

## **APPENDIX C**

### **LIQUEFACTION ARTICLE**

Keaton, J.R., and Anderson, L.R., 1995, Mapping liquefaction hazards in the Wasatch Front Region: Opportunities and Limitations: in Lund, W.R., ed., Environmental and Engineering Geology of the Wasatch Front Region: Salt Lake City, Utah Geological Association Special Publication 24, p. 453-468.

## **APPENDIX C**

### **LIQUEFACTION ARTICLE**

The article that is reproduced in this appendix is a general paper addressing liquefaction hazards in the Wasatch Front Region of north-central Utah (Keaton and Anderson, 1995). The relevant part of this article for the Brightwater project is on pages 462 to 464. This part describes a construction excavation in Murray, Utah, which exposed evidence of liquefaction-induced permanent ground deformation in deep-water sediments of Lake Bonneville (probably on the order of 15,000 years old). This location is more than one mile from the Wasatch fault and probably more than 5 miles from the West Valley fault; surface faulting is not suspected to be a factor contributing to the deformation at this location.

The construction excavation log on Figure 6 in the attached article shows small-scale reverse and normal faults that may have some component of lateral slip and impressive folding with essentially no dikes or injection features of liquefied sand or silt. The amplitude of the fold between Sta. 29 m and Sta. 35 m is greater than 2 m. Sand layers in this fold are overturned.

Strong earthquake shaking in the immediate vicinity of the construction excavation undoubtedly occurred repeatedly during the past 15,000 years, including at times when the location was submerged by lake water, as well as after the lake receded. Significant compressive stresses and soft-sediment deformation must have occurred at this location to produce the geologic conditions documented on the construction excavation log.

# MAPPING LIQUEFACTION HAZARDS IN THE WASATCH FRONT REGION: OPPORTUNITIES AND LIMITATIONS

JEFFREY R. KEATON<sup>1</sup> AND LOREN R. ANDERSON<sup>2</sup>

## ABSTRACT

Liquefaction is an earthquake-induced process in which a loose, sandy deposit below the water table loses much of its strength as load is transferred from grain-to-grain contacts to the water in the pore space. Liquefaction occurs when the pressure in the pore water equals the weight of the sediment column above the sandy layer. The effects of liquefaction have been observed in Utah in historical earthquakes, and evidence of liquefaction in the Wasatch Front region has been preserved in the stratigraphy of Lake Bonneville deposits. Liquefaction in historical earthquakes has caused significant damage to dams, buildings, buried utilities, roads, and bridges.

Mapping of liquefaction hazards in the Wasatch Front began in 1980 with a National Earthquake Hazards Reduction Program Grant to Utah State University for a study of Davis County. Davis County was selected because the urbanized part was relatively small, ground water was known to be shallow, and a substantial amount of subsurface geotechnical information was available. Liquefaction hazards were mapped on the basis of the susceptibility of subsurface sand deposits as indexed by Standard Penetration Test (SPT) blow counts using a conventional geotechnical procedure. The mode of potential liquefaction-induced ground displacement was equated to ground slope. The acceleration required to induce liquefaction was calculated for each site where subsurface data were available, and compared to the results of a probabilistic seismic ground motion evaluation done in 1978. Liquefaction-hazard maps showing high, moderate, low, and very low liquefaction potential were constructed using the computed values of critical acceleration integrated with engineering geology to guide the position and shape of the hazard-zone boundaries. Salt Lake County was mapped next in a similar way, except Cone Penetrometer Tests (CPT) were used to supplement the SPT blow counts. Utah County was the third area to be mapped, followed by Weber, eastern Box Elder, and Cache counties. The final liquefaction hazard evaluation included selected areas in central Utah from Park City to Richfield. In 1994, the Utah Geological Survey digitized and published summary maps of liquefaction hazard for parts of Davis, Salt Lake, Utah, and Weber counties based on this research.

Research following earthquakes in the 1980s has led to an appreciation that the potential for liquefaction-induced ground displacement is not necessarily accurately indexed to liquefaction susceptibility of sand layers. The thickness of and depth to susceptible sand layers was found to be important in determining the likelihood and extent of possible ground displacement. The importance of this factor was demonstrated in Salt Lake County where the liquefaction hazard maps were adopted by the Planning Department, and developments located in areas of mapped high liquefaction potential were required to have specific studies to evaluate the extent of the liquefaction hazard. Only about half of the sites were found to have high liquefaction susceptibilities. The maps of liquefaction potential developed in the 1980s along the Wasatch Front represent a first generation of this type of hazard mapping. Refinement is needed to translate the liquefaction-susceptibility maps into liquefaction-induced ground displacement maps showing not only the potential for such displacement, but the amount of displacement that can be expected for different probabilities of earthquake ground motion.

## INTRODUCTION

The purpose of this paper is to outline the history of liquefaction-hazard mapping in Utah, identify the

advancements and innovations arising from the research, and describe opportunities and limitations in applying liquefaction-hazard mitigation strategies. The history of liquefaction-hazard mapping is described first, followed by a

<sup>1</sup>AGRA Earth & Environmental, Inc., 4137 South 500 West, Salt Lake City, UT 84123-1399

<sup>2</sup>Utah State University, Department of Civil & Environmental Engineering, Logan, UT 84322-4110

discussion of the advancements. Comments are provided next on the regional mapping compared to the results of site-specific geotechnical evaluations. A section is included on foundation performance and site improvements to provide a basis for decisions about how a building owner might enhance the performance of an existing building or reduce liquefaction-induced ground displacement at an undeveloped site for a future building.

Liquefaction is the name given to the process in which loose, saturated fine-grained sandy deposits lose most of their shear strength as strong earthquake shaking causes rapid transfer of stress from the granular structure of the sediment to the pore water. If the pore-water pressure increases until the intergranular stress is reduced to zero, the condition of "initial liquefaction" is reached (Seed, 1976). For loose sands, this condition usually is accompanied by large permanent deformations. Surface effects of liquefaction include (1) sand boils, (2) ground settlement, (3) ground oscillation, (4) lateral spread landslides, (5) flow landslides, (6) loss of bearing capacity, (7) buoyant rise of buried facilities, and (8) failure of retaining walls (National Research Council, 1985). Youd and others (1975) related flow landslides, lateral-spread landslides, and loss of bearing capacity to the ground-surface slope, as shown in table 1.

## HISTORY AND BASIS OF MAPPING

Liquefaction-hazard mapping in Utah was funded by the U.S. Geological Survey through the National Earthquake Hazard Reduction Program (NEHRP) in a series of independent grants to Utah State University beginning in 1980, before the Wasatch Front became the focus of the NEHRP in the mid-1980s. Davis County was selected for the initial mapping project (Anderson and others, 1982) because the urban part of the county was relatively narrow, and the amount of existing subsurface geotechnical information was expected to provide an adequate basis for liquefaction-hazard mapping with limited additional geotechnical drilling. The plan for our liquefaction research in Davis County was to apply Seed's simplified procedure (Seed, 1976), along with the geological-age susceptibility

interpretation of Youd and Perkins (1978), to provide a basis for mapping liquefaction potential. Liquefaction *potential* is the combination of liquefaction *susceptibility* of the sediments (soils in the engineering sense) and the *opportunity* for strong ground shaking from earthquakes (Youd and Perkins, 1978).

The liquefaction susceptibility of a saturated soil deposit when subjected to ground shaking is determined by six factors: (1) soil type, (2) relative density, (3) initial confining pressure, (4) soil structure, (5) seismic history, and (6) intensity and duration of ground shaking, as summarized by Anderson and others (1987). Seed (1976) pointed out that the factors that tend to influence liquefaction susceptibility, such as relative density, age of the deposit, seismic history, and soil structure, also tend to influence the standard penetration resistance in a like manner. Seed and others (1977) developed an empirical relationship between the cyclic stress ratio generated by magnitude-7.5 earthquakes required to cause liquefaction and the standard penetration resistance blow count (SPT N-value) of the soil. Seed and others (1983) slightly modified this relationship and included the effect of earthquake magnitude on liquefaction susceptibility after the liquefaction-hazard mapping of Davis County had been completed. The magnitude of expected large earthquakes in the Davis County area was approximately 7.5; therefore, the results of the 1982 Davis County assessment were consistent with modified methods.

The basis for the simplified liquefaction evaluation procedure is a relationship between the cyclic stress ratio,  $\tau_{av}/\sigma'_o$ , required to cause liquefaction and the normalized blow count obtained from Standard Penetration Test (SPT) measurements in soil borings. The normalized blow count,  $(N1)_{60}$ , refers to SPT blow count values obtained using a standard 60-percent hammer-energy efficiency, and normalized to an effective overburden pressure of 1 ton per square foot (95.95 kPa). Seed and Idriss (1982) and Seed and others (1985) provide procedures to convert actual SPT blow counts measured in soil borings to  $(N1)_{60}$  values. Using the simplified procedure of Seed and Idriss (1971), values of  $\tau_{av}/\sigma'_o$  induced in the soils by the earthquake ground shaking can be calculated and compared with the values of  $\tau_{av}/\sigma'_o$  required to cause liquefaction, as determined by the site  $(N1)_{60}$  measurements. The simplified procedure equation for calculating the induced cyclic stress ratio is:

$$\frac{\tau_{av}}{\sigma'_o} = 0.65 \frac{a_{max}}{g} \frac{\sigma_o}{\sigma'_o} r_d$$

where:

- $\tau_{av}/\sigma'_o$  = induced cyclic stress ratio
- $a_{max}$  = maximum (peak) ground acceleration (g units)
- $\sigma_o$  = total overburden pressure at a depth of interest
- $\sigma'_o$  = effective overburden pressure at a depth of interest

Table 1. Mode of liquefaction-induced ground displacement as a function of ground-surface slope (modified from Youd and others, 1975).

Ground-Surface Slope	Mode of Ground Displacement
< 0.5 %	Loss of bearing capacity
0.5 % to 5 %	Lateral-spread landslide
> 5 %	Flow landslide

$r_d$  = a stress reduction factor that decreases from a value of 1.0 at the ground surface to a value of 0.9 at a depth of about 30 feet.

Anderson and Keaton (1982) solved the cyclic stress ratio equation for the acceleration required to induce liquefaction. This was called the "critical" acceleration, and became an index of the liquefaction *susceptibility* of the sandy deposits:

$$(a_{\max})_c = \frac{\tau_{av}}{\sigma'_o} \frac{\sigma'_o}{\sigma'_o} \frac{1}{0.65 r_d}$$

where:

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

This simple innovation produced liquefaction-hazard results that could be contoured and compared to probabilistic estimates of earthquake acceleration (liquefaction *opportunity*) to create a regional liquefaction *potential* map. The liquefaction-potential map for a part of Davis County is shown on figure 1.

Liquefaction potential along the Wasatch Front was mapped in terms of the probability that the critical acceleration would be equaled or exceeded (exceedance probability) in a 100-year time period. Qualitative descriptions of liquefaction potential are listed in table 2. At the time of the Davis County liquefaction research, limited probabilistic evaluations of earthquake ground motion were available, and the results of much research on earthquake hazards in general along the Wasatch Front were released after the liquefaction studies were completed. The critical acceleration values selected for the liquefaction potential evaluation in Davis, Salt Lake, and Utah counties were obtained from a study performed for the Utah Seismic Safety Council (Dames & Moore, 1978), and are listed in table 3.

We acknowledge that the values of acceleration selected for the liquefaction potential designations (table 3) are lower than what would be selected now. However, the exceedance probabilities and exposure-time period used to define zones of different liquefaction potential are somewhat arbitrary. Adjustments could be made in the exceedance probabilities

Table 2. Quantitative basis for qualitative liquefaction-potential descriptions.

Liquefaction Potential	Approximate 100-Year Exceedance Probability
High	> 50 %
Moderate	50 % to 10 %
Low	10 % to 5 %
Very Low	< 5 %

Table 3. Liquefaction potential related to critical acceleration.

Liquefaction Potential	Critical Acceleration
High	< 0.13 g
Moderate	0.13 g to 0.23 g
Low	0.23 g to 0.30 g
Very Low	> 0.30 g

or the exposure time to redefine the liquefaction-potential contours on the regional maps. Regardless of the quantitative definition of the liquefaction-potential zones, the existing regional maps serve to identify areas of relative liquefaction-hazard concern along the Wasatch Front.

Liquefaction hazards in Salt Lake County were mapped in similar fashion (Anderson and others, 1986a). Cone Penetrometer Tests (CPT) were used to supplement the SPT blow counts in evaluating the liquefaction susceptibility of sediments. The liquefaction-potential map for a part of Salt Lake County is shown on figure 2. Utah County (figure 3) was the third to be mapped (Anderson and others, 1986b), followed by Weber (figure 4), eastern Box Elder, and Cache Counties (Anderson and others, 1990a). The maps shown on the figures in this paper were prepared by the State of Utah (Anderson and others, 1994 a, b, c, d). The final area to be mapped consisted of selected urban areas in central Utah (Anderson and others, 1990b).

The liquefaction potential maps that were prepared for the Wasatch Front were recommended to be used in developing earthquake-hazard mitigation programs. We emphasized, however, that liquefaction is only one of many natural hazards that are present along the Wasatch Front, and that planning decisions should not be made on the basis of liquefaction alone.

The liquefaction potential maps indicate areas where liquefiable sediments with a given critical acceleration are likely to occur, based on subsurface data at selected locations

Figure 1. Liquefaction-potential map for a part of Davis County, Utah. (Utah Geological Survey Public Information Series 24). [Next page]

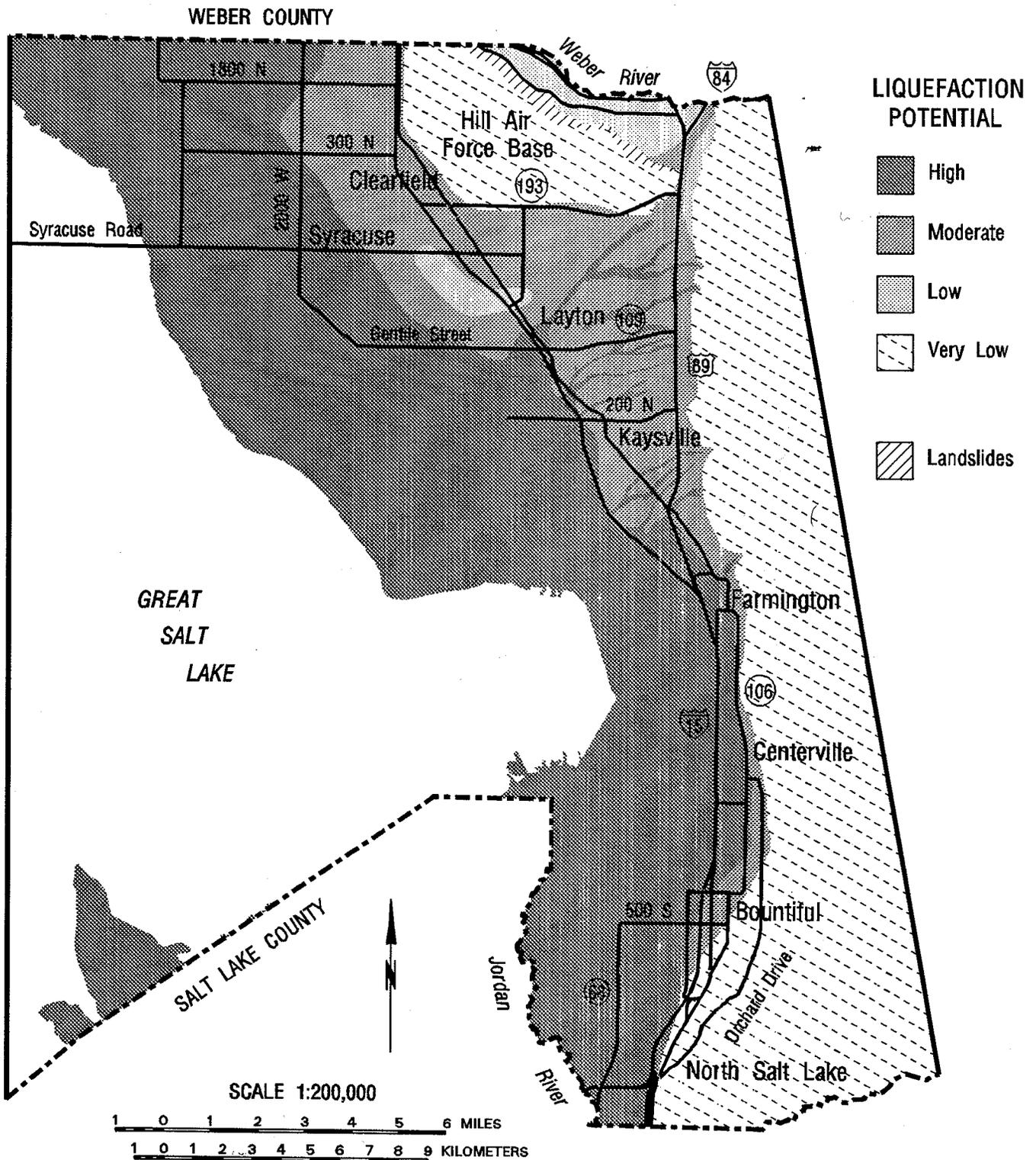
Figure 2. Liquefaction-potential map for a part of Salt Lake County, Utah. (Utah Geological Survey Public Information Series 25). [Page after next]

Figure 3. Liquefaction-potential map for a part of Utah County, Utah. (Utah Geological Survey Public Information Series 28). [Two pages after next]

Figure 4. Liquefaction-potential map for a part of Weber County, Utah. (Utah Geological Survey Public Information Series 27). [Three pages after next]

# LIQUEFACTION-POTENTIAL MAP FOR A PART OF DAVIS COUNTY, UTAH

UTAH GEOLOGICAL SURVEY  
Public Information Series 24  
July 1994



Digital compilation by Janine L. Jarva,  
Utah Geological Survey, facilitated by  
Automated Geographic Reference Center.

This map is for general reference only and was modified from Anderson, L.R., Keaton, J.R., Aubry, Kevin, and Ellis, S.J., 1994, Liquefaction potential map for Davis County, Utah: Utah Geological Survey Contract Report 94-2, 49 p., scale 1:48,000.

# LIQUEFACTION-POTENTIAL MAP FOR A PART OF SALT LAKE COUNTY, UTAH

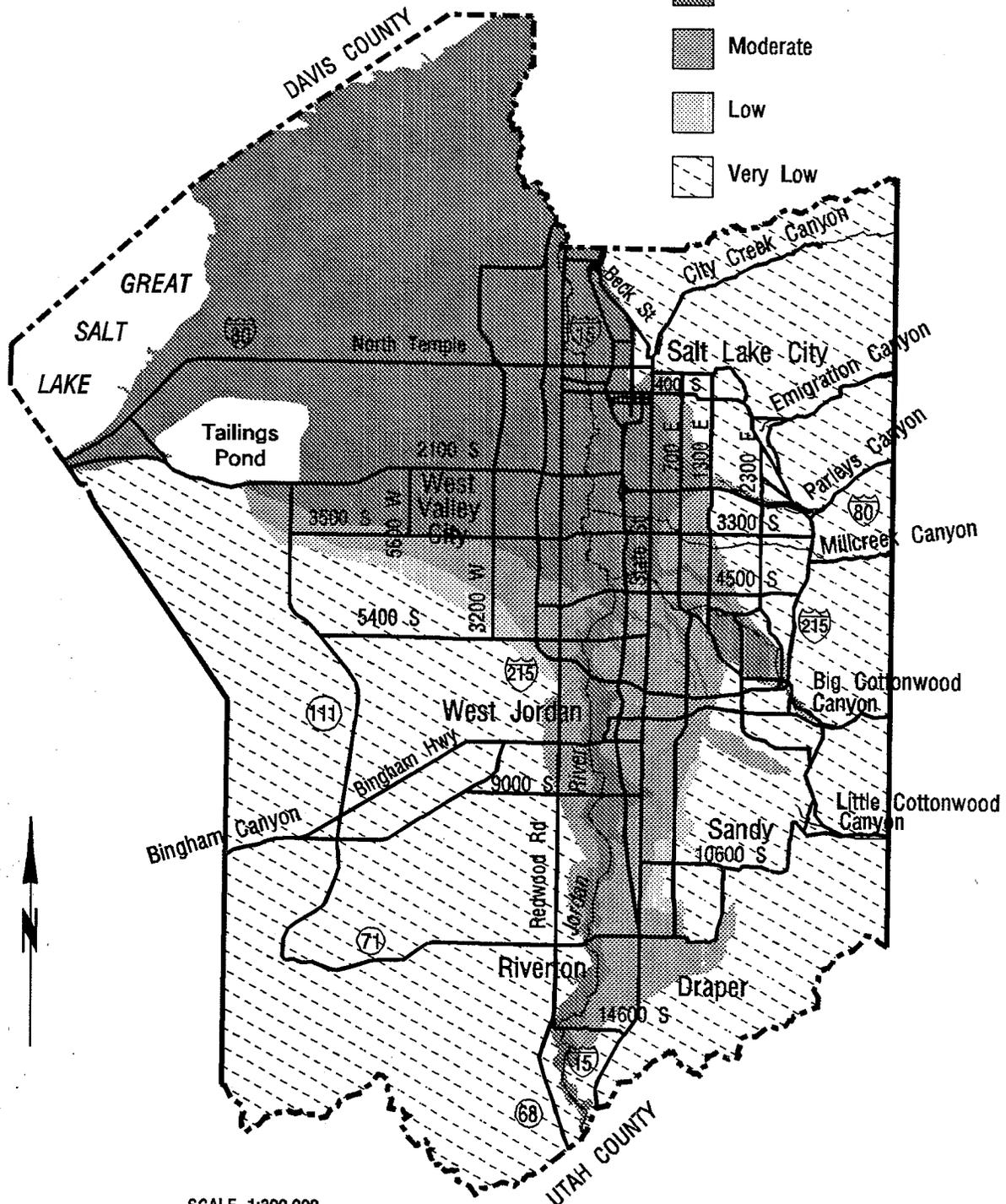
UTAH GEOLOGICAL SURVEY

Public Information Series 25

July 1994

## LIQUEFACTION POTENTIAL

-  High
-  Moderate
-  Low
-  Very Low



SCALE 1:300,000

5 0 5 10 MILES

5 0 5 10 15 KILOMETERS

Digital compilation by Janine L. Jarva,  
Utah Geological Survey

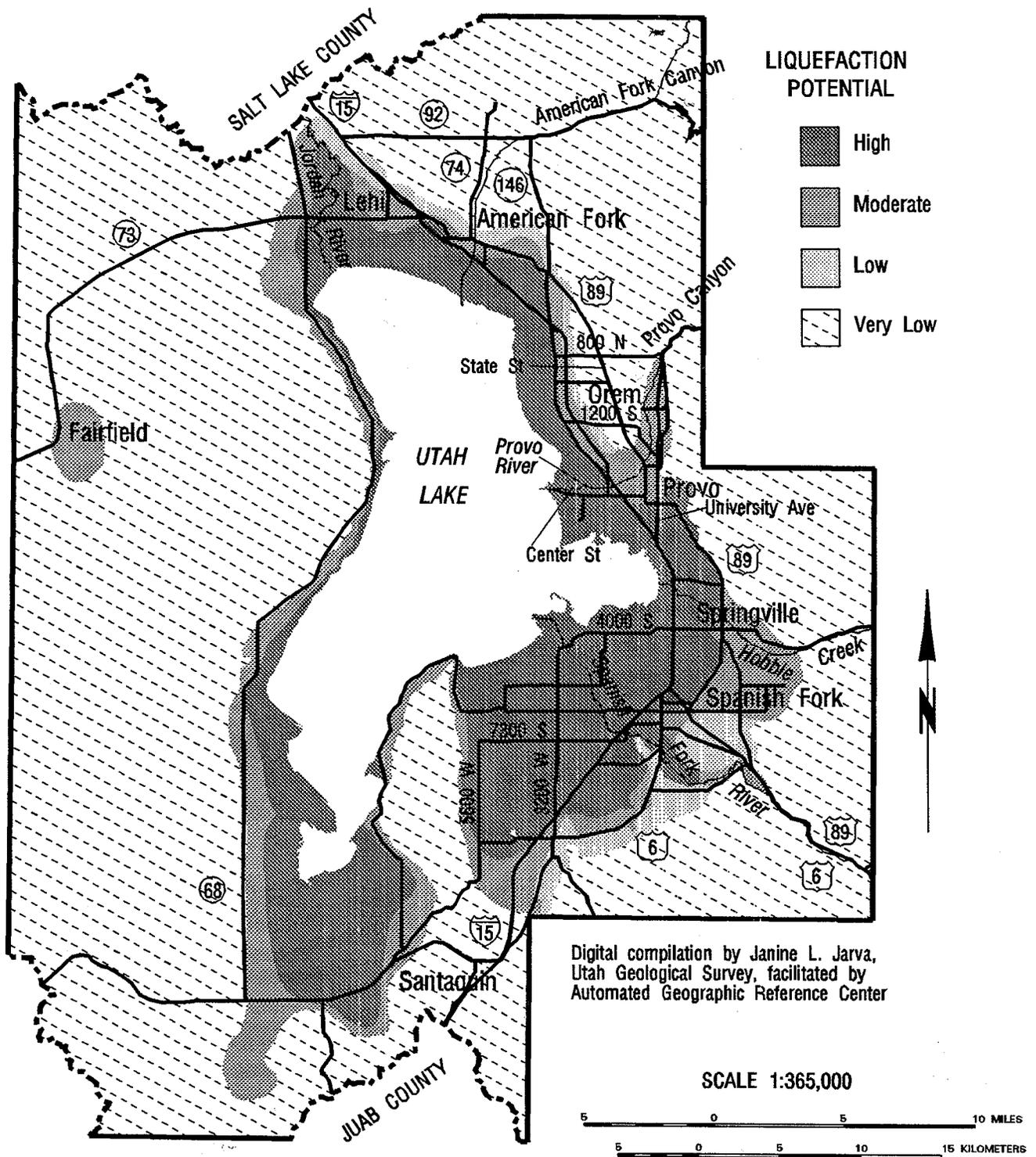
This map is for general reference only and was modified from Anderson, L.R., Keaton, J.R., Spitzley, J.E., and Allen, A.C., 1994, Liquefaction potential map for Salt Lake County, Utah: Utah Geological Survey Contract Report 94-4, 48 p., scale 1:48,000. Copies of this report are available at the Utah Geological Survey.

# LIQUEFACTION-POTENTIAL MAP FOR A PART OF UTAH COUNTY, UTAH

UTAH GEOLOGICAL SURVEY

Public Information Series 26

July 1994



This map is for general reference only and was modified from Anderson, L.R., Keaton, J.R., and Bischoff, J.E., 1994, Liquefaction potential map for Utah County, Utah: Utah Geological Survey Contract Report 94-3, 46 p., scale 1:48,000. Copies of this report are available at the Utah Geological Survey.

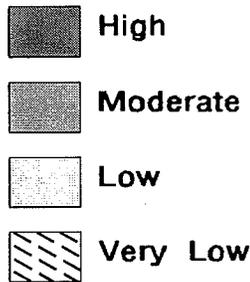
# LIQUEFACTION-POTENTIAL MAP FOR A PART OF WEBER COUNTY, UTAH

UTAH GEOLOGICAL SURVEY

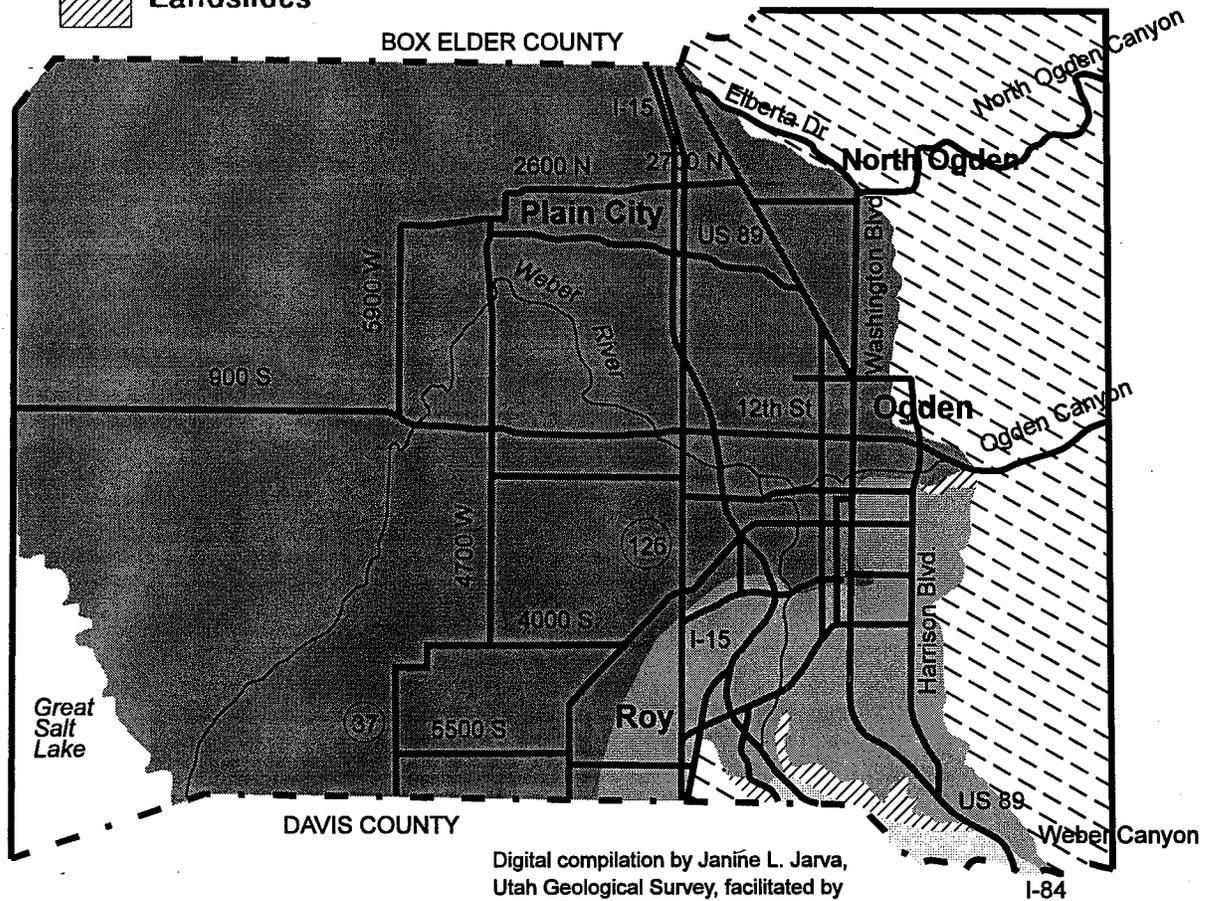
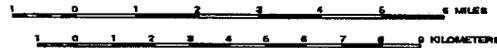
Public Information Series 27

August 1994

## LIQUEFACTION POTENTIAL



SCALE 1:200,000



Digital compilation by Janiñe L. Jarva,  
Utah Geological Survey, facilitated by  
Automated Geographic Reference Center

This map is for general reference only and was modified from Anderson, L.R., Keaton, J.R., and Bay, J.A., 1990, Liquefaction potential map for the northern Wasatch Front, Utah: Utah Geological Survey Contract Report 94-5, 150 p., scale 1:48,000. Copies of this report are available at the Utah Geological Survey.

and a fundamental understanding of the regional geology. It is possible that sites of low, or even very low, liquefaction potential may exist within the regions mapped as high liquefaction potential, even though the field evidence strongly supports a designation of high liquefaction potential.

Table 4 is the model, in matrix form, that we recommended to local governmental agencies indicating where and when site-specific liquefaction investigations should be made. The model is based on the liquefaction potential zone and the type of facility that is being considered. Note that, for high-consequence facilities (i.e., critical, lifelines, high occupancy, and industrial-severe consequence), the results of a site-specific investigation should be used as the basis for final decisions, rather than the regional maps.

Table 4. Matrix showing where and when site-specific investigations are recommended to be required by ordinance (after Anderson and others, 1987).

FACILITY	LIQUEFACTION POTENTIAL ZONE			
	HIGH	MODERATE	LOW	VERY LOW
Critical Hospital Fire Station Police Station	Yes	Yes	Yes	Maybe
Lifelines Communications Transportation Water, Gas, Power, Sewer	Yes	Yes	Yes	Maybe
High Occupancy - Public Schools City Hall, Courts Convention Center	Yes	Yes	Yes	Maybe
High Occupancy - Private Office Buildings Apartments, Hotels Shopping Malls	Yes	Yes	Yes	Maybe
Industrial - Severe Consequence Refineries Hazardous/Toxic Material Handling Sewage/Water Treatment Plants	Yes	Yes	Maybe	No
Industrial - Minor Consequence Trucking Shipping Light Manufacturing	No <sup>†</sup>	No <sup>†</sup>	No	No
Residential Subdivision	Maybe <sup>†</sup>	No <sup>†</sup>	No	No
Residential Single Lot	No <sup>†</sup>	No <sup>†</sup>	No	No

† Appropriate hazard disclosure required

## Advancements and Innovations

Five primary advancements or innovations were developed in the liquefaction-hazard mapping in Utah. The first was solving the cyclic stress ratio equation for the "critical" acceleration." As discussed above, this simple innovation produced liquefaction-hazard-results that could be contoured and compared to probabilistic estimates of earthquake acceleration on a regional basis.

The second advancement was direct use of integrated engineering geology and geotechnical engineering in mapping liquefaction potential. We integrated knowledge of the physical properties of the deposits with projections of age and distribution based on the environment of deposition. This provided the most reliable interpretation of the distribution of deposits susceptible to liquefaction processes.

The third advancement was recognition that the internally drained Lake Bonneville basin preserved high liquefaction susceptibility in sediments of Pleistocene age that, in coastal areas, would have moderate to low liquefaction susceptibility. Dewatering of the Pleistocene sediments in coastal areas resulted from lowered sea level (Youd and others, 1975). Desiccation of Lake Bonneville sediments in most of the urban area of the Wasatch Front was limited because of the elevation of the base of the internally drained basin.

The fourth advancement was recognition that lateral-spread ground displacement could be generated by liquefying layers that were too thin to be evaluated in terms of SPT-N values. This issue is discussed below under the heading "Geologic Evidence."

The fifth advancement was recognition of the significance of thin clay seams in liquefiable sand deposits. This issue also is discussed below under the heading "Geologic Evidence."

## VERIFICATION OF RESULTS

A strong earthquake has not occurred along the Wasatch Front to test the accuracy of the liquefaction-hazard maps. However, several communities have incorporated liquefaction into natural-hazards ordinances for land-use planning purposes. Salt Lake County is one of the jurisdictions to require site-specific evaluations of liquefaction in areas designated as having 'high' potential on the regional maps. The success of the Salt Lake County ordinance is discussed below.

Geologic evidence of prehistoric liquefaction-induced permanent ground deformation has been observed at a number of locations along the Wasatch Front, indicating that liquefaction should be expected to occur during future strong earthquakes. However, continuous, undeformed sediments more than 10,000 years old have been exposed in trenches at

locations where site-specific investigations have indicated a high potential for liquefaction. These issues are discussed in more detail below.

### Salt Lake County Ordinance

No systematic survey has been conducted of the results of site-specific liquefaction investigations performed to satisfy the requirements of the Salt Lake County Natural Hazards Ordinance. However, we understand from recent discussions with Mr. Brian Bryant, Salt Lake County Geologist, that approximately half of the investigations of sites within the area mapped as "high liquefaction potential" on the regional maps conclude that the sites actually do have high liquefaction potential. The results of the investigations on the other half of the sites conclude that the liquefaction potential is moderate, low, or very low. Given the method used to map liquefaction hazards in Salt Lake County, and the number and quality of subsurface investigations on which the map was based, an accuracy of 50 percent is reasonable.

Part of the explanation lies in the improved understanding of liquefaction processes developed in the 1980s. One of the important concepts relates the potential for ground displacement to occur given that liquefaction occurs in a buried sand deposit. Ishihara (1985) observed that the potential for liquefaction-induced ground displacement depends on the thickness of the liquefiable deposit and its depth. Essentially, a thick sand layer at shallow depth is more likely to result in ground displacement than an otherwise identical sand in a thin layer at greater depth. Some of the sites in areas mapped as high

liquefaction potential in Salt Lake County have had liquefaction hazards dismissed because the ground displacement potential is low even if liquefaction potential, *per se*, is high.

### Geologic Evidence

Geologic evidence of liquefaction-induced permanent ground deformation has been observed at a number of locations along the Wasatch Front. Two examples are discussed below. One example is from West Valley City on the west side of Interstate Highway 215 at approximately 4400 South. The other example is from Murray near the intersection of Vine Street and 5600 South Street. A third example, from Plain City, documents the continuous, undeformed character of deposits that the results of a geotechnical engineering investigation indicated should be highly susceptible to liquefaction.

### Lateral-Spread Landslide Caused By Liquefaction Of A Thin Sand Layer At Shallow Depth

A shallow exploratory trench at the site in West Valley City revealed clear evidence of lateral-spread displacement (figure 5). The stratigraphy exposed in the trench consisted of a plowed zone (Ap horizon), a C horizon, and deep-water sediments deposited in Lake Bonneville. The Lake Bonneville sediments were chiefly silty clay, but contained several distinctive marker laminae and beds of silt, fine sand, and fine to medium sand. Three markers are shown on figure 5; they consist of a double sand, a triple sand, and a sand bed that ranges from 4 to 10 cm (1.6 to 3.9 in).

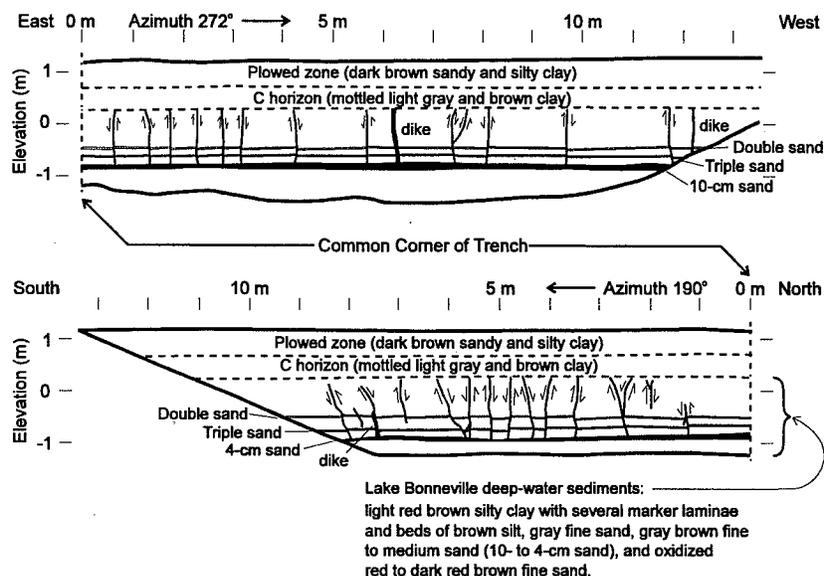


Figure 5. Log of trench in West Valley City showing lateral-spread displacement originating in a sand layer less than the thickness required for a Standard Penetration Test.

That the thin sand bed liquefied is clear based on two lines of evidence. First, dikes composed of the same sand as the thin sand bed extend upward from the thin sand bed, cross-cutting the triple-sand and the double-sand markers. The sand dike at Station 6.2 m West may have extended to the ground surface as a sand boil or sand volcano. Second, steeply dipping normal faults displacement Lake Bonneville sediments above the thin sand bed, but terminate in the thin sand bed. Furthermore, the amount of separation of marker laminae is greater at a height of 1 m (3 ft) above the thin sand bed than at a height of 10 cm (3.9 in). No evidence was observed to suggest that more than a single episode of liquefaction-induced ground displacement are recorded in the exposure.

The total amount of lateral-spread landsliding at this site is very small, and would not have caused damage to any but the most delicate buried facilities. At the time of observation of the trench exposure (April, 1982), the thin sand bed was above the ground-water table, and, therefore, not susceptible to repeated liquefaction. The brittle nature of the lateral-spread displacement in the deposits about the thin sand bed suggest that it had some strength greater than newly deposited lake-bottom sediment. The apparent termination of the lateral-spread normal "faults" at the base of the C horizon suggests that substantial soil-forming processes occurred after the thin sand bed liquefied. The West Valley City site is located at an approximate elevation of 1,311 m (4,300 ft). Lake Bonneville receded past this elevation approximately 12,000 years ago (Currey and Oviatt, 1985). The C horizon exposed in the trench probably began forming as soon as Lake Bonneville receded past the site. It seems logical to estimate the time of liquefaction to be early Holocene, and that the major soil-forming period may have been coincided with the hypsithermal interval (Deevey and Flint, 1957).

An important point demonstrated by the trench exposure in West Valley City is that ground displacement can be induced by liquefaction of a sand layer too thin to be characterized by conventional SPT N-value blow counts (blows per 1 ft [0.3 m] of sampler penetration). Assuming that the thin sand bed had an equivalent corrected SPT N-value  $\leq 15$ , an average thickness of 0.05 m (0.16 ft), 5 percent passing the No. 200 sieve, and a mean grain size of 0.4 mm (0.0016 in), the Bartlett and Youd (1992) procedure would predict lateral-spread displacement of 0.1 m (0.3 ft) resulting from a moment magnitude 7 earthquake 20 km (12.4 mi) away for a ground-surface slope of 0.5 percent.

#### **Evidence of Multiple Earthquakes and Ground Oscillation**

At least two pulses of earthquake energy were recorded in Lake Bonneville deep-water sediments exposed in a construction excavation in Murray (figure 6). The stratigraphy exposed in the excavation consists of a minor

veneer of fill overlying a well-developed argillic (Bt) horizon and C<sub>1</sub> horizon formed in deep-water sediments deposited in Lake Bonneville. The argillic horizon is grayish brown (10YR5/2d) to dark grayish brown (10YR4/2m) slightly sticky, slightly plastic silty clay with medium, angular, blocky structure, and thin discontinuous clay films on ped faces.

One pulse of seismic energy appears to have occurred at the time just prior to deposition of Marker Sand Layer S3 (figure 6). Persistent contorted silty sediment was present across the exposure at this stratigraphic position. The contortions could have been created by strong seismic shaking while the silty material was actual lake bottom. Minor contortions were observed in silty sediment beneath Marker Sand Layer S2 in the south 2 m (6.6 ft) of the exposure. These contortions could have been created by seismic shaking at the time this silty sediment was actual lake bottom, but the limited distribution of these contortions implies that such shaking was weaker than that which caused the contortions in the silty sediment beneath Marker Sand Layer S3.

The most prominent feature of the excavation log shown on figure 6 is the overturned fold at approximately Station 30 to 35. Clearly, here the Lake Bonneville sediments have been deformed in compression, apparently riding on a liquefied layer below the bottom of the excavation. Reverse separation on some faults (e.g., Station 27.5 and Station 55 on figure 6) also indicates horizontal compressive stresses. Differences in thickness of the Marker Sand Layers across the fault at Station 27.7 also indicates lateral separation; however, the thickness of the markers across most faults is relatively uniform, suggesting little lateral separation. It appears that the major deformation preserved in the sediments exposed at this site resulted from collision of relatively coherent blocks of non-liquefied lake deposit that became detached on a liquefied sand at an unknown depth below the excavation and shifted independently as ground oscillation.

The general level nature of the site and the apparent absence of deformation of the Bt or C horizons suggest that the second pulse of seismic energy occurred prior to the final regression of Lake Bonneville. This would allow the regression of the lake to smooth any topographic expression of permanent ground deformation at the site prior to soil formation. The apparent coherent nature of some of the oscillating blocks suggests that the site may have been subaerial at the time of the strong shaking. The elevation of the Murray site is approximately 1,320 m (4,330 ft). Subaerial exposure of this site probably occurred approximately 12,000 years ago (Currey and Oviatt, 1985).

An important point demonstrated by the exposure in the construction excavation in Murray is that major liquefaction-induced ground deformation has occurred in the Wasatch Front region. The amplitude of the major fold is approximately 2 m (6.6 ft), and the maximum vertical

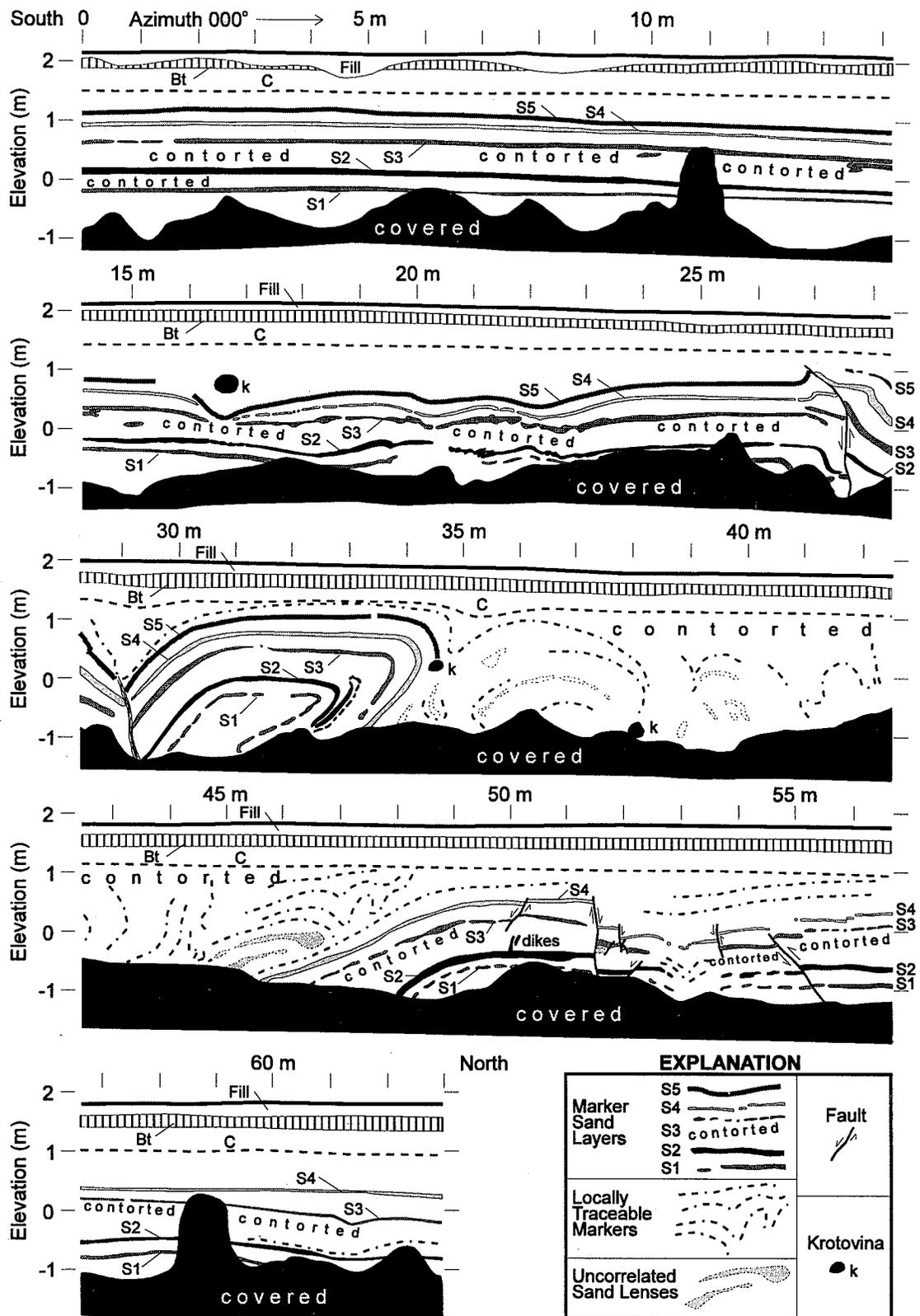


Figure 6. Log of construction excavation in Murray showing evidence of multiple pulses of earthquake energy, including major compressive ground-oscillation deformation in Lake Bonneville deep-water deposits.

isplacement is approximately 0.5 m (1.6 ft) on the reverse fault at Station 27.5 and the normal fault at Station 51.5. Deformations of these magnitudes probably would cause substantial damage to many facilities. At the time the exposure was observed (May, 1985), the depth to ground water was below the bottom of the excavation, and sediments at this site in Murray probably are not susceptible to future liquefaction-induced ground deformation of the magnitude observed.

### Influence of Thin Clay Seams

In addition to clear evidence of prehistoric liquefaction-induced ground deformation, some sites show clear evidence of stability, even though conventional geotechnical investigations indicate the presence of loose, saturated sandy sediments that are expected to liquefy at low accelerations. One such site is located in Plain City northwest of Ogden where borings revealed loose sand and silty sand deposits with thin clay seams below the water table. The 3-m- (10-ft) high Fremont Shoreline escarpment is located approximately 152 m (500 ft) west of the site.

The historical earthquake record for northern Utah indicates relatively few moderate earthquakes. Within the past 6,000 years, however, three or four surface-faulting earthquakes ( $M \geq 6.5$ ) occurred on the Weber segment of the Wasatch fault zone about 8 km (5 mi) east of the site (Machette and others, 1991). The site is below the 10,300-year-old Gilbert shoreline of Lake Bonneville, and above the 2,600-year-old Fremont shoreline of the ancestral Great Salt Lake (Murchison, 1989). The lake declined past the 1,292-m (4,240-ft) elevation of the site about 8,000 years ago, and the site has been above the lake level since that time. Thus, the near-surface sediments at the site are between 8,000 and 10,000 years old. Two trenches exposing nearly 283.5 m

(930 ft) of shallow stratigraphy across the site revealed continuous, undeformed, thinly-bedded deposits of the Gilbert Alloformation above undeformed deposits of the Bonneville Alloformation (figure 7).

The hydrograph of the Great Salt Lake since 6,000 years ago (Murchison, 1989) indicates all of the earthquakes which caused surface-fault rupture on the Weber segment near the site occurred when the level of the Great Salt Lake was approximately the same as today or higher (figure 8). However, two of the three or four surface-faulting earthquakes on the Weber segment of the Wasatch fault zone occurred prior to the erosion of the Fremont shoreline (figure 8). But some evidence of liquefaction-induced permanent ground deformation in the Bonneville Alloformation or the Gilbert Alloformation would be expected if the sediments were highly susceptible to liquefaction processes. Therefore, it is not valid to argue that the prehistoric large earthquakes occurred when the sediments were dewatered, and the undeformed sediments at the site do not indicate low susceptibility to liquefaction-induced ground deformation.

Keaton and Anderson (1994) estimated approximately 5.6 m (15 ft) of lateral-spread displacement for the 0.35 g Seismic Zone 3 design acceleration using the Bartlett and Youd (1992) procedure for a 3-m- (10-ft) high free-face located 152 m (500 ft) away. The explanation for the results of the geotechnical engineering investigation predicting high liquefaction potential, but the engineering geology demonstrating persistent stability of the site appears to lie in the thin clay seams included within the liquefiable sand deposit. The clay seams contribute to low SPT N-value blow counts, but are not liquefiable and apparently strengthen the soil deposit.

An important point demonstrated by the liquefaction research at the Plain City site is that geologic evidence of persistent stability can overrule the results of conventional,

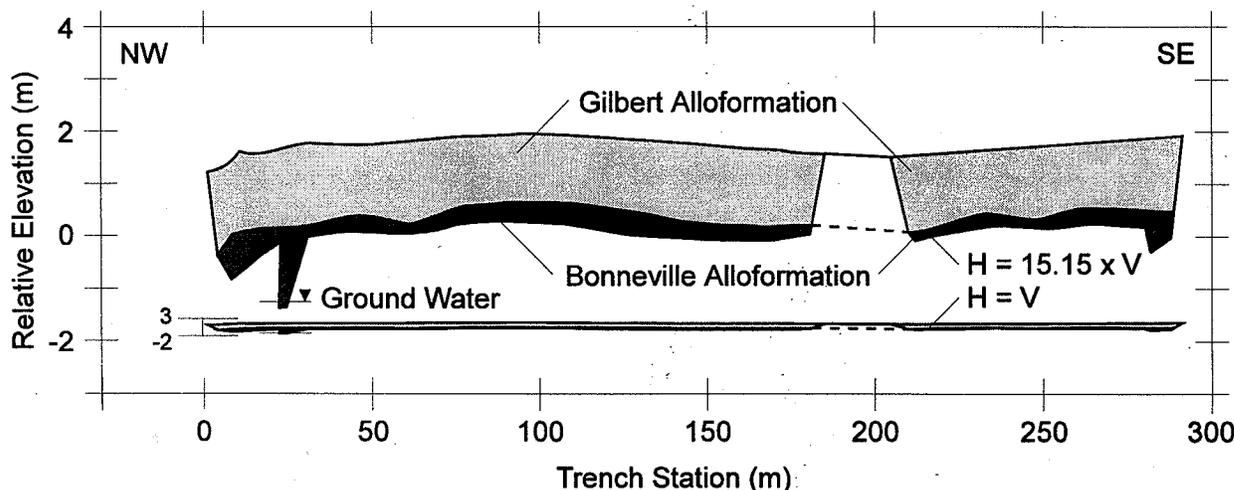


Figure 7. Log of exploration trench excavated at the Plain City site showing continuous, undeformed deposits of the Bonneville Alloformation and the Gilbert Alloformation.

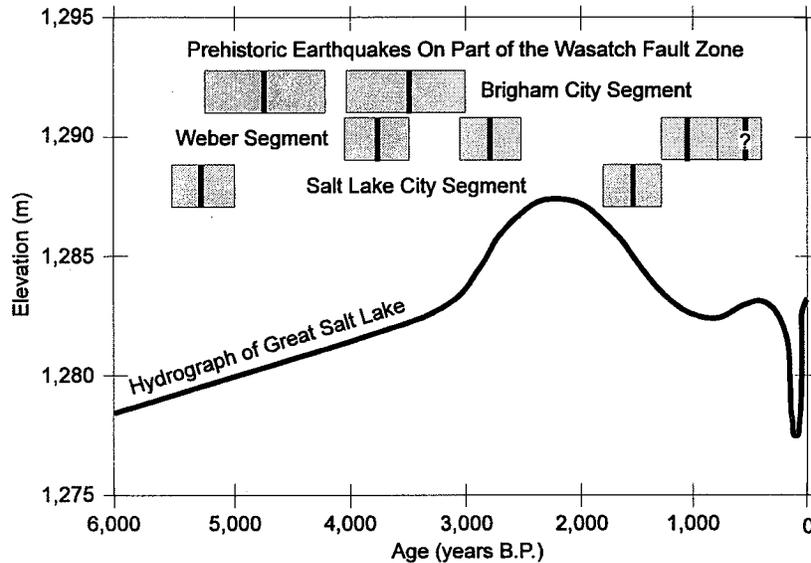


Figure 8. Hydrograph of the Great Salt Lake for the past 6,000 years and timing of surface-faulting earthquakes on the Weber, Brigham City, and Salt Lake City segments of the Wasatch fault zone (modified from Murchison [1989] and Machette and others [1991]).

site-specific geotechnical engineering investigations. The potential financial impact is tremendous if extensive soil-improvement measures are implemented at sites where they are not needed.

## FOUNDATION PERFORMANCE AND SITE IMPROVEMENT

Mitigating potential liquefaction hazards is sufficiently expensive that typically it is done only at sites of important, major facilities. Extensive liquefaction-induced damage has occurred in numerous earthquakes in the past few years. Observations in Kobe reported by Dr. T.L. Youd, Professor of Geotechnical Engineering at Brigham Young University in Provo, at a professional society presentation indicated that much of the potential damage to modern buildings up to approximately 4 stories in height effectively was mitigated by grade beams that were used to tie shallow foundations together.

Anticipating potential damage in the design and construction of new buildings is much more cost-effective than remediating potential damage in existing buildings. Little experience has been developed along the Wasatch Front in mitigating potential liquefaction-induced damage. The following paragraphs were adapted from text prepared by Mr. Maurice S. Power, Geomatrix Consultants in San Francisco, California, and contain descriptions of potentially useful mitigation schemes.

Conceptual schemes to mitigate the hazard of liquefaction-induced bearing-capacity reduction or settlements due to liquefaction-induced soil densification beneath a building fall into three categories: modify the structure; modify the foundation; or modify the soil conditions. Conceptual schemes to resist liquefaction-induced lateral spreading include stabilizing the soils beneath the building, and, if needed, stabilizing the soils sufficiently beyond the building so that liquefaction and spreading of the surrounding areas will not cause significant spreading beneath the building. Alternatively a buttress of stabilized ground can be constructed beyond the building to prevent significant lateral spreading behind the buttress. The buttress approach does not prevent settlement from occurring beneath the building, but if bearing-capacity failures are not expected (due to lightly loaded footings a sufficient distance above the liquefied zone) and densification settlements are tolerable for the desired performance objective of the structure, then the buttressing approach, by eliminating potentially large spreading-type movements beneath the structure, may be effective.

Ground-improvement techniques that can be considered to be used beneath an existing structure include soil grouting, installation of drains, and installation of permanent dewatering systems. In general, ground-modification techniques that involve vibratory densification of soils to reduce their liquefaction potential (e.g., vibrofloatation, vibroreplacement) cannot be implemented beneath existing buildings because of the potentially damaging settlements

induced during the process.

Compaction grouting, permeation grouting, and jet grouting may have application for mitigation of liquefaction hazard beneath existing buildings. Compaction grouting involves pumping a soil-cement slurry into the ground to form bulbs of grouted material. The formation of these bulbs compresses and densifies the surrounding soil and increases the lateral earth stresses, thus reducing its liquefaction potential. Effects may be somewhat non-uniform, depending on the spatial pattern of grout-bulb formation. The amount of densification that can be achieved may be limited because static compression is less effective than vibration in densifying sands. Compaction grouting must be done carefully to avoid creating unacceptable heaving or lateral displacements during the grouting process. Permeation grouting involves injecting chemical grout into liquefiable sands to essentially replace the pore water and create a non-liquefiable solid material in the grouted zone. The more fine-grained and silty the sands, the less effective is permeation grouting. If soils are suitable for permeation grouting, this technique potentially can eliminate their liquefaction potential. Jet grouting is a technique where high velocity jets cut and mix a stabilizing material, such as cement, into the soil. In addition to the use of grouting techniques to stabilize entire volumes of soil beneath a building, these techniques also can be used locally beneath individual footings to form stabilized columns of soil to transfer vertical foundation loads to deeper non-liquefiable strata.

Drain installation (e.g., stone or gravel columns) involves creating closely-spaced vertical columns of highly permeable material in the liquefiable soil strata. Their purpose is to dissipate soil-pore-water pressures as rapidly as they build up during earthquake shaking, thus preventing liquefaction from occurring.

Permanent dewatering systems lower ground-water levels below liquefiable soil strata, thus preventing liquefaction. This alternative scheme involves an ongoing cost for operating the dewatering system. Because lowering the water table increases the effective stresses in the soil, the potential for causing consolidation in any underlying compressible soil deposits should be evaluated when considering permanent dewatering systems. The dewatering process may also cause settlements in the liquefiable deposits, although such settlements typically would tend to be small in sands.

Ground-stabilization methodologies are discussed in a number of publications, including Mitchell (1981), Ledbetter (1985), National Research Council (1985), Mitchell and others (1990), Mitchell (1991), and Borden and others (1992). Additional information on these techniques is also available from contractors who specialize in ground modification.

## OPPORTUNITIES AND LIMITATIONS

The current regional liquefaction-potential maps of urban areas in Utah discriminate zones where liquefaction is relatively more likely to occur during strong earthquake shaking. The accuracy of the current maps probably is appropriate for their regional nature, and the primary benefit to the communities is identification of areas of relative concern for liquefaction-induced ground displacement.

It is useful to remember that liquefaction *potential* is the combination of liquefaction *susceptibility* and liquefaction *opportunity*. Maps depicting earthquake ground motions (liquefaction opportunity) are based on data more generalized than the data used to produce the liquefaction-potential maps.

Site-specific geotechnical investigations that include engineering geology are fundamentally important for safe and economical development. It would be a misuse of the regional liquefaction-potential maps to allow them to replace site-specific investigations. Site-specific liquefaction investigations required by local ordinance can provide the basis for designing buildings and/or site improvements to mitigate potential damage.

The primary limitation of the liquefaction-hazard maps prepared for the urban areas in Utah is that they depict the threshold critical accelerations at which pore-water pressures equal overburden pressures, satisfying the definition of "liquefaction." Maps depicting the threshold accelerations at which liquefaction-induced ground displacements are expected would be an improvement. Such maps would incorporate not only the susceptibility of sandy sediments to liquefaction processes, but also would include the stratigraphy and geometry of the liquefiable and non-liquefiable layers. Site-specific investigations still would be needed to assess the amount and direction of lateral-spread landsliding.

A systematic survey of the results of site-specific liquefaction evaluations required by local ordinances that were based on the regional liquefaction-hazard maps needs to be done. The results of the survey need to be compiled and integrated into the database used to prepare the first-generation maps. Second-generation maps would depict more accurately liquefaction hazards along the Wasatch Front.

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