LIQUEFACTION-HAZARD MAPPING

- Susceptibility
- Probability
- Potential
- Expected permanent ground displacement
    - Lateral spreading
    - Settlement

Susceptibility

- Youd and Perkins (1978)
  - Based on age, depositional environment, and material type of each map unit
  - Defined for Quaternary deposits in California
  - Does not consider ground-water depth
  - Not applicable to Utah's closed basins and Pleistocene lacustrine deposits (Anderson and others, 1986)

Type of Deposit	General Distribution of Cohesionless Sediments in Deposits	Likelihood that Cohesionless Sediments when Saturated would be Susceptible to Liquefaction (by Age of Deposit)			
		< 500 yr Modern	Holocene < 11 ka	Pleistocene 11 ka - 2 Ma	Pre-Pleistocene > 2 Ma
(a) Continental Deposits					
River channel	Locally variable	Very High	High	Low	Very Low
Flood plain	Locally variable	High	Moderate	Low	Very Low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very Low
Marine terraces and plains	Widespread	---	Low	Very Low	Very Low
Delta and fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine and playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very Low	Very Low
Tuff	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very Low	Very Low
Sebka	Locally variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Esturine	Locally variable	High	Moderate	Low	Very Low
Beach					
High Wave Energy	Widespread	Moderate	Low	Very Low	Very Low
Low Wave Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally variable	High	Moderate	Low	Very Low
Fore shore	Locally variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	---	---	---
Compacted Fill	Variable	Low	---	---	---

- McCalpin and Solomon (2001)
  - Numerical values of factors controlling development of liquefaction
  - Values assigned to potentially liquefiable layers in water wells
  - Relative numerical values not assigned on basis of association with historical liquefaction
  - Layers may be beyond resolution of water-well logs

➢ Solomon and others (2002)

- Based on site-response units (depositional environment and material type) and ground-water depth
- Good correlation with Anderson and others (1986)
- Must be modified based on local geologic units and age

Relative liquefaction susceptibility as a function of ground-water depth and site-response unit (Solomon and others, 2002, table 1).

		Ground-Water Depth (ft)		
		>30	<30	<10
Site-Response Unit	Lacustrine and alluvial silt and clay, with interbedded fine-grained sand	Low	Moderate	High
	Lacustrine sand, silt, and clay	Very Low	Moderate	Moderate
	Lacustrine and alluvial gravel	Very Low	Low	Moderate
	Pre-Bonneville alluvial-fan deposits	Very Low	Very Low	Low
	Glacial deposits	Very Low	Very Low	Very Low
	Rock	None	None	None

Suggested liquefaction susceptibility of Quaternary units shown on Wasatch fault zone strip maps (scale 1:50,000)

Type of Deposit	Map Unit	Age of Deposit				Ground-Water Depth (ft)		
		Upper Holocene	Middle and Lower Holocene	Upper Pleistocene	Middle Pleistocene	>30	<30	<10
Stream Alluvium	al1	X				L	M	H
	al2		X			L	M	M
	al3			X		VL	L	L
	aly	X	X			L	M	H
	alp			X		VL	L	L
	alb			X		VL	L	L
	alo				X	VL	L	L
	als		X			L	M	M
Fan Alluvium	af1	X				VL	L	M
	af2		X			VL	L	L
	af3			X		VL	VL	L
	af4				X	VL	VL	L
	af5				X	VL	VL	L
	afy	X	X			VL	L	M
	afp			X		VL	VL	L
	afb			X		VL	VL	L
	afo				X	VL	VL	L
Colluvial Deposits	cd1	X				VL	L	M
	cd2		X			VL	L	L
	cdy	X	X			VL	L	M
	cfs	X	X	X		VL	L	M
	chs	X	X	X		VL	L	M
	crt	X	X	X		VL	L	L
	cls	X	X	X	X	VL	L	M
	clsp	X	X	X	X	VL	L	M
	clsy	X	X	X		VL	L	M
	clso				X	VL	L	L
	ca	X	X	X	X	L	M	H
Eolian Deposits	es	X	X			L	M	H
Artificial Deposits	f (compacted)	X				L	M	H
	(uncompacted)	X				VL	L	L
Glacial Deposits	gbco			X		VL	VL	VL
	gbct			X		VL	VL	VL
	gdco				X	VL	VL	VL
	gdct				X	VL	VL	VL
Lacustrine Deposits	ly	X	X			L	M	H
	laly	X	X			L	M	H
	lpd			X		VL	M	M
	lpg			X		VL	L	M
	lps			X		VL	M	M
	lpm			X		L	M	H
	lbd			X		VL	M	M
	lbg			X		VL	L	M
	lbs			X		VL	M	M
	lbm			X		L	M	H
	lbpg			X		VL	L	M
	lbps			X		VL	M	M
	lbpm			X		L	M	H
Spring Deposits	st	X				VL	VL	VL

Probability

- Accounts for variations in soil properties within susceptibility units
- Estimates proportion of the area of each susceptibility category that may actually be susceptible
- According to HAZUS, probability is a function of:
  - Susceptibility
  - Amplitude of ground shaking (PGA)
  - Duration of ground shaking (**M**)
- Calculate probability using the procedure on the next page
  - Use values for PGA with a 10% probability of exceedance in 50 years
  - Estimate the magnitude of the controlling earthquake using the procedures outlined for evaluating earthquake-induced landsliding

➢ Procedure:

Solve HAZUS equation 4-18, using values determined in steps 1, 2, 3, and 4 below:

$P[Liquefaction_{SC}] = (P[Liquefaction_{SC}|PGA = a]/K_M \cdot K_w)(P_{ml})$

Step 1: Calculate $P[Liquefaction_{SC}|PGA = a]$ which is the conditional liquefaction probability for a given susceptibility category at a specified level of peak ground acceleration.

The value of this factor ranges from 0 to 1. Values are derived from HAZUS table 4.13, as modified for our categories. For points within each category, use the appropriate equations below, where "a" = PGA:

Susceptibility Category	$P[Liquefaction_{SC}\|PGA = a]$
High	9.09a-0.82 (this is the HAZUS equation for very high; we won't use the HAZUS equation for high)
Moderate	6.67a-1.00
Low	5.57a-1.18
Very Low	4.16a-1.08
None	0.00

When you solve these equations you will get some values less than 0 and some greater than 1. Change all values less than 0 to 0 and all values greater than 1 to 1.

Step 2: Calculate K_M, which is the correction factor for earthquakes with moment magnitudes (**M**) other than 7.5 (HAZUS equation 4-19).

$K_M = 0.0027\mathbf{M}^3 - 0.0267\mathbf{M}^2 - 0.2055\mathbf{M} + 2.9188 = 1.0981$ for $\mathbf{M} = 7$

Step 3: Calculate K_w which is the correction factor for groundwater depths other than 5 feet (HAZUS equation 4-20).

$K_w = 0.022d_w + 0.93$ where d_w = ground-water depth in feet

Step 4: Obtain values from HAZUS table 4.12 for P_{ml} which is the proportion of each map unit susceptible for liquefaction.

Susceptibility Category	Proportion of Map Unit (P_{ml})
High	0.23 (the average of HAZUS values for very high and high)
Moderate	0.10
Low	0.05
Very Low	0.02
None	0.00

Potential

- Probability of exceedance for critical accelerations
    - Critical accelerations are a function of susceptibility

Comparison of critical accelerations required to induce liquefaction (Anderson and others, 1986) and threshold ground accelerations corresponding to zero probability of liquefaction (Solomon and others, 2002, table 5; modified from National Institute of Building Sciences, 1999, table 4.14).

Relative Liquefaction Susceptibility	Critical Acceleration (Anderson and others, 1986)	Threshold Ground Acceleration (Solomon and others, 2002)	Source of Threshold Ground Acceleration
High	< 0.13 g	0.12 g	HAZUS "High"
Moderate	0.13 g to 0.23 g	0.15 g	HAZUS "Moderate"
Low	0.23 g to 0.33 g	0.21 g	HAZUS "Low"
Very Low	> 0.33 g	0.26 g	HAZUS "Very Low"
None	N/A	N/A	N/A

    - Return periods reflect opportunity

- Use Frankel and others (1996) to determine PGA in rock for different return periods (accessible on USGS Web site)
    - Easy way—determine PGA in corners of study area and interpolate
- Map site response (site classes) to determine amplification factors (site coefficients)
- Multiply PGA in rock by amplification factors to determine appropriate PGA for each site class

- Relate PGA of different return periods (corrected with amplification factors) to critical accelerations (a_c) of susceptibility categories to determine relative hazard potential
  - Because PGA changes with each grid point, changes in hazard-potential boundaries vary with both PGA and a_c—hazard-potential boundaries do not necessarily coincide with susceptibility-class boundaries
    - High—$PGA_{475} > a_c$
    - Moderate—$PGA_{975} > a_c \geq PGA_{475}$
    - Low—$PGA_{2475} \geq a_c \geq PGA_{975}$
    - Very Low—$PGA_{2475} < a_c$
  - In Wasatch Front liquefaction studies, because PGA remains constant throughout each study area, changes in hazard-potential boundaries are based on the probabilistic occurrence of a_c—each susceptibility unit has only one critical acceleration, therefore hazard-potential boundaries coincide with susceptibility-class boundaries

Expected Permanent Ground Displacement

- Lateral Spreading
  - Liquefaction severity index (Youd and Perkins, 1987) and ground-motion attenuation relationship (Sadigh and others, 1986)
    - Advantages
      - Relies primarily on earthquake factors
        - Distance from causative earthquake
        - Magnitude
      - Does not explicitly rely on soil properties
        - Soil properties accounted for in site-response units used to calculate PGA
    - Disadvantage
      - Poor agreement between measured and calculated displacements (Bardet and others, 2002), but this assessment does not consider LSI used with ground-motion attenuation relationships

- Multiple linear regression equations (six-parameter model) (Youd and others, in press)
  - Six parameters needed to solve equations
    - Magnitude
    - Distance
    - Free-face ratio or slope
    - Cumulative thickness of saturated granular layers in upper 20 meters
    - Average fines content of saturated granular layers
    - Mean grain size of saturated granular layers
  - Advantage
    - The most accurate model (82.6% correlation [Bardet and others, 2002]) when data for all 6 variables are measured
  - Disadvantage
    - Average fines content and mean grain size of saturated granular layers is rarely known in large areas

- Four-parameter MLR model (Bardet and others, 2002)
  - Four parameters needed to solve equations
    - Magnitude
    - Distance
    - Free-face ratio or slope
    - Cumulative thickness of saturated granular layers in upper 20 meters
  - Advantage
    - Slightly more accurate than six-parameter model of Bartlett and Youd (1992) (predecessor of Youd and others, in press) when average fines content and mean grain size are unknown and fixed to average estimated values
  - Disadvantage
    - Less accurate than six-parameter model when values for all six parameters are known

$$\log(D+0.01) = b_0+b_{off}+b_1M+b_2\log(R)+b_3R+b_4\log(W)+b_5\log(S)+b_6\log(T_{15})$$

where:

The values for coefficients (b) are given in table 4 below, using the FFGS4 model (either data set); for free-face conditions, $b_5 = 0$; for ground-slope conditions, b_4 and $b_{off} = 0$.

D = estimated lateral ground displacement, in meters.

M = earthquake moment magnitude.

R = horizontal distance from the seismic energy source, in kilometers.

W = free-face ratio, defined as the height (H) of the free face divided by the distance (L) from the base of the free face to the point in question, in percent.

S = ground slope, in percent.

T_{15} = cumulative thickness of saturated granular layers in the upper 15 meters of soil (excluding soil with >15% clay content) with corrected blow counts, $(N_1)_{60}$, less than 15, in meters.

where:

T_{15} = (Potential T_{15})((15-Gwdepth)/15)

Potential T_{15} is determined for each unconsolidated map unit:

Step 1: Identify all granular layers in geotechnical boreholes (all layers except those with USCS classes of PT, OH, OL, CH, CL, and GC) less than 15 m deep with SPT values less than 15.

Step 2: Calculate the average thickness of these layers for each unconsolidated map unit with geotechnical data.

Step 3: For units with insufficient data, estimate the average thickness by comparison with units of similar texture and susceptibility having subsurface data.

Table 4. Values of MLR coefficients and adjusted R^2 for the Bartlett and Youd (1992) and FFGS4 models

Coefficients	Bartlett and Youd (1992)		FFGS4	
	Original	F_{15}=13% and $D50_{15}$=0.292 mm	Data set A	Data set B
b_0	−15.787	−7.274	−6.815	−6.747
b_{off}	−0.579	−0.579	−0.465	−0.162
b_1	1.178	1.178	1.017	1.001
b_2	−0.927	−0.927	−0.278	−0.289
b_3	−0.013	−0.013	−0.026	−0.021
b_4	0.657	0.657	0.497	0.090
b_5	0.429	0.429	0.454	0.203
b_6	0.348	0.348	0.558	0.289
b_7	4.527	-	-	-
b_8	−0.922	-	-	-
R^2 adjusted	82.60%	61.00%	64.25%	64.27%
Number of data	467	467	467	213

Table 5. Range of values for MLR variables in data sets A and B, and their free-face and ground-slope subsets

Variables	Data Set A			Data Set B		
	Complete FFGS-A	Free-Field FF-A	Ground-Slope GS-A	Complete FFGS-B	Free-Field FF-B	Ground-Slope GS-B
D (m)	0–10.15	1–10.15	0–5.35	0–1.99	0–1.98	0–1.99
M	6.4–9.2	6.4–9.2	6.4–9.2	6.4–9.2	6.4–9.2	6.4–9.2
R (km)	0.2–100	0.5–100	0.2–100	0.2–100	0.5–100	0.2–100
W	1.64–55.68	1.64–55.68	-	1.64–48.98	1.64–48.98	-
S (%)	0.05–5.90	-	0.05–5.90	0.05–2.5	-	0.05–2.5
T_{15} (m)	0.2–19.7	0.2–16.7	0.7–19.7	0.2–19.7	0.2–13.6	0.7–19.7

- Settlement
  - Amount of settlement proportional to susceptibility
    - Strong correlation between volumetric strain (settlement) and soil relative density (a measure of susceptibility) (Tokimatsu and Seed, 1987; Ishihara, 1991)
    - Deposits of higher susceptibility tend to have greater thicknesses of potentially liquefiable soils
  - Very little dependence of settlement on ground motion level given the occurrence of liquefaction
    - Settlement will occur once critical acceleration is exceeded
    - Amount of settlement does not increase with increasing ground motion above critical acceleration
  - Settlement displacement is the product of the probability of liquefaction for a given ground motion level (calculated in step 1 of the procedure for probability) and the characteristic settlement amplitude appropriate to the susceptibility category (see table below)

Ground-settlement amplitudes for relative liquefaction-susceptibility categories (Solomon and others, 2002, table 6; modified from National Institute of Building Sciences, 1999, table 4.15).

Relative Liquefaction Susceptibility	Settlement (inches)	Source of Settlement Amplitude
High	9	Average of HAZUS "High" and "Very High"
Moderate	2	HAZUS "Moderate"
Low	1	HAZUS "Low"
Very Low	0	HAZUS "Very Low"
None	0	HAZUS "None"

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