LIQUEFACTION POTENTIAL MAP FOR THE NORTHERN WASATCH FRONT, UTAH COMPLETE TECHNICAL REPORT

by
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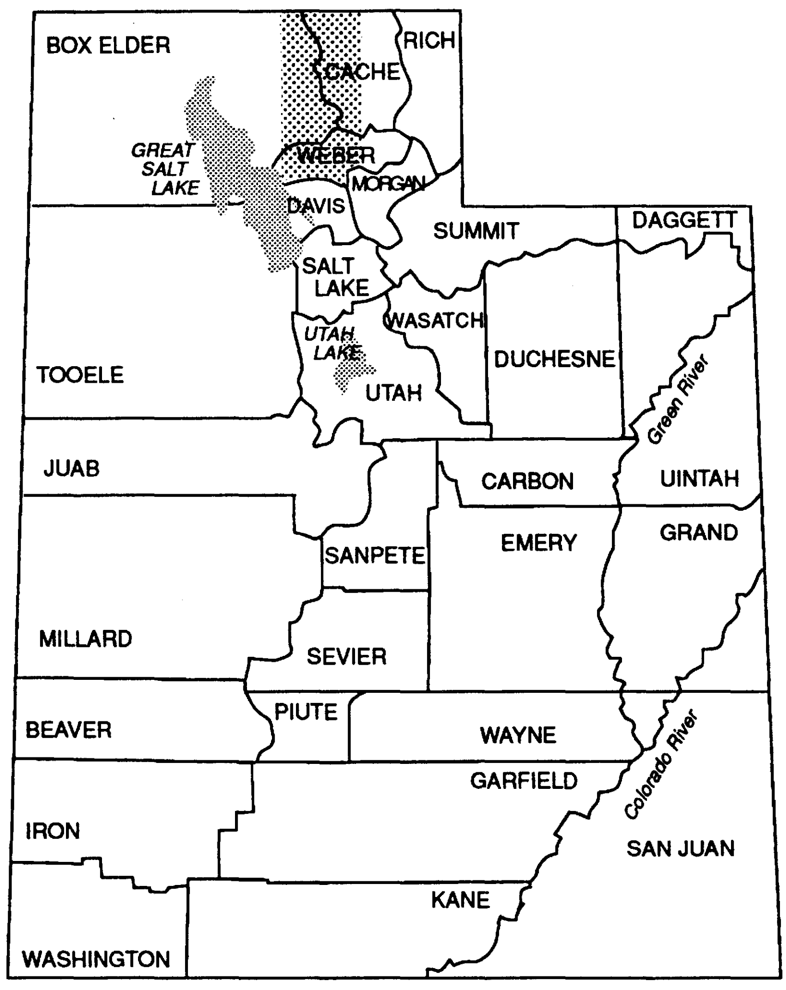

CONTRACT REPORT 94-6 **September 1994**
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

LIQUEFACTION POTENTIAL MAP

for

THE NORTHERN WASATCH FRONT, UTAH

Sponsored by: U.S. Geological Survey
Contract: 14-08-0001-22015

by

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February 1990

ACKNOWLEDGMENTS

This project was sponsored by the U.S. Geological Survey as part of their Earthquake Hazards Reduction Program. The financial support and the technical advice of the Survey is gratefully acknowledged.

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ABSTRACT

The primary purpose of this project was to develop liquefaction potential maps for Weber, Box Elder and Cache Counties. Secondary purposes were to develop software to automate the analysis of liquefaction potential, to collect a library of subsurface data that will be available for future research, and to analyze a site where liquefaction occurred in the 1962 Cache Valley Earthquake.

To accomplish these purposes, subsurface date was collected from consulting firms and public agencies. This was supplemented with data collected during a field investigation as part of the study. Programs were written to manage and analyze the data. A data acquisition system was designed and built to automate the data acquisition from an electric cone penetrometer used in field investigation. All data collected for the study are now on file at Utah State University.

The liquefaction potential maps are intended to be used by local government agencies to mitigate the risk associated with the hazard of soil liquefaction during earthquakes.

INTRODUCTION

Purpose of Study

Around the world earthquakes are a recurring cause of death, suffering and destruction. Identifying regions that are threatened by earthquakes, and assessing the nature and magnitude of that threat, is essential to protect society from the adverse effects of earthquakes. Earthquake damage can result from surface faulting, ground shaking, liquefaction induced-ground failure, landslides, avalanches, tsunamis, seiche and tectonic deformations. This study deals only with liquefaction-induced ground failure; however, it is important to consider all possible damage mechanisms in decision making processes.

The American Society of Civil Engineers (ASCE) defines liquefaction as:

> the act or process of transforming any substance to a liquid, in cohesionless soils, the transformation is from a solid state to a liquid state as a result of increased pore pressure and reduced effective stress. (ASCE, 1978, p. 1198)

Liquefaction can cause three types of ground failure depending on the slope of the ground surface: 1) a loss of bearing capacity, 2) a lateral spread, or 3) a flow landslide (Youd, 1978).

Soil Liquefaction has been a major cause of property damage in earthquakes such as the 1906 San Francisco, California, Earthquake (Youd and Hoose, 1976), the 1964 Niigata, Japan, Earthquake and the 1964 Anchorage, Alaska, Earthquake (Ross, Seed and Migliaccio, 1969; Seed and Idriss, 1967; Seed and Wilson, 1976). Liquefaction is a concern along the Wasatch Front because the soil, groundwater, and seismic conditions make the region especially susceptible to liquefaction damage. Liquefaction was observed during the 1934 Hansel Valley Earthquake in Box Elder County and the 1962 Cache Valley Earthquake in Cache County (Hill, 1979). The geology of Weber County suggests that prehistoric earthquakes caused large liquefaction-induced lateral spread landslides (Anderson, Keaton, and Bay, 1987). In Salt Lake and Davis Counties, several large-scale prehistoric lateral spread landslides have been mapped, and evidence of unmapped lateral spreads have been found in shallow excavations and test pits.

The purpose of this study was to produce liquefaction potential maps that can be used to help mitigate the hazards of soil liquefaction.

Objectives and Scope of Study

Objectives

The primary objective of this study was to produce liquefaction potential maps of parts of Weber, Box Elder and Cache Counties, Utah. In addition to preparing the liquefaction potential maps, another objective of the study was to automate the data collection and analysis processes so that further liquefaction studies can be handled more efficiently. To automate data collection in the field investigation, hardware and software were developed to record electric cone penetrometer soundings on a Campbell Scientific 21X datalogger. The management of the vast amounts of collected soil data was facilitated by developing software to create data files of boring logs using a digitizer. Existing software to analyze critical accelerations from both cone soundings and standard penetration testing was modified and extended to utilize these data files.

During the 1962 Cache Valley earthquake, liquefaction occurred at several sites in the valley. In conjunction with this study one of these sites was analyzed to compare its predicted behavior represents what occurred in 1962.

A secondary objective of the study was to create a library of subsurface data for the study area. This library is one file at Utah State University and is available to other researchers.

Scope

The determination of liquefaction potential in the three county region is based upon the subsurface conditions, the geology, and the seismicity of the region. Subsurface data were obtained from private consulting firms, state agencies and a field investigation that was performed as a part of this project. Geologic data was obtained from previous mapping and from the field investigation. Estimates of the region's seismicity were made after reviewing several seismicity studies from different sources.

Geographically, the study area was limited to the more urbanized regions within the counties. Excluded from the study were: the mountain valleys of Weber County, sparsely populated Western Box Elder County, and all mountainous regions.

Study Area

Location

The location of the study area is shown in Figure 1. Weber and Box Elder Counties are in the Great Salt Lake Valley. The Wasatch Fault zone passes through the East side of both counties. Cache County contains the Utah portion of Cache Valley. Cache Valley is situated between the Wellsville Mountains and the Bear River Range.

Several significant cities are located within the study area. Ogden is the county seat of Weber County and has a population of 64,407, making it the fourth largest city in the state. Brigham City is the county seat of Box Elder County and has a population of 15,596. Logan is the county seat of Cache County and has a population of 26,844. The population of Weber County is 144,616, Box Elder is 33,222, and Cache is 57,176.

Geology

Northern Utah has been shaped since early Tertiary time by fault movement that gradually created fault-bounded mountains separated by deep basins. The urbanized portions of the study area are in one of these basins, The Great

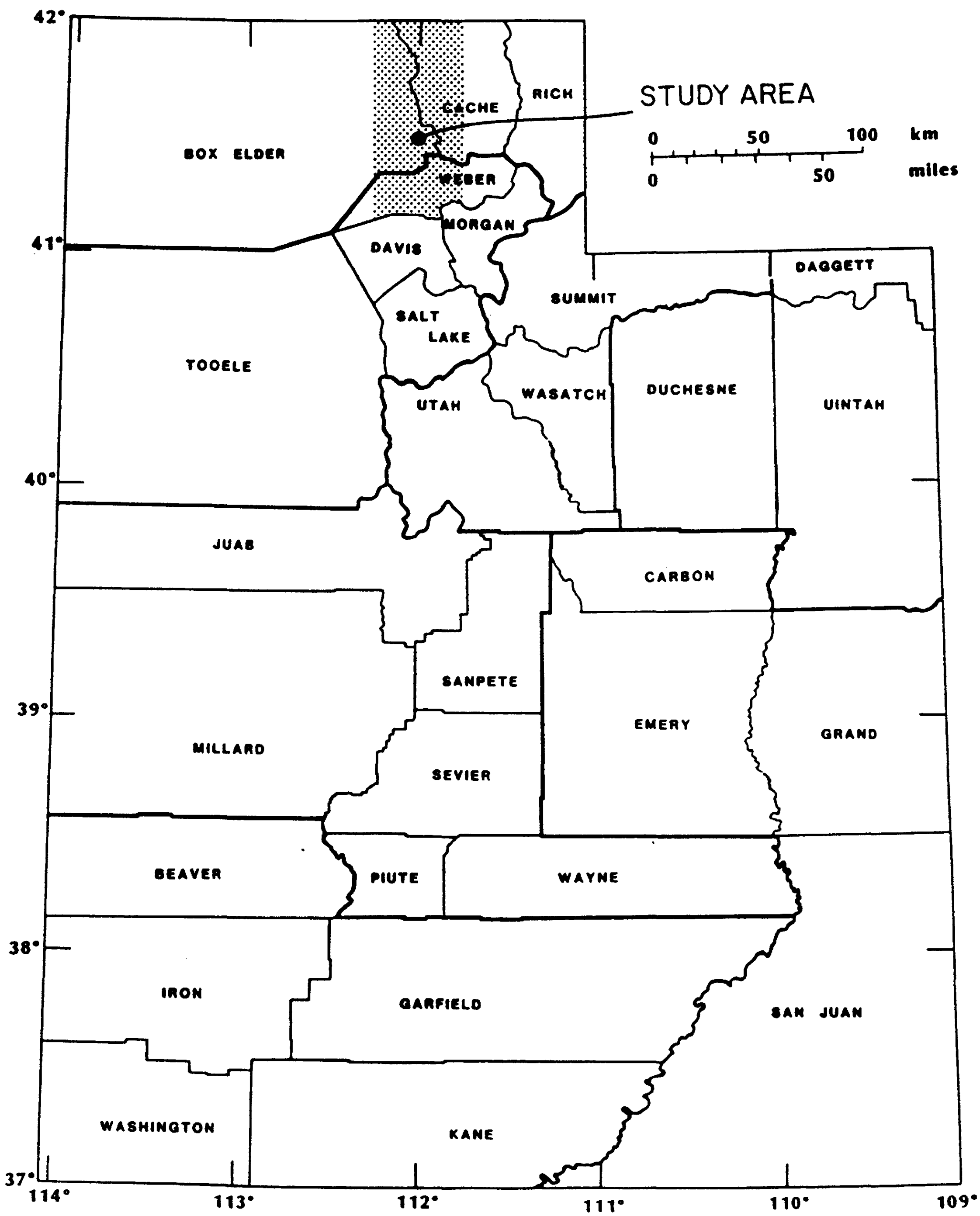


Figure 1. Map showing location of study area.

Salt Lake Basin. Some of the most notable geologic features in the Great Salt Lake Basin are the shorelines of a major Pleistocene lake, Lake Bonneville.

Lake Bonneville began rising about 30,000 years before present (B.P.) when the Bear River was rechanneled into the Great Salt Lake Basin. It reached its highest level at about elevation 5200 feet at what is now called the Bonneville Shoreline about 16,000 years B.P. The lake remained at the Bonneville level for about 1,000 years, when Red Rock Pass in Northern Cache Valley washed out causing the lake to drop to the Provo shoreline at about elevation 4800 feet. The lake remained relatively stable at the Provo level for another 1,000 years. The Provo shoreline is the most prominent shoreline in the valley. The lake continued falling, creating minor shorelines until about 11,000 years B.P. when it reached the approximate level of the present Great Salt Lake (Hintze, 1973).

For the most part, pre-Lake Bonneville deposits are quite dense and cemented and not susceptible to liquefaction. Lake Bonneville deposits can have liquefaction susceptibilities ranging from very low to high depending upon the groundwater conditions, and the soil types of the deposits. Post-Lake Bonneville materials are not wide spread, but are often highly susceptible to liquefaction. Post-Lake Bonneville deposits are found along stream channels, and in alluvial and debris fans (Anderson, Keaton and Bay, 1987).

Seismicity

The study area is within the Intermountain seismic belt. Figure 2 shows the magnitudes and locations of earthquake epicenters from July 1962 and September 1974 in the State of Utah.

Many Quaternary faults have been mapped in Utah as shown in Figure 3. The Wasatch Fault passes through Weber and Box Elder counties, and poses the most significant threat to those counties. It is estimated that large earthquakes with magnitudes from 6.5 to 7.5 could occur as frequently as 50 to 430 years (Swan, Schwartz and Cluff, 1980). The major fault in Cache county is the East Cache Fault. Although it is not as active as the Wasatch Fault it has the potential of producing a large magnitude earthquake (Young, Swan, Power, Schwartz and Green, 1987). In Cache Valley the largest earthquake threat comes from background or unmapped sources (Young, Swan, Power, Schwartz and Green, 1987). A background source produces an earthquake with little or no surface rupture and of magnitude 6.0 or less.

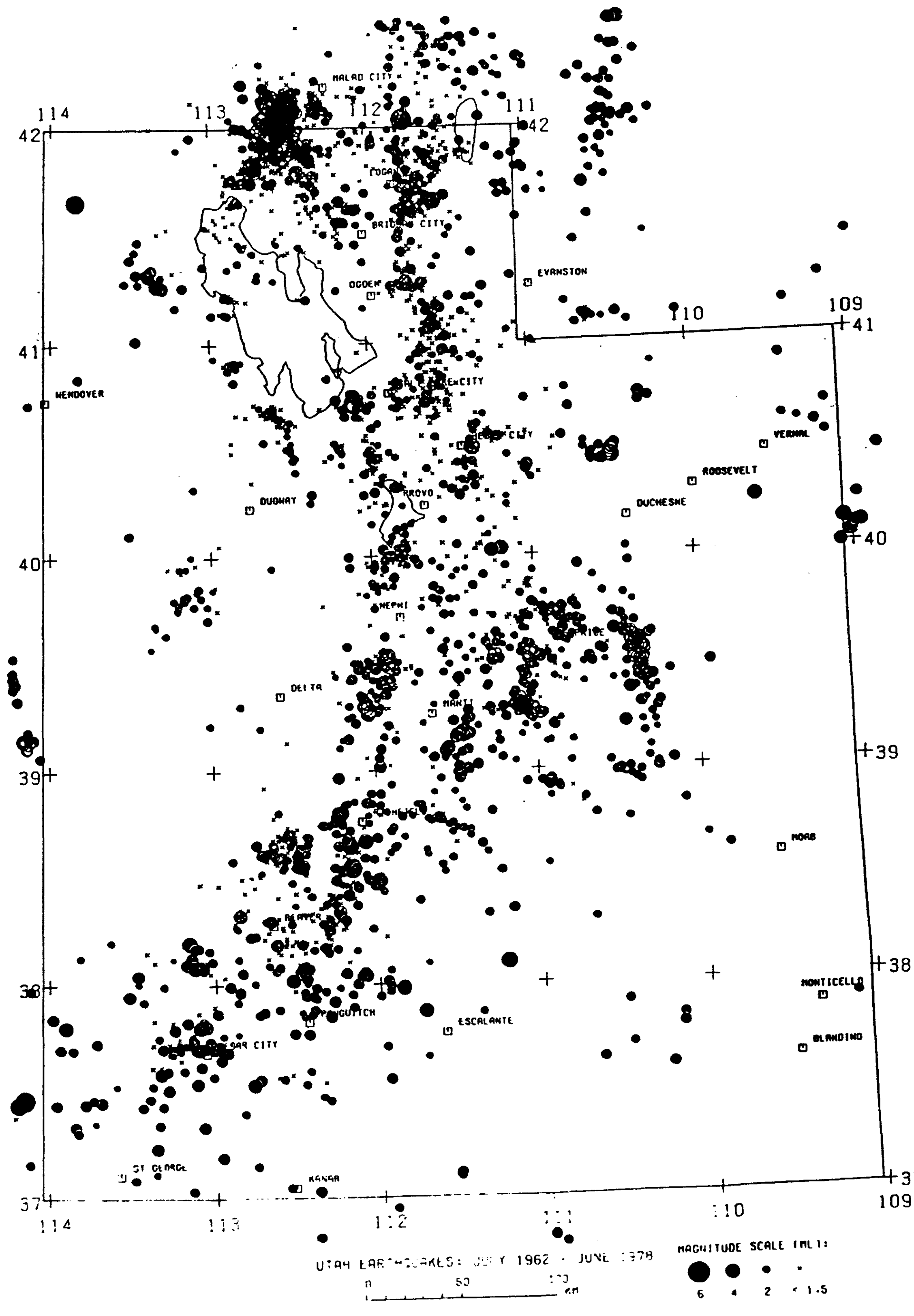


Figure 2. Locations and magnitudes of earthquake epicenters in Utah, July 1962-September 1974 (after Arabaz, Smith, and Richins, 1979).

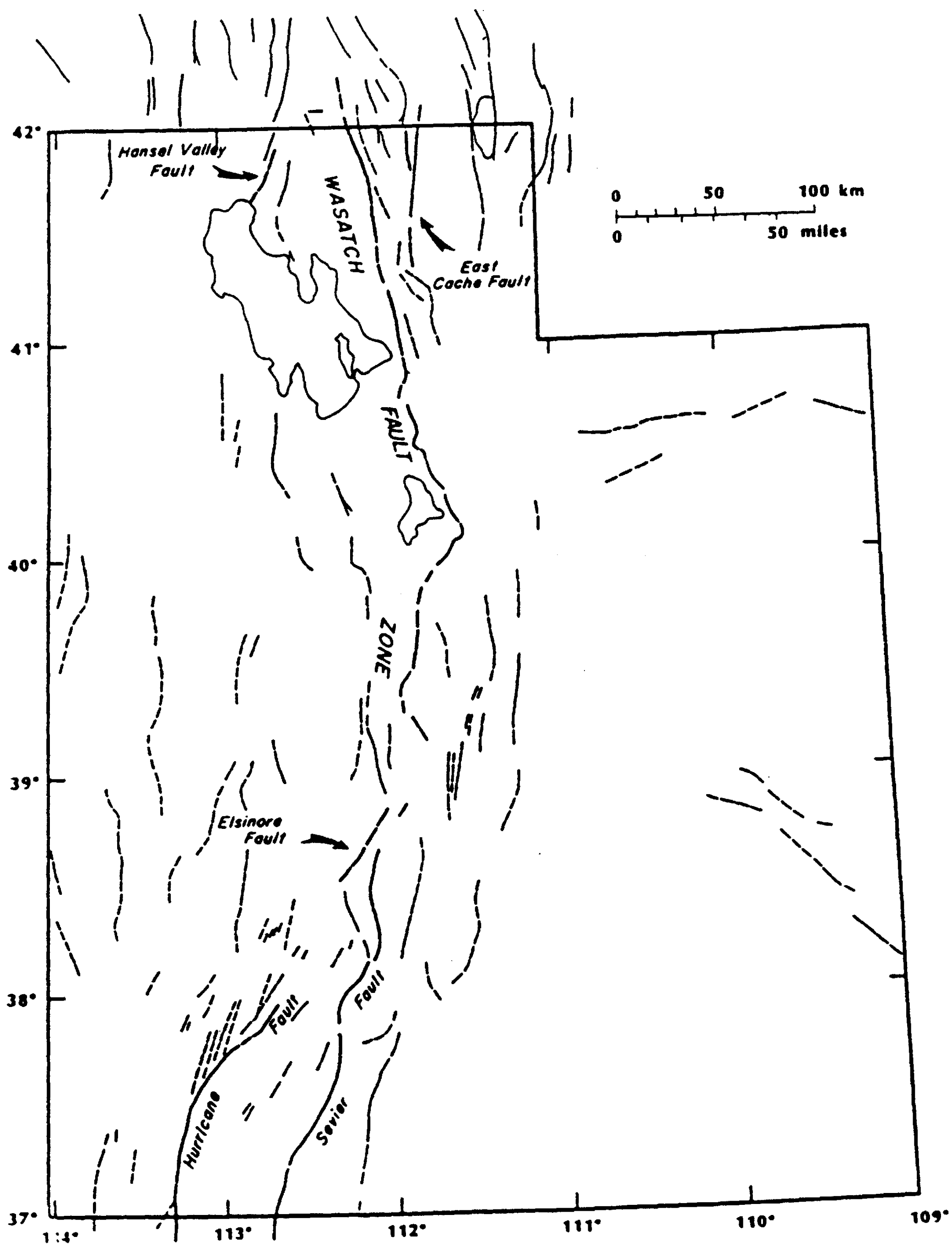


Figure 3. Known and suspected Quaternary faults in Utah (after Anderson and Miller, 1979).

REVIEW OF LITERATURE

History of Liquefaction Research

In 1920, Hazen (1920) first referred to soil liquefying in describing the failure of the Calavaras Dam (Castro and Paulos, 1977). Casagrande (1936) introduced the concept of a critical void ratio and explained the mechanism of pore pressure build-up during undrained loading of sand. However, before 1964 little was published specifically dealing with soil liquefaction during earthquakes and procedures had not been developed to predict the susceptibility of soil to liquefaction. In 1964, two earthquakes caused large amounts of liquefaction-induced damage and awakened geotechnical engineers to the serious threat of soil liquefaction during earthquakes.

The first of these was in Niigata, Japan. During this earthquake buildings suffered tilting and large settlements due to the soils loss of bearing capacity, as shown in Figure 4. Quay walls and bridge piers were damaged by liquefaction, and lateral spread landslides tore buildings apart, damaged bridges and ruptured pipelines (Seed and Idriss, 1967). The other earthquake was the Anchorage, Alaska Good Friday earthquake. During this earthquake liquefaction-induced landslides caused tremendous damage in Anchorage, and lateral spread landslides compressed or buckled more than 250 bridges (National Research Council (NRC), 1985). These two events focused the attention of

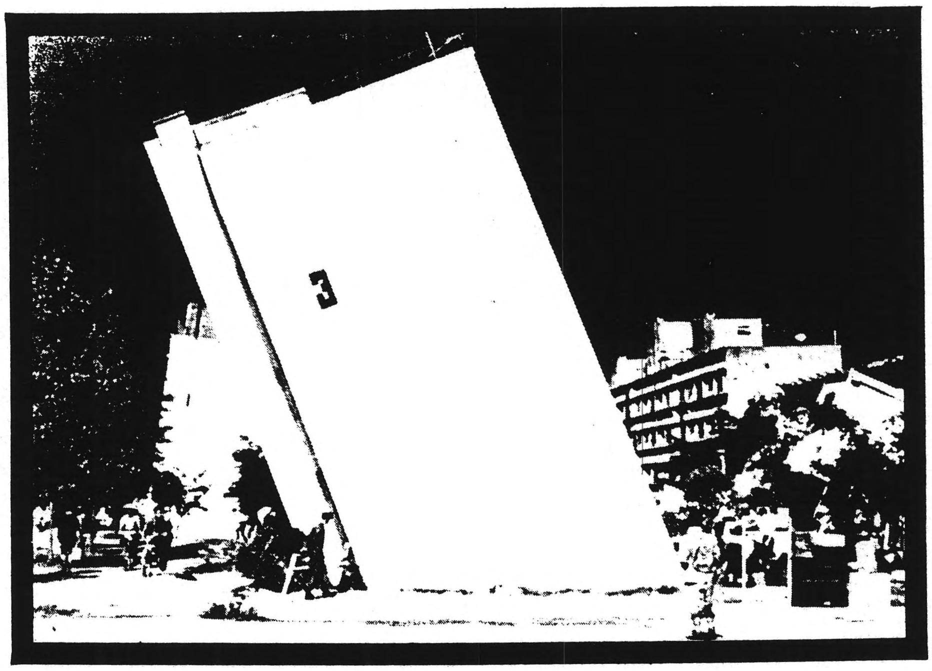


Figure 4. Niigata, Japan apartment building suffering from loss of bearing capacity due to liquefaction during 1964 earthquake (after NRC, 1985).

many geotechnical engineers around the world on liquefaction.

Subsequent seismic events in California, China, Chile, and elsewhere have further pointed out the serious threat soil liquefaction poses to property and structures. Since these events much research has been conducted on soil liquefaction and now a good understanding exists of the mechanisms involved in soil liquefaction, and methods to predict the susceptibility of soil to liquefaction.

Liquefaction Mechanisms

Densification by cyclic loading

When dry or fully drained loose sand is subjected to cyclic loading the soil particles will rearrange into a denser configuration. This process is controlled by the amount of strain the soil is subject to (Youd, 1972). It has been found that a strains below approximately 0.01 percent will cause no rearrangement of soil particles (Dobry, Stokoe, Ladd and Youd, 1981).

Increase in pore pressure during undrained cyclic loading

Changes in soil volume cannot occur during cyclic loading if the soil is saturated with an incompressible fluid and drainage is prevented. In saturated loose sands the tendency to contract during undrained loading results in a transfer of stress from the soil grains to the pore water (Seed, 1979). This process is shown in Figure 5.

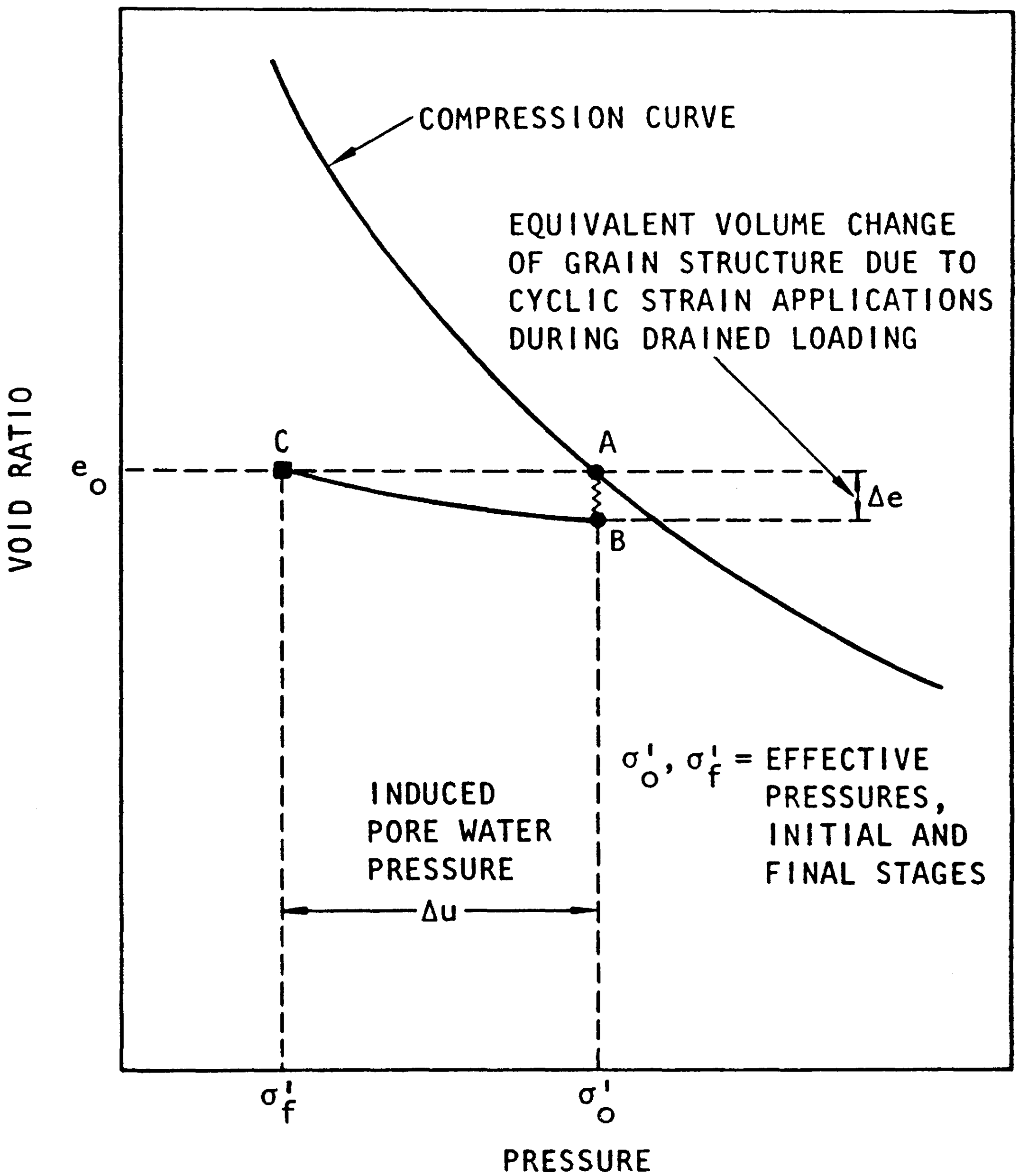


Figure 5. Schematic of pore pressure increase (after Seed, 1979).

The void ratio has a tendency to decrease by the amount that would be sustained during drained loading (A-B), but because the void ratio is held constant by the pore water the effective stress must instead decrease to the point where the rebound curve from B intercepts the constant void ratio. The decrease in effective stress is equal in magnitude to the increase in pore water pressure.

In 1966, Seed and Lee first demonstrated this build-up of pore water using cyclic triaxial testing (Seed and Lee, 1966). Figure 6 is a plot of some of their results. It

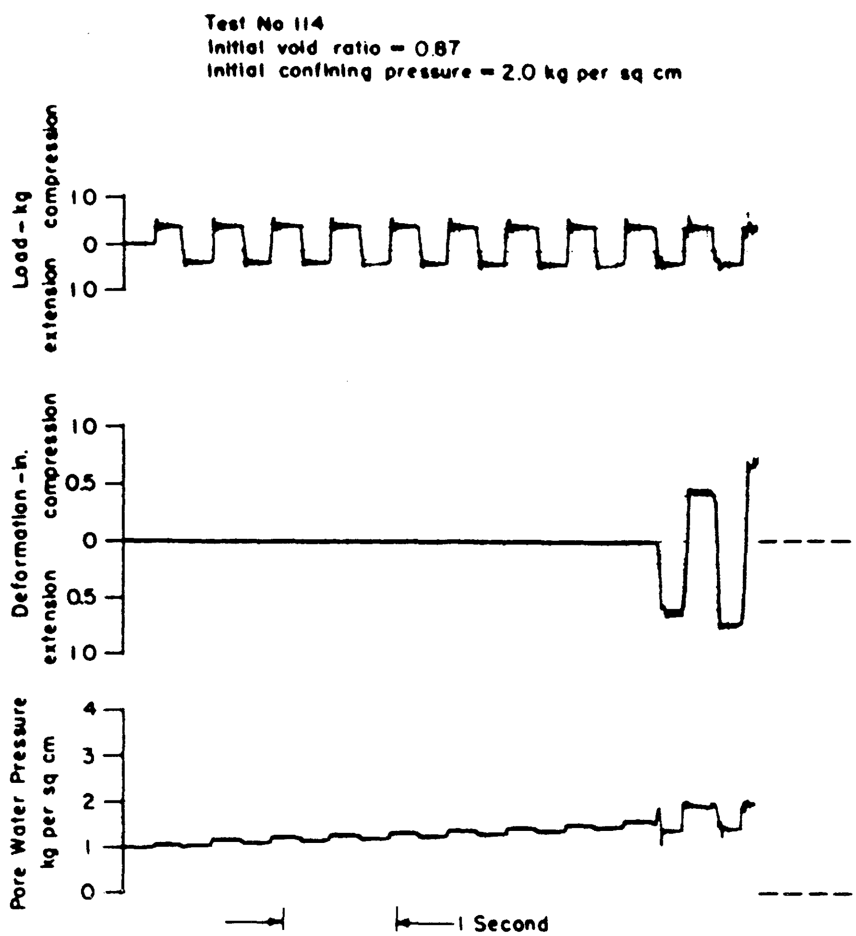


Figure 6. Results of cyclic triaxial test on loose sand (after Seed and Lee, 1966).

can be seen that the pore pressure increases with each cycle until it becomes equal to the initial confining pressure. This condition when the effective stress first goes to zero is referred to as initial liquefaction.

The number of cycles required to induce initial liquefaction is controlled by the density of the soil and the magnitude of the applied stress (DeAlba, Seed and Chan, 1976). Figure 7 shows how increasing soil density, or decreasing cyclic stresses increases the number of cycles to initial liquefaction.

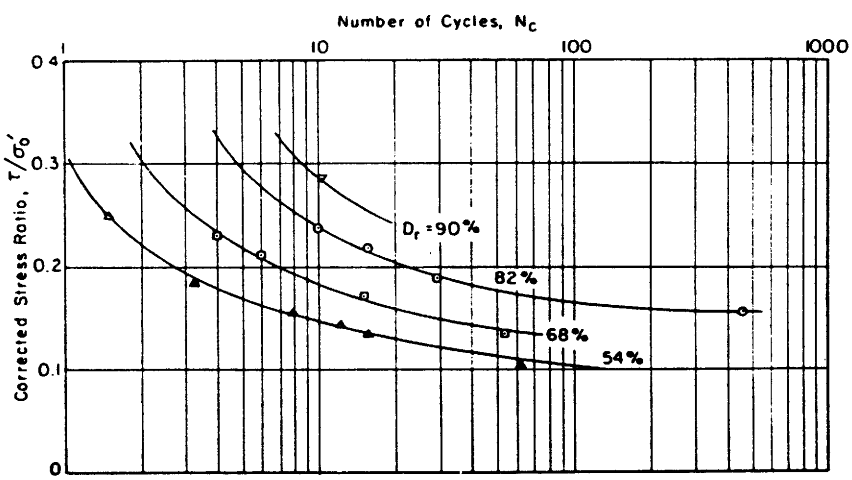


Figure 7. Number of cycles to initial liquefaction versus soil density and stress ratio (after DeAlba, Seed and Chan, 1976).

Effects of soil void ratio and confining pressure on volumetric strain

When a loose drained sand is subjected to a shearing strain it will contract as the particles move into a more efficient packing arrangement. Dense sands are already in an effective packing arrangement, so the soil will dilate as the particles move by each other. Whether the soil will contract or dilate is determined by the void ratio and confining pressure of the soil (Casagrande, 1936). This relationship is summarized graphically in Figure 7.

If a loose, saturated, undrained sand at point A in Figure 8 is subjected to a shearing stress, initially it will be restrained from straining because it is not able to contract. This tendency to contract, however, will cause the pore pressure to increase and the effective stress to decrease. This decrease in effective stress with no changes in void ratio is represented by a shift to the left in Figure 8 to point C. At point C the soil no longer has the tendency to contract so it is able to strain. Shearing strain with no volumetric strain, like this, is called steady state deformation.

If a dense, saturated, undrained sand at point B is subjected to a shearing stress, it will also be restrained from straining initially because it is not able to dilate. However, the tendency to dilate will cause the pore pressure to decrease, which will increase the effective stress. This is represented by a shift to the right in Figure 8 to point C. The soil will then be able to strain with a steady state deformation (Holtz and Kovacs, 1981).

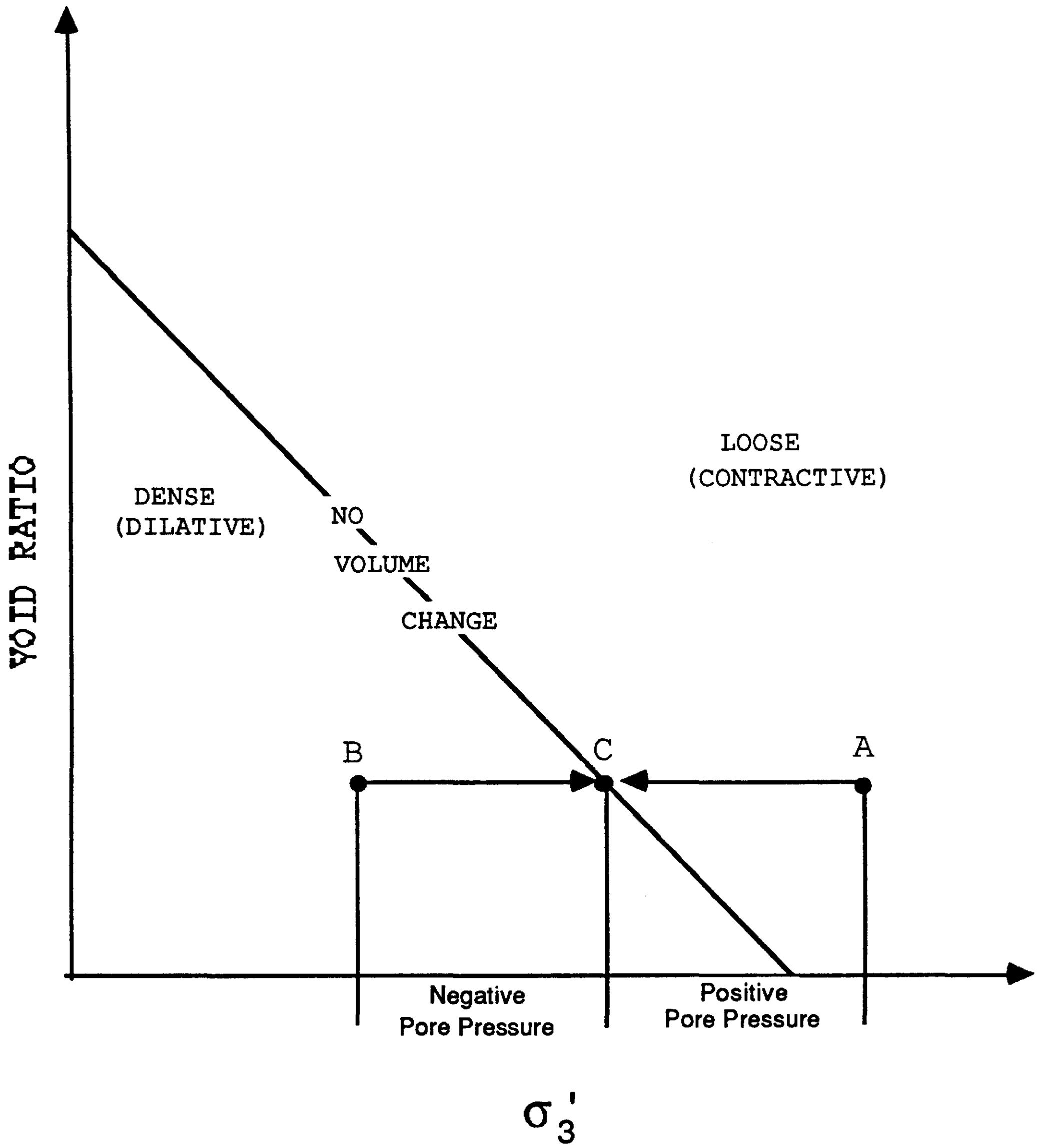


Figure 8. Volumetric strain in soils.

Soil strength following
cyclic loading

Figure 9a shows the stress-strain behavior of a loose sand. It is seen that the ultimate shearing strength is less than the peak shearing strength. Steady state deformation will take place when the soil is at its ultimate shearing strength. Cyclic loading, by increasing pore pressures, acts like large monotonic strains to push the soil beyond its peak strength to its ultimate (or steady state) shearing strength. If the initial static shearing stress is greater than the steady state shearing strength, then the soil will collapse or experience a flow failure.

Figure 9b shows the stress-strain behavior of a dense sand. It is seen that the ultimate or steady-state shearing strength is greater than the small strain shearing strength. Therefore, the shearing strength will increase as cyclic loading brings the soil to a steady state deformation condition. Thus, dense sands are not subject to

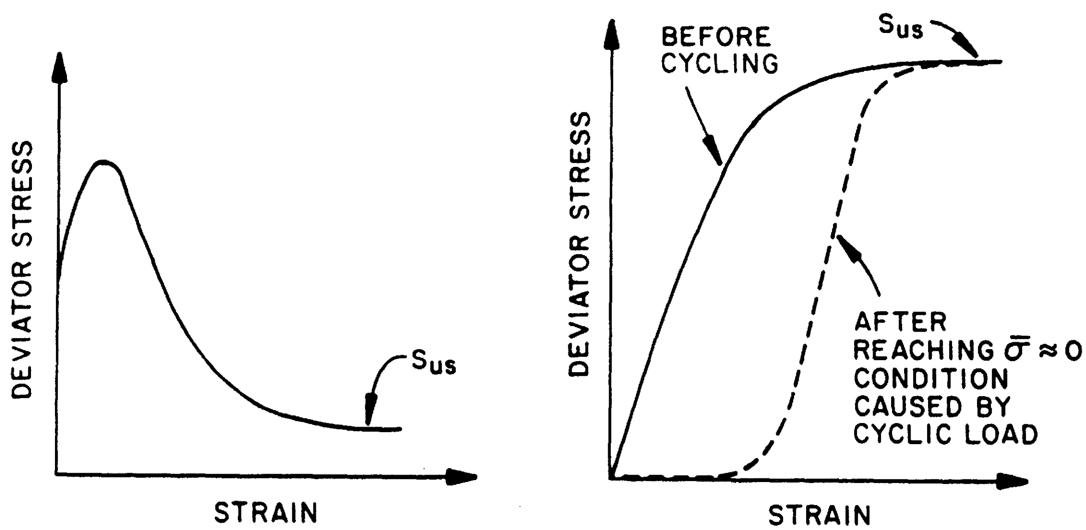


Figure 9. Stress strain relationships for: a) loose sand, b) dense sand (after NRC, 1985).

total collapse or flow failures, but will deform intermittently during cyclic loading. This is called cyclic mobility.

<u>Liquefaction in soils without sustained shearing stresses</u>

In tests without sustained shearing stresses (direct shear tests with reversal in shearing stress, and isotropically consolidated triaxial tests) the strains in the soil increase dramatically with initial liquefaction (Seed, 1976). This rapid increase in shearing strain is seen in Figure 7. Seed also demonstrated that the amount of strain per cycle after initial liquefaction is controlled by the density of the soil. Loose soils experience large strains while denser soils exhibit less strain. This is shown in Figure 10.

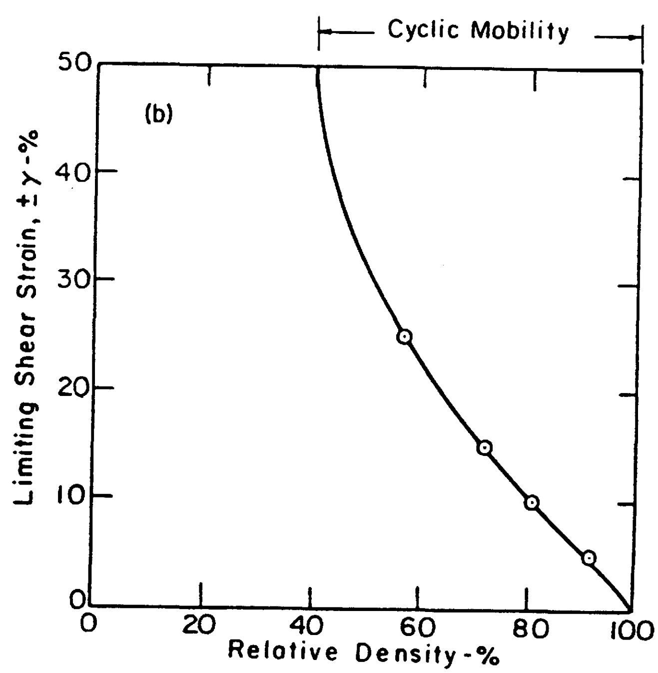


Figure 10. Limiting strain per cycle as a function of soil density (after Seed, 1979).

Figure 11 is a stress path of a soil subject to undrained cyclic loading up to the point of initial liquefaction. As the pore pressure increases the effective stress path moves to the left due to a decrease in effective stress. Initial liquefaction occurs when the effective stress path crosses the origin. At initial liquefaction the soil has no shearing strength and the stress path moves up and down the K_f lines generating large deformations.

Liquefaction in soils with sustained shearing stresses

The presence of a continuous shearing stress has a pronounced effect on undrained soils during cyclic loading. Figure 12 shows the stress path of a soil with a sustained shearing stress. It is seen that the effective stress path moves to the left with an increase in pore pressure. When it reaches the K_f line large strains will occur. However, the pore pressure increase is retarded and initial liquefaction never occurs. In other words, the strength of the soil decreases until it is equal to the sustained shearing stress. Then a steady state deformation occurs with no further increases in pore pressure. Even a small reversal in shearing stress will allow initial liquefaction to occur (Hedberg, 1977).

Sustained shearing stresses will exist in sloping ground, under foundations, and in other cases. It will be

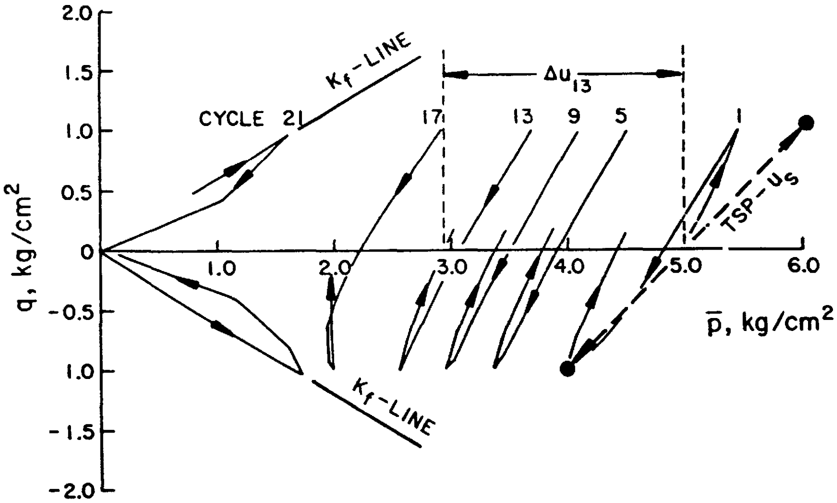


Figure 11. Stress path of undrained sand undergoing cyclic shearing with no sustained shearing stress (after Hedberg, 1979).

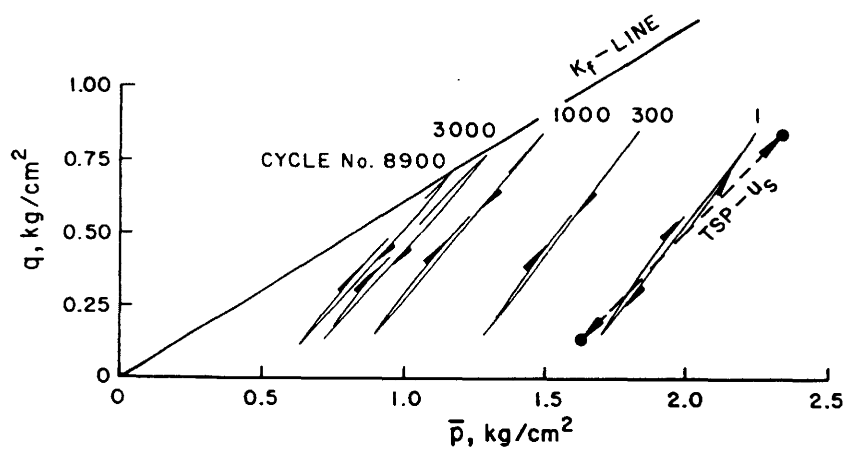


Figure 12. Stress path of undrained sand undergoing cyclic shearing with sustained shearing stress (after Hedberg, 1979).

shown later how this affects the type of failure that can occur during liquefaction.

Failure Mechanisms

Failures mechanisms associated with unloaded horizontal ground

Sand boils. Excesses pore pressure generated during liquefaction causes an upward flow of water. If the upward gradient is large enough soil particles will be carried upward by the water. When this sand and water emerges at the ground surface it is called a sand boil. Sand boils are probably the most common evidence of liquefaction during earthquakes, however, they cause little or no damage. Figure 13 shows a very large sand boil that occurred at the Niigata airport (Seed and Idriss, 1982). Sand boils also accompanied the 1937 Hansel Valley Earthquake and the 1962 Cache Valley Earthquake.

Subsidence and settlement. "Dissipation of excess pore pressure will be accompanied by densification of the soil and settlement of the surface" (NRC, 1985, p. 73). During the 1964 Alaska Earthquake this caused settlements of nearly five feet in some locations (Grantz, Plafker and Kachadoorian, 1964). Subsidence can cause inundation if it occurs at sites with shallow groundwater or next to bodies of surface water.

Differential transient motions. This failure mechanism is associated with subsidence. Subsidence will not be uniform in either the horizontal or vertical direc-

Figure 13. Sand boil, Niigata, Japan earthquake (after Seed and Idriss, 1982).

tions (NRC, 1985). Therefore, linear structures such as pipelines and tunnels extending across a region of subsidence will experience bending or rupture. Differential vertical subsidence will similarly draw down friction piles.

Ground oscillations. Ground oscillations occur when soil blocks at the surface slide back and forth over a liquefied layer at some depth. This oscillation is seen by observers as ground waves and is accompanied by the opening and closing of ground fissures (NRC, 1985).

Failure mechanisms associated with slopes and foundations

Soils on a slope or loaded by a foundation will behave like the soil with a sustained shearing stress that was discussed previously. Large strains or even a total collapse can occur without the soil ever reaching the point of zero strength at initial liquefaction. Most damaging of all failures are in this category.

There has been disagreement in the profession as to exactly what failure mechanisms contribute to bearing and slope failures during liquefaction. Whitman summarized the possible mechanisms as follows:

> Seed has emphasized the build-up of excess pore pressure during cyclic straining, and the large strains that develop after a condition of zero effective stress is first reached.
>
> Casagrande and Castro have focused upon conditions where sands can deform continuously under the actions of only very small shear stresses.

> Schofield has pointed out that a combination of low effective stress and large gradients within pore water can cause soil to fail in a brittle manner. (Whitman, 1985, p. 1923).

Whitman explains liquefaction failure mechanisms by classifying sands in one of two states.

Soil states. State I is characterized by an undrained stress path with a monotonically decreasing p' ($p' = (\sigma'_1 + \sigma'_3)/2$), and final shearing resistance considerably lower than the peak shearing resistance. This is the same as the behavior of loose sands described by Figure 9a. The stress path for this soil condition is shown in Figure 14a.

State II is characterized by an undrained stress path with a monotonically increasing q ($q = (\sigma_1 - \sigma_3)/2$), and the final shearing strength is the peak shearing strength. This is the same as the dense sand described by Figure 9b. The stress path of this soil condition is shown in Figure 14b.

Disintegrative failures. "Disintegrative failure describes a condition where a soil can deform continuously under a shear stress less than or equal to the static shear stress applied to it." (Whitman, 1985, p. 1924). Disintegrative failures are flow failures or bearing failures where equilibrium is only restored after large deformations. Soils in State I are always susceptible to disintegrative failures. Cyclic loading will decrease the effective stress and if the amplitude and duration are

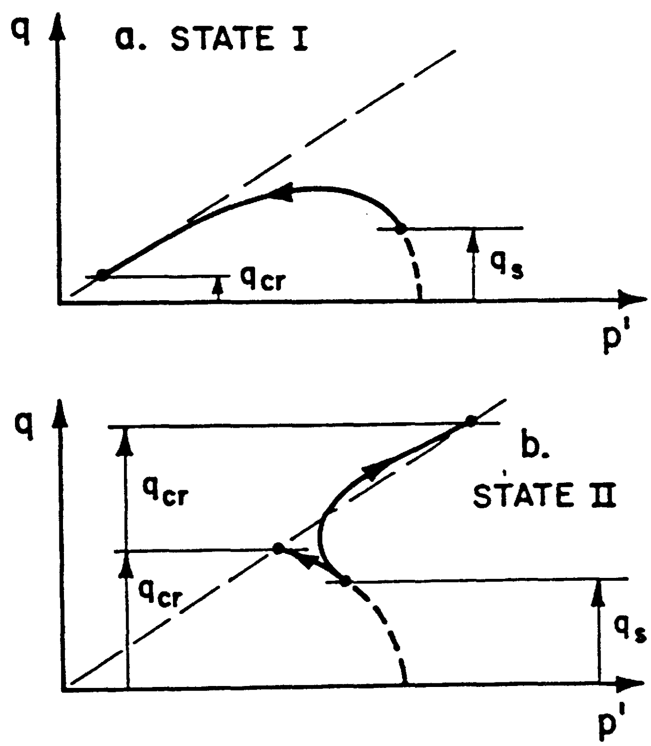


Figure 14. Soil states as defined by Whitman (after Whitman, 1985).

sufficient it will push the soil over the peak in Figure 14a. If the static shearing stress (q_s) is greater than the ultimate shear strength (q_{cr}) then the soil will flow until equilibrium is reached.

Soils in State II can also experience a disintegrative failure through a redistribution of void ratio within the soil mass. Two possible ways this could occur are as follows.

The granular soil could be enclosed between two relatively impervious layers as shown in Figure 15. When initial liquefaction occurs the sand is suspended in water and has a tendency to settle out. This causes the soil to

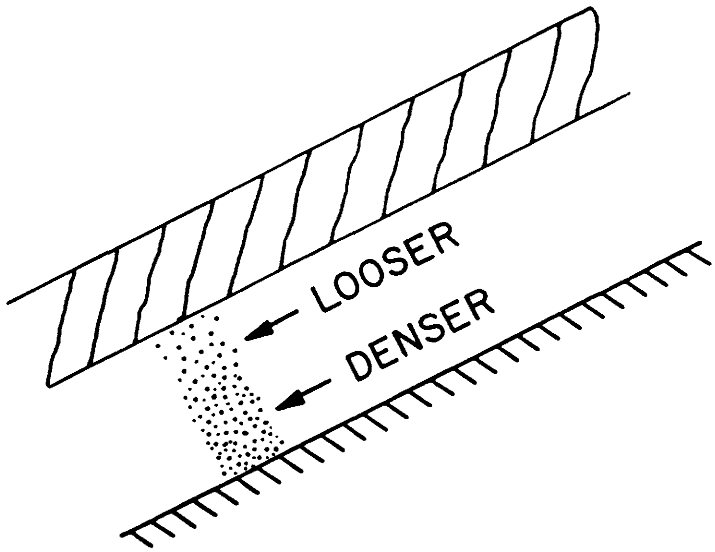


Figure 15. Disintegrative failure by void ratio redistribution (after NRC, 1985).

densify near the bottom of the layer and become looser near the top. A disintegrative failure will occur if even a thin layer loosens to the point that the steady state strength is less than the static stress. This mechanism has never been verified in the field; however, laboratory tests suggest its validity (NRC, 1985).

The other possible mechanism is through fracturing of overlying soils as shown in Figure 16. Sand and water can be forced into cohesive soils, reducing their shearing strength and possibly transforming the solid ground into a soil avalanche (Schofield, 1981).

Non-disintegrative failures. "Non-disintegrative failures involve unacceptably large permanent displacements or settlements during (and/or immediately after) shaking,

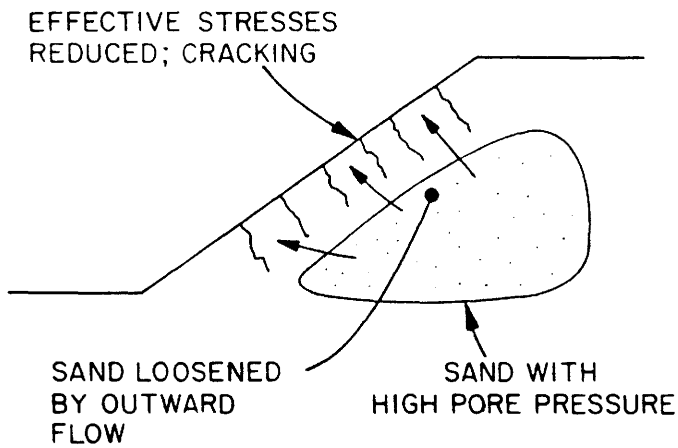


Figure 16. Disintegrative failure by fracturing (after NRC, 1985).

but the earth mass remains stable following shaking without great changes in geometry" (Whitman, 1985, p. 1924). Soils of State II are primarily responsible for this type of failure; however, soils of both states could be involved. Three possible mechanisms exist for non-disintegrative failures in State I soils: 1) The stresses in the soil could momentarily reach steady state resistance, causing intermittent plastic deformations; 2) deformations could develop from stresses less than the steady state resistance; 3) one part of an earth mass could lose its strength, but the stresses could be transferred to a more rigid part of the mass arresting large deformations.

Determining Soil Liquefaction Susceptibility

Factors affecting soil liquefaction susceptibility

A susceptibility of a soil to liquefaction is sensitive to a large number of soil properties. These include (Seed and Idriss, 1982):

1. Soil type
2. Relative density
3. Confining pressure
4. Soil structure
5. Grain size distribution
6. Age and depositional environment
7. Soil cementation
8. Dynamic shear modulus
9. Seismic history

Because of the number of properties affecting liquefaction susceptibility, and the fact that some of these properties are not readily quantifiable (such as soil structure), it is not feasible to predict soil liquefaction susceptibility based upon all of these properties combined. Several alternate methods have been developed.

General method

One method of predicting a soil's liquefaction susceptibility is to subject a sample of the soil to cyclic undrained loading in the laboratory. Undisturbed soil samples can be subjected to a cyclic load through; torsional shear, direct shear, or triaxial shear. The number and magnitude of cycles to induce liquefaction are measured, and comparisons made to the loading expected during seismic shaking.

There are three major draw backs to this method. First, extremely high quality undisturbed samples are needed to reflect field conditions. The amount of soil disturbance associated with normal sampling procedures has large effects on the samples behavior in cyclic undrained loading (NRC, 1985). To obtain suitable samples methods such as soil freezing must be used. Second, it has been found that the results are quite sensitive to the method of applying the cyclic load and the frequency at which it is applied (NRC, 1985). And third, void ratio redistribution is commonly observed in laboratory samples after cyclic loading. This may or may not reflect true field conditions.

Seed's simplified method

Seed observed that the same factors that affect soil liquefaction affect standard penetration blow counts and in a like manner. Seed and other investigators have empirically related standard penetration blow counts to the cyclic stress ratio (τ_{avg}/σ'_o) required to induce liquefaction (Seed, 1979). To obtain the correlation between blow counts and liquefaction,standard penetration tests were performed at sites that did and did not liquefy after earthquake shaking. To determine the shearing stress induced at depth a modified rigid body model was applied as follows:

$$(\tau_{max})_d = \gamma \cdot h/g \cdot a_{max} \cdot r_d \quad (1)$$

$(\tau_{max})_d$ = Maximum shearing stress at depth
γ = Unit weight of the soil
h = Depth of soil in question
g = Acceleration of gravity
a_{max} = maximum earthquake acceleration
r_d = Stress reduction factor that accounts for differences between soil and a rigid body (Figure 17).

Seed also observed that the average stress induced by one cycle of earthquake shaking is about 65 percent of the stress induced by the maximum cycle.

$$(\tau_{avg})_d = (\tau_{max})_d \cdot 0.65 \quad (2)$$

Blow count values (N) measured in the field represent the soil properties and the confining pressure. To eliminate the influence of confining pressure it is necessary to use a normalized resistance N_1. N_1 is the blow count value of the equivalent soil with a 1 ton/sq ft overburden pressure. N_1 is obtained from Equation 3 where C_N is found in the plot in Figure 18.

$$N_1 = C_N \cdot N \quad (3)$$

Figure 19 shows Seed's results for magnitude 7.5 events. To expand these results to earthquakes with different magnitudes a statistical analysis was performed to determine the number of representative cycles (equivalent to 0.65 τ_{max}) for different magnitude earthquakes (Seed, 1979). The results are shown in Table 1. Then a series of cyclic triaxial tests were performed to determine the relationship between magnitude of shearing stress and number of cycles to induce liquefaction. The results are shown in Figure 20. τ_1 represents the shear stress

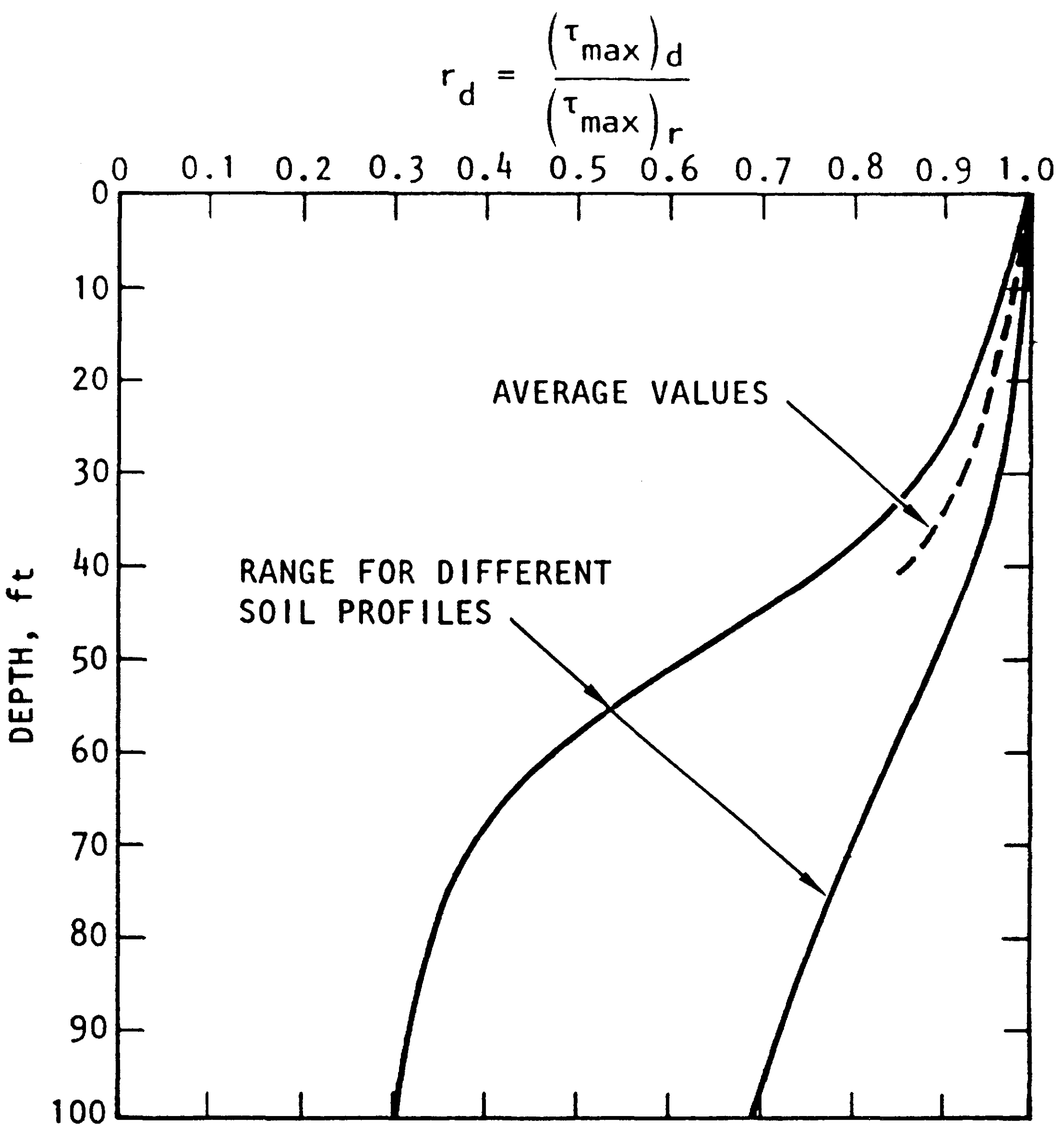


Figure 17. Plot of R_d, stress reduction factor (after Seed, 1979).

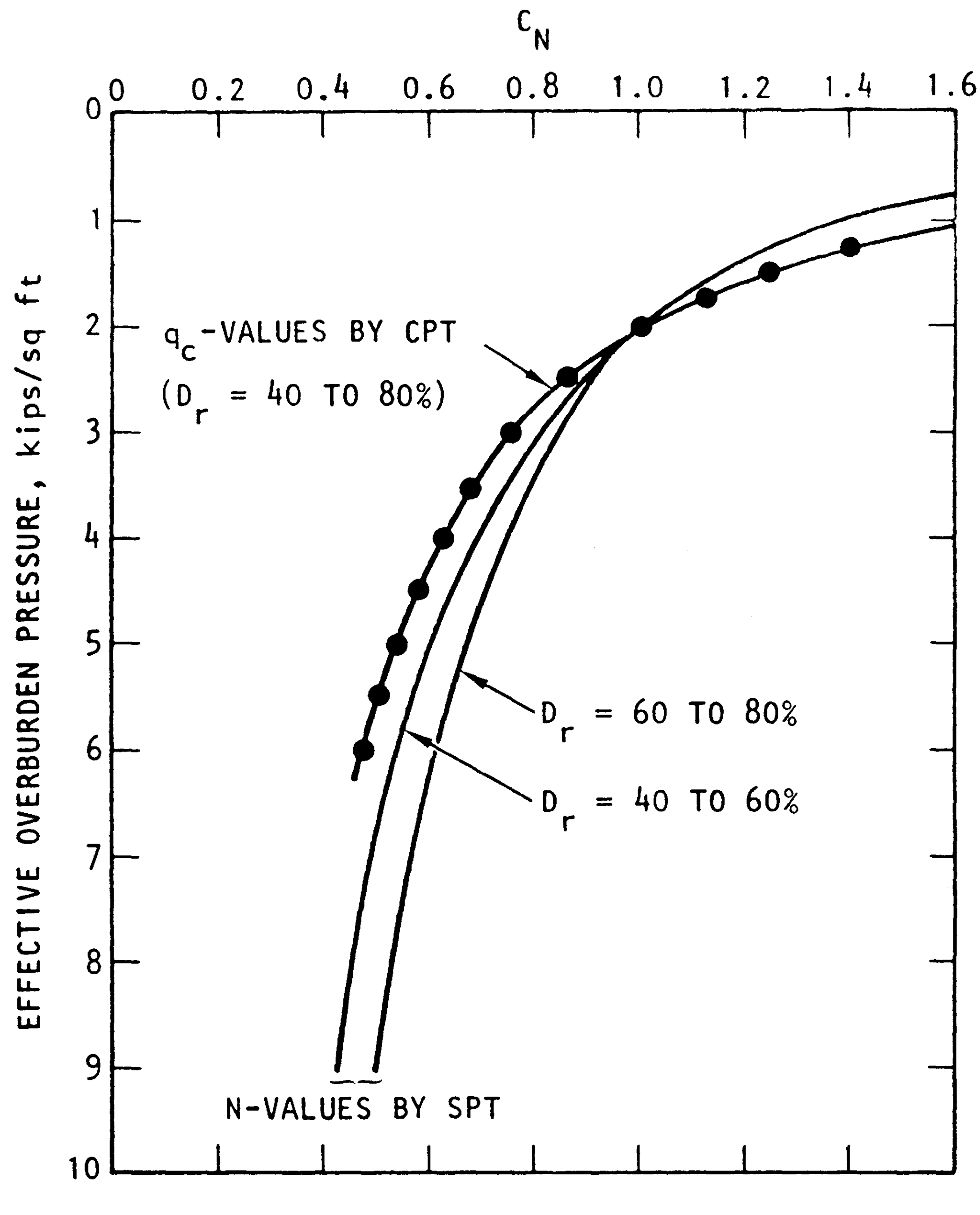


Figure 18. Plot of C_N factor to normalize blow counts for depth (after Seed, 1979).

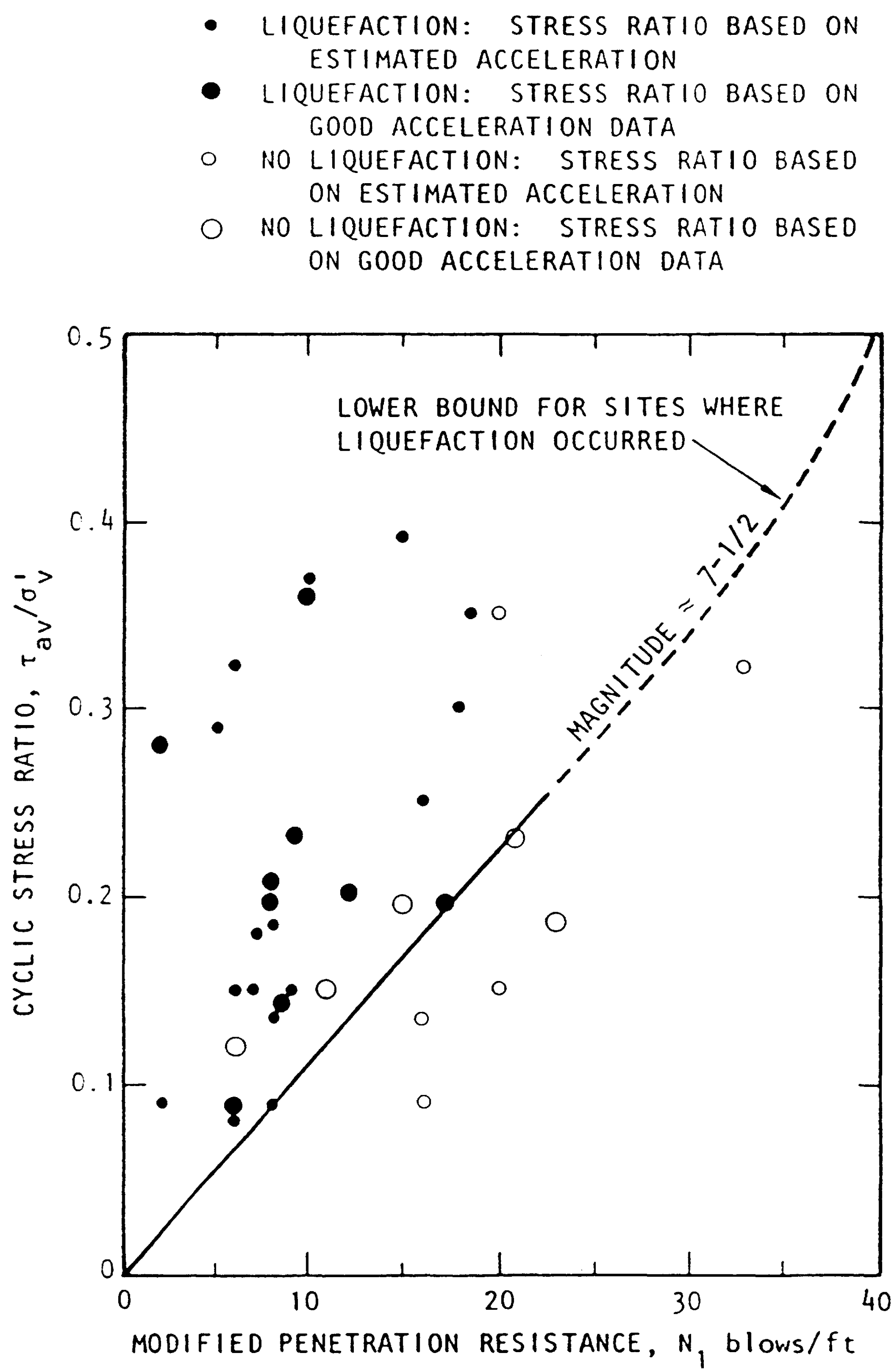


Figure 19. Plot of cyclic stress ratio to induce liquefaction versus blow counts, for M = 7.5 (after Seed, 1979).

Table 1. Number of representative cycles for earthquakes of various magnitudes (after Seed, 1979).

Earthquake Magnitude, M	Number of representative cycles at 0.65 max
8.5	26
7.5	15
6.75	10
6.0	5-6
5.25	2-3

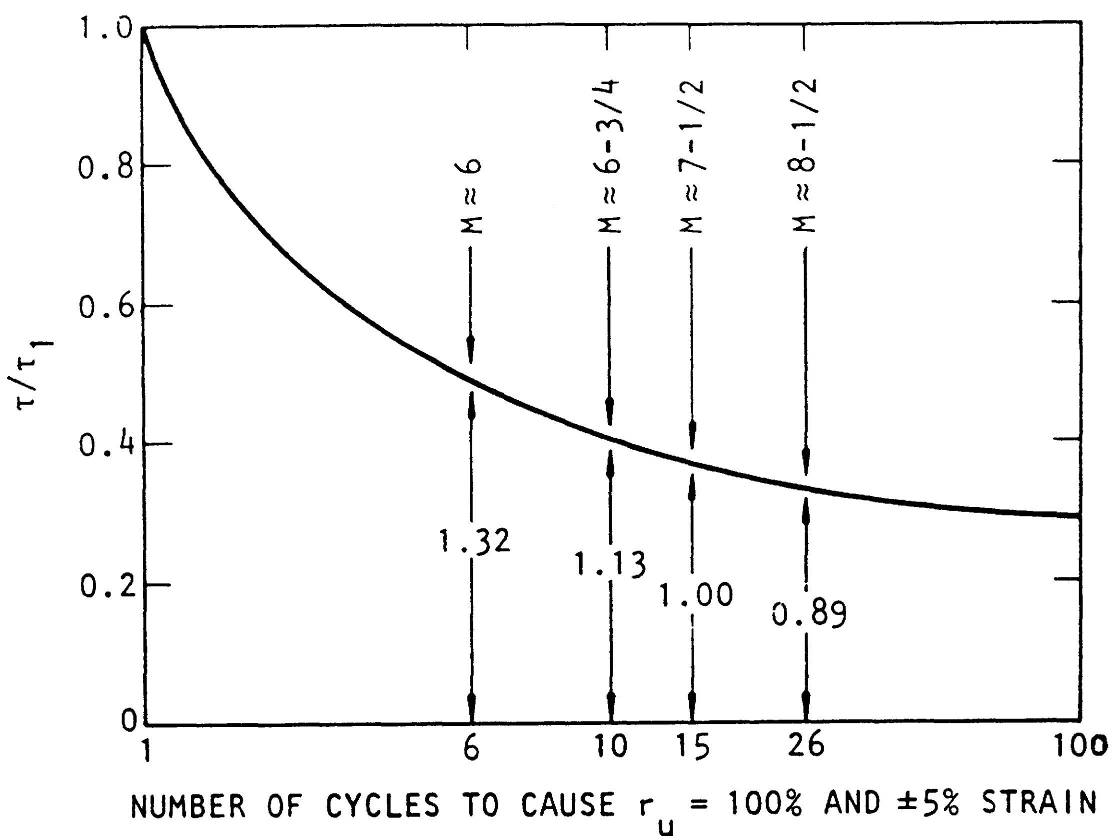


Figure 20. Plot of τ_n/τ_1 versus number of cycles to induce liquefaction (after Seed, 1979).

required to induce liquefaction in one cycle and τ_n is the shearing stress required to induce liquefaction in n cycles. By comparing the ratios of τ_n/τ_1 for the number of representative cycles for various magnitudes of earthquakes to that for a magnitude 7.5 earthquake, multipliers for cyclic stress ratio can be obtained to generate curves similar to Figure 19 as shown in Figure 21.

The relationships in Table 1 only apply for clean sands with a $D_{50} > 0.25$ mm. A similar analysis was performed for sands with $D_{50} < 0.15$ mm. The results are shown in Figure 22. Seed recommends adding 7.5 to the blow counts for silty sands with a $D_{50} < 0.15$ and using the curves for clean sands in Figure 21 (Seed and Idriss, 1982).

<u>Influence of standard penetration testing procedure</u>. Seed and other investigators have found that the procedure used in standard penetration testing has a large effect on the results (Seed, Tokimatsu, Harder and Chung, 1985). When doing a liquefaction analysis it is important that either standardized testing procedures are used, or that non-standard blow counts are corrected to equivalent standard values.

A standardized test is one where 60 percent of the energy from a 140 pound hammer dropping 30 inches is delivered to the drill rod. It is further specified that the boring be 4-5 inches in diameter and filled with drilling mud, and that a 1 $^3/_8$ inch I.D. ASTM sampler is used.

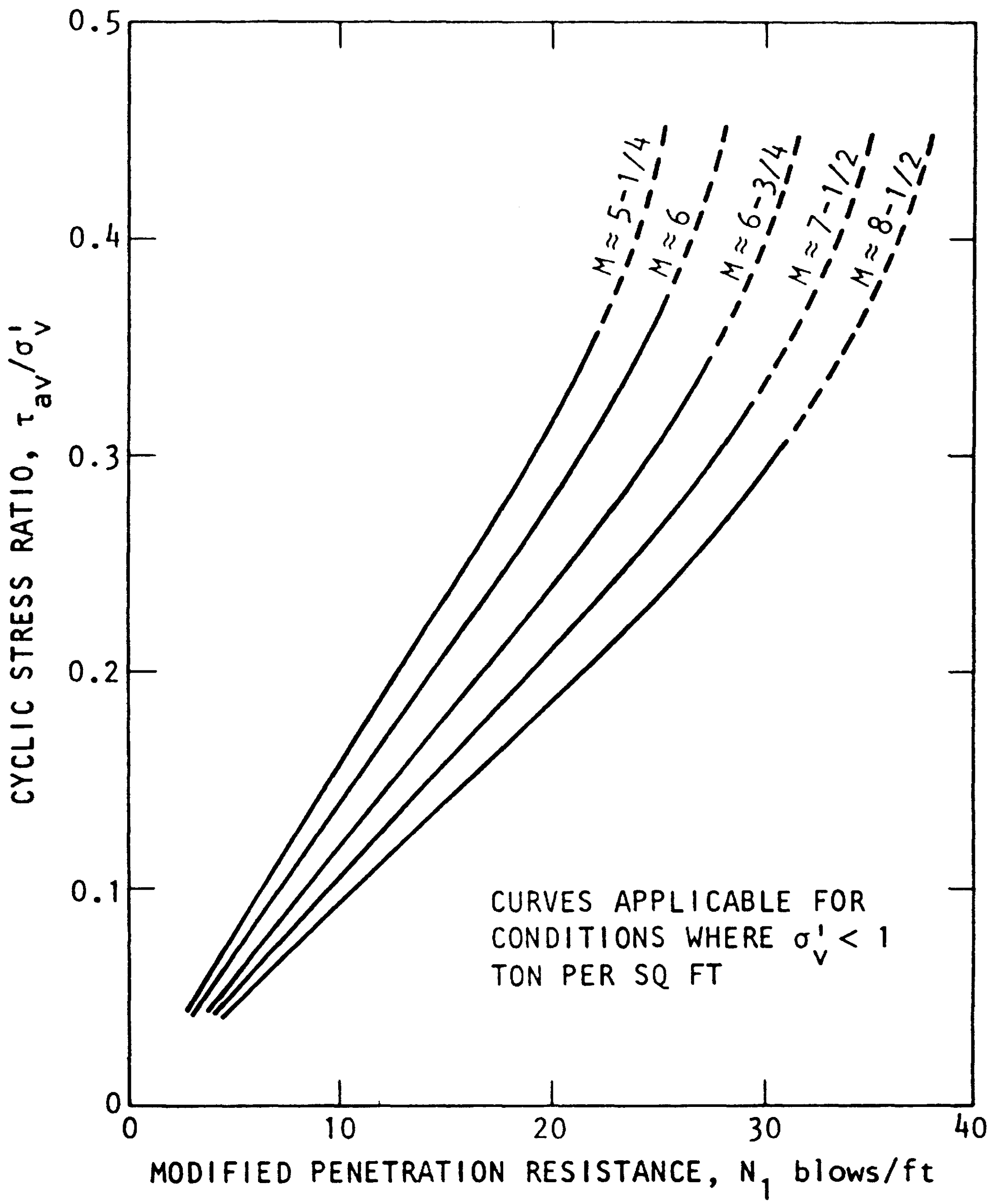


Figure 21. Plot of cyclic stress ratio to induce liquefaction versus blow counts, for various earthquake magnitudes (after Seed and Idriss, 1982).

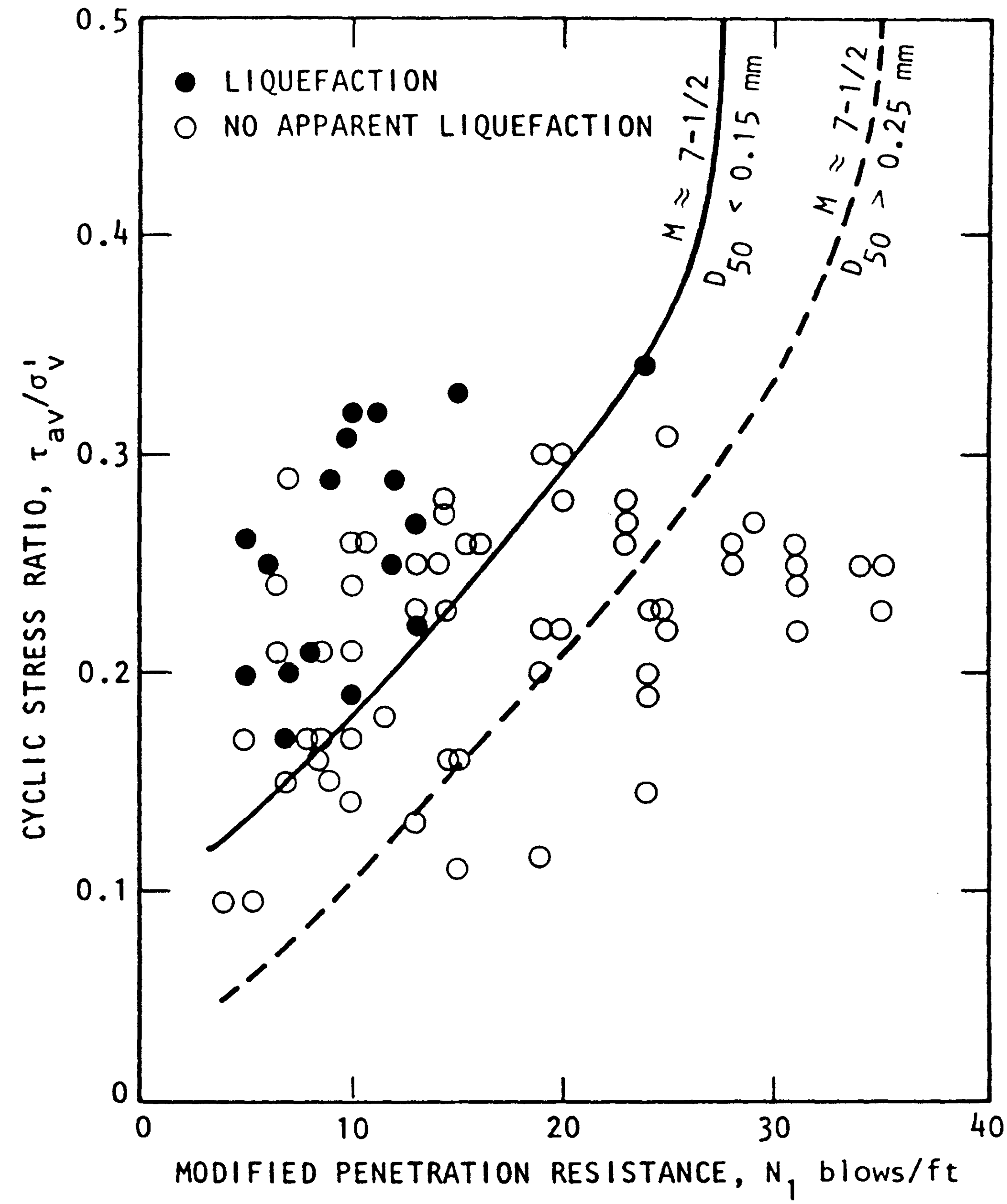


Figure 22. Plot of cyclic stress ratio to induce liquefaction versus blow counts, for silty-sand (after Seed and Idriss, 1982).

The energy requirement is generally met by using a safety hammer and two wraps of a one inch diameter rope around a rotating pulley. Using other procedures will vary the energy delivered to the drill rods considerably. For instance, using a mechanical trip hammer can deliver up to 90% of the energy to the drill rods, while using a donut hammer with rope and pulley will only deliver 45%. The following equation can be used to convert blow counts obtained using non-standard hammers to standardized blow counts:

$$N_{60} = N_m \cdot ER_m/60 \qquad (4)$$

N_{60} = Standard blow counts at 60% energy
N_m = Blow counts for method used
ER_m = Energy rod ratio for method used

Relationships have also been established between blow counts, soil density, and the weight of hammer, height of the drop, and dimensions of the sampler (Lowe and Zaccheo, 1975). By using these relationships blow counts obtained using non-standard samplers can be converted to standard results.

<u>Using electric cone penetrometer</u>. Using electric cone penetrometer data to predict liquefaction potential has several advantages over standard penetration testing: 1) Cone soundings give continuous subsurface soil data while standard penetration data is intermittent; 2) the cone will test thin layers while standard penetration test can only test layers one foot or thicker; and 3) cone testing is

more consistent area to area and operator to operator than standard penetration testing.

There are, however, two disadvantages to using the cone in liquefaction analysis: 1) Cone testing does not allow the recovery of samples to determine soil properties; and 2) large amounts of data have been compiled correlating liquefaction potential to standard penetration blow counts and a similar body of data does not exist for the cone. These disadvantages can be partially overcome to make the cone a useful tool in evaluating liquefaction potential.

Even though samples cannot be recovered while performing cone soundings, much can be determined about the soil from the relationship between the tip resistance and the friction resistance (Douglas and Olsen, 1981). Figure 23 shows a soil classification chart for the electric cone based upon tip resistance and friction ratio (the ratio of tip resistance to friction resistance).

Because there is little data to directly correlate liquefaction potential to cone resistance it is necessary to convert cone resistance to blow count resistance. Many investigators have studied the relationship between tip resistance and blow counts. Table 2 is a summary of various investigators results.

There is considerable scatter in the correlations between cone resistance and blow counts. It has been suggested that such correlations vary in different geologic

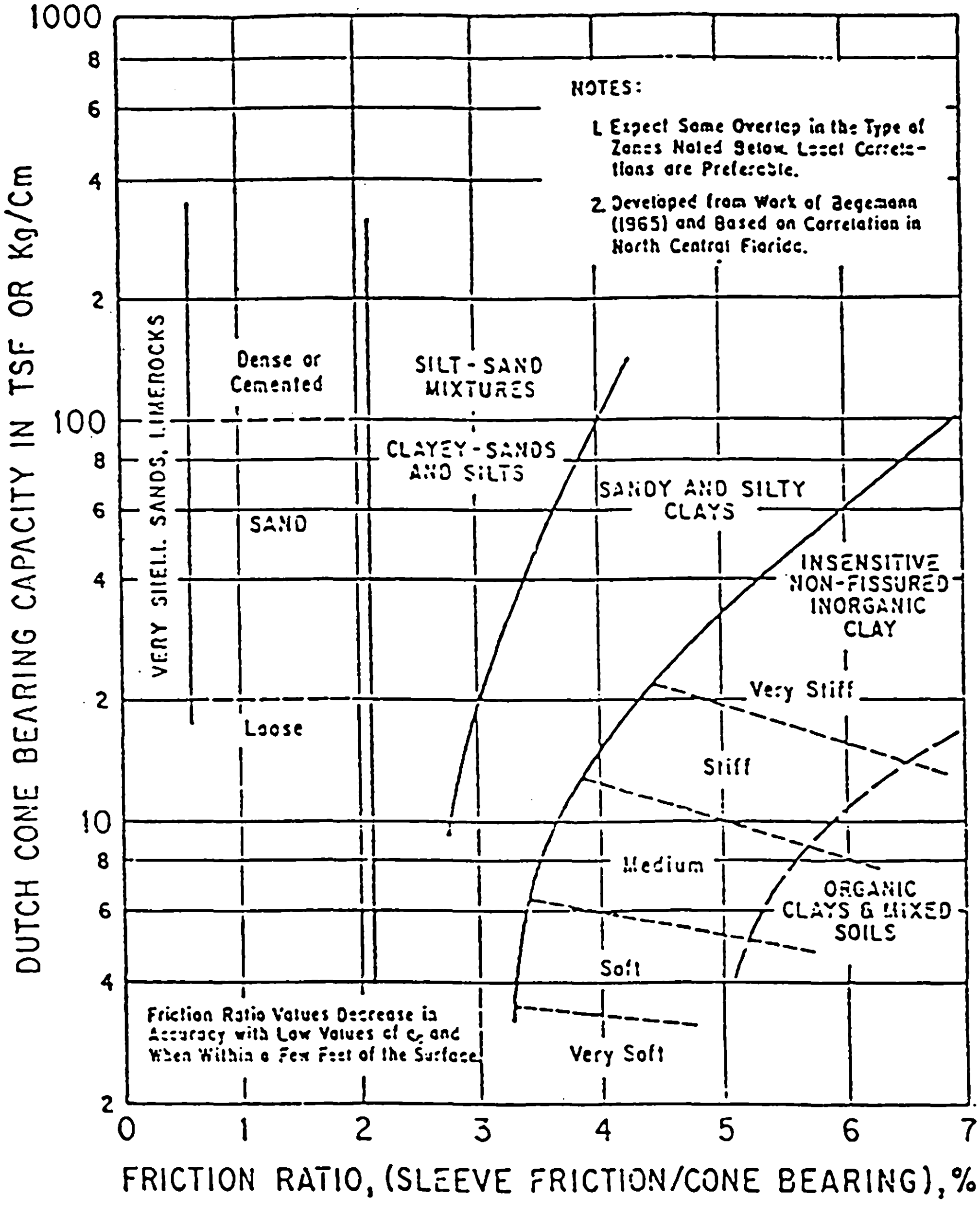


Figure 23. Soil classification for electric cone penetrometer (after Schmertmann, 1977).

Table 2. Values of Q_c/N from various investigations (after Kruizinga, 1982).

Soil Type	Qc/N	# of Tests	Author
A	8-10		Schmertmann
A	18		Meigh-Nixon
B	5-6		Schmertmann
C	8		Meigh-Nixon
C	10	122	Velloso
C	4		Meyerhof
D	3-4		Schmertmann
D	6	104	Velloso
E	3-5	131	Velloso
F	2	120	Velloso
F	2		Schmertmann
F	4-5		Franki
G	3-5	202	Velloso
G	2-3		Franki

A = sandy gravels and gravels
B = coarse sands and sands with little gravel
C = sand
D = clean, fine to medium sands, slightly silty sands
E = sandy silt
F = Sandy clay, silty clay, cohesive silt-sand mixtures
G = clay, silty clay, clayey silt

regions (Schmertmann, 1977). Therefore, it is advisable to establish correlations for the specific region being studied.

Seed has suggested curves for predicting soil liquefaction susceptibility based upon cone resistance as shown in Figure 24. These curves use average values for cone resistance-blow count correlations (Seed and Idriss, 1982).

Probabilistic liquefaction analysis

Yegian and Whitman (1978) propose a method of estimating the probability of liquefaction occurring by estimating both the probability of an earthquake occurring and the probability that the earthquake will cause ground failure. This can be expressed as:

$$P[F_L] = P[F_L|M,R] \cdot P[M,R] \tag{5}$$

$P[F_L]$ = probability that liquefaction will occur
$P[F_L|M,R]$ = probability that liquefaction will occur given an earthquake of magnitude M and hypocentral distance R
$P[M,R]$ = probability of an earthquake of magnitude M and hypocentral distance R occurring.

To obtain the probability of liquefaction occurring due to earthquakes of all possible magnitudes and hypocentral distances, Equation 5 can be summed or integrated.

To evaluate $P[F_L|M,R]$, an empirical expression representing the cyclic stress induced by the earthquakes was developed. It is given as:

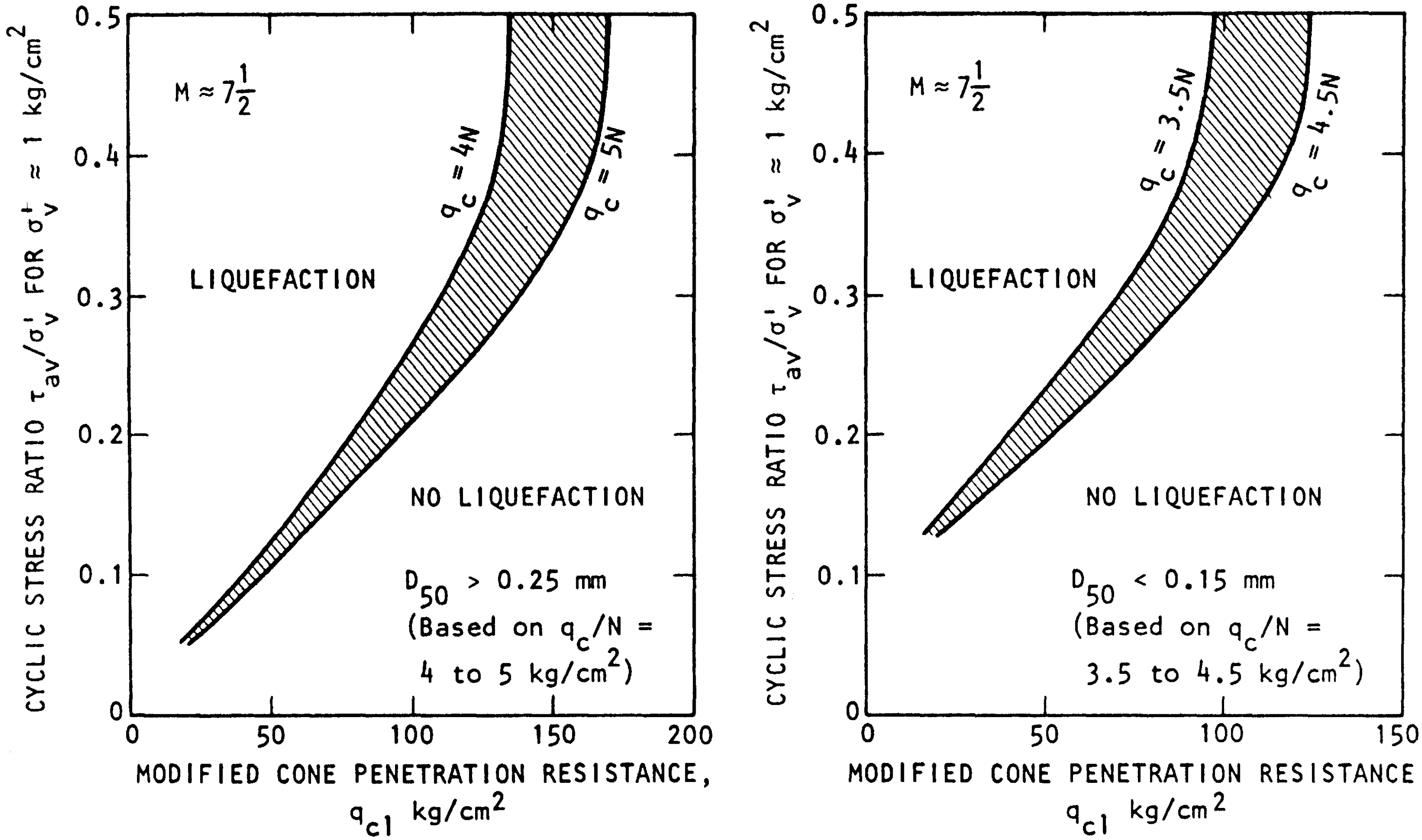
$$S_c = (e^{0.5M} \cdot H)/((R+16) \cdot \sigma'_v) \tag{6}$$

S_c = variable representing cyclic stress
M = earthquake magnitude
H = depth to liquefiable layer
R = hypocentral distance

Values of S_c were plotted versus blow counts for sites that did and did not experience liquefaction as shown in Figure 25. The boundary between liquefaction and no liquefaction is defined as S_c'.

The Liquefaction Potential Index (LPI) is defined as the ratio of the cyclic shear stress caused by an earthquake divided by the resistance of the soil to shaking. It is given as:

$$LPI = (S_c)_{earthquake} / S_c' \tag{7}$$



(a) Clean sands

(b) Silty sands

Figure 24. Plots of cyclic stress ratio to induce liquefaction versus cone resistance (after Seed and Idriss, 1982).

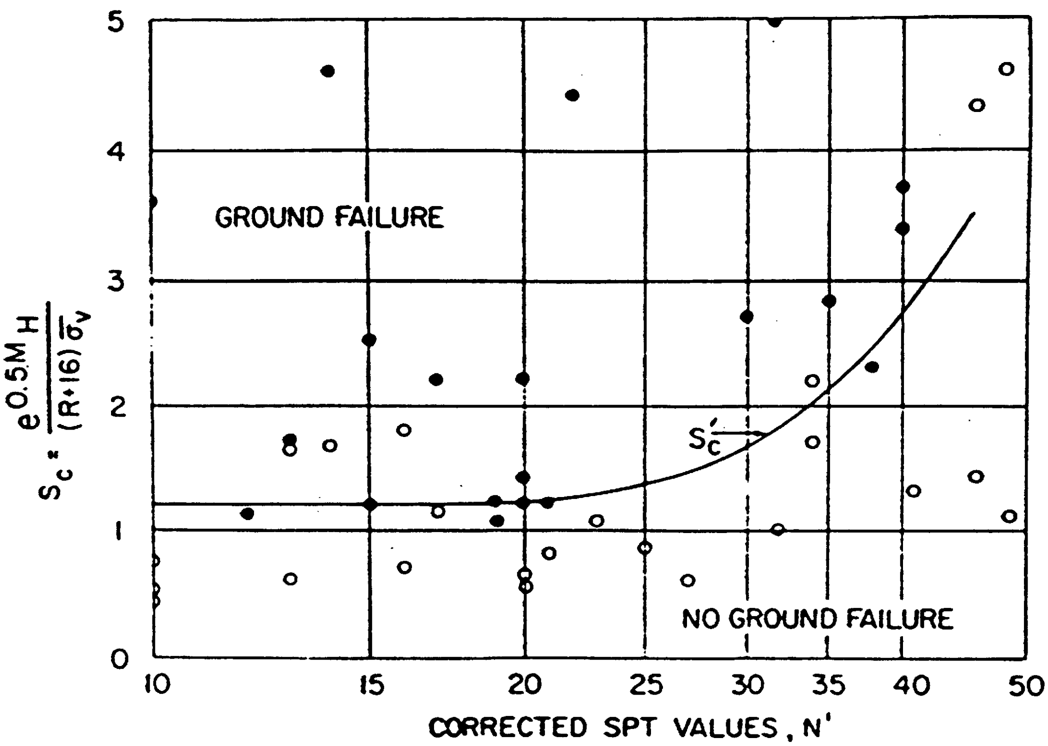


Figure 25. S_c' versus corrected blow counts (after Yegian and Whitman, 1978).

Liquefaction is expected for values of LPI greater than 1.0 and values less than 1.0 indicate some safety against liquefaction.

In their 1978 paper, Yegian and Whitman propose a probabilistic method of evaluating the expressions given above to determine the annual probability of a site experiencing liquefaction.

Threshold strain method

Laboratory tests have shown that there is a threshold cyclic strain below which no excess pore pressure accumulates. This strain is typically 0.01 percent (NRC, 1985). Thus, if this threshold strain will not be exceeded during earthquake shaking then the soil will not liquefy. This provides a conservative method to determine liquefaction potential. It is conservative because soils may not liquefy even if the threshold strain is exceeded.

The peak strain induced by an earthquake can be determined using the following equation:

$$\gamma = \tau/G = ((a/g)\cdot\sigma_o\cdot r_d)/G \qquad (8)$$

γ = Maximum shearing strain
τ = Maximum shearing stress
G = Shear modulus of the soil
a = Maximum earthquake ground acceleration
g = Acceleration of gravity
σ_o = Total vertical stress
r_d = Stress reduction factor (Figure 2-18)

Equation 8 can be simplified by assuming that the mass density of the soil is constant with depth, and noting that:

$$\sigma_o = P \cdot g \qquad (9)$$

P = mass density of the soil

And:

$$V_s^2 = G/P \qquad (10)$$

To obtain:

$$\gamma = a \cdot z \cdot r_d / ((G/G_{max})_\gamma \cdot V_s^2) \qquad (11)$$

z = Depth
$(G/G_{max})_\gamma$ = Modulus reduction factor for large strains
V_s = Shear wave velocity

(G/G_{max}) is actually a function of the strain, but it is reasonable to assume $(G/G_{max})_\gamma = 0.8$ for strains near the threshold strain. By also using an average value for r_d the following is obtained:

$$\gamma = 1.2 \cdot a \cdot z \,/\, V_s^2 \qquad (12)$$

By measuring the shear wave velocity of a soil at depth, the maximum shearing strain can be determined for an earthquake with a given maximum ground acceleration by using Equation 12. If the strain is below the threshold value of 0.01%, then the soil is safe against liquefaction.

<u>Liquefaction severity index</u>

Youd has observed that methods such as Seed's simplified Method only indicate whether or not liquefaction will occur, but give no indication of the expected severity of damage due to liquefaction. After reviewing case histories of buildings damaged and undamaged during earthquakes, Youd and Perkins have concluded that:

> Most buildings can withstand 50 to 100 mm (2 to 4 in) of differential ground displacement with little damage; that 120 to 600 mm (5 to 24 in) of displacement generally produces damage requiring minor to major repairs; and that displacements greater than 760 mm (30 in) are likely to cause major damage (Youd and Perkins, 1987, p. 2)

The amount of damage is a complex function of many factors which can be divided into the following catagories: seismological, sedimentological, topographic, hydrologic and engineering. Youd and Perkins introduce a parameter, liquefaction severity (S), which represents the amount of differential displacement in millimeters divided by 25 (inches). The parameter S is a function of all of the above parameters.

A second parameter, liquefaction severity index (LSI) is also introduced. This parameter is normalized with respect to all of the factors listed above except the seismological factors. LSI is the maximum S-value for a lateral spread on late Holocene flood plains or deltas associated with river channel widths greater than 10 m. By specifying this setting all of the above factors except the seismological are held relatively constant. Also the LSI is conservative because the above setting is generally the worst case for liquefaction damage. Displacements greater than 2.5 m are assigned a limiting LSI value of 100.

By normalizing LSI with respect to all factors except seismological, LSI becomes a factor of ground motion. Ground motion can be characterized by an amplitude, A, and a duration, D:

$$LSI = f(A,D) \qquad (13)$$

The parameter A attenuates logarithmically with distance from the earthquake rupture, while D increases slightly with increases in distance. Also, both A and D increase with increases in earthquake magnitude. Thus it was hypothesized that LSI is also a function of earthquake magnitude and the logarithm of the distance from the rupture:

$$LSI = f(M, \log R) \qquad (14)$$

To test this hypothesis LSI values were measured for a number of sites subject to earthquake shaking and meeting the specified site criteria. A linear least squares analysis of the data yields the following relationship:

$$\text{Log } LSI = -3.49 - 1.86 \log R + 0.98\, M_W \qquad (15)$$

It is important to remember that equation 15 only applies to the Western United States were the data were gathered. Earthquake attenuation relationships are quite different in other regions making Equation 15 non-applicable.

This method is convenient for mapping liquefaction hazards as Youd and Perkins did for the San Diego, California area (Youd and Perkins, 1987).

Soil Liquefaction Potential Mapping

Mapping based upon geologic criteria

Youd and Perkins (1978) have developed a procedure for liquefaction potential mapping in California based upon geologic data. This method is being used widely by the

U.S. Geological survey and others. The procedure involves developing a liquefaction susceptibility map based upon geology and groundwater and establishing liquefaction opportunity based upon the seismicity. The liquefaction potential is determined by combining the susceptibility and opportunity.

Standard penetration studies were used to establish the susceptibility of deposits of different ages. The following deposits were found to be susceptible to liquefaction:

Latest Holocene; 0-1,000 years
Earlier Holocene; 1,000-10,000 years
Late Pleistocene; 10,000-130,000 years

Table 3 shows liquefaction susceptibility based upon geologic age and depth to groundwater. High liquefaction susceptibility characterizes a soil that will liquefy when subject to a ground motion of 0.2 g with 10 equivalent cycles (M=6.5), or an equivalent combination of acceleration and equivalent cycles as determined by Figure 20. Moderate susceptibility characterizes a soil that will liquefy with the equivalent of 0.5 g and 30 cycles (M=8.0).

Liquefaction potential is then determined by looking at the seismicity of each region (opportunity) and the ground shaking required to induce liquefaction (susceptibility) and arriving at a recurrence interval for liquefaction.

Table 3. Liquefaction susceptibility by geologic age and depth to ground water (after Youd and Perkins, 1978).

	Depth to Groundwater (ft)		
Age of Deposit	0-10	10-30	>30
Latest Holocene	high	low	nil
Earlier Holocene	moderate	low	nil
Late Pleistocene	low	nil	nil

The USU method

The geologic method is useful in the area it was developed but does not necessarily apply to other regions. Anderson and Keaton observed that practically all deposits along the Wasatch Front are Late Pleistocene and therefore Youd and Perkin's 1978 method is not applicable for that region. In liquefaction potential studies for Davis, Salt Lake, and Utah counties Anderson has developed an alternate method utilizing engineering data and Seeds method (Anderson and Keaton, 1982).

The USU method involves collecting all available standard penetration data and cone penetration data for the region. A critical cyclic stress ratio can then be obtained by entering Figure 21 with a N value corrected for overburden and silt, if necessary. The critical ground acceleration to induce liquefaction can then be obtained from:

$$(a_{max})_c = (\tau_{avg}/\sigma'_o)\cdot(\sigma'_o/\sigma_o)\cdot(1/0.65\cdot r_d) \qquad (16)$$

$(a_{max})_c$ = critical acceleration to induce liquefaction
(τ_{avg}/σ'_o) = critical cyclic stress ratio

Liquefaction potential is then determined by looking at the seismicity of the region. If the critical acceleration has a 50 percent exceedence probability in 100 years it is given a high liquefaction potential. A 10-50 percent exceedence probability was taken to represent moderate liquefaction potential, 5-10 percent represents low, and < 5 percent represents very low.

Critical accelerations are calculated for all sites where subsurface data is available. Liquefaction potential zones are then determined based upon the critical accelerations and geology.

Utilizing Liquefaction Potential Maps

Liquefaction potential maps can provide planners with a valuable tool if used properly. However, it is extremely important that other geo-hazards are not ignored when dealing with liquefaction. A knowledge of how all geo-hazards can affect a site is crucial to good planning.

It is also important to remember exactly what the liquefaction potential maps represent. Not all sites in a high liquefaction zone will experience liquefaction during a large earthquake; however, liquefaction damage can be expected to be confined to liquefaction zones commensurate with the degree of ground shaking. Site specific analyses are essential to determine how specific sites will perform.

Anderson and Keaton have proposed the matrix shown in Table 4 to determine when a site specific analysis should be required.

At sites where critical structures would be threatened by liquefaction, several options are available: 1) Liquefiable soils could be removed, 2) the groundwater could be controlled so susceptible soils are not saturated, 3) soils could be densified in situ, 4) a safer site could be utilized for the structure and appropriate uses found for the hazardous site, 5) deep foundations, established below liquefiable soils could be utilized if other potentially damaging effects of liquefaction could be mitigated.

Table 4. Required site specific investigation for liquefaction potential zones (after Anderson, Keaton, Bay and Rice, 1987).

Facility	Liquefaction Potential Zone High	Moderate	Low	Very Low
CRITICAL Hospital Fire Station Police Station Other emergency facilities	YES	YES	YES	MAYBE
LIFELINES Communications Transportation Water Supply Electricity Natural Gas Sewage Plants	YES	YES	YES	MAYBE
HIGH OCCUPANCY PUBLIC OWNED Schools State Capitol City Hall County Courts Airports Sports/Convention Cntr.	YES	YES	YES	MAYBE
HIGH OCCUPANCY PRIVATE OWNED Offices Apartments Shopping Malls Hotels	YES	YES	YES	MAYBE
INDUSTRIAL SEVERE CONSEQUENCE Refineries Sewage Plants Hazard/Toxic Explosive	YES	YES	MAYBE	NO
INDUSTRIAL MINOR CONSEQUENCE Trucking Shipping Light Manufacturing	NO*	NO*	NO	NO
RESIDENTIAL SUBDIVISION	MAYBE*	NO*	NO	NO
RESIDENTIAL SINGLE LOTS	NO*	NO*	NO	NO

*Appropriate Disclosure Required

METHODOLOGY

General

Liquefaction potential maps of the study area were prepared by using the USU Method as discussed previously. The study was carried out the same manner as previous studies done for Davis County (Anderson, Keaton, Aubrey and Ellis, 1982), Salt Lake County (Anderson, Keaton, Spitzley and Allen, 1986) and Utah County (Anderson, Keaton and Bischoff, 1986); however, the procedure was improved by automating much of the data compilation and analysis. The six steps outlined below were followed in preparing the maps:

1. Sub-surface data were collected from public and private agencies.
2. A field investigation was conducted to supplement the existing data.
3. Standard penetration data and cone penetration data were analyzed using Seed's simplified method to determine the critical ground acceleration to induce liquefaction at each site.
4. The seismicity of the region was characterized by exceedence probability curves.
5. The region was divided into units according to the geology of surficial deposits.
6. The region was divided into zones of liquefaction potential based upon the calculated critical accelerations, the area seismicity and the geology.

Collecting Subsurface Data

To obtain all existing sub-surface data, a search was conducted of the files of local geotechnical consulting firms, the Utah Department of Transportation, and state county agencies. Photo copies were made of the logs of all borings conducted in the study area. The locations of each study was plotted on 50% reductions of U.S.G.S. 7 1/2 minute quadrangle maps. Copies of the boring logs and the location maps are on file at the Geotechnical Engineering Division, Utah State University.

Supplementary Field Investigation

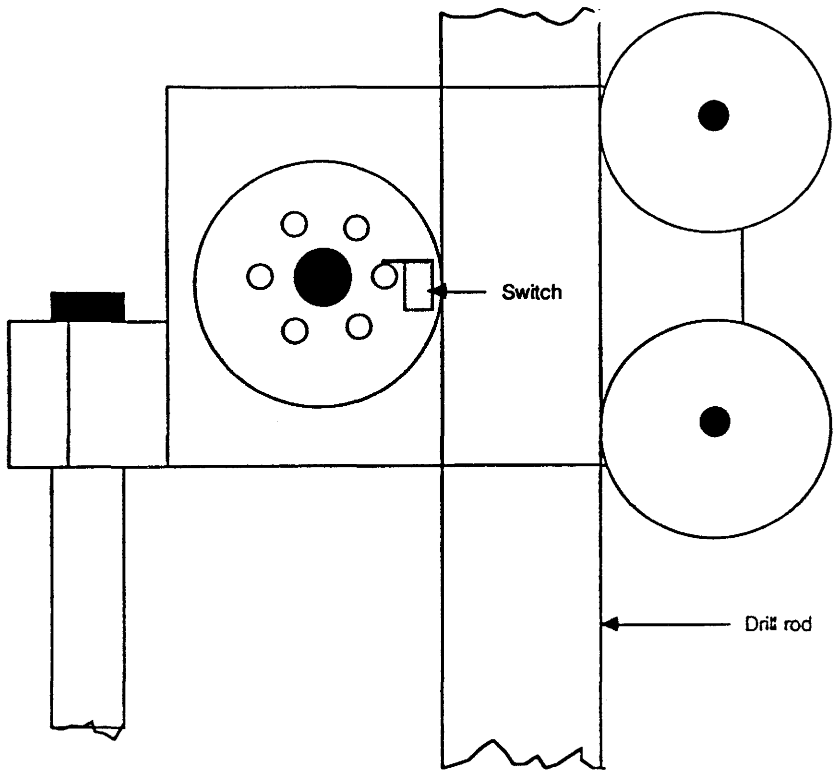
A field investigation was conducted in areas where little or no existing data were available. The investigation primarily involved 40 cone penetrometer soundings and 10 borings with standard penetration testing. The borings were performed at the sites of cone soundings and were used to establish local correlations between cone penetration resistance and standard penetration resistance.

Instrumenting electric cone penetrometer

The only electric cone penetrometer available locally had a manual data acquisition system. This requires manually recording values of tip and friction resistance from a LCD display that was updated each 10 cm the cone progressed. For this investigation, it was important to have reading spaced closer than 10 cm and to be able to able to record the data electronically, so a new data acquisition system was designed and constructed.

The primary element of the new data acquisition system was a programable Campbell Scientific 21X datalogger. A device to monitor the depth of cone penetration was also built. A diagram of this device is shown in Figure 26. This device works by means of a wheel that rotates against the advancing drill rod. Every time the cone progresses one inch a switch closes and opens creating an electronic pulse which is counted by the datalogger. This device was named the "pulser".

Briefly, the data acquisition system works as follows: Whenever the data logger receives a pulse from the pulser, it measures the voltages of analog signals of tip and friction resistance generated by load cells in the cone. The datalogger then multiplies the voltages by appropriate factors to give resistance values in tons/sq ft. These resistance values are then stored digitally on a magnetic tape cassette. The datalogger, equipped with a built in clock, also keeps track of the time interval between pulses and estimates when the cone has progressed $^1/_2$ inch and takes another reading. The system also produces a field copy of the cone sounding by sending analog signals of tip and friction resistance to a two-channel strip-chart recorder. Every time the cone progresses a foot, the datalogger sends one channel of the strip chart recorder a full scale voltage, followed by a zero voltage, then the initial



Cut a way view

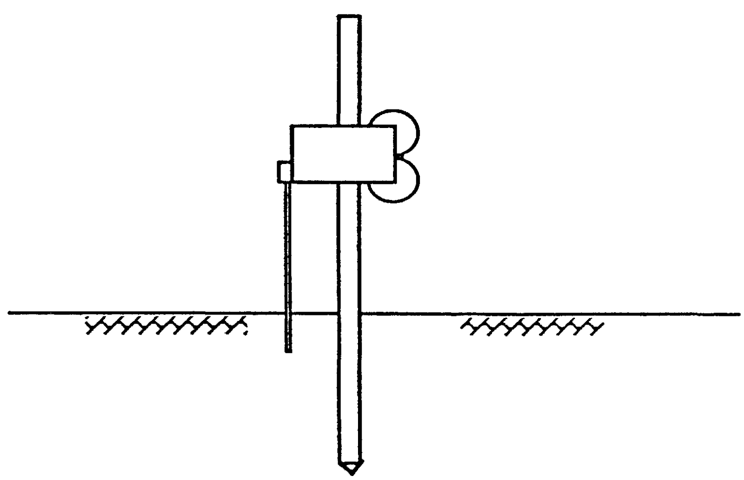


Figure 26. Diagram of pulser device.

voltage. This creates a horizontal line on the field record marking each foot the cone progresses.

The cone returns a 7.5 mV full-scale analog signal for tip and friction resistance, however the datalogger is only capable of measuring a 5.0 mV signal, so a voltage reducing circuit was included to reduce all signals from the cone by $^2/_3$.

A switch to initiate and conclude the data acquisition and indicator lights were incorporated into a control box.

Figure 27 is a schematic diagram of the electric cone penetrometer data acquisition system. Appendix A includes a copy of the program used in the datalogger.

<u>Cone penetration testing</u>

Forty cone soundings were taken throughout the region. The locations and results of these tests are on file at Utah State University with the other subsurface data collected for the project. The cone was pushed to a depth of 60 feet or refusal. At six locations shallow gravel was encountered causing sounding to be terminated at less than 20 feet; these soundings were not used in the analysis. Figure 28 shows an example of a cone sounding smoothed over 6-inch intervals.

<u>Standard penetration testing</u>

In addition to the cone soundings, ten borings with standard penetration testing were conducted adjacent to cone soundings. Decisions of where to sample were made by

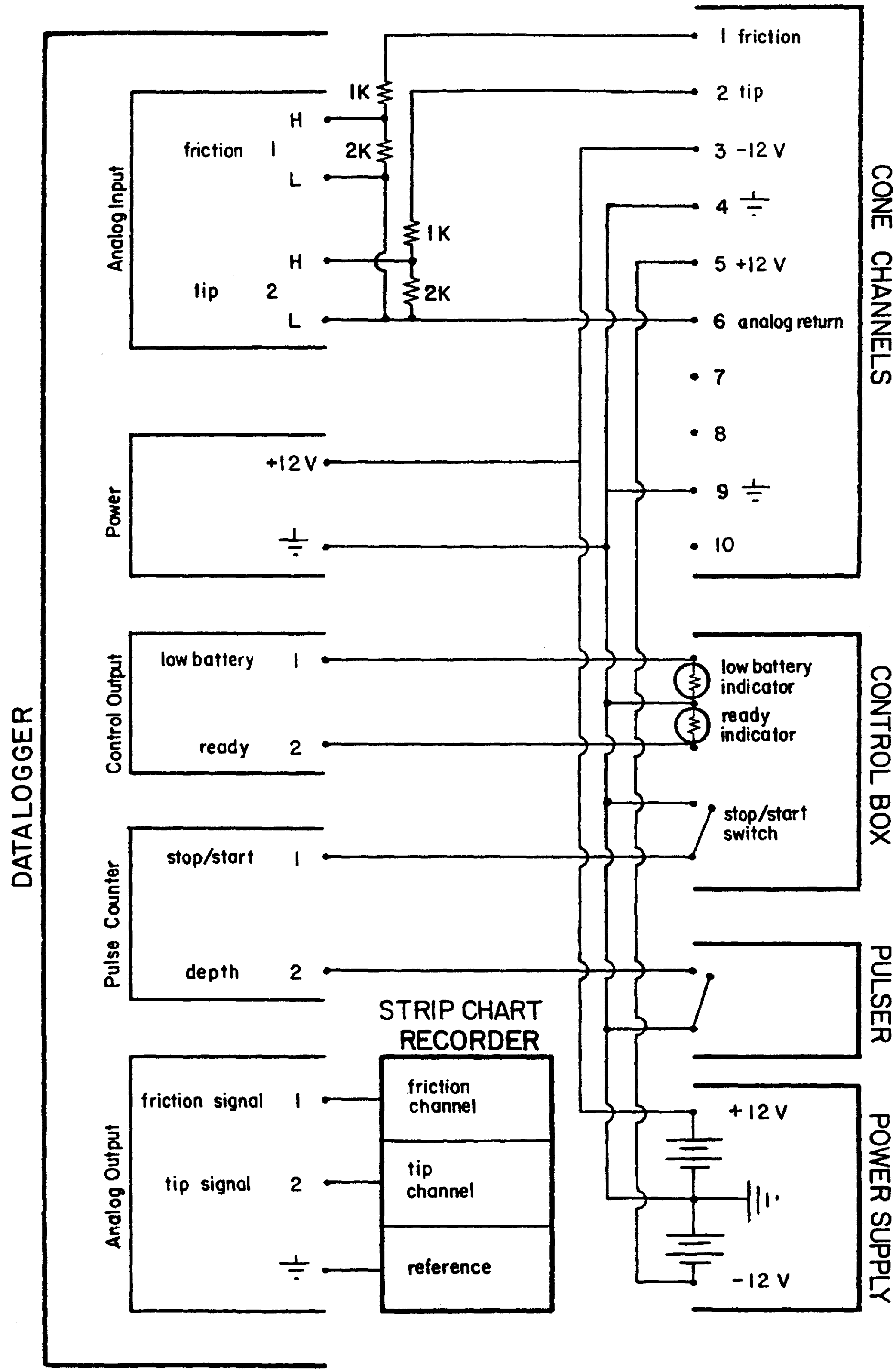


Figure 27. Schematic diagram of data acquisition system for electric cone penetrometer.

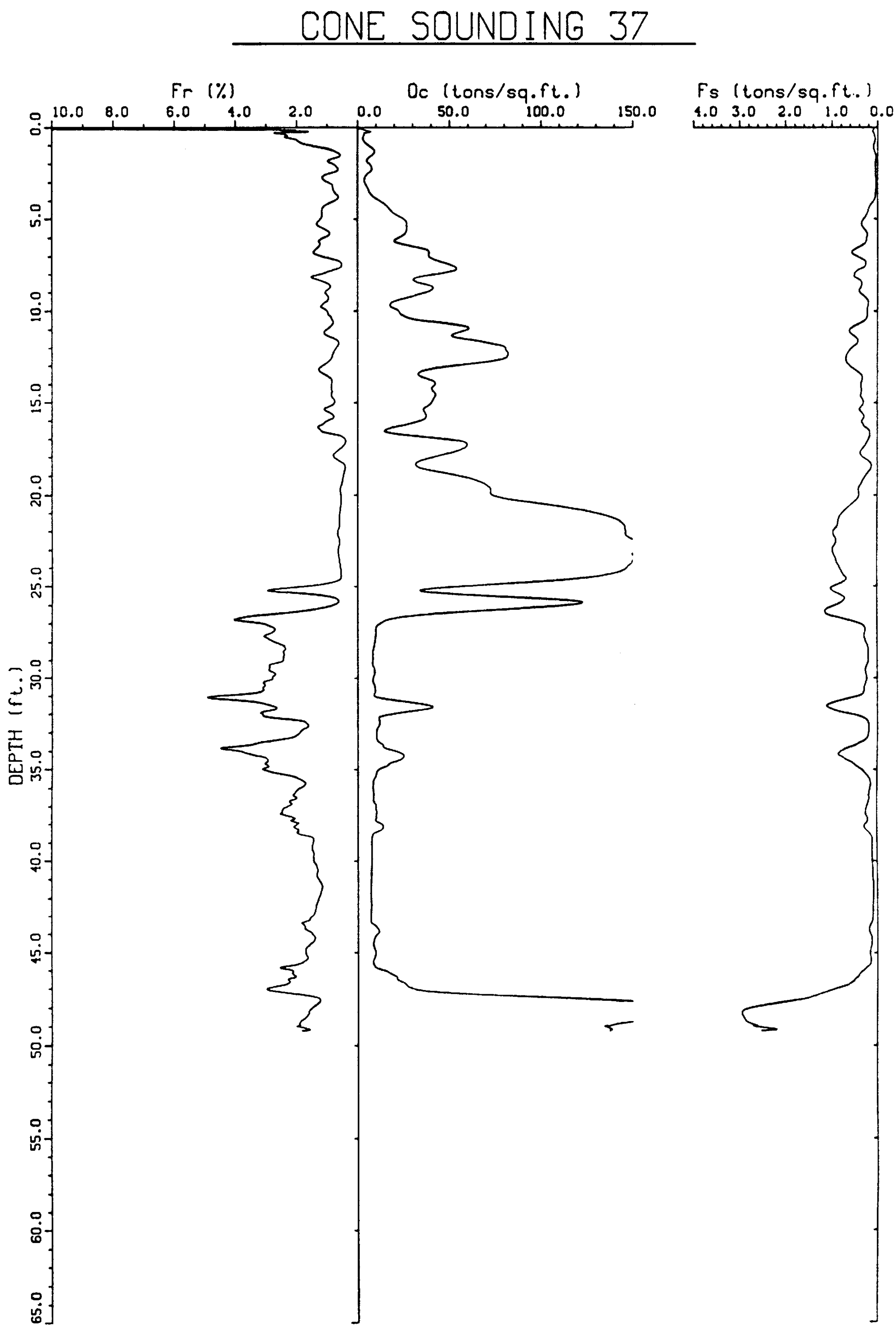


Figure 28. Example of cone sounding smoothed over 6 inches from field investigation.

consulting field copies of the cone soundings. The purpose of the standard penetration testing and sampling was to provide correlations between cone resistance and standard penetration resistance, and to provide samples to develop correlations between cone resistance and soil type.

The first six borings were rotary wash with bentonite mud. On the last four borings, hollow stem augers were utilized. Special precautions were taken with the hollow stem borings. A head of water was maintained in the boring at least equal to the head in the soil. A plug was used in the end of auger, and the auger was lifted off the bottom of the hole while sampling so as to not increase the vertical pressure with the weight of the auger.

Figure 29 is a copy of the log of the boring drilled parallel to the sounding shown in Figure 28. Copies of all the boring logs and their locations are on file at Utah State University.

Laboratory testing

All samples obtained from borings were classified according to the Unified Soil Classification System. This involved grain size analysis for all granular material and Atterberg limits for all cohesive and silty material. The D_{50} of all silty sands were noted to make proper silt corrections. Appendix B contains the tabulated soil data.

BORE HOLE NO. 10
LOCATION: THOMPSON'S FARM, 6700W 1900N, WARREN
HOLLOW STEM AUGER
OCT 25, 1986

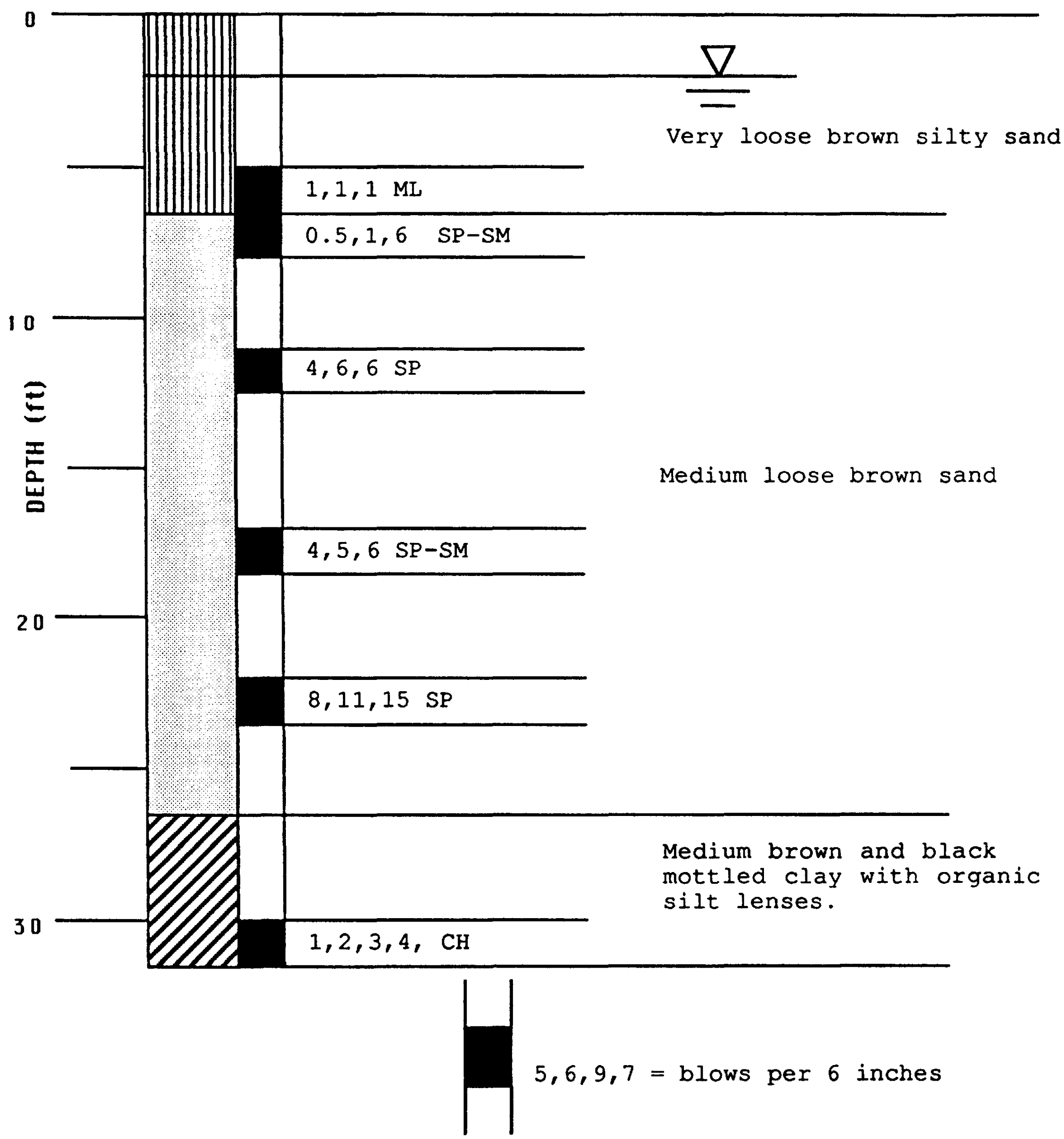


Figure 29. Example of boring log from field investigation.

Analyzing Soil Data

Creating soil data files

Computer files were made containing all pertinent soil data. To create these files, first, all of the boring locations were digitized to establish their UTM coordinates. This was done by means of the program BAL (Boring Area Locator). Then the pertinent soil data was entered using the program SDI (Soil Data Input). To use SDI, a copy of the boring log is attached to the digitizer table, the axis is scaled; then the top and bottom of the boring, the ground water depth, the soil layers and the sample locations are all digitized. SDI then creates two files, the first is a library file containing all the soil data and the location of the areas, the second is an index file containing the location of each area, the depth of the deepest boring at the area, and the depth of the shallowest groundwater at each area. These index files will allow others to find borings in the USU files in any region of interest to them.

The programs BAL and SDI are included in Appendix C.

Determining critical accelerations from standard penetration data

The program CA (Critical Acceleration) written by Jon Bischoff and John Spitzley (Bischoff, 1985) was modified and extended to make the program CRAC (CRitical ACceleration) which determines critical accelerations from the data in library files created with SDI. Briefly, CRAC works as follows. Each sample is evaluated to see if it is below the water table and in a liquefiable material; if so, a critical acceleration is calculated based upon blow counts using the methods outlined in previous sections dealing with Seed's Simplified Method and the USU Method. The program checks for non-standard penetration tests and converts them to a standard penetration resistance using the relationships established by Lowe and Zaccheo (1975). If the D_{50} of a soil is known, a silt correction is calculated. If The D_{50} is not known, default silt correction values are assigned for each soil type. These values are based upon the average silt corrections of soils encountered in the field investigation.

Appendix D contains a copy of the program CRAC. Figure 30 is the output from the boring shown in Figure 29.

<u>Interpreting cone soundings</u>

Q_c/N values tend to vary considerable in different studies as was shown in Table 2. For this reason Q_c/N values were established based upon the results of the field investigation. Table 5 shows these results.

Table 5. Average Qc/n values from field investigation.

Soil Type	Average Qc/N	Standard Deviation	Number of Samples
Clean Sand	4.45	0.86	8
Silty Sand	3.90	1.39	23
Clay	2.23	1.04	25

AREA NUMBER 4010

BORING NUMBER 1
BORING DEPTH= 32.00 ft. GROUND WATER DEPTH= 2.00 ft.

DEPTH (ft.)	CRITICAL ACCELERATION (a/g)	SOIL TYPE	N	N1	SILT CORRECTION
5.75	0.1160	ML	2.0	3.2	7.5
7.25	0.1601	SP,	7.0	11.2	4.5
11.75	0.1767	SP,	12.0	18.9	0.0
17.75	0.1422	SP,	11.0	14.3	1.5
22.75	0.2890	SP	26.0	30.5	0.0

MINIMUM CRITICAL ACCELERATION FOR BORING= 0.1160

MINIMUM CRITICAL ACCELERATION FOR AREA= 0.1160

Figure 30. Example of output from CRAC.

To determine the soil type from cone soundings soil types were plotted against tip resistance and friction ratio and boundaries were fit between the soil types to generate the soil classification chart shown in Figure 31.

Determining critical accelerations from cone penetration data

A program similar to CRAC was written to calculate critical accelerations from cone data, (CRACCO, CRitical ACcelerations from COne soundings). Figure 32 is a simplified flow chart of CRACCO. CRACCO is included in Appendix E. Figure 33 shows an example of the plot generated by the program. It is from the cone sounding shown in Figure 28.

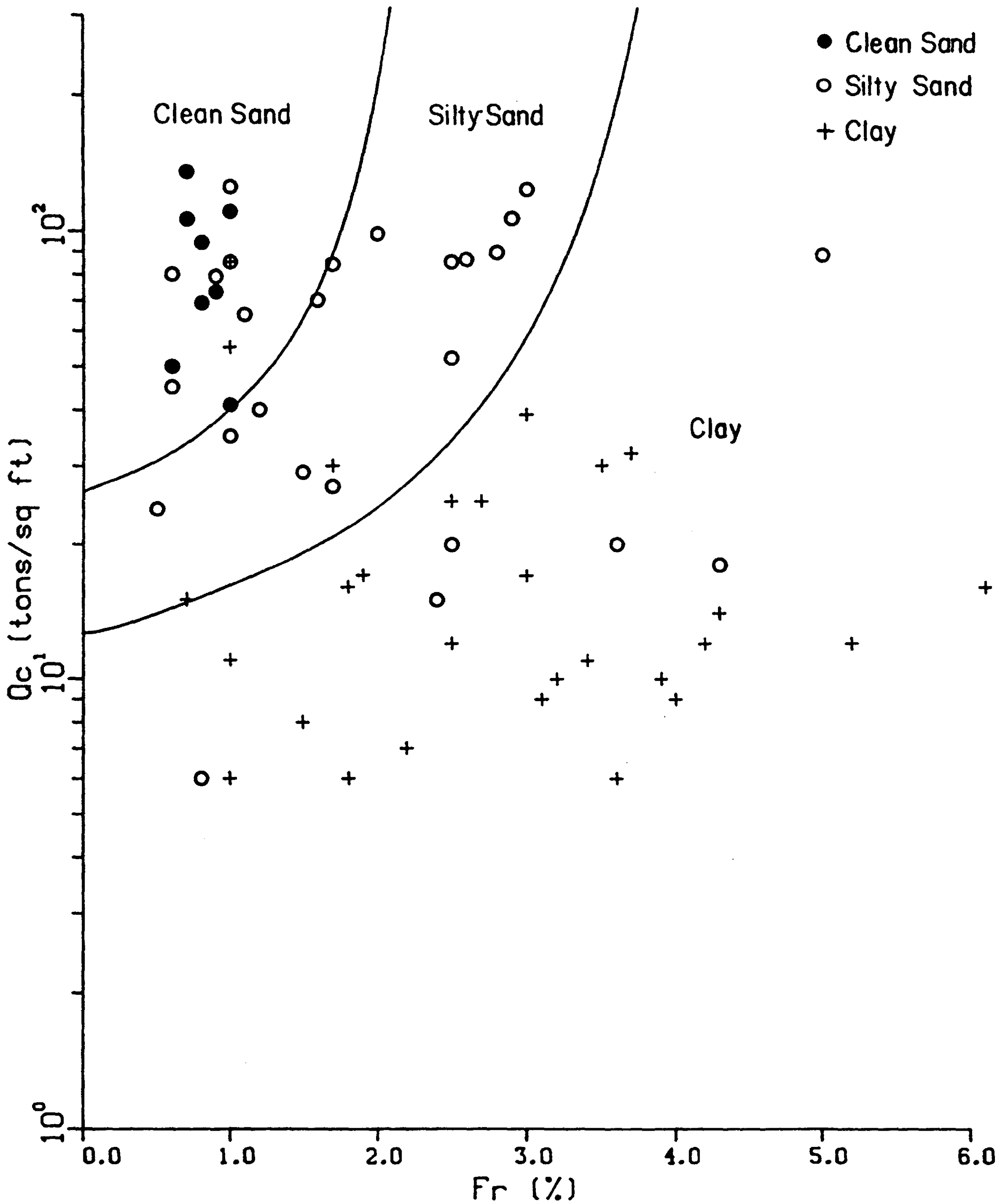


Figure 31. Soil classification chart for cone soundings, generated from field investigation.

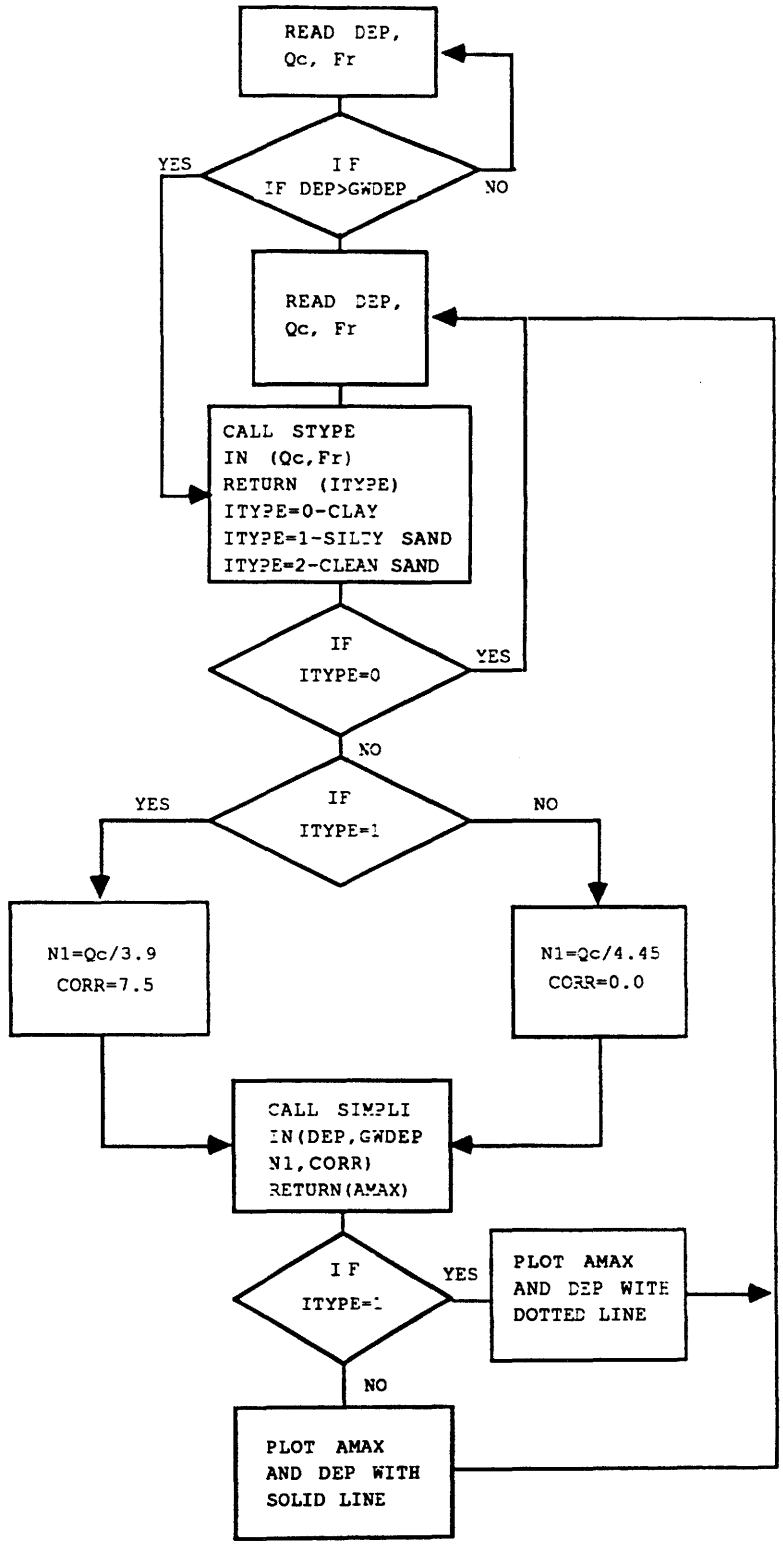


Figure 32. Simplified flow chart for CRACCO.

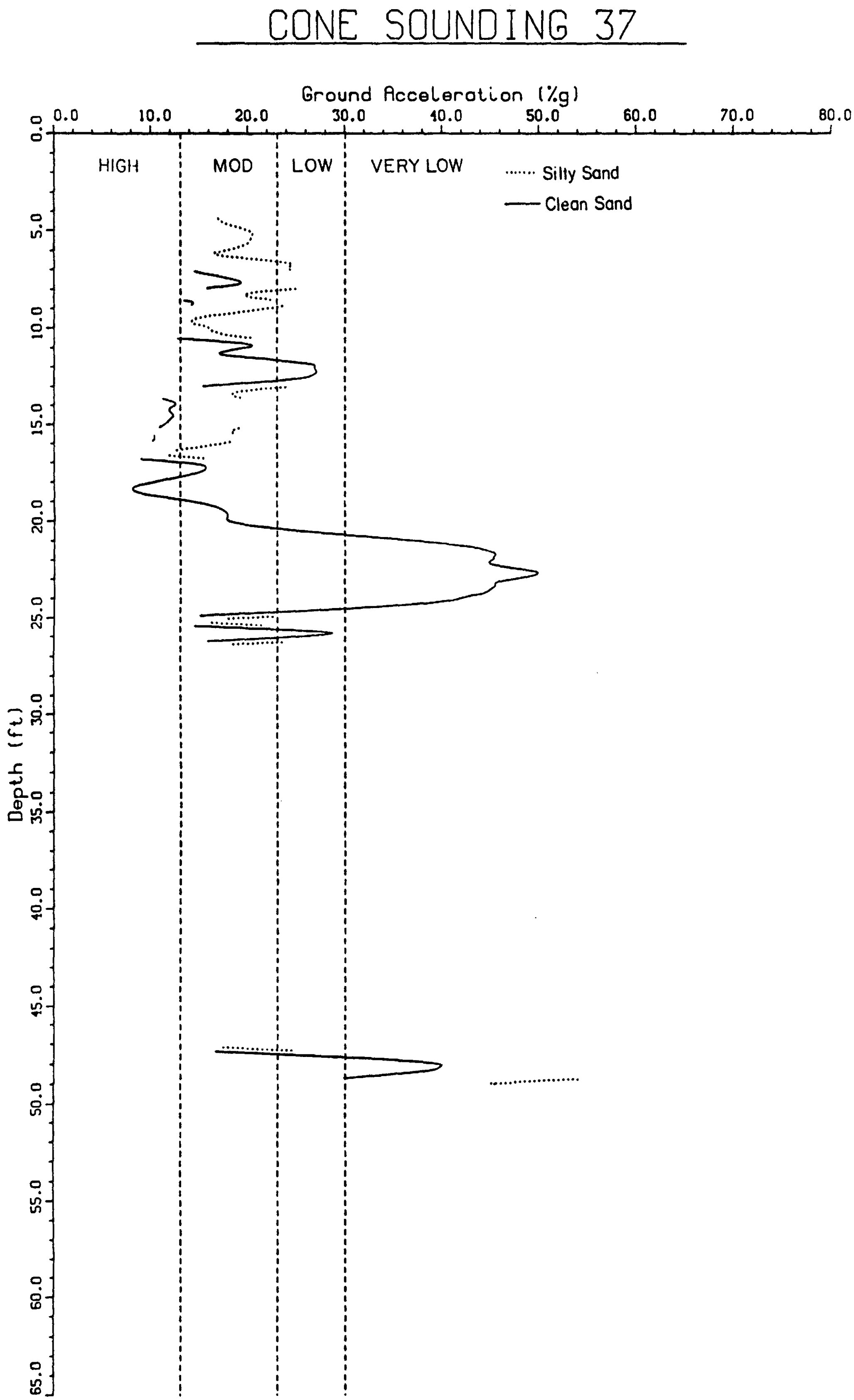


Figure 33. Example plot from CRACCO.

Assigning sites critical accelerations

The site of each boring or cone sounding was assigned a critical acceleration. To obtain this value critical accelerations were calculated for every liquefiable layer encountered in the area (using the programs CRAC and CRACCO), and generally used the lowest value at each site was used as the site's critical acceleration.

Critical accelerations for layers deeper than 80 feet were disregarded because: 1) The modified rigid body model for determining cyclic strain looses much accuracy below 80 feet (see Figure 17); 2) Seed's method was developed on shallower deposits and may or may not apply at great depths; 3) Evidence from previous earthquakes indicates that liquefaction damage is a result of liquefaction of relatively shallow deposits.

The results on borings that were less than 20 feet were considered inconclusive unless highly susceptible soils were encountered. This was because more susceptible layers could be present at depths greater than 20 feet.

At some sites, low blow count values were found that did not seem representative of neighboring borings or adjacent tests. Judgment was used in these cases, and sometimes the lowest critical acceleration values were disregarded.

The critical accelerations were then used to classify each site as having liquefaction susceptibility as high, moderate, low, or very low liquefaction susceptibility.

These susceptibilities were plotted on maps to aid in defining liquefaction potential zones.

Seismicity of the Study Area

Weber and Box Elder Counties

Studies conducted by Dames and Moore (1975), and Geomatrix (Young, Swan, Power, Schwartz and Green, 1987) indicate that the seismicity of Weber and Box Elder Counties is quite similar to the seismicity of Salt Lake and Davis Counties. Therefore, nearly the same exceedence probability curve was used for Weber and Box Elder Counties as was used in the Salt Lake County investigation. This exceedence probability curve is shown in Figure 34. Table 6 shows the liquefaction potential classifications for Weber and Box Elder Counties. Figure 35 shows the relative contributions of different sources to the seismicity of Weber and Box Elder County. It is seen that the primary contribution comes from the Wasatch Fault. It is felt that the Wasatch Fault usually generates a magnitude 7.0 - 7.5 event (Schwartz and Coppersmith, 1984), therefore a magnitude 7.5 event was used to calculate critical accelerations for Weber and Box Elder Counties.

Table 6. Liquefaction potential classifications for Weber and Box Elder Counties.

High	< 0.10 g	> 50%
Moderate	0.10 - 0.18 g	50 - 10%
Low	0.18 - 0.25 g	10 - 5%
Very Low	> 0.25 g	< 5%

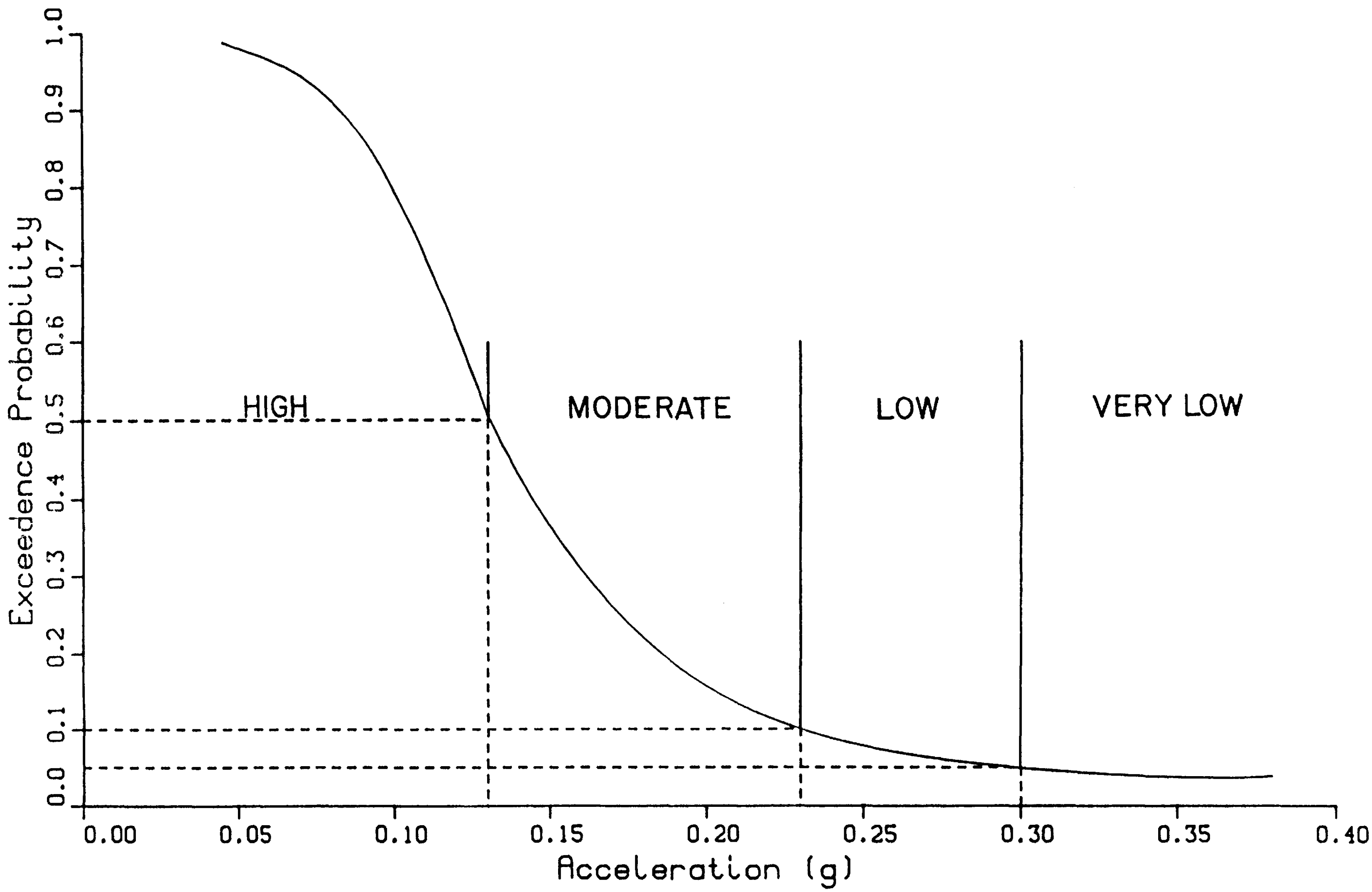


Figure 34. 100 year exceedence probability curve for Weber and Box Elder Counties.

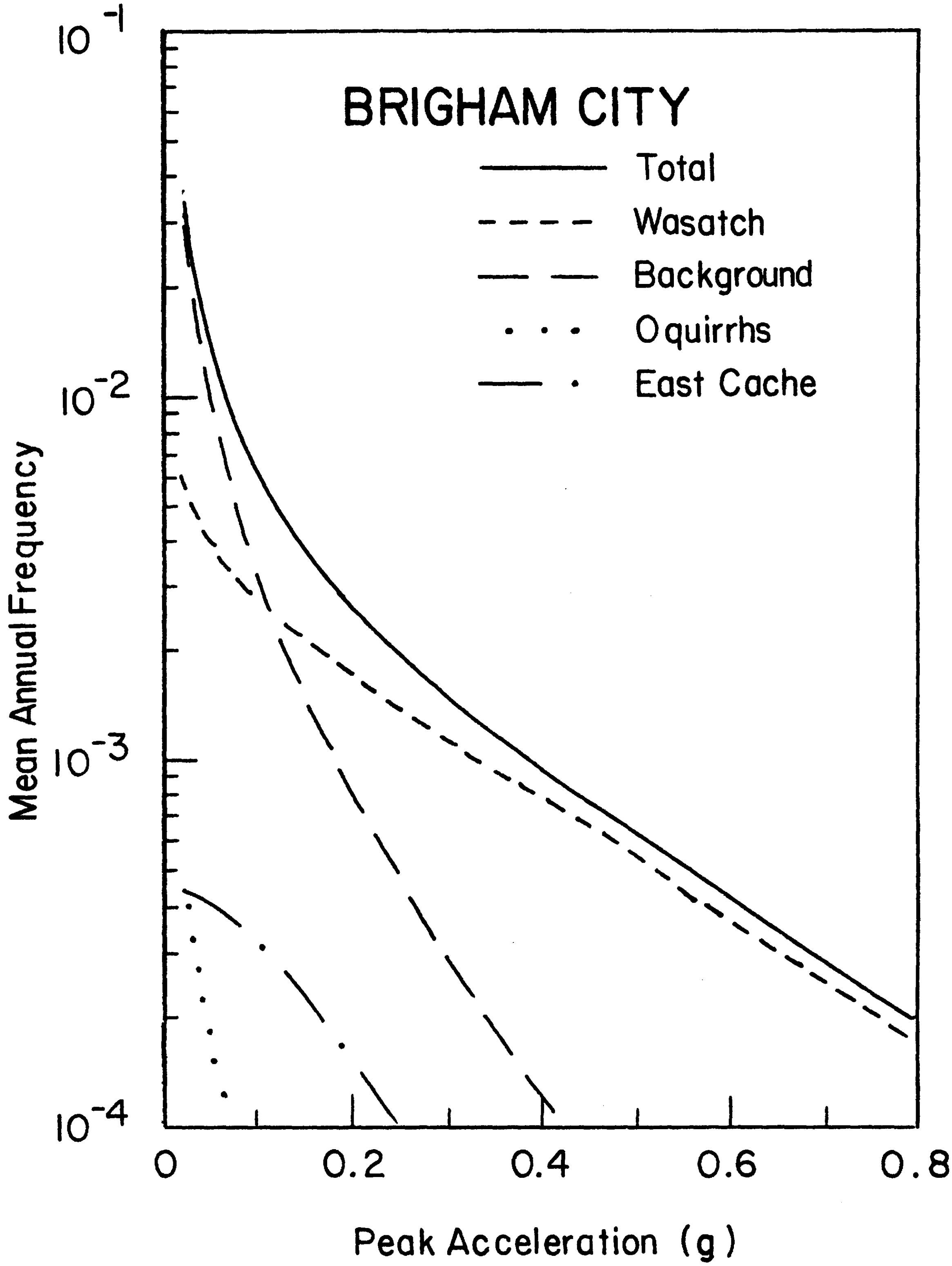


Figure 35. Contribution of various sources to Brigham City seismicity (after Young, Swan, Power, Schwartz and Green, 1987).

Cache County

No detailed seismicity studies exist for Cache County. Therefore, the exceedence probability for this investigation was estimated based upon the work of Geomatrix (Young, Swan, Power, Schartz and Green, 1987). Figure 36 shows the estimated exceedence probability curve for Cache County. Table 7 shows the liquefaction potential classifications for Cache County. Figure 37 shows the relative contribution of various sources to the regions seismicity. It is seen that the background earthquake makes the largest contribution to peak acceleration for mean annual frequencies greater than about 2 X 10^{-4}. Background earthquakes come from unmapped faults which are not expected to produce events with surface rupture and would therefore be of magnitude 6.0 or less. A magnitude 6.0 earthquake was used to calculate critical accelerations in Cache County, because it represents the magnitude of the likely Cache County event.

Table 7. Liquefaction potential classifications for Cache County.

Liquefaction Potential	Critical Acceleration	Approximate 100 year Exceedence Probability
High	< 0.10 g	> 50%
Moderate	0.10 - 0.18 g	50 - 10%
Low	0.18 - 0.25 g	10 - 5%
Very Low	> 0.25 g	< 5%

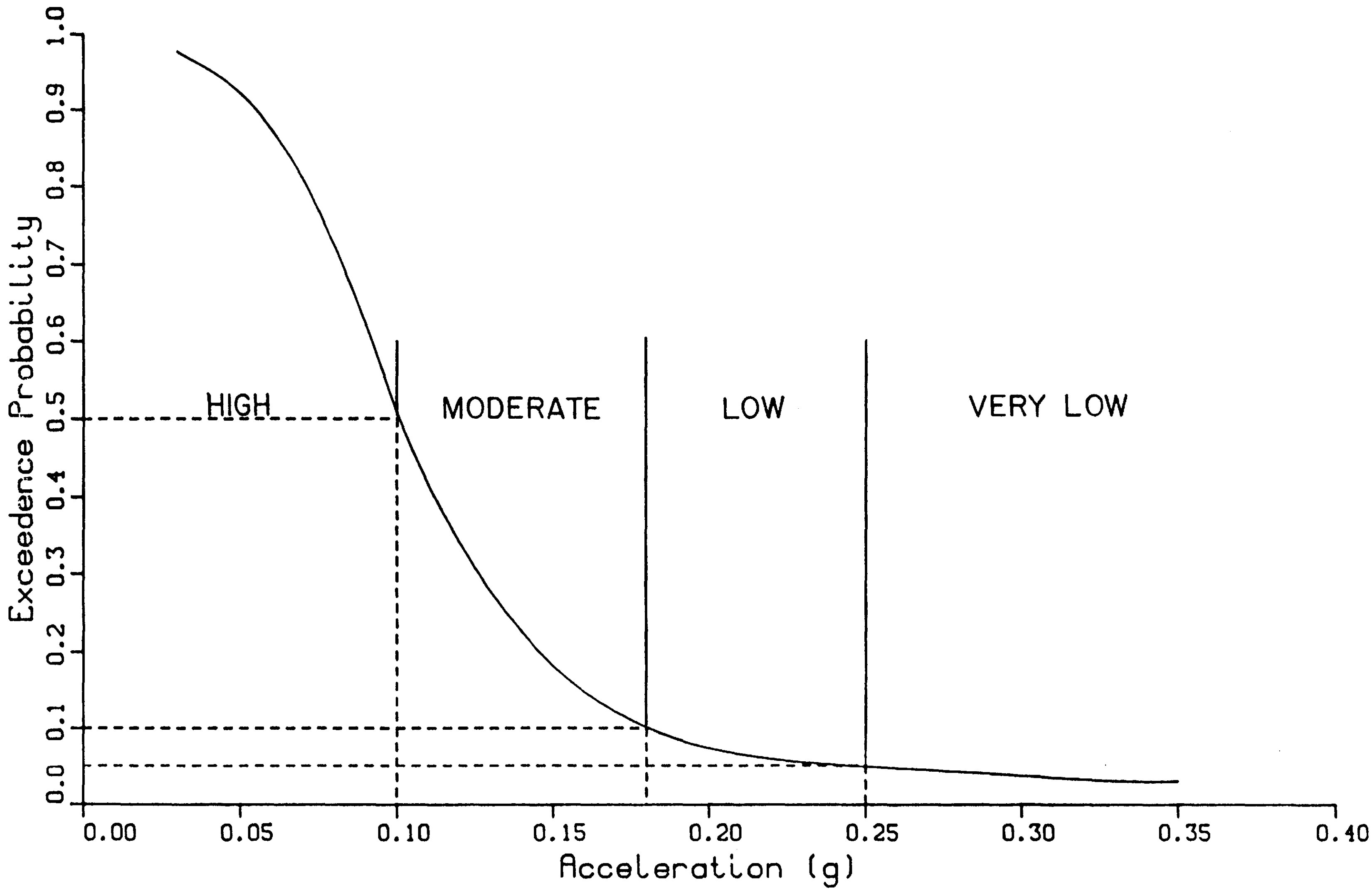


Figure 36. 100 year exceedence probability curve for Cache County.

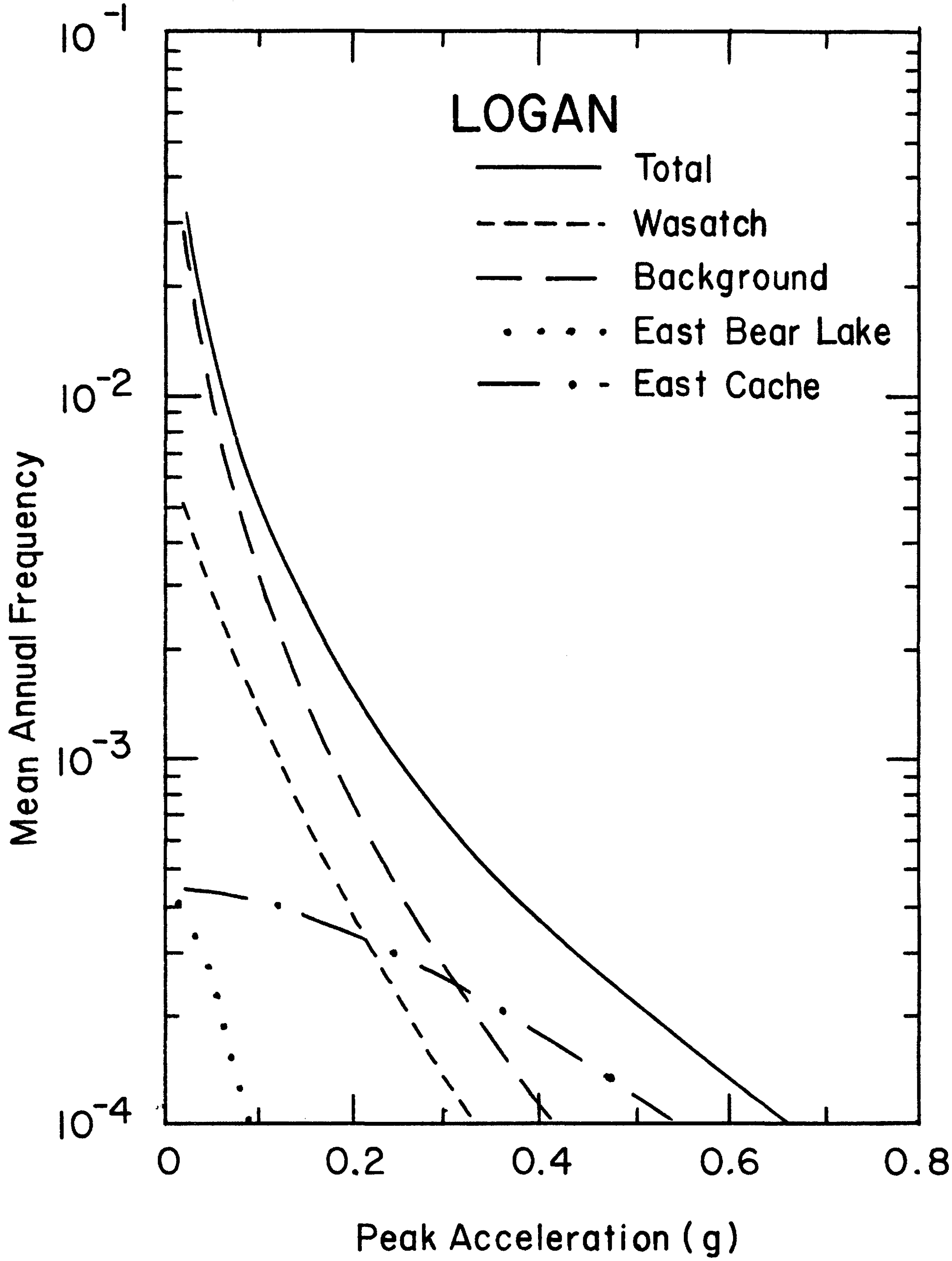


Figure 37. Contribution of various sources to Logan seismicity (after Young, Swan, Power, Schwartz and Green, 1987).

Determining Liquefaction Potential Zones

Liquefaction zones were determined by comparing the critical accelerations calculated at the various areas to their geologic and topographic setting. Maps of surficial geologic deposits were prepared and the critical accelerations were plotted on topographic maps. Then natural boundaries between liquefaction potential zones were found. Natural boundaries included: Contacts between geologic units, topographic contour lines, and changes in ground slope. In areas where critical accelerations were not available, other regions with similar geology and topography were used as guides to estimate liquefaction potential zones. Final adjustments in boundaries were made after making site specific field checks of geology and topography.

RESULTS AND CONCLUSIONS

Liquefaction Potential Maps

Plates 1 through 6 are the liquefaction potential maps of the study area. The data used to develop these maps were much more sparse than the data used for the maps in Salt Lake, Davis and Utah Counties. Because of the scarcity of data, experience from previous investigations was used to relate the geology of the area to liquefaction potential. Also split classifications were used in areas where the data were so sparse that there was a high degree of uncertainty in the classification. A county by county summary of liquefaction follows.

Weber County

Much of Weber county is in a high liquefaction potential zone. The Weber River flood plain running through Ogden has been classified as a high liquefaction potential zone. Meanders of the Weber River and other smaller streams have deposited loose cohesionless material across much of the valley floor, making all of the valley bottom west of Ogden a high liquefaction potential zone. A very large prehistoric lateral spread landslide is located in the vicinity of North Ogden. This lateral spread landslide has been classified as moderate-high liquefaction potential.

Regions above the valley floor but below about elevation 4400 feet are in a moderate-low liquefaction potential zone. This includes much of Ogden City. Because of localized perched groundwater the groundwater depth in this region is extremely variable. Many borings in this area encountered no groundwater to great depths, while borings in close proximity encountered groundwater at relatively shallow depths. The borings where groundwater was encountered generally had critical accelerations representing a moderate liquefaction potential.

Regions above about 4400 feet were found to have low to very low liquefaction potentials. This area includes North Ogden and the Ben Lomond area in Ogden.

Box Elder County

In Box Elder County, the flood plains of the Bear and Malad Rivers comprise high liquefaction potential zones. In addition a high liquefaction potential zone extends from the edge of the alluvial fan at Brigham City to the Bear River. West of the Bear River, and in the valley bottom north of Brigham City the soil contains more silts and clays making it a moderate-high liquefaction potential zone.

A series of alluvial fans extend into the valley from drainages of the Wellsville Mountains. Brigham City is located on the largest of these. These alluvial fans generally have very low liquefaction potential due to deep groundwater and dense gravelly sands. However, there is some possibility of liquefaction at the outer edge of the fan. For this reason a band around Brigham City was assigned moderate-low liquefaction potential. A similar region exists on the other fans, but it is too narrow to plot on the maps.

In the Malad Valley, at the north end of the county, The soils are primarily clay with some silt. This region is assigned moderate-low liquefaction potential.

Cache County

Cache County generally has lower liquefaction potential than the other counties. This is largely due to its lower seismicity, but also because of the nature of the parent material from which the soil weathered, and the higher elevation of the valley floor.

In the south end of the valley, along the flood plains of the Bear, the Little Bear, Blacksmith Fork, and the Logan Rivers, most borings indicate moderate liquefaction potential. However, because the sparse number of borings, and the possibility of encountering loose sand the southern flood plains are assigned moderate-high liquefaction potential.

North of Logan, the soils in the flood plain of the Bear River become increasingly coarse. Therefore, around Smithfield, the Bear River flood plain grades from moderate-high to high. Also, north of Smithfield, ancient levies bound the Bear River flood plain on the west. These levies are assigned moderate liquefaction potential.

All other areas, including most of Logan, Hyrum, Wellsville, Smithfield, and Richmond are in low to very low zones.

The Cache Valley Liquefaction Site

A site on the Bear River, 4.5 miles west of Richmond experienced liquefaction during the 1962 Cache Valley earthquake (Hill, 1979). The surface expression of the liquefaction was a large number of sand boils that ejected a mixture of clay, sand and water over a large region. The remnant of one large sand boil remains. This remnant is shown in Figure 38.

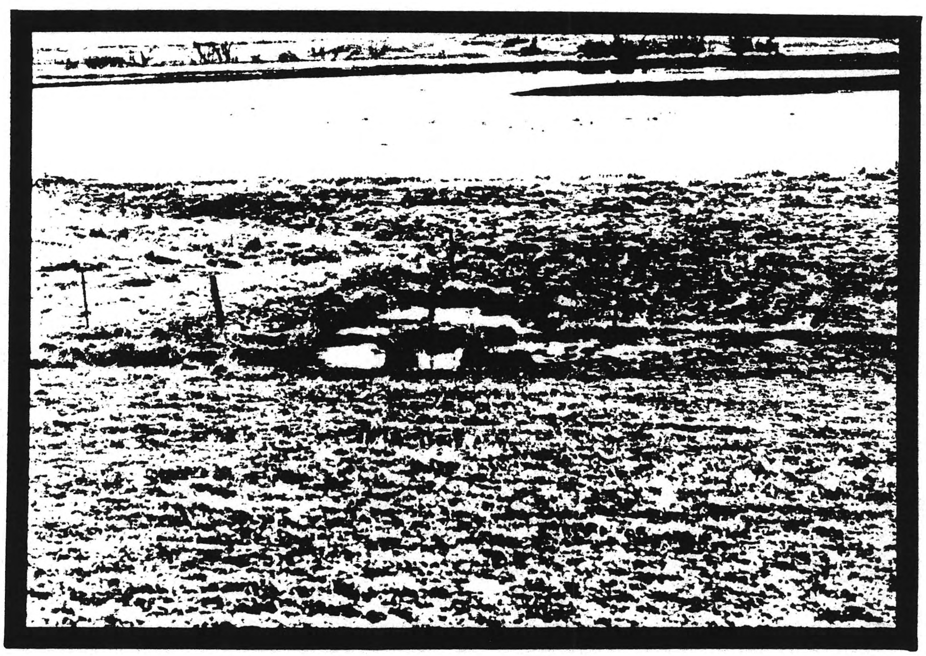


Figure 38. Remnant of sand boil from 1962 Cache Valley earthquake, near Richmond.

The epicenter of the 1962 Cache Valley Earthquake was approximately 20 miles away, just across the Idaho state-line, and had a magnitude of 5.7 (Arabaz, Smith and Richins, 1979). According to attenuation relationships established by Schnabel and Seed (1972) the maximum bedrock acceleration at the site should have been about 0.09 g. Relationships between bedrock and ground accelerations established by Seed and Idriss (1982) for soft soil sites indicate that the ground acceleration at the site should have been about 0.11 g.

Two cone soundings were taken in the area. The first was just out of the flood plain, above the sand boil remnant. Groundwater was encountered at about 12.5 feet. No liquefiable materials were encountered until a depth of 60 feet, and the critical acceleration at that depth was about 0.30 g. This indicates that liquefaction probably did not occurred at this location.

The second cone sounding was performed in the flood plain, adjacent to the sand boil remnant. This sounding is shown in Figure 39. Critical accelerations are plotted in Figure 40. Some shallow liquefiable layers were encountered, but nothing that should have liquefied in the 1962 event.

A boring was performed next to the cone sounding. The boring log is shown in Figure 41. Figure 42 contains the critical accelerations calculated for the boring. A loose

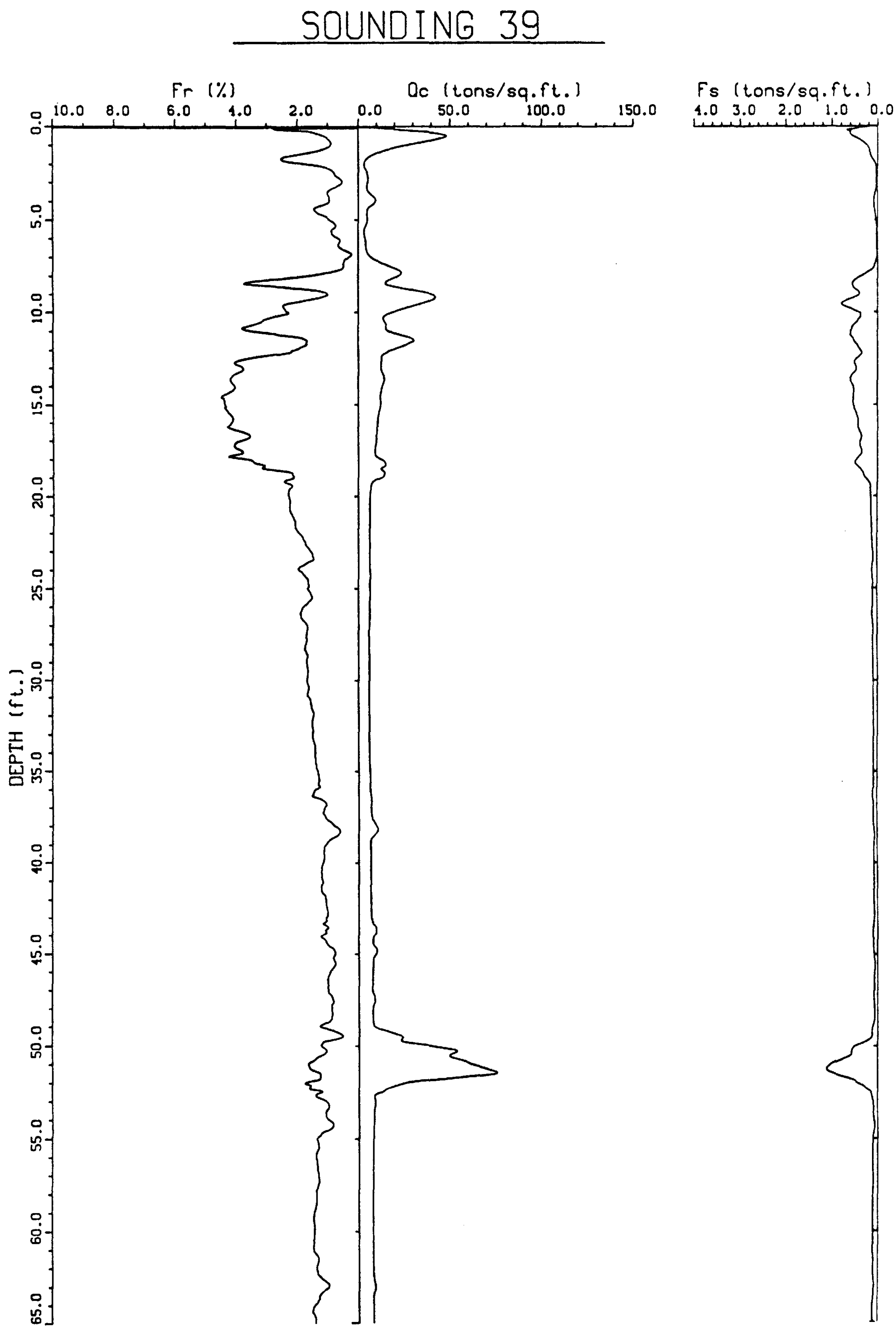


Figure 39. Cone sounding from liquefaction site.

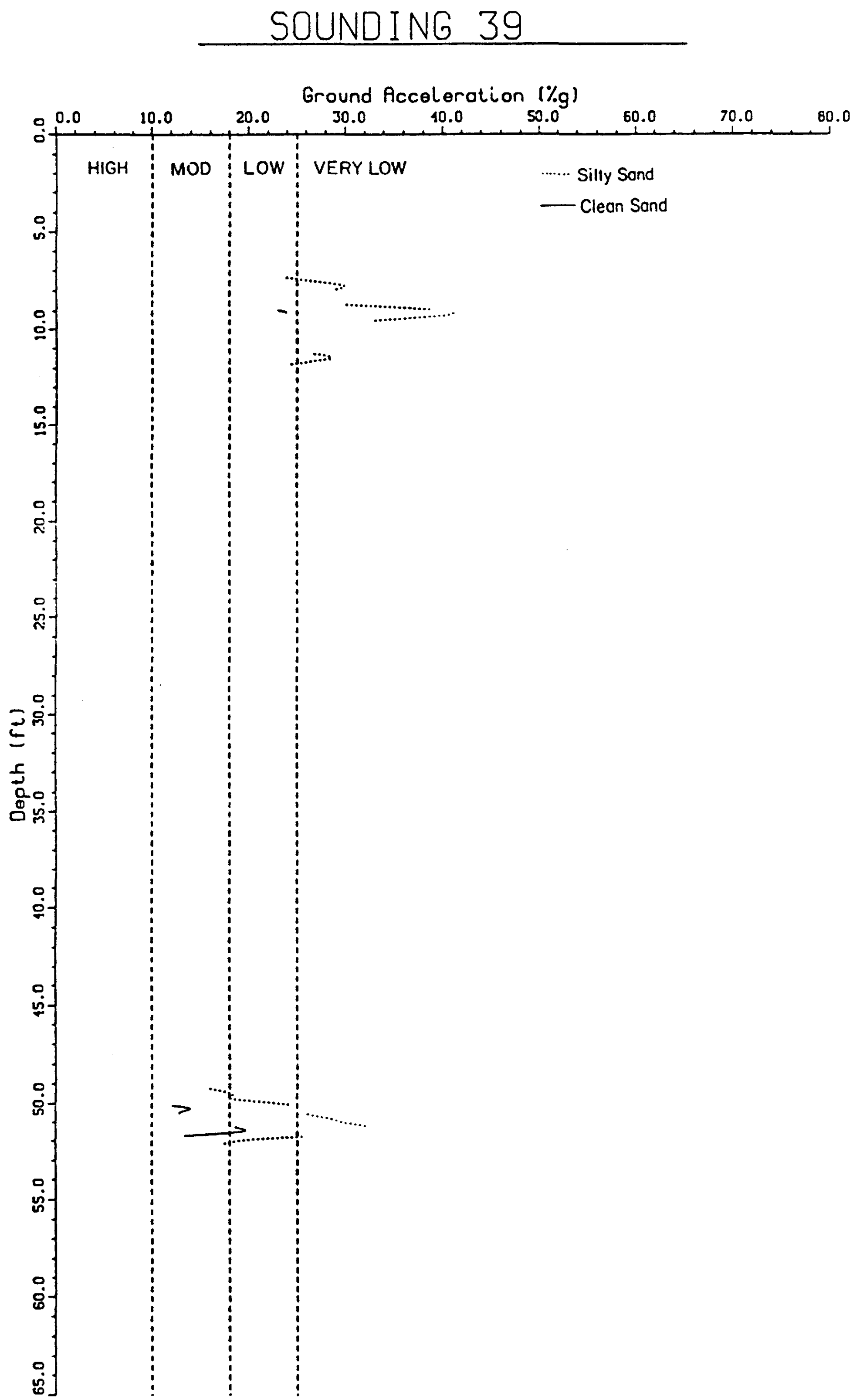


Figure 40. Critical accelerations from cone sounding at liquefaction site.

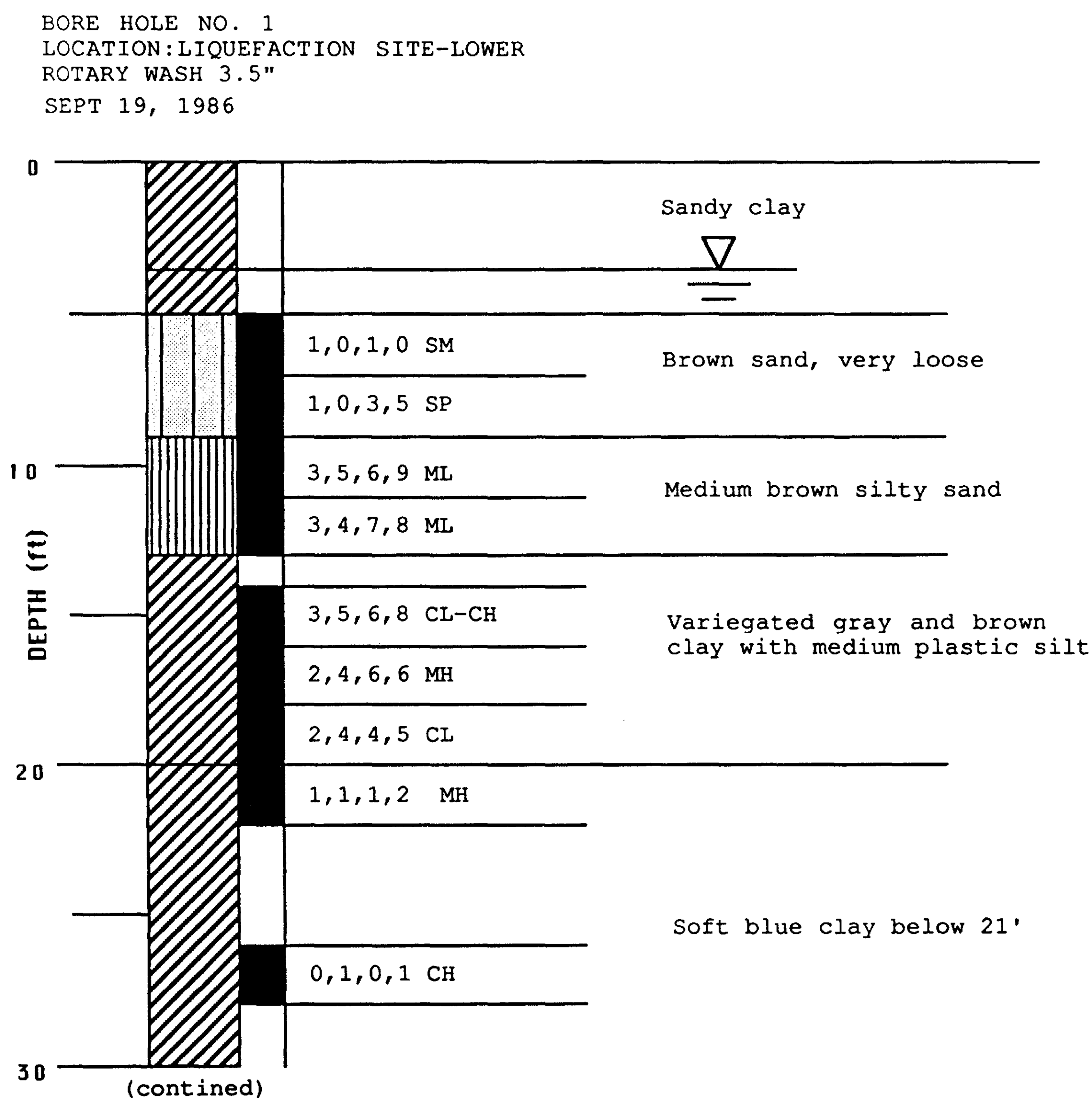


Figure 41. Boring log from liquefaction site.

BORE HOLE NO. 1 CONTINUED

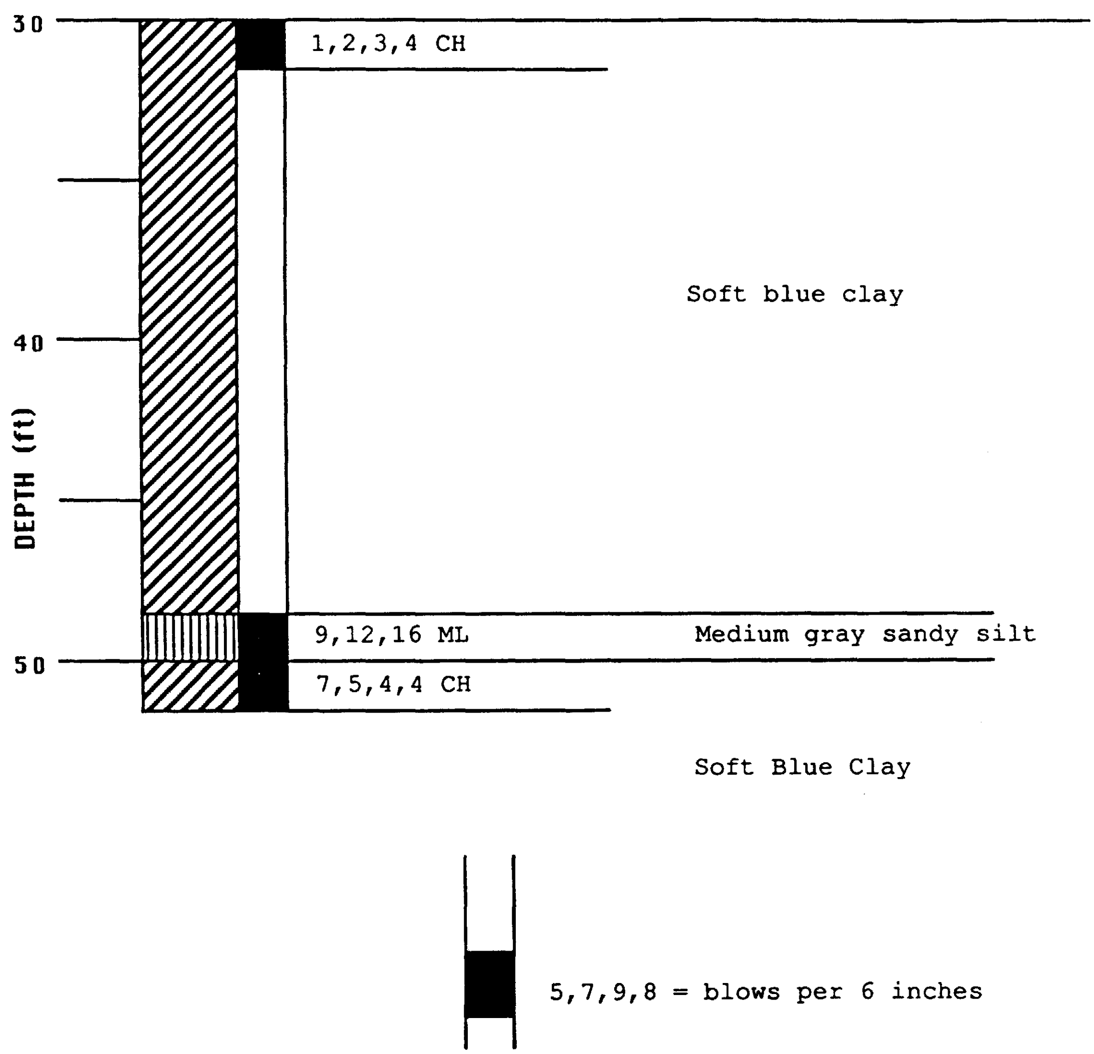


Figure 41. Continued.

CRITICAL ACCELERATIONS FOR SOIL PROFILES IN CACB.DAT
EARTHQUAKE MAGNITUDE=6.00

AREA NUMBER 4001

BORING NUMBER 1
BORING DEPTH= 51.50 ft. GROUND WATER DEPTH= 3.50 ft.

DEPTH (ft.)	CRITICAL ACCELERATION (a/g)	SOIL TYPE	N	N1	SILT CORRECTION
6.00	0.1429	SM,	1.0	1.6	6.8
8.00	0.0744	SP,	3.0	4.8	0.0
10.00	0.3767	ML	11.0	17.4	7.5
12.00	0.3361	ML	11.0	16.1	7.5
49.25	0.5464	ML	28.0	22.6	7.5

MINIMUM CRITICAL ACCELERATION FOR BORING= 0.0744

MINIMUM CRITICAL ACCELERATION FOR AREA= 0.0744

Figure 42. Critical accelerations calculated from boring data at liquefaction site.

sand layer with a critical acceleration of about 0.07 g was encountered in the boring at 8-10 feet. This layer probably liquefied in the 1962 event.

The cone sounding indicates a silty sand with a critical acceleration of about 0.28 g at 8-10 feet. There are two possible explanations for the discrepancy between the cone sounding and boring: First, it could be that the relationships used to establish soil type and equivalent blow counts from the cone sounding did not apply in this case. In most cases there was a very good correlation between the cone soundings and the borings, however, there were large discrepancies in several other cases. Some inconsistencies are expected in converting cone resistance to standard penetration resistance. The second possibility is that different soils were sampled in the cone sounding and the boring six feet apart. The stratigraphy of the bottom of the flood plain would be very complex due to constantly changing river channels. It is possible that the boring was near the edge of the loose sand deposit and the cone sounding missed it all together.

Conclusions

Liquefaction poses a significant threat in the study area. Much heavily developed area in Weber County is in high or moderate liquefaction potential zones. Bridge sites along rivers in all three counties are especially vulnerable to liquefaction damage in the event of a large earthquake. Much of the relatively undeveloped land is also in high to moderate zones, and it is anticipated that some of this land will be developed in the future. It is imperative that the threat of liquefaction is considered in all future land use planning. The liquefaction potential maps presented herein, can be a valuable tool in dealing with this threat.

The instrumentation developed for the electric cone penetrometer was extremely effective. The field copies of the soundings allowed a preliminary analysis of the soundings to be made in the field. Decisions on where to perform borings and the depths to be sampled in borings were based upon this preliminary analysis. The digital records of the soundings stored on magnetic tape was up-loaded to a computer, for a detailed analysis of the soundings.

The software that was developed to use the digitizer to create data files of subsurface data from boring logs worked very well. It was found that data files could be created more quickly using the digitizer, than typing data in manually.

The software developed to calculate critical accelerations from standard penetration and cone penetration data also worked very well. Using this software saved time, allowed more samples to be analyzed, and improved the accuracy of the analysis.

The instrumentation for the cone penetrometer, and the data management and analysis programs can and should be used to expedite future liquefaction potential studies.

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APPENDIXES

Appendix A

Geotechnical Conditions in the North Counties of the Wasatch Front

Geology Related to Liquefaction Susceptibility

Introduction

The geology of the Northern Wasatch Front 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 most of the study area; however, in Cache Valley in the north-eastern part of the study area, the East Cache fault is the dominant structural feature.

Geologic materials in the northern Wasatch Front can be characterized into three types: pre-Lake Bonneville materials, Lake Bonneville materials, and post-Lake Bonneville materials. Pre-Lake Bonneville materials generally are not susceptible to liquefaction because they are dense and 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 discussed below.

Pre-Lake Bonneville materials

These materials constitute the Wasatch Range, the Bear

River Range, the Wellsville Mountains, the West Mountains, Clarkston Mountain, and Little Mountain, and underlie lake deposits in the remainder of the area. The exposed rocks in the mountains range in age from Precambrian to Quaternary and range in composition from gneiss to tuffaceous siltstone. Common bedrock types also include limestone, siltstone, shale, sandstone, conglomerate and volcanic rocks (Stockes, 1963).

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 and post-lake sediments. The pre-Lake Bonneville materials 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 could have been derived from remote locations. However, substantial rivers contributed much sediment to the system resulting in significant deltas in the northern part of Cache Valley from the Bear River and near Ogden from the Ogden and Weber Rivers. Currents to the lake tended to drift the materials toward the south along the east side of the basin.

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 shoreline created by the largest lake in the basin. The elevation of the highest shoreline 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.

<u>Age and elevation of lake levels.</u> Three 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 and others, 1983; Currey and Oviatt, 1985; MaCalpin, 1986; and

Oviatt and others, 1987). 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.

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/Holecene 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 liquefaction potential analysis of the northern Wasatch Front 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 in northern Utah and the results previously published for Davis County Salt Lake County and Utah County (Anderson and others, 1984, 1986a, 1986b) 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 suggest that the large volume of water constituting glacier on land masses at this time contributed not only to lowering 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 Salt Lake basin.

Post-Lake Bonneville materials

These materials have limited distribution in northern Utah. Chiefly, they are present along the principal drainage channels. Relatively isolated alluvial and debris fans are scattered throughout the area.

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 northern Utah is restricted to the North Ogden area. Other landslides in lake deposits have been mapped by Miller (1980) and Pasbley and Wiggins (1972).

Post-Lake Bonneville materials have been mapped in the study area by Bjorklund and McGreevy (1971, 1974); Bryant (1984), Feth and others (1966), Lofgren (1955), Miller (1980), Mullens and Izett (1964), Sorensen and Crittenden (1972, 1974, 1976), Williams (1948, 1958, 1962). 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 3floods which consist of viscous slurries of clay, silt and said. This process was active in the spring of 1983 due to snowmelt (Anderson and others, 1984).

Most post-lake deposits in the study area are associated with the channels of Bear River, Ogden River, Weber River, and Malad River 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 Bear and Ogden Rivers between Brigham City and Ogden.

Soil development

In general, aside from local accumulations of alluvial fan, debris fan, and stream deposits, lacustrine materials in the study area have been continuously exposed as lake levels dropped. The soil survey of the Ogden area was prepared by Erickson and others (1968); the survey of eastern Box Elder County was prepared by Chadwick and others (1975). These surveys show generally youthful soil profiles (A-C) across the study area.

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. Since relatively few areas have been exposed long enough for soil horizons to acquire argillic B horizons, soil development is not a particularly useful criteria for evaluating liquefaction in northern Utah.

Appendix B

Cone Program

```
Program:cone.dld
Flag Usage:
  1 stop/start-green light
  2
  3 battery-red light
Input Channel Usage:
  1 friction  resistance
  2 tip resistance
Excitation Channel Usage: None
Continuous Analog Output Usage:
  1  friction resistance (mv)
  2  tip resistance (mv)
Control Port Usage:
  1 battery light red
  2 stop-start light green
Pulse Input Channel Usage:
  1 stop start
  2 depth counter
Output Array Definitions:
  01   0106  start time
   2   julian date
   3   military time

  01   0139 1/2 inch reading
  02   friction resistance (tons/ftsq)
  03   tip resistance (tons/ftsq)

  01   0152 full inch readings
  02   depth (ft)
  03   friction resistance (tons/ftsq)
  04   tip resistance (tons/ftsq)

  01   0159 end time
  02   julian day
  03   military time


*      1        Table 1 Programs
  01: .10000    Sec. Execution Interval

01:  P20        Set Port
  01: 11        Set according to flag 1
  02: 2         Port Number

02:  P3         Pulse
  01: 1         Rep
  02: 1         Pulse Input Chan
  03: 2         Switch Closure
  04: 9         Loc [:conepulse]
  05: 1.0000    Mult
  06: 0.0000    Offset

03:  P33        Z=X+Y
  01: 9         X Loc conepulse
  02: 1         Y Loc stopstart
  03: 1         Z Loc [:stopstart]
```

Page 2 Table 1

```
04: P89         If X<=>F
  01: 1         X Loc stopstart
  02: 1         =
  03: 0.0000    F
  04: 0         Go to end of Program Table

05: P89         If X<=>F
  01: 1         X Loc stopstart
  02: 1         =
  03: 1.0000    F
  04: 30        Then Do

06: P86         Do
  01: 10        Set flag 0 (output)

07: P86         Do
  01: 11        Set flag 1

08: P77         Real Time
  01: 110       Day,Hour-Minute

09: P30         Z=F
  01: 0.0000    F
  02: 3         Z Loc [:depth(ft)]

10: P30         Z=F
  01: 2.0000    F
  02: 1         Z Loc [:stopstart]

11: P30         Z=F
  01: 0.0000    F
  02: 2         Z Loc [:lastdepth]

12: P30         Z=F
  01: 6.0000    F
  02: 12        Z Loc [:1/21stdep]

13: P30         Z=F
  01: 0.0000    F
  02: 15        Z Loc [:ftcounted]

14: P30         Z=F
  01: 0.0000    F
  02: 16        Z Loc [:0 (mv)    ]

15: P30         Z=F
  01: 4500.0    F
  02: 17        Z Loc [:4500 (mv)]

16: P2          Volt (DIFF)
  01: 2         Reps
  02: 5         5000 mV slow Range
  03: 1         IN Chan
  04: 13        Loc [:frcoffset]
  05: 1.0000    Mult
  06: 0.0000    Offset
```

Page 3 Table 1

```
17:  P53         Scaling Array (A*loc +B)
  01: 13         Start Loc [:frcoffset]
  02: .00205     A1
  03: .17462     B1
  04: .18130     A2
  05: 0.0000     B2
  06: 1.0000     A3
  07: 0.0000     B3
  08: 1.0000     A4
  09: 0.0000     B4

18:  P95         End

19:  P89         If X<=>F
  01: 1          X Loc stopstart
  02: 1          =
  03: 2.0000     F
  04: 30         Then Do

20:  P3          Pulse
  01: 1          Rep
  02: 2          Pulse Input Chan
  03: 2          Switch Closure
  04: 10         Loc [:deppulse ]
  05: .08333     Mult
  06: 0.0000     Offset

21:  P33         Z=X+Y
  01: 10         X Loc deppulse
  02: 3          Y Loc depth(ft)
  03: 3          Z Loc [:depth(ft)]

22:  P33         Z=X+Y
  01: 10         X Loc deppulse
  02: 15         Y Loc ftcounted
  03: 15         Z Loc [:ftcounted]

23:  P89         If X<=>F
  01: 15         X Loc ftcounted
  02: 3          >=
  03: .99000     F
  04: 30         Then Do

24:  P34         Z=X+F
  01: 15         X Loc ftcounted
  02: -.99996    F
  03: 15         Z Loc [:ftcounted]

25:  P21         Analog Out
  01: 2          CAO Chan
  02: 16         mV Loc 0 (mv)val=0 (mv)

26:  P21         Analog Out
  01: 2          CAO Chan
  02: 17         mV Loc 4500 (mv)(mv)
```

Page 4 Table 1

```
27:  P21        Analog Out
  01: 2         CAO Chan
  02: 7         mV Loc tip (mv)

28:  P95        End

29:  P2         Volt (DIFF)
  01: 2         Reps
  02: 5         5000 mV slow Range
  03: 1         IN Chan
  04: 4         Loc [:friction ]
  05: 1.0000    Mult
  06: 0.0000    Offset

30:  P53        Scaling Array (A*loc +B)
  01: 4         Start Loc [:friction ]
  02: .00205    A1
  03: .17462    B1
  04: .18130    A2
  05: 0.0000    B2
  06: 1.0000    A3
  07: 0.0000    B3
  08: 1.0000    A4
  09: 0.0000    B4

31:  P35        Z=X-Y
  01: 4         X Loc friction
  02: 13        Y Loc frcoffset
  03: 4         Z Loc [:friction ]

32:  P35        Z=X-Y
  01: 5         X Loc tip
  02: 14        Y Loc tipoffset
  03: 5         Z Loc [:tip      ]

33:  P37        Z=X*F
  01: 4         X Loc friction
  02: 1350.0    F
  03: 6         Z Loc [:fric (mv)]

34:  P37        Z=X*F
  01: 5         X Loc tip
  02: 30.000    F
  03: 7         Z Loc [:tip (mv) ]

35:  P21        Analog Out
  01: 1         CAO Chan
  02: 6         mV Loc fric (mv)

36:  P21        Analog Out
  01: 2         CAO Chan
  02: 7         mV Loc tip (mv)

37:  P32        Z=Z+1
  01: 11        Z Loc [:counter  ]
```

Page 5   Table 1

```
38:  P91        If Flag
  01: 13        3 is set
  02: 30        Then Do

39:  P88        If X<=>Y
  01: 11        X Loc counter
  02: 3         >=
  03: 12        Y Loc 1/21stdep
  04: 30        Then Do

40:  P86        Do
  01: 10        Set flag 0 (output)

41:  P70        Sample
  01: 2         Reps
  02: 4         Loc friction

42:  P86        Do
  01: 23        Reset flag 3

43:  P95        End

44:  P95        End

45:  P88        If X<=>Y
  01: 3         X Loc depth(ft)
  02: 1         =
  03: 2         Y Loc lastdepth
  04: 0         Go to end of Program Table

46:  P31        Z=X
  01: 3         X Loc depth(ft)
  02: 2         Z Loc [:lastdepth]

47:  P31        Z=X
  01: 11        X Loc counter
  02: 12        Z Loc [:1/21stdep]

48:  P37        Z=X*F
  01: 12        X Loc 1/21stdep
  02: .50000    F
  03: 12        Z Loc [:1/21stdep]

49:  P89        If X<=>F
  01: 12        X Loc 1/21stdep
  02: 3         >=
  03: 10.000    F
  04: 30        Then Do

50:  P30        Z=F
  01: 6.0000    F
  02: 12        Z Loc [:1/21stdep]

51:  P95        End
```

Page 6 Table 1

```
52:  P30       Z=F
  01: 0.0000   F
  02: 11       Z Loc [:counter  ]

53:  P86       Do
  01: 10       Set flag 0 (output)

54:  P70       Sample
  01: 3        Reps
  02: 3        Loc depth(ft)

55:  P86       Do
  01: 13       Set flag 3

56:  P95       End

57:  P89       If X<=>F
  01: 1        X Loc stopstart
  02: 3        >=
  03: 3.0000   F
  04: 30       Then Do

58:  P86       Do
  01: 21       Reset flag 1

59:  P30       Z=F
  01: 0.0000   F
  02: 1        Z Loc [:stopstart]

60:  P86       Do
  01: 10       Set flag 0 (output)

61:  P77       Real Time
  01: 110      Day,Hour-Minute

62:  P95       End

63:  P         End Table 1


*     2        Table 2 Programs
  01: 60.000   Sec. Execution Interval

01:  P10       Battery Voltage
  01: 8        Loc [:batt     ]

02:  P89       If X<=>F
  01: 8        X Loc batt
  02: 4        <
  03: 10.000   F
  04: 30       Then Do

03:  P86       Do
  01: 13       Set flag 3

04:  P94       Else
```

Page 7   Table 2

```
05:  P86        Do
  01: 23        Reset flag 3

06:  P95        End

07:  P20        Set Port
  01: 13        Set according to flag 3
  02: 1         Port Number

08:  P          End Table 2


*     3         Table 3 Subroutines

01:  P          End Table 3


*     4         Mode 4 Output Options
  01: 10        (Tape ON) (Printer OFF)
  02: 0         Printer 300 Baud


*     A         Mode 10 Memory Allocation
  01: 28        Input Locations
  02: 64        Intermediate Locations


*     C         Mode 12 Security
  01: 00        Security Option
  02: 0000      Security Code
```

Page 8   Input Location Assignments (with comments):

(Key: T=Table Number   E=Entry Number   L=Location Number)

```
 T: E: L:
 1: 3: 1:  Z Loc [:stopstart]
 1:10: 1:  Z Loc [:stopstart]
 1:59: 1:  Z Loc [:stopstart]
 1:11: 2:  Z Loc [:lastdepth]
 1:46: 2:  Z Loc [:lastdepth]
 1: 9: 3:  Z Loc [:depth(ft)]
 1:21: 3:  Z Loc [:depth(ft)]
 1:29: 4:  Loc [:friction ]
 1:30: 4:  Start Loc [:friction ]
 1:31: 4:  Z Loc [:friction ]
 1:32: 5:  Z Loc [:tip      ]
 1:33: 6:  Z Loc [:fric (mv)]
 1:34: 7:  Z Loc [:tip (mv) ]
 2: 1: 8:  Loc [:batt     ]
 1: 2: 9:  Loc [:conepulse]
 1:20:10:  Loc [:deppulse ]
 1:37:11:  Z Loc [:counter  ]
 1:52:11:  Z Loc [:counter  ]
 1:12:12:  Z Loc [:1/21stdep]
 1:47:12:  Z Loc [:1/21stdep]
 1:48:12:  Z Loc [:1/21stdep]
 1:50:12:  Z Loc [:1/21stdep]
 1:16:13:  Loc [:frcoffset]
 1:17:13:  Start Loc [:frcoffset]
 1:13:15:  Z Loc [:ftcounted]
 1:22:15:  Z Loc [:ftcounted]
 1:24:15:  Z Loc [:ftcounted]
 1:14:16:  Z Loc [:0 (mv)   ]
 1:15:17:  Z Loc [:4500 (mv)]
```

Page 9 First 99 Input Location Labels:

1:stopstart	51:________
2:lastdepth	52:________
3:depth(ft)	53:________
4:friction	54:________
5:tip	55:________
6:fric (mv)	56:________
7:tip (mv)	57:________
8:batt	58:________
9:conepulse	59:________
10:deppulse	60:________
11:counter	61:________
12:1/2lstdep	62:________
13:frcoffset	63:________
14:tipoffset	64:________
15:ftcounted	65:________
16:0 (mv)	66:________
17:4500 (mv)	67:________
18:________	68:________
19:________	69:________
20:________	70:________
21:________	71:________
22:________	72:________
23:________	73:________
24:________	74:________
25:________	75:________
26:________	76:________
27:________	77:________
28:________	78:________
29:________	79:________
30:________	80:________
31:________	81:________
32:________	82:________
33:________	83:________
34:________	84:________
35:________	85:________
36:________	86:________
37:________	87:________
38:________	88:________
39:________	89:________
40:________	90:________
41:________	91:________
42:________	92:________
43:________	93:________
44:________	94:________
45:________	95:________
46:________	96:________
47:________	97:________
48:________	98:________
49:________	99:________
50:________	

Appendix C

Soil Data

Table 8. Clean sands D_{50} > 0.25 mm.

Sample	N	Q_c (tons/ft sq)	F_r %	D_{50} mm	Unified Soil Class	Q_c/N
BH 4-7	23	73	0.9	0.28	SP-SM	3.2
BH 4-8	20	106	0.7	0.45	SP	5.3
BH 4-10	23	94	0.8	0.27	SP-SM	4.1
BH 1-4	8	41	1.0	0.35	SP	5.1
BH 3-2	34	135	0.7	0.27	SP	4.0
BH 3-8	28	110	1.0	0.43	SP-SM	4.2
BH 10-2	12	50	0.6	0.48	SP-SM	4.2
BH 10-3	12	69	0.8	0.60	SP	5.8

Table 9. Silty sands 0.15 mm < D_{50} < 0.25 mm.

Sample	N	Q_c (tons/ft sq)	F_r %	D_{50} mm	Unified Soil Class	Q_c/N
BH 8-2	18	52	2.5	-	ML	2.9
BH 8-5	24	84	1.7	0.12	SM	3.5
BH 8-6	9	40	1.2	-	ML	4.4
BH 6-2	35	106	2.9	0.13	SM	3.0
BH 6-3	20	88	5.0	-	ML	4.4
BH 6-4	29	98	2.0	0.15	SM	3.4
BH 6-5	24	86	2.6	-	SM-ML	3.6
BH 6-8	20	125	8.3	0.14	SM	6.3
BH 4-4	12	18	4.3	-	ML	1.5
BH 3-6	21	79	0.9	0.13	SP	3.8
BH 3-10	11	15	2.4	-	ML	1.4
BH 3-13	15	70	1.6	-	ML	4.7
BH 5-5	19	85	1.0	0.15	SM	4.5
BH 5-6	11	27	1.7	0.09	SM	2.5
BH 1-3	3	20	2.5	0.22	SP-SM	6.7
BH 10-4	11	45	0.6	0.23	SP-SM	4.1
BH 6-1	21	85	2.5	0.18	SM	4.0
BH 3-1	14	35	1	0.18	SP-SM	2.5
BH 3-3	38	125	1.0	0.19	SP-SM	3.3
BH 3-4	38	150	6.8	0.16	SP-SM	3.9
BH 7-7	18	65	1.1	0.18	SP-SM	3.8
BH 9-1	19	89	2.8	0.20	SP-SM	4.7
BH 9-5	12	80	0.6	0.18	SP-SM	6.7

Table 10. Clays and plastic silts (non-liquefiable soils).

Sample	N	Q_c (tons/ft sq)	F_r %	LL %	PI	Unified Soil Class	Q_c/N
BH 1-10	11	12	4.2	51	29	CL-CH	1.1
BH 1-7	11	30	1.7	34	11.7	ML	2.7
BH 7-3	16	32	3.7	48	19	ML	2.0
BH 1-7	11	25	2.5	34	12	ML	2.7
BH 1-12	8	12	2.5	49	27	CL	1.5
BH 1-13	2	7	2.2	58	25	MH	3.5
BH 7-5	12	16	1.8	38	13	CL	1.3
BH 7-2	19	39	3.0	31	8	ML	2.1
BH 7-3	16	32	3.7	48	19	ML	2.0
BH 2-3	8	14	4.3	57	29	CH	1.8
BH 2-5	5	9	4.0	73	46	CH	1.8
BH 2-6	2	6	3.6	79	47	CH	3.0
BH 9-9	9	17	30	43	19	CL	1.9
BH 5-10	4	8	1.5	35	8	ML	2.0
BH 5-1	34	25	2.7	41	21	CL	0.7
BH 5-4	19	85	1.0	46	14	ML	4.5
BH 5-9	4	17	1.9	31	4	ML	4.3
BH 10-5	5	9	3.1	52	25	CH	1.8
BH 6-6	4	15	0.7	46	28	CL	3.8
BH 1-11	10	10	3.9	57	25	MH	1.0
BH 2-2	14	12	5.2	45	21	CL	0.9
BH 8-1	11	30	3.5	25	11	CL	2.7
BH 6-7	4	15	0.7	42	15	ML	3.3
BH 4-5	8	11	3.4	63	38	CH	1.4

Appendix D

Data Input Programs

```
*       Boring Area Locator
*       James A. Bay
*       April 1, 1986
*
*       This program calls digitizer subroutines to create a file
*       of boring area coordinates.
*
*       VARIABLE LIST
*
*       CK=            character variable for responses to prompts
*       IAN=           Area Number, 2 byte integer
*       COORN=         Northing coordinate, real
*       COORE=         Easting coordinate, real
*       ICOORN=        Northing coordinate, 4 byte integer
*       ICOORE=        Easting coordinate, 4 byte integer

        CHARACTER FIL*9

*       Prompting for output file

        WRITE(5,*) ' ENTER NAME OF FILE TO BE CREATED OR ADDED TO'
        READ(5,50) FIL
50      FORMAT(A9)

*       Opening output file. It is an unformatted index file
*       keyed to the area number (IAN).

        OPEN(UNIT=1,STATUS='UNKNOWN',FORM='UNFORMATTED',FILE=FIL,
     $ORGANIZATION='INDEXED',ACCESS='KEYED',RECL=10,KEY=(1:2:INTEGER))

        CALL DIGINI ! Initializes digitizer

*       Prompts to scale axis or for new area number

100     WRITE(5,200)
200     FORMAT('      ENTER'/'  AREA NUMBER, OR:'/
     $'  0=END SESSION'/' -1=SCALE OR RESCALE AXIS')

        READ(5,*) IAN

        IF(IAN.LT.0)THEN ! Rescaling axis

*       Choosing scaling method

        WRITE(6,350)
350     FORMAT(' ENTER'/' 2=TWO POINT SCALING (DEFAULT)'/' 3=THREE RANDOM ',
     $'POINT SCALING')

        READ(5,300) CK
300     FORMAT(A1)

        IF(CK.EQ.'3')THEN
        CALL RNDSCL
        GOTO 100
        ELSE
        CALL SCALE2
        GOTO 100
        END IF

        ELSE IF(IAN.EQ.0) THEN ! end program
        GOTO 9999
```

```
        CALL POINT(IAN)
        END IF

        GOTO 100 ! get next IAN

9999    CLOSE(UNIT=1)
        STOP
        END


*       Subroutine to digitize points

        SUBROUTINE POINT(IAN)
        INTEGER*4 ICOORN,ICOORE

*       Prompt user to digitize point

        WRITE(5,30) IAN
30      FORMAT(' DIGITIZE AREA ',I4,' WITH ANY BUTTON')

        CALL DIGURU(COORE,COORN,I) ! reads coordinates from digitizer

*       Multiplying coordinates and rounding to nearest 50 m

        ICOORN=NINT(COORN*20)*50
        ICOORE=NINT(COORE*20)*50

*       Writing coordinates to screen

        WRITE(6,35) ICOORE,ICOORN
35      FORMAT(/' (',I7,',',I7,')'/)

*       Writing coordinates to output file

        WRITE(UNIT=1,ERR=40) IAN,ICOORE,ICOORN

        RETURN

*       Checking errors

40      CALL ERRSNS(IERR)
        IF(IERR.EQ.50) THEN
        WRITE(5,50) IAN
50      FORMAT(' AREA ',I4,' HAS ALREADY BEEN USED, TRY AGAIN')
        RETURN
        ELSE
        WRITE(5,60) IERR
60      FORMAT(' ERROR # ',I3,' DURING WRITE')
        STOP
        END IF
        END
```

```
*               James A. Bay
*               April 2, 1986

*               This program creates two data files.
*                  Soil Profile Library
*                  Soil Profile Library Index

*      This program requires one indexed file containing
*      the UTM coordinates of each area

*               VARIABLE LIST
*               IREC=     Record Counter
*               LC=  Line Code, character
*               IDT= Greatest Depth of Boring in area, integer, key for index file
*               IGW= Least Ground Water Depth in area, integer, key for index file
*               CK=  Responce to prompts, character
*               IBN= Boring Number
*               IAN= Area Number
*               IERR=     Error Code
*               ICOORN=   Northing Coordinate of area
*               ICOORE=   Easting Coordinate of area
*               JREC=     Record number of first record in area
*               X()= Array of X coordinates of tops of boring segments
*               Y()= Array of Y coordinates of tops of boring segments
*               TL()=     Array of cumulative Lengths of boring segments
*               IBTN=     Integer value of button used to digitize point
*               XT=  Temporary X coordinate
*               YT=  Temporary Y coordinate
*               IT=  Temporary button number
*               DTOT=     Total Depth of boring
*               DGW= Depth to Ground Water
*               BL=  Depth to bottom of layer
*               STYP=     Soil Type, character
*               DEP= Depth to point of interest
*               SN=  Blows per foot, either standard penetration or Dames & Moore
*               D50= D50 Grain Size (mm)


                INTEGER*4 ICOORN,ICOORE
                CHARACTER LC*1,CK*1,STYP*3,LIB*15,IND*15,COOR*15
                DIMENSION X(10),Y(10),TL(10)

                COMMON/IO/LUNO,LUNI

                CALL DIGINI ! initializing digitizer

                WRITE(6,*) ' ENTER NAME OF LIBRARY FILE TO BE CREATED OR ADDED TO'
                READ(5,50) LIB
50              FORMAT(A15)
                WRITE(6,*) ' ENTER NAME OF INDEX FILE TO CREATED OR ADDED TO'
                READ(5,50) IND
                WRITE(6,*) ' ENTER NAME OF FILE WHERE COORDINATES ARE FOUND'
                READ(5,50) COOR


                OPEN(UNIT=11,FILE=IND,STATUS='UNKNOWN',FORM='UNFORMATTED',
     $ORGANIZATION='INDEXED',ACCESS='KEYED',RECL=16,KEY=(1:2:INTEGER,
     $3:6:INTEGER,11:12:INTEGER,13:14:INTEGER))

                OPEN(UNIT=12,FILE=LIB,STATUS='UNKNOWN',FORM='FORMATTED',
     $ORGANIZATION='RELATIVE',ACCESS='DIRECT',RECL=25)
```

```
     $ORGANIZATION='INDEXED',ACCESS='KEYED',RECL=10,KEY=(1:2:INTEGER))

                  WRITE(6,75)
75                FORMAT(///
     $          ' ***************************************************'/
     $                 ' * CAP LOCK MUST BE ON FOR COMPUTER TO READ PROMPTS *'/
     $          ' ***************************************************'
     $///)

* The following routine finds the end of the SPL file

                  IREC=0
100               IREC=IREC+1
                  READ(UNIT=12,REC=IREC,ERR=250,FMT=3040) LC
3040              FORMAT(X,A1)
                  IF(LC.NE.'x')GOTO 100
                  IREC=IREC-1
                  GOTO 200

* In case END OF FILE is encountered

250               CALL ERRSNS(IERR)
                  IF(IERR.NE.36) THEN
                  WRITE(6,*) 'ERROR IN FINDING END OF SPL'
                  STOP
                  ELSE
                  IREC= IREC-1
                  END IF

* Initial values for total depth and ground water depth, beginning of
* data entry for area.

200               ITD=0
                  IGW=30000

* Prompts to scale axis, end session or for area number

                  IBN=0
500               WRITE(6,600)
600               FORMAT(//'  ENTER AREA NUMBER, OR'/'  0=END SESSION'/
     $' -1=SCALE AXIS'//)

                  READ(5,*) IAN

                  IF(IAN.EQ.0) THEN ! ending session
                  IREC=IREC+1
                  WRITE(UNIT=12,REC=IREC,ERR=1111,FMT=700) 'x'
700               FORMAT(X,A1)
                  GOTO 9999

                  ELSE IF(IAN.LT.0) THEN ! scaling axis
                  CALL BORSCL
                  GOTO 500
                  END IF

* Reading UTM coordinates from coordinate file

                  READ(UNIT=13,KEYID=0,KEYEQ=IAN,ERR=800) I,ICOORE,ICOORN
                  GOTO 1000

* Errors reading from coordinate file
```

```
                IF(IERR.EQ.36)THEN
                WRITE(6,900) IAN
900             FORMAT(//' AREA NUMBER ',I4,' NOT FOUND, TRY AGAIN'//)
                GOTO 200
                ELSE
                WRITE(6,950) IERR
950             FORMAT(//' ERROR #',I3,' DURING READ, TRY AGAIN'//)
                GOTO 200
                END IF

* Writing area number and coordinates to library file

1000            IREC=IREC+1
                WRITE(UNIT=12,REC=IREC,ERR=1111,FMT=3000) 'a',IAN,ICOORN,ICOORE
3000            FORMAT(X,A1,X,I5,X,I8,X,I7)

                WRITE(6,1050) IAN,ICOORN,ICOORE ! to the screen
1050            FORMAT(//' IAN=',I4,' ICOORN=',I8,' ICOORE=',I8//)

                JREC=IREC ! Record number of first record of area

* Digitizing depth of boring

1100            IBN=IBN+1
                WRITE(6,1150) IBN
1150            FORMAT(//' FOR BORING #',I2)
1200            DTOT=0

* Digitizing top of boring

                WRITE(6,*) ' DIGITIZE TOP OF BORING WITH ANY BUTTON'
1250            CALL DIG(X(1),Y(1),IBTN)

                IF(IBTN.LT.0)THEN ! * or # button used on digitizer
                WRITE(6,*) ' DO NOT USE THE * OR # BUTTONS, RE-DIGITIZE POINT'
                GOTO 1250
                END IF

* Digitizing bottom of boring or boring segment

                IT=1
1300            WRITE(6,1400)
1400            FORMAT(//' IF BORING CONTINUES DIGITIZE BOTTOM OF SEGMENT',
     $' WITH ANY BUTTON,'/' OTHERWISE DIGITZE THE BOTTOM OF THE'
     $' BORING WITH THE "0" BUTTON'/)
                CALL DIG(XT,YT,IBTN)
                TL(IT)=DTOT
                DTOT=TL(IT)+SQRT((XT-X(IT))**2+(YT-Y(IT))**2)
                IF (IBTN.EQ.0) GOTO 1600

* Digitizing top of boring segment

                IT=IT+1
                WRITE(6,1500) IT
1500            FORMAT(/' DIGITIZE TOP OF SEGMENT ', I1/)
1550            CALL DIG(X(IT),Y(IT),IBTN)
                IF(IBTN.LT.0)THEN
                WRITE(6,*) ' DO NOT USE THE * OR # BUTTONS, RE-DIGITIZE POINT'
                GOTO 1550
                END IF
                GOTO 1300
```

```
* Checking boring depth

                 WRITE(6,1700) DTOT
1700             FORMAT(/' BORING DEPTH=',F7.2,' Y/N,Y=DEFAULT ',$)
                 READ(5,400) CK
400              FORMAT(A1)
                 IF(CK.EQ.'N') GOTO 1200
1800             WRITE(6,1850)

* Digitizing Groundwater depth

1850             FORMAT(///' DIGITIZE GROUNDWATER LEVEL WITH BUTTON MATCHING'/
     $' SEGMENT NUMBER, OR "0" BUTTON IF NOT ENCOUNTERED'/)
1875             CALL DIG(XT,YT,IBTN)
                 IF(IBTN.LT.0)THEN
                 WRITE(6,*) ' DO NOT USE THE * OR # BUTTONS, RE-DIGITIZE POINT'
                 GOTO 1875
                 END IF

                 IF(IBTN.EQ.0) THEN ! groundwater not encountered
                 DGW=9999
                 WRITE(6,1900)
1900             FORMAT(/' GROUND WATER NOT ENCOUNTERED, Y/N, Y=DEFAULT ',$)
                 READ(5,400) CK
                 IF(CK.EQ.'N') GOTO 1800
                 GOTO 2050
                 END IF

* Calculating groundwater depth

                 IT=IBTN
                 DGW=TL(IT)+SQRT((XT-X(IT))**2+(YT-Y(IT))**2)
                 DGW=RND(DGW)

* Checking groundwater depth

                 WRITE(6,2000) DGW
2000             FORMAT(/' DEPTH TO GROUND WATER= ',F7.2,' Y/N,Y=DEFAULT ',$)
                 READ(5,400) CK
                 IF(CK.EQ.'N') GOTO 1800

* Writing boring number, boring depth and groundwater depth to
* library file

2050             IREC=IREC+1
                 WRITE(UNIT=12,REC=IREC,ERR=1111,FMT=3010) 'b',IBN,DTOT,DGW
3010             FORMAT(X,A1,X,I2,2(X,F7.2))

                 WRITE(6,2075) IBN,DTOT,DGW ! writing to screen
2075             FORMAT(//' IBN=',I2,' DTOT=',F7.2,' DGW=',F7.2//)

* Determining if boring is deepest or groundwater shallowest
* at area

                 IF(DTOT.GT.ITD) THEN
                 ITD=INT(DTOT)
                 END IF
                 IF(DGW.LT.IGW) THEN
                 IGW=INT(DGW)
                 END IF
```

```
                WRITE(6,*) ' ENTER SOIL LAYER DATA BEGINNING AT THE TOP LAYER'
2100            WRITE(6,2150)
2150            FORMAT(//' DIGITIZE BOTTOM OF LAYER WITH PROPER BUTTON OR THE'/
     $' "0" BUTTON IF FINISHED WITH LAYERS'//)
2175            CALL DIG(XT,YT,IBTN)
                IF(IBTN.LT.0)THEN
                WRITE(6,*) ' DO NOT USE THE * OR # BUTTONS, RE-DIGITIZE POINT'
                GOTO 2175
                END IF
                IF(IBTN.EQ.0) GOTO 2400 ! finished with soil layers
                IT=IBTN
                BL=TL(IT)+SQRT((XT-X(IT))**2+(YT-Y(IT))**2)
                BL=RND(BL)

* Checking depth to bottom of layer

                WRITE(6,2200) BL
2200            FORMAT(/' DEPTH TO BOTTOM OF LAYER=',F7.2/)

* Reading soil type and D50

2250            WRITE(6,*) ' ENTER SOIL TYPE (OR XX TO REDIGITIZE DEPTH),
     $ AND D50 (IF AVAILABLE) '
                READ(5,2300) STYP,D50
2300            FORMAT(A3,F)
                IF(STYP.EQ.'XX')GOTO 2100

 Writing soil layer data to library file

                IREC=IREC+1
                WRITE(UNIT=12,REC=IREC,ERR=1111,FMT=3020) 'c',BL,STYP,D50
3020            FORMAT(X,A1,X,F7.2,X,A3,X,F6.4)
                WRITE(6,2350) BL,STYP,D50 ! writing to screen
2350            FORMAT(/' BL=',F7.2,' STYP=',A3,' D50=',F6.4/)
                GOTO 2100

* Digitizing penetration data

2400            WRITE(6,2500)
2500            FORMAT(//' ENTER IN SITU TEST'/' DEFAULT=SPT'/
     $' D=DAMES & MOORE D SAMPLER'/' U=DAMES AND MOORE U SAMPLER'
     $/' N=NONE'//)
                READ(5,400) CK
                IF(CK.EQ.'N') GOTO 2900
                IF(CK.EQ.'D')THEN
                LC='d'
                ELSE IF(CK.EQ.'U') THEN
                LC='u'
                ELSE IF((CK.NE.'D').OR.(CK.NE.'U'))THEN
                LC='e'
                END IF
2600            WRITE(6,2650)
2650            FORMAT(/' DIGITIZE SAMPLE TEST LOCATION WITH PROPER BUTTON OR'/
     $' "0" BUTTON IF FINISHED WITH IN SITU TESTS'//)
2675            CALL DIG(XT,YT,IBTN)
                IF(IBTN.LT.0)THEN
                WRITE(6,*) ' DO NOT USE THE * OR # BUTTONS, RE-DIGITIZE POINT'
                GOTO 2675
                END IF
                IF(IBTN.EQ.0) GOTO 2900 ! finished with penetration data
                IT=IBTN
```

```
                DEP=RND(DEP)
                WRITE(6,2700) DEP
2700            FORMAT(/' DEPTH= ',F7.2/)

* Reading blow counts

                WRITE(6,*) ' ENTER N (blows/ft.) OR -1 TO REDIGITIZE DEPTH'
                READ(6,*) SN
                IF(SN.LT.0) GOTO 2600

* Writing penetration data to library file

                IREC=IREC+1
                WRITE(UNIT=12,REC=IREC,ERR=1111,FMT=3030) LC,DEP,SN
3030            FORMAT(X,A1,X,F7.2,X,F5.1)
                WRITE(6,2750) DEP,SN ! writing to screen
2750            FORMAT(/' DEP=',F7.2,' SN=',F5.1/)
                GOTO 2600

2900            CONTINUE  !END OF IN SITU TEST INPUT

* Checking if finished with area

                WRITE(6,4400)
4400            FORMAT(//' ARE THERE MORE BORINGS AT THIS LOCATION?,'
     $' Y/N, DEFAULT=Y ',$)
                READ(5,400) CK
                IF(CK.EQ.'N') THEN

* Writing area data to index file

                WRITE(UNIT=11,ERR=2222) IAN,ICOORN,ICOORE,IGW,ITD,JREC

                GOTO 200
                END IF

* Checking if axis needs to be rescaled for next boring

                WRITE(5,4500)
4500            FORMAT(//' DO YOU WANT TO RESCALE THE AXIS? Y/N, DEFAULT=N ',$)
                READ(5,400) CK
                IF(CK.EQ.'Y') THEN
                CALL BORSCL
                END IF

                GOTO 1100 ! going back to begin next boring

* Errors in reading or writing to files

1111            STOP 'ERROR IN WRITING TO SPL.DAT'
2222            WRITE(6,*) ' AREA ALREADY IS RECORDED IN INDEX FILE'
                GOTO 200
9999            CLOSE(UNIT=1)
                CLOSE(UNIT=2)
                STOP
                END

*               FUNCTION RND

* This function rounds depths to nearest 0.25 feet
```

```
RND=INT(X*4+0.5)/4.0
END
```

Appendix E

Program CRAC

```
*               Program to calculate critical accelerations
*
*               By James A. Bay
*               Based upon CA written by Jon Bischoff, and John Spitzley



*               LIST OF VARIBLES (in order of use)
*
*               BL = Array containing depths to bottom of soil layers (ft)
*               FA = Logical, indicates first area analyzed
*               FILIN = Character, name of input file
*               FILOUT = Character, name of output file
*               EQ = Earthquake magnitude 6.0, 6.75, or 7.5
*               IREC = Record number to be read from input file
*               TSTD = Logical array indicating if a layer has been tested
*               AMINA = Minimum critical acceleration for area
*               AMINB = Minimum critical acceleration for boring
*               LC = First character of input record indicating what record
*                    contains as follows:
*                    a    area number, UTM coordinates
*                    b    boring number, boring depth, groundwater depth
*                    c    depth to bottom of layer, soil type, D50
*                    d    depth to sample, blow counts (D type sampler)
*                    e    depth to sample, blow counts (SPT)
*                    u    depth to sample, blow counts (U type sampler)
*                    x    last line of file
*               IAN = Area number
*               ICOORE = UTM  East coordinate
*               ICOORN = UTM  North coordinate
*               IMAX = Number of layers encountered in boring
*               FB = Logical indicating first boring in area
*               IBN = Boring number
*               DTOT = Depth of boring
*               DGW = Depth to groundwater
*               STYP = Character array containing soil types of each soil layer
*               D50 = Array containing D50 of soil layers
*               DEP = depth to sample
*               SN = Blow counts
*               CORR = Silt correction
*               AMAX = Critical acceleration
*               N1 = Blow counts corrected for over burden
*               IERR = Error code
*
*************************************************************************
*************************************************************************

                REAL N1,ML
                INTEGER*4 ICOORN,ICOORE
                CHARACTER FILIN*15,FILOUT*15,LC*1,CK*1,STYP*3,NOR*1,EAS*1
                LOGICAL TSTD,FA,FB
                DIMENSION BL(0:51),STYP(50),D50(50),TSTD(50)
                COMMON EQ

* Default values for silt corrections

                PARAMETER(GW=0)
                PARAMETER(GP=0)
                PARAMETER(GM=7.5)
                PARAMETER(SW=0)
                PARAMETER(SP=0)
```

```
                PARAMETER(SC=7.5)
                PARAMETER(ML=7.5)
                PARAMETER(A1a=0)
                PARAMETER(A1b=0)
                PARAMETER(A3=0)
                PARAMETER(A24=5.0)
                PARAMETER(A26=7.5)
                PARAMETER(A4=7.5)

*               Opening input and output files, input file is direct access
*               and output file is sequential access

                WRITE(5,*) ' ENTER NAME OF SOIL LIBRARY FILE'
                READ(5,25) FILIN
25              FORMAT(A15)
                WRITE(5,*) ' ENTER NAME OF OUTPUT FILE'
                READ(5,25) FILOUT


                OPEN(UNIT=1,FILE=FILIN,STATUS='OLD',FORM='FORMATTED',
     $ORGANIZATION='RELATIVE',ACCESS='DIRECT',RECL=25,ERR=1111)

                OPEN(UNIT=2,FILE=FILOUT,STATUS='NEW',ERR=1111)

*               Entering earthquake magnitude to be used in analysis

                WRITE(5,50)
50              FORMAT(' ENTER EARTHQUAKE MAGNITUDE FOR LIQUEFACTION ANALYSIS',/
     $' EITHER 6.0, 6.75 OR 7.5')
                READ(5,*) EQ

*               Writing heading to output file

                WRITE(2,75) FILIN,EQ
75              FORMAT(/T12,'CRITICAL ACCELERATIONS FOR SOIL PROFILES IN ',A15/
     $T12,'EARTHQUAKE MAGNITUDE=',F4.2/T12,60('-')/T12,60('-')///)

                IREC=1 ! initializing record number

*               Initializing TSTD array indicating that no layers have been tested

                DO 85, I=1,50
                TSTD(I)=.FALSE.
85              CONTINUE

*               Initializing minimum critical acceleration values for area and boring

                AMINA=100
                AMINB=100

                BL(0)=0 ! makes ground surface at a depth of 0

                FA=.TRUE. ! indicates first area analyzed

*               Reading first or next line of input

100             READ(UNIT=1,FMT=4000,REC=IREC,ERR=2222) LC
4000            FORMAT(X,A1)

                IF(LC.EQ.'a')THEN ! first line of area

                IF(FA) GOTO 176 ! first area, no out put from last area
```

```
*               Outputing data from last boring and last area

                IF(AMINB.GE.99)THEN
                WRITE(2,255)
255             FORMAT(/T19,'NO LIQUEFIABLE DEPOSITS ENCOUNTERED IN BORING'/)
                ELSE
                WRITE(2,250) AMINB
                END IF
                IF(AMINA.GE.99)THEN
                WRITE(2,185)
185             FORMAT(/T12,'NO LIQUEFIABLE DEPOSITS ENCOUNTERED IN AREA'/'1')
                ELSE
                WRITE(2,175) AMINA
175             FORMAT(/T12,'MINIMUM CRITICAL ACCELERATION FOR AREA=',F7.4/
     $T12,60('-')/'1')
                END IF

*               Initializing minimum critical accelerations for area and boring

                AMINA=1000
                AMINB=1000

176             FA=.FALSE.  ! not first area
                FB=.TRUE.  ! is first boring in area

*               Reading area data

                READ(UNIT=1,FMT=4010,REC=IREC,ERR=2222) LC,IAN,ICOORE,ICOORN
4010            FORMAT(X,A1,X,I5,X,I8,X,I7)

*               Writing out area data

                WRITE(2,200) IAN,(ABS(ICOORN)),'N',(ABS(ICOORE)),'E'
200             FORMAT(/T12,'AREA NUMBER ',I5,',',' LOCATION=',I8,A1,
     $',',I8,A1,' UTM coordinates'/)

                IREC=IREC+1 ! incrementing record number

                GOTO 100 ! returning to line 100 to read next line

                ELSE IF(LC.EQ.'b')THEN ! first line of boring

*               Initializing layer data

                DO 150, I=1,IMAX
                BL(I)=0
                TSTD(I)=.FALSE.
150             CONTINUE

                IF(FB) GOTO 251 ! first boring of area

*               Outputing data from last boring

                IF(AMINB.GE.99)THEN
                WRITE(2,255)
                ELSE
                WRITE(2,250) AMINB
250             FORMAT(/T20,'MINIMUM CRITICAL ACCELERATION FOR BORING=',F7.4//)
                END IF

251             FB=.FALSE. ! not first boring
```

```
*              Reading in boring data

               READ(UNIT=1,FMT=4020,REC=IREC,ERR=2222) LC,IBN,DTOT,DGW
4020           FORMAT(X,A1,X,I2,2(X,F7.2))

*              Writing out boring data

               IF(DGW.GT.9998)THEN ! groundwater not encountered
               WRITE(2,300) IBN,DTOT
300            FORMAT(/T22,'BORING NUMBER ',I2/T22,'BORING DEPTH=',F6.2,' (ft.)'/
     $T22,'GROUND WATER NOT ENCOUNTERED'/)
               IREC=IREC+1
               GOTO 100
               END IF

               WRITE(2,400) IBN,DTOT,DGW
400            FORMAT(/T22,'BORING NUMBER ',I2/T22,'BORING DEPTH=',F6.2,' ft.',
     $' GROUND WATER DEPTH=',F6.2,' ft.'//
     $T23,'CRITICAL',T37,'SOIL',T63,'SILT'/
     $T12,'DEPTH',T21,'ACCELERATION',T37,'TYPE',
     $T46,'N',T53,'N1',T60,'CORRECTION'/T12'(ft.)',T24,'(a/g)'/
     $T12,60('-'))

               IREC=IREC+1
               GOTO 100

               ELSE IF(LC.EQ.'c')THEN ! line contains soil layer data

*              Reading soil layer data for all layers

               I=1
500            READ(UNIT=1,FMT=4030,REC=IREC,ERR=2222) LC,BL(I),STYP(I),D50(I)
4030           FORMAT(X,A1,X,F7.2,X,A3,X,F6.4)

               IF(LC.NE.'c')THEN ! done with soil layers
               IMAX= I-1
               GOTO 100
               END IF

               I=I+1
               IREC=IREC+1
               GOTO 500

               ELSE IF((LC.EQ.'d').OR.(LC.EQ.'e').OR.(LC.EQ.'u'))THEN ! sampling data

               I=1
600            READ(UNIT=1,FMT=4040,REC=IREC,ERR=2222) LC,DEP,SN
4040           FORMAT(X,A1,X,F7.2,X,F5.1)

               IF((LC.NE.'d').AND.(LC.NE.'e').AND.(LC.NE.'u')) GOTO 100 ! done with
*                                                         sampling data

               IF(DEP.LT.DGW)THEN ! checking if sample is below water table
               IREC=IREC+1
               GOTO 600
               END IF

700            IF(DEP.GT.BL(I))THEN ! Checking if sample is in next soil layer

               IF(TSTD(I))THEN ! checking if layer was tested before
*                                going to next layer
```

```
                GOTO 700

                ELSE

*               Checking if soil is a liquefiable soil type

                IF(STYP(I).EQ.'GW')GOTO 800
                IF(STYP(I).EQ.'GP')GOTO 800
                IF(STYP(I).EQ.'GM')GOTO 800
                IF(STYP(I).EQ.'SW')GOTO 800
                IF(STYP(I).EQ.'SP')GOTO 800
                IF(STYP(I).EQ.'SM')GOTO 800
                IF(STYP(I).EQ.'SC')GOTO 800
                IF(STYP(I).EQ.'ML')GOTO 800
                IF(STYP(I).EQ.'A1a')GOTO 800
                IF(STYP(I).EQ.'A1b')GOTO 800
                IF(STYP(I).EQ.'A3')GOTO 800
                IF(STYP(I).EQ.'A24')GOTO 800
                IF(STYP(I).EQ.'A26')GOTO 800
                IF(STYP(I).EQ.'A4')GOTO 800

                I=I+1
                GOTO 700

800             IF(DGW.LT.BL(I))THEN ! checking if layer is saturated

*               Writing out that liquefiable layer was not tested

                WRITE(2,900) BL(I-1),BL(I),STYP(I)
900             FORMAT(T12,F5.2,'-',F5.2,T25,A3,
     $' SOIL BELOW WATER TABLE NOT TESTED')

                ELSE

                I=I+1
                GOTO 700

                END IF ! END CHECKING IF LAYER IS SATURATED

                END IF ! END CHECKING IF LAYER WAS TESTED

                END IF ! END CHECKING IF SAMPLE IS IN CURRENT LAYER

                TSTD(I)=.TRUE. ! LAYER HAS BEEN TESTED

*               Calculating silt correction based on D50

                IF((D50(I).LE.0.15).AND.(D50(I).GT.0.00000001))THEN
                  CORR=7.5
                  GOTO 1000
                ELSE IF((D50(I).GT.0.15).AND.(D50(I).LT.0.25))THEN
                  CORR=7.5*((0.25-D50(I))/0.1)
                  GOTO 1000
                ELSE IF(D50(I).GE.0.25)THEN
                  CORR=0
                  GOTO 1000
                END IF

*               No D50, using default silt corrections

                IF(STYP(I).EQ.'GW')THEN
                  CORR=GW
```

```
      ELSE IF(STYP(I).EQ.'GP')THEN
        CORR=GP
        GOTO 1000
      ELSE IF(STYP(I).EQ.'GM')THEN
        CORR=GM
        GOTO 1000
      ELSE IF(STYP(I).EQ.'SW')THEN
        CORR=SW
        GOTO 1000
      ELSE IF(STYP(I).EQ.'SP')THEN
        CORR=SP
        GOTO 1000
      ELSE IF(STYP(I).EQ.'SM')THEN
        CORR=SM
        GOTO 1000
      ELSE IF(STYP(I).EQ.'SC')THEN
        CORR=SC
        GOTO 1000
      ELSE IF(STYP(I).EQ.'ML')THEN
        CORR=ML
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A1a')THEN
        CORR=A1a
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A1b')THEN
        CORR=A1b
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A3')THEN
        CORR=A3
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A24')THEN
        CORR=A24
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A26')THEN
        CORR=A26
        GOTO 1000
      ELSE IF(STYP(I).EQ.'A4')THEN
        CORR=A4
        GOTO 1000
      ELSE IF(STYP(I).NE.'SW')THEN ! in case of invalid soil type
        CORR=0
        GOTO 1000
      END IF

1000  CONTINUE

*     Converting Dames and Moore samplers to standard values

      IF(LC.EQ.'d')THEN
      SN=0.5624*(SN**0.9944)
      END IF
      IF(LC.EQ.'u')THEN
      SN=0.3358*(SN**1.0517)
      END IF

*     Determining critical acceleration

      CALL SIMPLI(DEP,DGW,SN,CORR,N1,AMAX)

*     Checking if N1C is off curve

      IF((N1+CORR).GE.35)THEN
```

```
                GOTO 600
                END IF

*               Checking if critical acceleration is lowest at boring

                IF(AMAX.LT.AMINB)THEN
                AMINB=AMAX
                END IF

*               Checking if critical acceleration is lowest at area

                IF(AMAX.LT.AMINA)THEN
                AMINA=AMAX
                END IF
*               Writing out sample data

                WRITE(2,1100) DEP,AMAX,STYP(I),SN,N1,CORR
1100            FORMAT(T12,F6.2,T23,F7.4,T38,A3,T44,F4.1,T52,
     $F4.1,T64,F3.1)
                IREC=IREC+1
                GOTO 600

                ELSE IF(LC.EQ.'x')THEN ! end of file

*               Writing out last critical accelerations

                IF(AMINB.GE.99)THEN
                WRITE(2,255)
                ELSE
                WRITE(2,250) AMINB
                END IF
                IF(AMINA.GE.99)THEN
                WRITE(2,185)
                ELSE
                WRITE(2,175) AMINA
                END IF

                END IF

*               Closing files

                CLOSE(UNIT=1)
                CLOSE(UNIT=2)
                STOP
*               Errors

1111            WRITE(5,*) ' ERROR IN OPENING FILES'
                STOP

2222            CALL ERRSNS(IERR)
                IF(IERR.EQ.36)THEN
                CLOSE(UNIT=1)
                CLOSE(UNIT=2)
                STOP
                ELSE
                WRITE(5,1300) IERR
1300            FORMAT(' ERROR NUMBER ',I3,' IN READING FROM LIBRARY  FILE')
                CLOSE(UNIT=1)
                CLOSE(UNIT=2)
                STOP
                END IF
                END
```

```
*********************************************************************
*
*       Subroutine to compute CN, CYSTRA, AMAX, and RD
*
*********************************************************************

*               New variables (in order of use)

*               OP = Total overburden pressure (lb/ft sq)
*               EOP = Effective overburden pressure (lb/ft sq)
*               EOPK = Effective overburden pressure (kips/ft sq)
*               CN = Multiplier to normalize blow counts
*               N1C = Blow counts normalized and corrected for silt
*               RD = Stress reduction factor for cyclic shear at depth


                SUBROUTINE SIMPLI(D,GW,SPT,CORR,N1,AMAX)
                REAL N1,N1C
                OP=D*120.
                EOP=D*120.-(D-GW)*62.4
                EOPK=EOP/1000.
                N1=SPT*CN(EOPK)
                N1C=N1+CORR
                CYSTRA=CYC(N1C,EQ)
                RD=RDF(D)
                AMAX=CYSTRA/(.65*OP*RD/EOP)
                RETURN
                END

**********************************************************************
*
*       Function that computes CN
*
**********************************************************************

                FUNCTION CN(EOPK)

                IF(EOPK.LT.2)THEN
                CN=3.6277191415429115-4.8152955498141120*EOPK
     $+3.9741213110419062*EOPK**2-1.7410758816220399
     $*EOPK**3+0.3806176422109025*EOPK**4-0.0327332078074373
     $*EOPK**5

                ELSE

                CN=1.7913465152184169-0.5944497565011283*EOPK
     $+0.1304264429961489*EOPK**2-0.0166862573350987
     $*EOPK**3+0.0011302845218605*EOPK**4-0.0000310167938285
     $*EOPK**5

                END IF

                IF(CN.GT.1.6) CN=1.6
                IF(CN.LT.0.4) CN=0.4

                RETURN
```

```
************************************************************************
*
*     Function that computes cyclic stress ratio
*     given N1C for earthquake magnitude 6.0, 6.75 or 7.5
*
************************************************************************

                 FUNCTION CYC(N1C)

                 REAL*8 A(3,2,6)
                 COMMON EQ
        REAL N1C

*                COEFFECIENTS FOR MAG 7.5 EARTHQUAKE

                 A(1,1,1)=-0.0024425232362363
                 A(1,1,2)= 0.0113927708367214
                 A(1,1,3)=-0.0000802625511081
                 A(1,1,4)= 0.0000020653208783
                 A(1,1,5)= 0.0000000000000000
                 A(1,1,6)= 0.0000000000000000
                 A(1,2,1)=-0.2537752087228000
                 A(1,2,2)= 0.0451104082747489
                 A(1,2,3)=-0.0015880462265690
                 A(1,2,4)= 0.0000245452223647
                 A(1,2,5)= 0.0000000000000000
                 A(1,2,6)= 0.0000000000000000

*                COEFFCIENTS FOR MAG. 6.75 EARTHQUAKE

                 A(2,1,1)= 0.0049081059365437
                 A(2,1,2)= 0.0092074507682916
                 A(2,1,3)= 0.0004513754644203
                 A(2,1,4)=-0.0000284530507291
                 A(2,1,5)= 0.0000006028351606
                 A(2,1,6)= 0.0000000000000000
                 A(2,2,1)=-0.1494495401779811
                 A(2,2,2)= 0.0170314249335128
                 A(2,2,3)= 0.0011458660475855
                 A(2,2,4)=-0.0000802532707088
                 A(2,2,5)= 0.0000014456142903
                 A(2,2,6)= 0.0000000000000000

*                COEFFIECIENTS FOR A MAGNITUDE 6.0 EARTHQUAKE

                 A(3,1,1)=-0.0093171129433008
                 A(3,1,2)= 0.0190505902325310
                 A(3,1,3)=-0.0010120339477064
                 A(3,1,4)= 0.0000961672816506
                 A(3,1,5)=-0.0000043056343401
                 A(3,1,6)= 0.0000000727876744
                 A(3,2,1)=-0.0093171129433008
                 A(3,2,2)= 0.0190505902325310
                 A(3,2,3)=-0.0010120339477064
                 A(3,2,4)= 0.0000961672816506
                 A(3,2,5)=-0.0000043056343401
                 A(3,2,6)= 0.0000000727876744
```

```
      IF(EQ.GT.7.49)THEN
      I=1
      ELSE IF(EQ.GT.6.74)THEN
      I=2
      ELSE IF(EQ.LT.6.01)THEN
      I=3
      END IF

      IF(N1C.LT.20.0)THEN
      J=1
      ELSE
      J=2
      END IF

      CYC=0

      DO 100,K=1,6
100   CYC=CYC+A(I,J,K)*N1C**(K-1)

      RETURN
      END


***********************************************************************
*
*       Function that computes RD
*
***********************************************************************

      FUNCTION RDF(D)
      RDF=1.07459-1.379E-4*D**2+1.2644E-10*D**5
      IF(D.LT.45.238) RDF=.973781-2.937E-5*D**2-2.287E-8*D**4
      IF(D.LT.30.231) RDF=.999699-.0017497*D-6.132E-7*D**3
      IF(D.LT.13.439) RDF=.99885-1.7371E-3*D+6.78E-6*D**2-4.378E-8*D**4
      RETURN
      END
```

Appendix F

Program CRACCO

```
*   PROGRAM CRACCO  CRitical ACceleration from COne soundings
*   JAMES A. BAY
*   JUNE 8, 1987

*   Program to plot ground acceleration to induce liquefaction verses
*   soil depth, using solid lines for clean sands and dotted lines for
*   silty sands. Critical accelerations are calculated by converting
*   cone resistance to equivalent standard penetration resistance and
*   using Seeds method.


*               Variables (in order of use)
*
*               EQ = Earthquake magnitude to be used in analysis
*               LINE =  Array to used to define a solid line in CALCOMP
*               INFILE = Name of file containing the names of cone files,
*                        the county it is in, and the ground water depth
*               DAT = Name of file digitized cone sounding
*               COUNTY = County sounding is in: WE=Weber,BE=BoxElder,CA=Cache
*               GWDEP = Depth to groundwater (ft)
*               NQ = Character counter
*               TITLE = Title of cone sounding
*               DEPTH = Depth of reading (ft)
*               IPLS = Number of silty sand points to plot
*               IPLC = Number of clean sand points to plot
*               FR = Friction resistance (tons/ft sq)
*               QC = Tip resistance (tons/ft sq)
*               CA = Array containing critical accelerations to be plotted (%g)
*               DEP = Array containing depths to be plotted (ft)
*               HIGH = Array containing boundary between high and moderate
*                      critical acceleration (%g)
*               MOD = Array containing boundary between moderate and low
*            critical acceleration (%g)
*               LOW = Array containing boundary between low and very low
*                     critical acceleration (%g)
*               Y = Array to plot high, moderate, and low lines against
*               RATIO = Friction ratio (%)
*               ITYPE = Code for soil type: 0=Clay,1=SiltySand,2=CleanSand
*               SN = Equivalent blow counts (blows/foot)
*               CORR = Silt correction
*               AMAX = Critical Acceleration to induce liquefaction



                REAL LINE(2),CA(100),DEP(100),HIGH(2),MOD(2),LOW(2),Y(2)
      CHARACTER INFILE*15,TITLE*40,COUNTY*2,DAT*8
      COMMON EQ

*               Initializing the line definitions

      LINE(1)=999
                LINE(2)=1

*               Inputing name of file containing the names of the cones sounding
*               files, their counties, and groundwater depths

      WRITE(6,5)
5               FORMAT(' ENTER NAME OF FILE CONTAINING LIST OF: DATA FILES,'/
     $' COUNTIES, AND GROUNDWATER DEPTHS'//)
      READ(5,10) INFILE
10              FORMAT(A15)
```

```
20              READ(1,30) DAT,COUNTY,GWDEP
30              FORMAT(A8,X,A2,X,F)

                IF(DAT.EQ.'XXXXXXXX')THEN ! indicates end of soundings
                STOP
                END IF

*               Setting earthquake magnitudes: 6.0 for Cache, 7.5 for Weber
*               and Box Elder

                IF(COUNTY.EQ.'CA')THEN
                EQ=6.0
                ELSE
                EQ=7.5
                END IF

*               Opening cone sounding

                OPEN(UNIT=2,FILE=DAT,STATUS='OLD')

        READ(2,50) NQ,TITLE
50      FORMAT(Q,A)
        READ(2,*) ! line containing unneeded information
        READ(2,*) ! line containing unneeded information

*               Advancing through sounding to readings below the water table

40      READ(2,*) DEPTH
        IF(DEPTH.LT.GWDEP)GOTO 40

*               Initializing plot counters

        IPLS=0
        IPLC=0

*               Setting up plot

        CALL CALCMP

        CALL HWROT('AUTO')
        CALL PAGE(11.,17.)
        CALL NOBRDR
        CALL GRACE(0)
        CALL CROSS
        CALL PHYSOR(2.0,0.5)
        CALL AREA2D(8.0,13.0)
        CALL YTICKS(5)
        CALL XTICKS(5)
        CALL XNAME('Ground Acceleration (%g)$',-100)
        CALL YNAME('Depth (ft)$',100)
        CALL HEADIN(%REF(TITLE),NQ,-2.0,1)
        CALL GRAF(0.0,10.0,80.0,65.0,-5.0,0.0)

*               Reading new line of data

100             READ(2,*) DEPTH,FR,QC

*               Checking if it is the last line of the file

        IF(DEPTH.LT.0)THEN
```

```
      IF(IPLC.GT.0)THEN
      CALL MRSCOD(1,2,LINE)
      CALL CURVE(CA,DEP,IPLC,0)
      IPLC=0
      ELSE IF(IPLS.GT.0)THEN
      CALL DOT
      CALL CURVE(CA,DEP,IPLS,0)
      IPLS=0
      END IF

*              Plotting dividing lines between liquefaction potentials

               IF((COUNTY.EQ.'WE').OR.(COUNTY.EQ.'BE'))THEN
               HIGH(1)=13
               HIGH(2)=13
               MOD(1)=23
               MOD(2)=23
               LOW(1)=30
               LOW(2)=30

               ELSE IF(COUNTY.EQ.'CA') THEN
               HIGH(1)=10
               HIGH(2)=10
               MOD(1)=18
               MOD(2)=18
               LOW(1)=25
               LOW(2)=25

               END IF

               Y(1)=0
               Y(2)=65
               CALL DASH
               CALL CURVE(HIGH,Y,2,0)
               CALL CURVE(MOD,Y,2,0)
               CALL CURVE(LOW,Y,2,0)

*              Ending plot

      CALL ENDPL(0)
      CLOSE(UNIT=2)
      GOTO 20 ! goes to next sounding
      END IF

*              Plotting data if arrays are filled

      IF(IPLC.GE.99)THEN
      CALL MRSCOD(1,2,LINE)
      CALL CURVE(CA,DEP,IPLC,0)
      CA(1)=CA(IPLC) ! makes plots continuous
      DEP(1)=DEP(IPLC) ! makes plots continuous
      IPLC=1
      ELSE IF(IPLS.GE.99)THEN
      CALL DOT
      CALL CURVE(CA,DEP,IPLS,0)
      CA(1)=CA(IPLS) ! makes plots continuous
      DEP(1)=DEP(IPLS) ! makes plots continuous
      IPLS=1
      END IF

      RATIO=100*FR/QC ! calculating fricton ratio
```

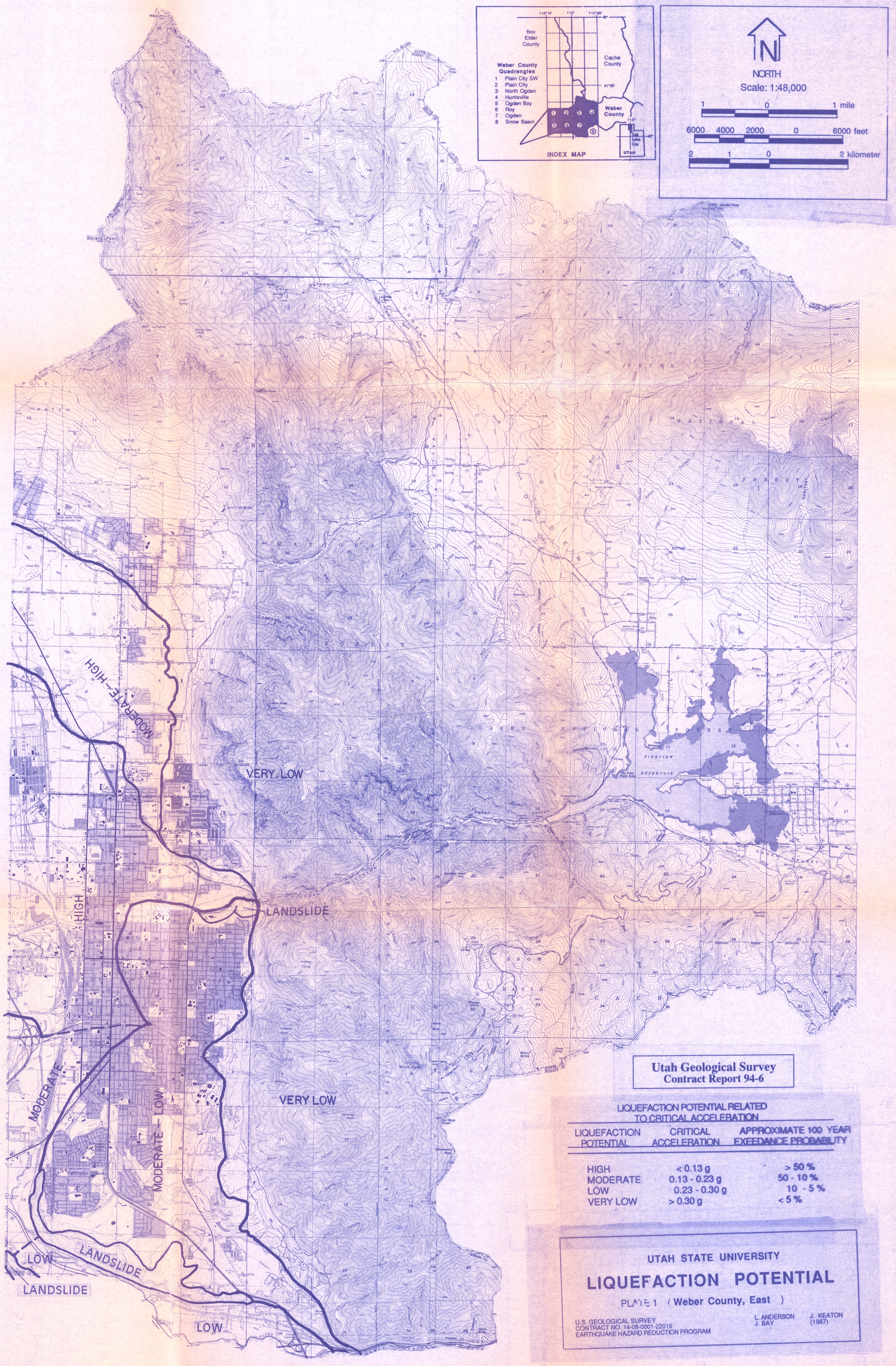
```
      CALL STYPE(RATIO,QC,ITYPE) ! determining soil type

      IF(ITYPE.EQ.0)THEN ! soil type is clay

*              Plotting any unplotted clean or silty data

      IF(IPLC.GT.0)THEN
      CALL MRSCOD(1,2,LINE)
      CALL CURVE(CA,DEP,IPLC,0)
      IPLC=0
      ELSE IF(IPLS.GT.0)THEN
      CALL DOT
      CALL CURVE(CA,DEP,IPLS,0)
      IPLS=0
      END IF
      GOTO 100

      ELSE IF(ITYPE.EQ.1)THEN ! Soil is silty
      SN=QC/3.9 ! equivalent standard pentration blow counts
      CORR=7.5 ! silt correction

*              Plotting any unplotted clean data

      IF(IPLC.GT.0)THEN
      CALL MRSCOD(1,2,LINE)
      CALL CURVE(CA,DEP,IPLC,0)
      IPLC=0
      END IF

               ELSE IF(ITYPE.EQ.2)THEN ! soil is clean sand
      SN=QC/4.5 ! equivalent standard pentration blow counts
      CORR=0 ! silt correction

*              Plotting any unplotted silty data

      IF(IPLS.GT.0)THEN
      CALL DOT
      CALL CURVE(CA,DEP,IPLS,0)
      IPLS=0
      END IF


      END IF

*              Determining critical acceleration

      CALL SIMPLI(DEPTH,GWDEP,SN,CORR,AMAX)

*              Checking if critical acceleration goes of the plot

      IF(AMAX.GT.0.8)THEN

*              Plotting any unplotted data

      IF(IPLC.GT.0)THEN
      CALL MRSCOD(1,2,LINE)
      CALL CURVE(CA,DEP,IPLC,0)
      IPLC=0
      ELSE IF(IPLS.GT.0)THEN
      CALL DOT
      CALL CURVE(CA,DEP,IPLS,0)
      IPLS=0
```

```
      GOTO 100
      END IF

*               Incrementing plotting counter and storing values in array

      IF(ITYPE.EQ.1)THEN
      IPLS=IPLS+1
      DEP(IPLS)=DEPTH
      CA(IPLS)=100*AMAX
      END IF

      IF(ITYPE.EQ.2)THEN
      IPLC=IPLC+1
      DEP(IPLC)=DEPTH
      CA(IPLC)=100*AMAX
      END IF


      GOTO 100
      END




*   SUBROUTINE STYPE TO DETERMINE SOIL TYPE FROM Fr AND Qc

      SUBROUTINE STYPE(FR,QC,ITYPE)


      IF(FR.GT.3.8)THEN
      ITYPE=0
      RETURN
      END IF

      CLAY=10**(1.10049703+FR*0.02385008+(FR**2)*0.21987915-
     $(FR**3)*0.23909713+(FR**4)*0.13504428-(FR**5)*0.03521643+
     $(FR**6)*0.00368401)

      IF(QC.LT.CLAY)THEN
      ITYPE=0
      RETURN
      END IF

      IF(FR.GT.2.1)THEN
      ITYPE=1
      RETURN
      END IF

      SILT=10**(1.41892159+FR*0.14249950-(FR**2)*0.12555632+
     $(FR**3)*0.35318569-(FR**4)*0.26414058+(FR**5)*0.07877631)

      IF(QC.LT.SILT)THEN
      ITYPE=1
      RETURN
      END IF

      ITYPE=2
      RETURN
      END
```

```
************************************************************************
*
*        Subroutine to compute CN, CYSTRA, AMAX, and RD
*
************************************************************************

*                New variables (in order of use)

*                OP = Total overburden pressure (lb/ft sq)
*                EOP = Effective overburden pressure (lb/ft sq)
*                EOPK = Effective overburden pressure (kips/ft sq)
*                CN = Multiplier to normalize blow counts
*                N1C = Blow counts normalized and corrected for silt
*                RD = Stress reduction factor for cyclic shear at depth



                 SUBROUTINE SIMPLI(D,GW,SPT,CORR,AMAX)
                 REAL N1,N1C
                 OP=D*120.
                 EOP=D*120.-(D-GW)*62.4
                 EOPK=EOP/1000.
                 N1=SPT*CN(EOPK)
                 N1C=N1+CORR
                 CYSTRA=CYC(N1C,EQ)
                 RD=RDF(D)
                 AMAX=CYSTRA/(.65*OP*RD/EOP)
                 RETURN
                 END

************************************************************************
*
*        Function that computes CN
*
************************************************************************

                 FUNCTION CN(EOPK)

                 IF(EOPK.LT.2)THEN
                 CN=3.6277191415429115-4.8152955498141120*EOPK
     $+3.9741213110419062*EOPK**2-1.7410758816220399
     $*EOPK**3+0.3806176422109025*EOPK**4-0.0327332078074373
     $*EOPK**5

                 ELSE

                 CN=1.7913465152184169-0.5944497565011283*EOPK
     $+0.1304264429961489*EOPK**2-0.0166862573350987
     $*EOPK**3+0.0011302845218605*EOPK**4-0.0000310167938285
     $*EOPK**5

                 END IF

                 IF(CN.GT.1.6) CN=1.6
                 IF(CN.LT.0.4) CN=0.4

                 RETURN
                 END
```

```
*********************************************************************
*
*     Function that computes cyclic stress ratio
*     given N1C for earthquake magnitude 6.0, 6.75 or 7.5
*
*********************************************************************

            FUNCTION CYC(N1C)

            REAL*8 A(3,2,6)
            COMMON EQ
      REAL N1C

*           COEFFECIENTS FOR MAG 7.5 EARTHQUAKE

            A(1,1,1)=-0.0024425232362363
            A(1,1,2)= 0.0113927708367214
            A(1,1,3)=-0.0000802625511081
            A(1,1,4)= 0.0000020653208783
            A(1,1,5)= 0.0000000000000000
            A(1,1,6)= 0.0000000000000000
            A(1,2,1)=-0.2537752087228000
            A(1,2,2)= 0.0451104082747489
            A(1,2,3)=-0.0015880462265690
            A(1,2,4)= 0.0000245452223647
            A(1,2,5)= 0.0000000000000000
            A(1,2,6)= 0.0000000000000000

*           COEFFCIENTS FOR MAG. 6.75 EARTHQUAKE

            A(2,1,1)= 0.0049081059365437
            A(2,1,2)= 0.0092074507682916
            A(2,1,3)= 0.0004513754644203
            A(2,1,4)=-0.0000284530507291
            A(2,1,5)= 0.0000006028351606
            A(2,1,6)= 0.0000000000000000
            A(2,2,1)=-0.1494495401779811
            A(2,2,2)= 0.0170314249335128
            A(2,2,3)= 0.0011458660475855
            A(2,2,4)=-0.0000802532707088
            A(2,2,5)= 0.0000014456142903
            A(2,2,6)= 0.0000000000000000

*           COEFFIECIENTS FOR A MAGNITUDE 6.0 EARTHQUAKE

            A(3,1,1)=-0.0093171129433008
            A(3,1,2)= 0.0190505902325310
            A(3,1,3)=-0.0010120339477064
            A(3,1,4)= 0.0000961672816506
            A(3,1,5)=-0.0000043056343401
            A(3,1,6)= 0.0000000727876744
            A(3,2,1)=-0.0093171129433008
            A(3,2,2)= 0.0190505902325310
            A(3,2,3)=-0.0010120339477064
            A(3,2,4)= 0.0000961672816506
            A(3,2,5)=-0.0000043056343401
            A(3,2,6)= 0.0000000727876744

            IF(EQ.GT.7.49)THEN
            I=1
            ELSE IF(EQ.GT.6.74)THEN
```

```
                ELSE IF(EQ.LT.6.01)THEN
                I=3
                END IF

                IF(N1C.LT.20.0)THEN
                J=1
                ELSE
                J=2
                END IF

                CYC=0

                DO 100,K=1,6
100             CYC=CYC+A(I,J,K)*N1C**(K-1)

                RETURN
                END


************************************************************************
*
*       Function that computes RD
*
************************************************************************

      FUNCTION RDF(D)
      RDF=1.07459-1.379E-4*D**2+1.2644E-10*D**5
      IF(D.LT.45.238) RDF=.973781-2.937E-5*D**2-2.287E-8*D**4
      IF(D.LT.30.231) RDF=.999699-.0017497*D-6.132E-7*D**3
      IF(D.LT.13.439) RDF=.99885-1.7371E-3*D+6.78E-6*D**2-4.378E-8*D**4
      RETURN
      END
```



Utah Geological Survey
Contract Report 94-6

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 - 0.30 g	10 - 5 %
VERY LOW	> 0.30 g	< 5 %

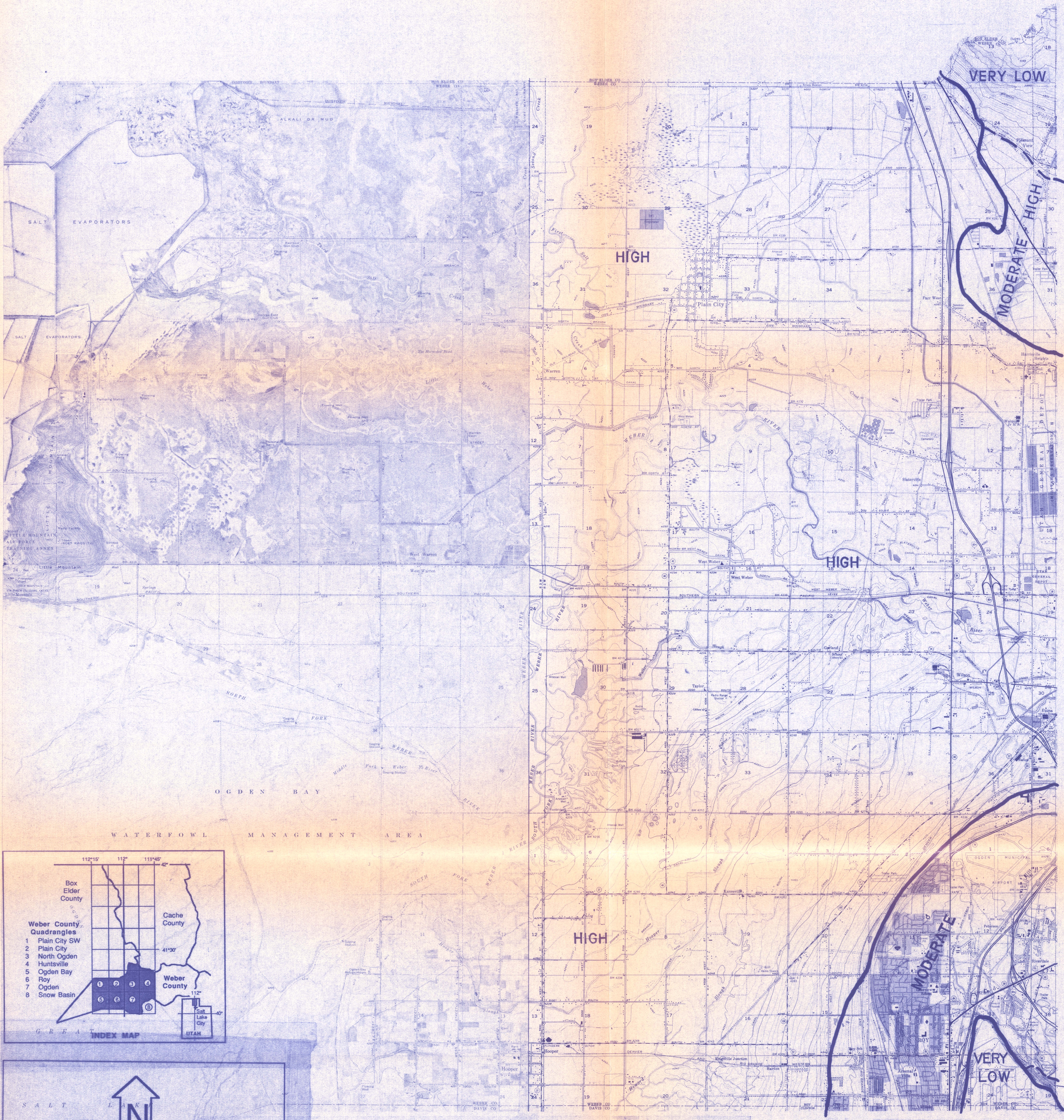
UTAH STATE UNIVERSITY

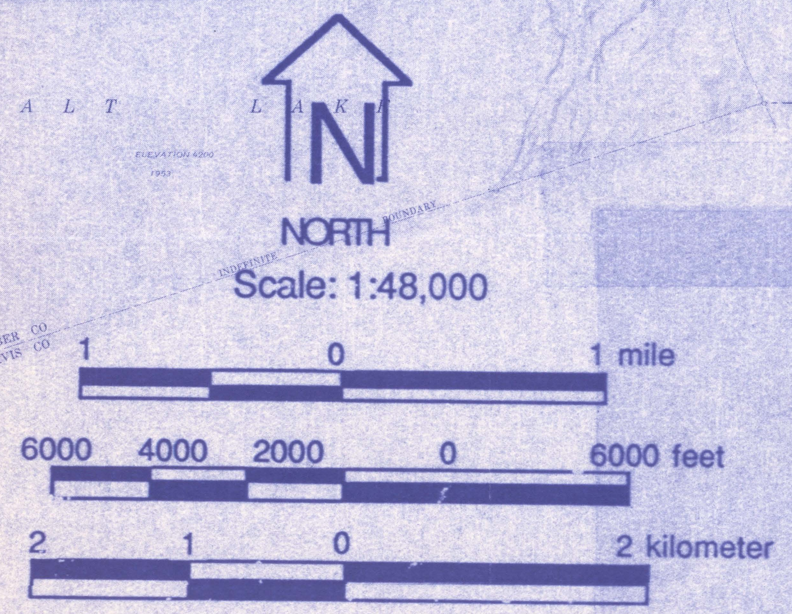
LIQUEFACTION POTENTIAL

PLATE 1 (Weber County, East)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-22015
EARTHQUAKE HAZARD REDUCTION PROGRAM

L. ANDERSON J. KEATON
J. BAY (1987)





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 - 0.30 g	10 - 5 %
VERY LOW	> 0.30 g	< 5 %

Utah Geological Survey
Contract Report 94-6

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LIQUEFACTION POTENTIAL

PLATE 2 (Weber County, West)

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EARTHQUAKE HAZARD REDUCTION PROGRAM

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N
NORTH
Scale: 1:48,000
1 0 1 mile
6000 4000 2000 0 6000 feet
2 1 0 2 kilometer
Utah Geological Survey
Contract Report 94-6
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 - 0.30 g | 10 - 5 %
VERY LOW | > 0.30 g | < 5 %
UTAH STATE UNIVERSITY
LIQUEFACTION POTENTIAL
PLATE 3 (Box Elder County, South)
U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14 08-0001-22015
EARTHQUAKE HAZARD REDUCTION PROGRAM
L. ANDERSON
J. BAY
J. KEATON
(1987)
MODERATE - HIGH
HIGH
VERY LOW
MODERATE - LOW
INDEX MAP
IDAHO
UTAH
112°15'
112°
111°45'
42°
41°30'
40°
Box Elder County
Cache County
Weber County
Salt Lake City
Southern Box Elder County Quadrangles
1 Tremonton
2 Honeyville
3 Bear River City
4 Brigham City
5 Mount Pisgah
6 Whistler Canal
7 Willard
8 Mantua
9 Plain City SW
10 Plain City
11 North Ogden

Utah Geological Survey
Contract Report 94-6
NORTH
Scale: 1:48,000
1 mile
6000 feet
2 kilometer
IDAHO
UTAH
Box Elder County
Northern Box Elder County Quadrangles
1 Portage
2 Clarkston
3 Riverside
4 Cutler Dam
5 Tremonton
6 Honeyville
Cache County
Weber County
Salt Lake City
INDEX MAP
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 - 0.30 g 10 - 5 %
VERY LOW > 0.30 g < 5 %
UTAH STATE UNIVERSITY
LIQUEFACTION POTENTIAL
PLATE 4 (Box Elder County, North)
U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-22015
EARTHQUAKE HAZARD REDUCTION PROGRAM
L. ANDERSON
J. BAY
J. KEATON
(1987)
MODERATE - LOW
MODERATE - LOW
VERY LOW
VERY LOW
MODERATE - LOW
HIGH
HIGH
VERY LOW
MODERATE - HIGH
MODERATE - HIGH
MODERATE - HIGH

Utah Geological Survey
Contract Report 94-6

LIQUEFACTION POTENTIAL RELATED TO CRITICAL ACCELERATION

LIQUEFACTION POTENTIAL	CRITICAL ACCELERATION	APPROXIMATE 100 YEAR EXEEDANCE PROBABILITY
HIGH	< 0.10 g	> 50 %
MODERATE	0.10 - 0.18 g	50 - 10 %
LOW	0.18 - 0.25 g	10 - 5 %
VERY LOW	> 0.25 g	< 5 %

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LIQUEFACTION POTENTIAL

PLATE 5 (Cache County, South)

U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-22015
EARTHQUAKE HAZARD REDUCTION PROGRAM

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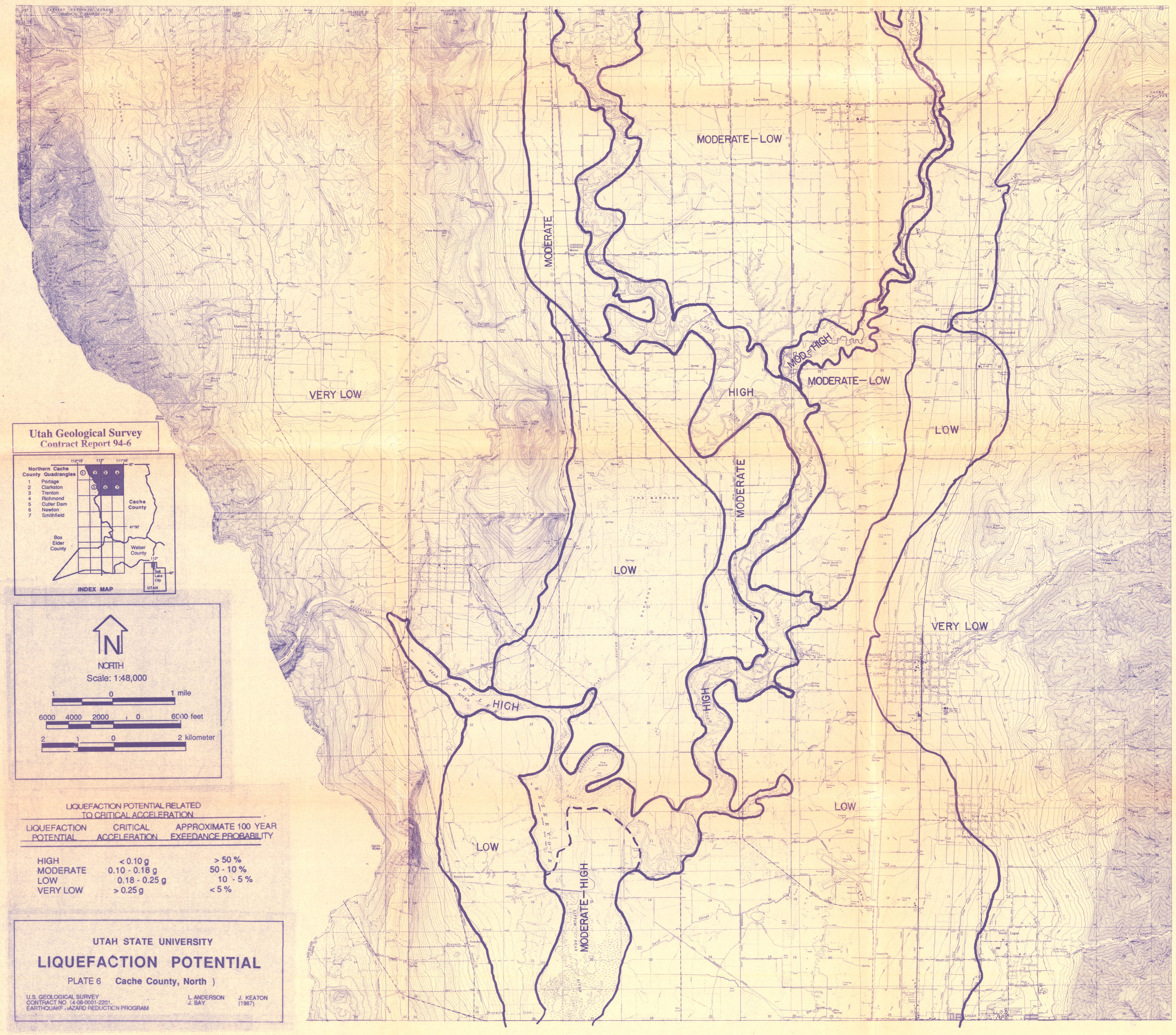
J. KEATON
(1987)


Utah Geological Survey
Contract Report 94-6
Northern Cache County Quadrangles
1 Portage
2 Clarkston
3 Trenton
4 Richmond
5 Cutler Dam
6 Newton
7 Smithfield
Cache County
Box Elder County
Weber County
Salt Lake City
UTAH
INDEX MAP
NORTH
Scale: 1:48,000
1 0 1 mile
6000 4000 2000 0 6000 feet
2 1 0 2 kilometer
LIQUEFACTION POTENTIAL RELATED TO CRITICAL ACCELERATION
LIQUEFACTION POTENTIAL | CRITICAL ACCELERATION | APPROXIMATE 100 YEAR EXEEDANCE PROBABILITY
HIGH | < 0.10 g | > 50 %
MODERATE | 0.10 - 0.18 g | 50 - 10 %
LOW | 0.18 - 0.25 g | 10 - 5 %
VERY LOW | > 0.25 g | < 5 %
UTAH STATE UNIVERSITY
LIQUEFACTION POTENTIAL
PLATE 6 Cache County, North)
U.S. GEOLOGICAL SURVEY
CONTRACT NO. 14-08-0001-2201
EARTHQUAKE HAZARD REDUCTION PROGRAM
L. ANDERSON
J. BAY
J. KEATON
(1987)
MODERATE—LOW
MODERATE
VERY LOW
MOD HIGH
MODERATE—LOW
HIGH
LOW
MODERATE
LOW
VERY LOW
HIGH
HIGH
LOW
LOW
MODERATE—HIGH