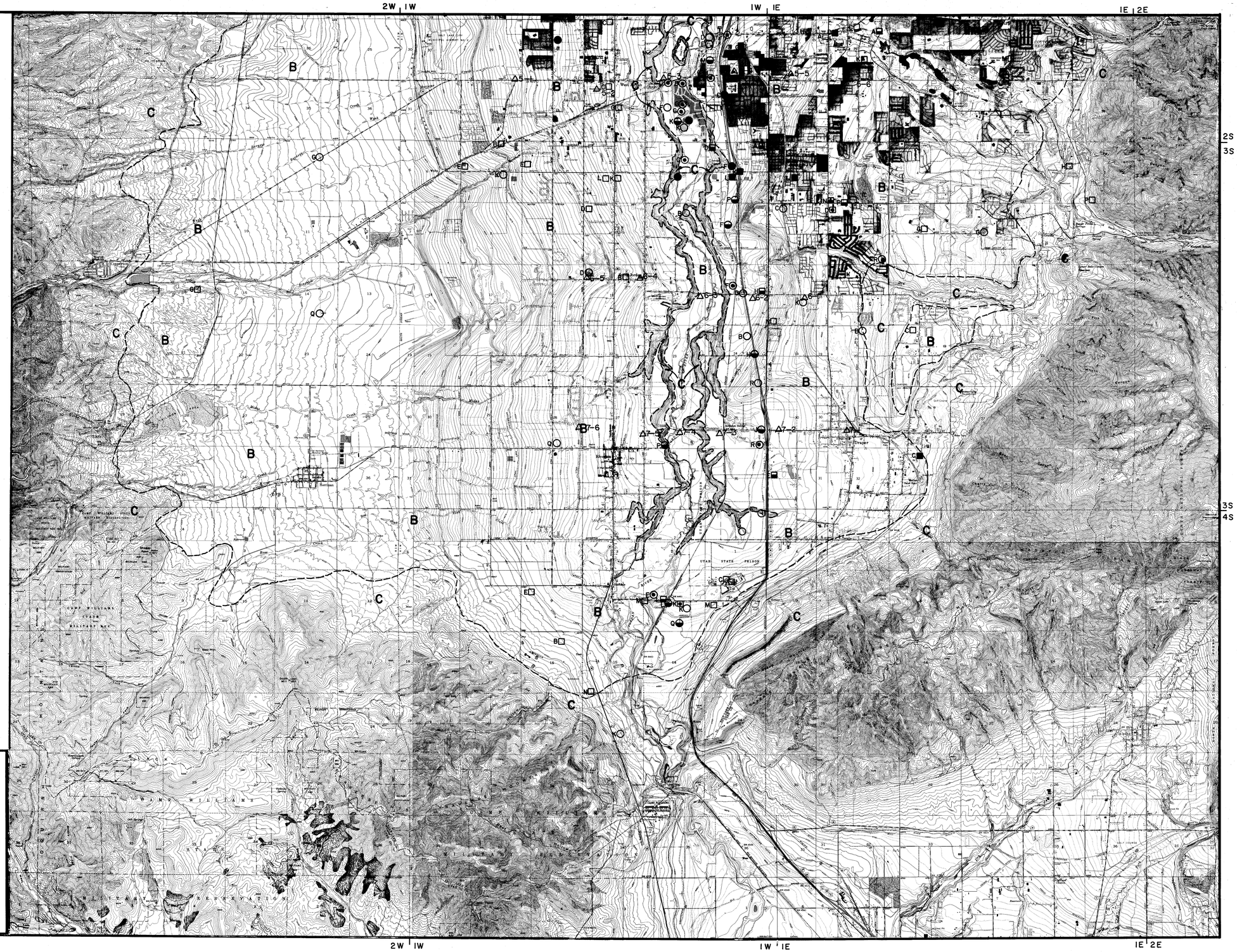
| Symbol | Susceptibility | Ground Acceleration Required to Induce Liquefaction |
|---|---|---|
| ● ■ | High | 0.0 - 0.13g |
| ◒ ◨ | Moderate | 0.13 - 0.23g |
| ⊙ ⊡ | Low | 0.23 - 0.33g |
| ○ □ | Very Low | > 0.33g |

Ground Slope Data

Letter indicates ground slope

| Letter | Slope | Failure Mode |
|---|---|---|
| A | < 0.5% | Bearing Capacity |
| B | 0.5 - 5.0% | Lateral Spreading |
| C | > 5.0% | Flow Landslides |

Note: Critical Acceleration Data found in Appendix




Utah Geological Survey
Contract Report 94-9

UTAH STATE UNIVERSITY / DAMES & MOORE

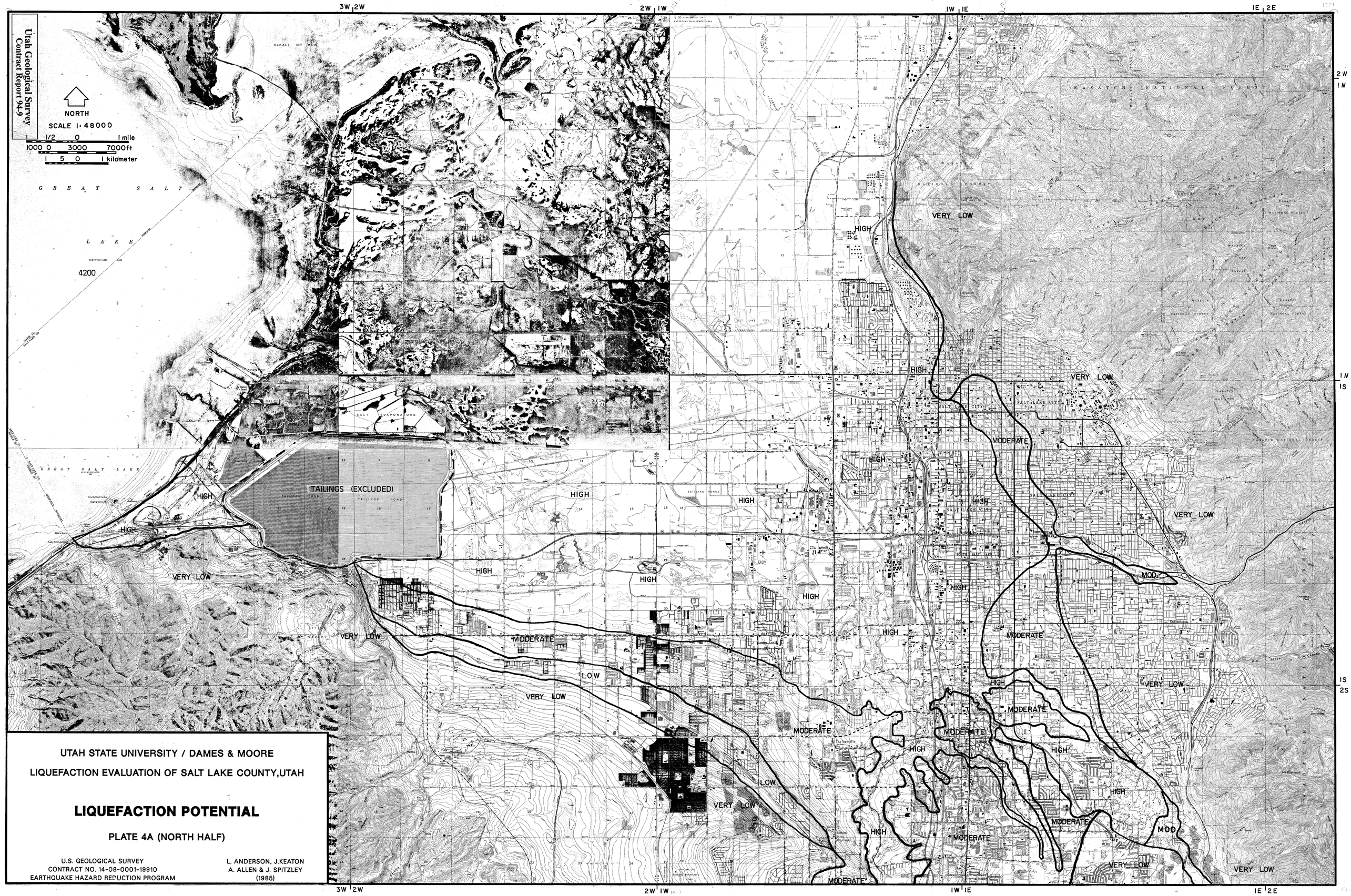
LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# GROUND SLOPE AND CRITICAL ACCELERATION

PLATE 3B (SOUTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J.KEATON
A. ALLEN & J. SPITZLEY
(1985)




UTAH STATE UNIVERSITY / DAMES & MOORE

LIQUEFACTION EVALUATION OF SALT LAKE COUNTY,UTAH

# LIQUEFACTION POTENTIAL

PLATE 4A (NORTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J.KEATON
A. ALLEN & J. SPITZLEY
(1985)

Utah Geological Survey
Contract Report 94-9

NORTH

SCALE 1:48000

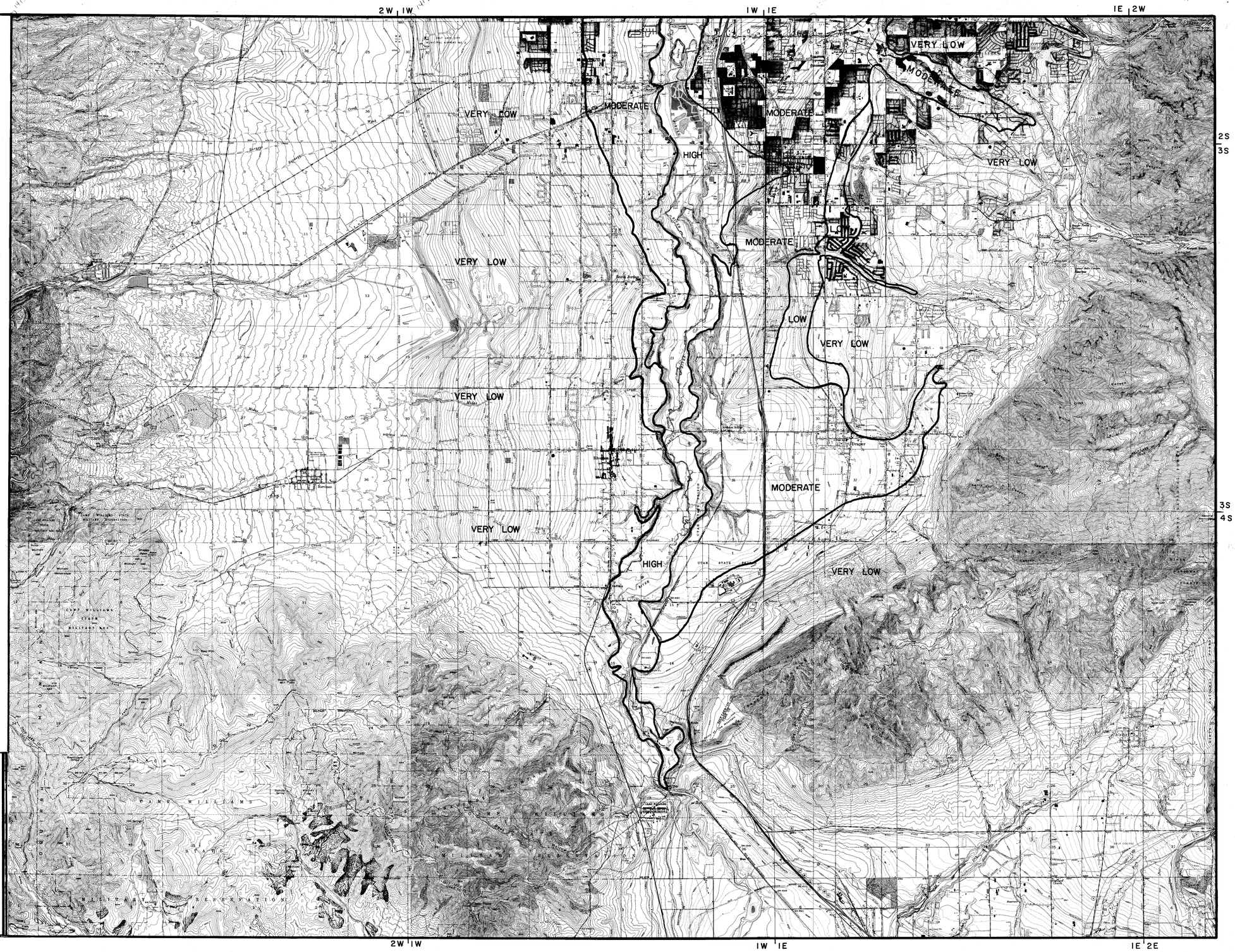
1 1/2 0 1 mile

1000 0 3000 7000 ft

1 .5 0 1 kilometer

LIQUEFACTION POTENTIAL RELATED TO CRITICAL ACCELERATION

| LIQUEFACTION POTENTIAL | CRITICAL ACCELERATION | APPROXIMATE 100 YEAR EXEEDANCE PROBABILITY |
|---|---|---|
| High | < 0.13 g | > 50% |
| Moderate | 0.13 - 0.23 g | 50 - 10% |
| Low | 0.23 - 0.33 g | 10 - 5% |
| Very Low | > 0.33 g | < 5% |




UTAH STATE UNIVERSITY / DAMES & MOORE

LIQUEFACTION EVALUATION OF SALT LAKE COUNTY, UTAH

# LIQUEFACTION POTENTIAL

PLATE 4B (SOUTH HALF)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-19910
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON, J.KEATON
A. ALLEN & J. SPITZLEY
(1985)