Liquefaction Evaluation

1 Introduction

Soil liquefaction may substantially increase the cost of bridge and highway projects. If liquefaction is not reported in a timely manner, there may be an incorrect allocation of funds and resources. For instance, if the soil is erroneously assumed to liquefy, the project engineer may develop an expensive preliminary design with large diameter piles, deep foundations, and unneeded soil mitigation. Conversely, if the project engineer erroneously assumes that liquefaction will not occur then the project may be significantly delayed because the project cost estimate did not account for liquefaction design.

Planning phase (K or 0) liquefaction investigations consist of evaluating existing information for a site (see Geotechnical Investigations Module). If liquefaction potential is *unknown or cannot be determined based on the available information* at type selection, then the wrong foundation type may be selected. If the consequences of liquefaction are potentially substantial, the geoprofessional should discuss with the Project Development Team (PDT) the option of performing subsurface investigations prior to type selection to reduce or eliminate the level of uncertainty associated with liquefaction. The geoprofessional should read Memos to Designers (MTD) 20-14, "*Quantifying the Impacts of Soil Liquefaction and Lateral Spreading on Project Delivery*."

This module presents:

- Criteria for preliminary screening at the site by assessing the liquefaction potential based on available information (hazard maps, As-Built Plans, etc). The results of this (generally qualitative) preliminary screening are reported in the DPGR, SPGR, or PFR. (Section 2)
- Guidance for field investigations in potentially liquefiable soils. (Section 3)
- The methodology for performing quantitative analysis of liquefaction potential in order to determine if liquefaction will occur based on site specific field and lab data (Youd, 2001). This information will be presented in an FR and/or a GDR. (Section 4)
- An example illustrating the SPT (Youd, 2001) procedure (Appendix A).

This module does not address the effects of liquefaction on the proposed project, mitigation of the liquefaction hazard, or design of projects in areas of liquefaction.

2 Preliminary Screening of Potentially Liquefiable Soils

Preliminary screening is the evaluation of a site for site liquefaction potential using existing information, such as mapping, groundwater information, reports, as-built plans, and in some cases existing sampling and testing (See Geotechnical Investigations). The purpose of the preliminary screening is to alert the PDT to the potential for liquefaction.

Six criteria are used for preliminary screening. (See CGS 117A for additional details.):

1. Groundwater Table (historic, current, or anticipated future level)
2. Liquefaction Hazard Maps
3. Age of Soil
4. Soil Type
5. Soil Density
6. Peak Ground Acceleration

Use all six criteria to make a preliminary screening assessment. If the preliminary screening indicates no liquefaction potential, the site investigation should be planned as if liquefaction is not expected. If there is a potential for liquefaction, or the potential is unknown, the geoprofessional must report as discussed below, and the field investigation should be planned to include appropriate drilling and sampling.

Groundwater Table

Sites with potentially liquefiable soils and groundwater table within the upper 50 feet are generally considered to be most susceptible to liquefaction. If the groundwater table is within 50 feet of the ground surface the geoprofessional should anticipate the need to sample and test for liquefaction determination unless none of the remaining criteria are met. If the groundwater is below 50 feet, the site should be considered non-liquefiable for preliminary screening purposes.

Sources of groundwater data include “As-Built” boring logs, County well log data, water wells (Department of Water Resources), and historic ground water levels (USGS) and ground water plates published in the State Seismic Hazard Zone maps.

Liquefaction Hazard Maps

State Seismic Hazard Zone Maps and USGS Liquefaction Hazard Maps identify areas that are prone to liquefy. The USGS also maintains a website showing liquefaction in past earthquakes. Sites shown as liquefiable on these maps must be assumed to be liquefiable until shown otherwise by a field investigation and, if appropriate, quantitative analysis.

Age of Soil

Holocene deposits (younger than 11,000 years) and man-made fills ranging from very loose to medium dense are susceptible to liquefaction. Geologic deposits older than Holocene age (> 11,000 years) are considered to have low liquefaction susceptibility. A source of soil age data is the CGS California Geologic Map.

Soil Type

Soils that should be considered potentially liquefiable are sands, low plasticity silts (PI<7), and, in unusual cases, gravel. Rock and most clay soil are not liquefiable.

Soil Density

Granular soils with an SPT blow count $(N_1)_{60} < 30$, or a normalized Cone Penetration Test (CPT) resistance $(q_{c1N}) < 160$ are potentially liquefiable. However, increased fines content reduces the liquefaction potential and granular soils with the following combinations of $(N_1)_{60}$ and percent fines are not liquefiable:

$(N_1)_{60}$	% Fines
>30	≥5%
> 25	≥15%
> 21	≥35%

Peak Ground Acceleration

Liquefaction potential increases with ground shaking. Peak Ground Acceleration is obtained from ARS Online.

3 Field Investigation

If preliminary screening indicates liquefaction potential exists or is unknown, the field investigation should gather information for liquefaction assessment including the nature (soil type, grain size, and density) and distribution of the potentially liquefiable soil, and the groundwater level. This may require increasing the number of borings and samples (decreasing the SPT interval over what might be normal for a field investigation), including CPT to aid in determining the continuity of liquefiable layers, and additional lab tests.

Because the presence of liquefiable soils can substantially increase project costs, it is important to thoroughly characterize the site. It is not enough to just identify the presence of liquefiable soils, it is also necessary to show that the liquefiable soils are extensive enough, both laterally and vertically, to actually constitute a hazard.

SPT Borings

A field investigation at a site with potentially liquefiable soils should include SPT sampling from the groundwater surface to 50 feet below the ground surface or 20 feet below the expected pile tip elevation whichever is deeper. The geoprofessional must recognize that a critical liquefiable layer may be thinner than the sampling interval. SPT samples should be taken within each liquefiable layer, which may require more closely

spaced samples than 5 feet. Continuous sampling and/or careful logging of drill cuttings may be required to identify relatively thin liquefiable layers. Samples should be sent to the laboratory for testing if the SPT indicates that the soil will liquefy (see *Soil Density* above).

Do not use hollow stem augers below the water table elevation for liquefaction assessment using the SPT.

Ground Water Level

Measure the stabilized groundwater elevation in the borehole or piezometer.

CPT

The CPT is particularly useful in identifying thin soil layers which may be missed when drilling and using the SPT. If the CPT is the only method used for the field investigation and the normalized CPT resistance (q_{c1N}) < 160 and the soils are borderline cases, the geoprofessional must verify the soil type with at least one SPT boring along with laboratory testing.

Geophysical Investigation

In gravelly soils where SPT blow counts are unreliable (or at depths greater than 70 feet) consider the shear wave velocity (Vs) method for performing liquefaction assessment. The seismic cone, P-S logging, or surface wave methods are all available to obtain shear wave velocity.

Laboratory Testing

In potentially liquefiable soils that may have enough fines to render the soil non-liquefiable the following tests must be performed for a final determination:

- Particle Size Analysis (ASTM D 422)
- Atterberg Limits (ASTM D 4318)
- Moisture Content (ASTM D 2216)

4 Quantitative Liquefaction Analysis

Quantitative liquefaction analysis uses site-specific field and laboratory test data. Use the procedure of Youd, et al (2001): *Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils October, 2001* for quantitative liquefaction analysis. The procedure consists of the following general steps:

1. Determine groundwater elevation. Use the ground water elevation measured during the field investigation. A higher elevation may be used if there is clear evidence for seasonal or long-term fluctuations. Do not combine liquefaction analysis with other extreme events, such as maximum scour and/or temporary or abnormally high groundwater levels. Combining extreme events results in conservative, costly, and unnecessary overdesign.
2. Determine which soil layers are to be evaluated for quantitative liquefaction analysis.
3. Correct SPT Blow Counts
4. Determine Cyclic Stress Ratio (CSR)
5. Determine Fines Content Correction
6. Calculate Cyclic Resistance Ratio $(CRR)_{7.5}$
7. Calculate the Magnitude Scaling Factor (MSF)
8. Calculate the Factor of Safety Against Liquefaction

Modifications or elaborations to Youd et al (2001) are as follows:

- Use Youd et al (2001) to depths of 50 feet; with caution to 70 feet; do not use below 70 feet.
- Extreme conditions below 70 feet (e.g.: loose fine sands without fines, thick layers, etc) require special analysis and consideration that is beyond the scope of this module.
- Use the Seed and Idriss formula (1997) found in Youd et al (2001) for the fines correction.
- Do not use the "Modified Chinese Criteria" as it is unconservative for determining if certain fine grained soils are liquefiable. Use the method in Bray and Sancio (2006) which states that fine grained soils will not liquefy (regardless of SPT blow count or CSR) if PI >12 or Wc < .85*LL
- Use the more conservative of the deterministic or probabilistic earthquake (5% probability of exceedance in 50 years or 975 year return period) to determine the PGA (a_{max}) and M_{Max}. (Youd uses the term a_{max} for PGA)
- For *deterministic* liquefaction seismic parameters run ARS Online to obtain the deterministic PGA and M_{Max}.
- For *probabilistic* liquefaction seismic parameters run ARS Online to obtain the PGA associated with a 975 year return period. Do a deaggregation using the 2008 USGS tool and use the larger of the M_{Median} or M_{Mode} value for M_{Max}. (Youd uses the term Mw for $\mathbf{M}_{Max}$)
- When the California minimum acceleration controls use the actual ground acceleration for liquefaction determination.
- Use a factor of safety against liquefaction of 1. (Soils with FS≥1 are not liquefiable.) Borderline cases where the factor of safety ranges between 0.95 and

1.05 may need further investigation depending on the consequences of liquefaction.

See Appendix A for an example liquefaction analysis.

5 Reporting

Liquefiable soil can have significant impact on a project's scope, schedule and budget; it is important to communicate liquefaction information to the PDT in a timely manner. The content and confidence of recommendations, especially during the planning phase, will depend largely on the type of information available. If as-built LOTB and laboratory data are available then quantitative liquefaction analysis may occur earlier than typical, and the results presented in the DPGR or SPGR. Alternatively, if little information is available, then only a qualitative assessment, i.e. preliminary screening, can be presented.

Liquefaction potential is discussed in the following reports:

- District Preliminary Geotechnical Report (DPGR)
- Geotechnical Design Report (GDR)
- Structure Preliminary Geotechnical Report (SPGR)
- Preliminary Foundation Report (PFR)
- Foundation Report (FR)

Preliminary Reports

Language used in reporting liquefaction potential must be clear and direct. Do not use indefinite terms such as "*low*", "*moderate*" and/or "*high*". Acceptable language for preliminary reports (SPGR, PFR, and DPGR) includes:

- *"Liquefaction potential exists"*,
- *"Liquefaction potential is unknown or cannot be determined based on the available information"*,
- *"Liquefaction potential does not exist"*.

If the results of preliminary screening (reported in the SPGR or DPGR) indicate that liquefaction potential either exists or is unknown, the Project Development Team (PDT) should decide whether to perform some or all drilling prior to type selection to more accurately report liquefaction potential in the PFR. For District items, such as standard plan structures and embankments, the PDT should decide whether liquefaction will be considered in the design. If the design will not be modified for liquefaction it is unnecessary to perform quantitative liquefaction analysis and related field work.

Final Reports

The results of the site investigation and quantitative analysis must be reported in the PFR (if applicable), FR and/or GDR. The report should include:

- Areal limits of liquefaction
- Vertical limits of liquefaction
- Identification of liquefiable soils
- For complex projects, or if requested by the designer, include a three dimensional plot of liquefiable soils at the site.

(Discussion of the consequences and mitigation of liquefaction hazards will be in separate modules. This would include: lateral spreading, seismic settlement, layer thickness, extent, connectivity, etc.)

References

1. Caltrans, Memo to Designers 20-14, 2008, *"Quantifying the Impacts of Soil Liquefaction and Lateral Spreading on Project Delivery,"* Caltrans Division of Engineering Services, Office of Earthquake Engineering
2. Caltrans, *"Foundation Report Preparation for Bridges,"* Caltrans Division of Engineering Services, Geotechnical Services, December 2009
3. Caltrans, *"Guidelines for Preparing Geotechnical Design Reports, Version 1.3,"* Caltrans Division of Engineering Services, Geotechnical Services, December 2006
4. Youd, T.L., et al., 2001, *"Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils,' in* Journal of Geotechnical and Geo-environmental Engineering, October 2001
5. California Department of Conservation, Division of Mines and Geology, 2008, "*Guidelines for Evaluating and Mitigating Seismic Hazards in California*," CDMG Special Publication 117A
6. Bray, J. D. and Sancio, R. B. 2006, *"Assessment of the Liquefaction Susceptibility of Fine-grained Soils,*" Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 132, No. 9

APPENDIX A

LIQUEFACTION EVALUATION EXAMPLE

Example Liquefaction Evaluation

Live Oak Creek Bridge is a proposed single span bridge crossing Live Oak Creek. Preliminary screening, based on the "As-Built" LOTBs for the existing Live Oak Creek Bridge (Br. No. 57-0070), indicate the possibility of liquefaction. A quantitative liquefaction analysis is required following the procedures described in Youd et al, (2001).

The following information is required:

- Seismic parameters including peak ground acceleration (a_{max}) and the Earthquake magnitude. These data are obtained by running ARS online using the latitude and longitude 33.31525 N, -117.194225W.
- Soil data. SPT results, hammer efficiency and soil descriptions are shown on the LOTB dated 11-1-2012 (attached).
- Groundwater data. Shown on the LOTB dated 11-1-2012 (attached).

Step 1: Determine Groundwater Elevation

The design groundwater elevation is the level shown on the LOTB for Boring RC-11-001. There is no reason to adjust the groundwater elevation.

Step 2: Identify the Soil Layers for Quantitative Liquefaction Analysis.

The LOTB shows two borings with soil data to be evaluated: RC-11-001 and RC-11-002. RC-11-001 shows five soil layers; preliminary liquefaction evaluation results are presented in Table 1.

Table 1: Preliminary Liquefaction Evaluation for Boring RC-11-001.

Layer	Elevation	Soil Type	Thickness	Preliminary Evaluation	Reason for Evaluation
1	210-205	SP	5'	Not Liquefiable	Above the groundwater surface
2	205-200	SM	5'	Not Liquefiable	Above the groundwater surface, fines content > 30%
3	200-194	SP	3' 3'	Not Liquefiable above 197' Liquefiable below 197'	Above the groundwater surface Granular, No fines, SPT N<30, below the groundwater surface
4	194-179	SW	15'	Liquefiable	Granular, No fines, SPT N<30, below the groundwater surface
5	179-150	SP	29'	Liquefiable	Granular, No fines, SPT N<30, below the groundwater surface

Most of the soils show the potential for liquefaction based on preliminary qualitative analysis. For this example, layer 4 from RC-11-001 will be analyzed. Based on the results, it may be appropriate to extend to the results to the other layers in both borings, or it may necessary to perform the analysis for one or more additional layers.

Step 3: Correct SPT Blow Count Data

From Youd, equation (8 and Table 2) the corrected SPT N-value is:

$\mathbf{(N_1)_{60}} = N_m\ C_N\ C_E\ C_B\ C_R\ C_S$, where

- $(N_1)_{60}$ = corrected normalized SPT blow count.
- N_m= measured SPT blow count.
- C_N = depth correction factor = $C_N=(P_a\ /\sigma'_{vo})^{0.5}$ from Youd equation (9)
  - P_a = 1 atm = 2088 pcf and σ'_{vo} = effective overburden pressure at the time the SPT was done.
- C_E = hammer energy correction factor (ERi / 60)
- C_B = borehole diameter correction factor.
- C_R = rod length correction factor
- C_S = correction factor for samplers with or without liner.

For this example:

- N_m= 16 (Blowcount at 25' depth)
- C_N = 2088 / 2225 = .94
- C_E = 68 / 60 = 1.13
- C_B = 1
- C_R = .95
- C_S = 1.2 (no liner used)

Thus

$(N_1)_{60} = N_m\ C_N\ C_E\ C_B\ C_R\ C_S$

$= 16 \times .94 \times 1.13 \times 1 \times .95 \times 1.2$

$= 19$

Step 4: Determine Cyclic Stress Ratio (CSR)

From Youd, equation (1), CSR = $0.65\ a_{max}(\sigma_o\ /\sigma'_o)r_d$

Where:

- σ_o and σ'_o are total and effective vertical overburden stresses, respectively.
- a_{max} is peak horizontal acceleration (PGA) in g.
- r_d is a stress reduction coefficient.

For this example:

a_{max} = 0.4g

Unit weights of the soil layers (from Soil Properties Module) are:

- Layer 1: 120 pcf. $(N_1)_{60}$ = 16 (estimated).
- Layer 2: 110 pcf. $(N_1)_{60}$ = 12 (estimated).
- Layer 3: 120 pcf from 200' to 197', 57.6 pcf from 197' to 193' $(N_1)_{60}$ = 11 (estimated).
- Layer 4: 67.6 pcf . $(N_1)_{60}$ = 19 (estimated).

<u>Step 2A: Calculate Overburden Stresses.</u>

Use the approximate center of the layer at 185' (depth = 25').

σ'_0=120 x 5 + 110 x 5 + 120 x 3 + 3 x 57.6 + 67.6 x 8 =2225 psf

σ_0 = 120 x 5 +110 x 5 + 120 x 6 + 130 x 8 = 2910 psf

<u>Step 2B: Determine Stress Reduction Coefficient, r_d.</u>

Depth (z) is 25'= 7.6m

From Youd, equation (2a),

r_d=1.0-0.00765 · z

r_d =1.0-0.00765 · 7.6 = 0.94

<u>Step 2C: Determine CSR</u>

From Youd, equation (1)

CSR = 0.65 $a_{max}(\sigma_o / \sigma'_o)r_d$

CSR= 0.65 x (0.4) x (2910/2225) x 0.94 = 0.32

Step 5: Fines Content Correction

From Youd, equation (5)

$(N_1)_{60cs} = \alpha + \beta(N_1)_{60}$, where

- $(N1)_{60cs}$ is the blow count corrected for fines content
- α and β are coefficients that depend on the fines content.

For this example

- α= 0 (Youd equation 6a since the sample has no fines)

- β= 1.0 (Youd equation 7a since the sample has no fines)

$(N_1)_{60cs} = \alpha + \beta(N_1)_{60}$

$(N_1)_{60cs} = 0 + 1(19)$

$= 19$

Step 6: Calculate Cyclic Resistance Ratio $(CRR)_{7.5}$

From Youd equation (4)

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10(N_1)_{60cs} + 45]^2} - \frac{1}{200}$$

For this example:

$(N_1)_{60cs} = 19$

$$CRR_{7.5} = \frac{1}{34 - 19} + \frac{19}{135} + \frac{50}{[10(19) \quad + 45]^2} - \frac{1}{200}$$

$CRR_{7.5} = 1/15 + 19/135 + 50/235^2 - 1/200$

$= 0.067 + 0.14 + .00091 - .005$

$= 0.20$

$CRR_{7.5}$ can alternatively be read directly from Youd Figure 2.

Step 7: Calculate the Magnitude Scaling Factor (MSF)

For this example, $M_w = 7.6$

From Youd equation 24

$MSF = 10^{2.24}/M_w^{2.56}$

$MSF = 10^{2.24}/7.6^{2.56}$

$= 0.97$

Step 8: Calculate the Factor of Safety against Liquefaction

From Youd, equation 23 (Use equation 30 for sloping ground or high overburden stresses)

$FS = (CRR_{7.5}/CSR) \times MSF$

$FS = (.20/.32) \times .97$

$= .61$

Since FS is less than 1, there is a potential of liquefaction for this layer and the geotechnical report should state that liquefaction will occur in this layer.

To complete the liquefaction analysis for the site, repeat the above steps for each layer identified as susceptible to liquefaction via preliminary evaluation.

DIST	COUNTY	ROUTE	POST MILES TOTAL PROJECT	SHEET No.	TOTAL SHEETS
11	SD	076			

REGISTERED CIVIL ENGINEER DATE

PLANS APPROVAL DATE

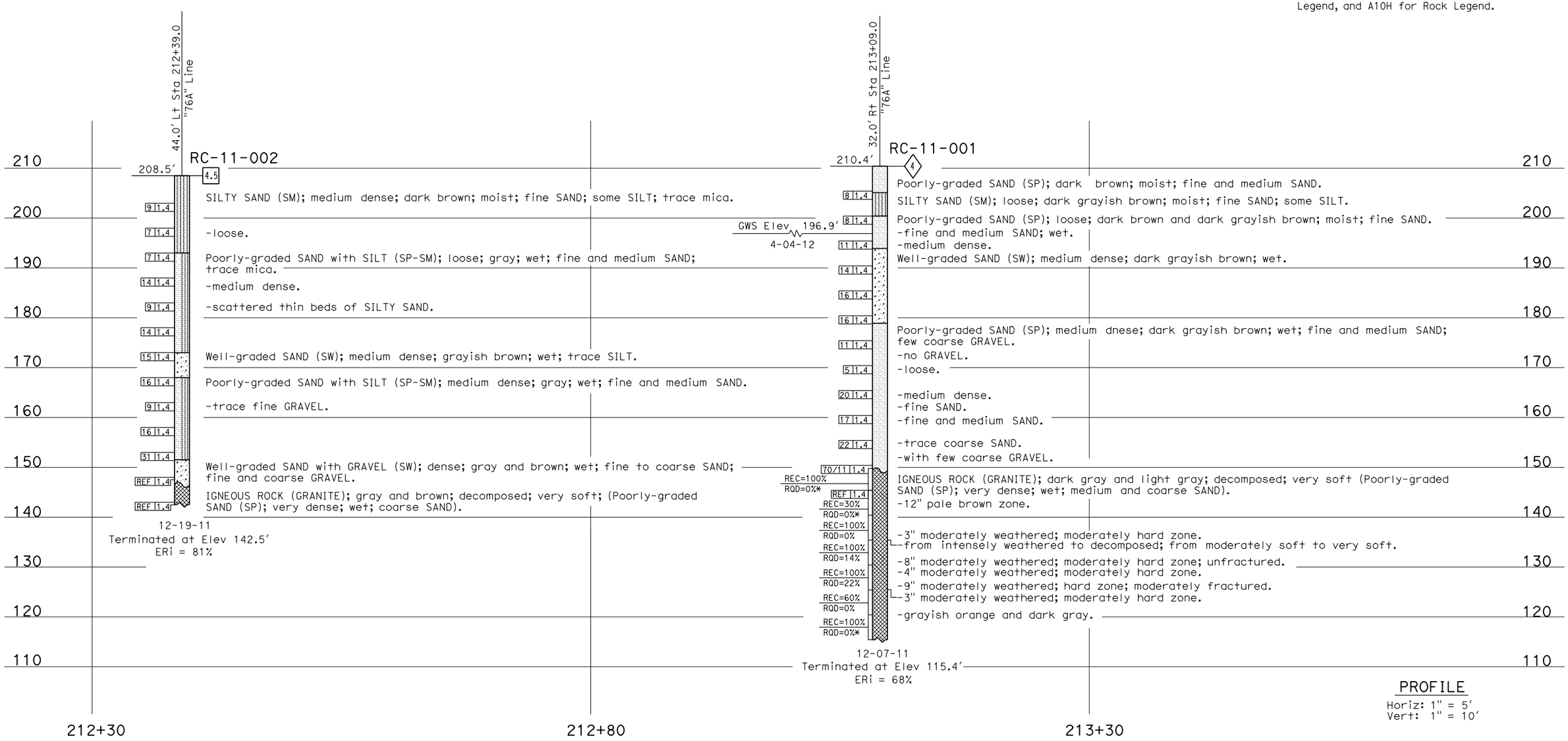
REGISTERED PROFESSIONAL ENGINEER No. Exp. CIVIL STATE OF CALIFORNIA

The State of California or its officers or agents shall not be responsible for the accuracy or completeness of electronic copies of this plan sheet.

This LOTB sheet was prepared in accordance with the Caltrans Soil & Rock Logging, Classification, & Presentation Manual (2010 Edition).

See 2010 Standard Plans A10F and A10G for Soil Legend, and A10H for Rock Legend.

FOR PLAN VIEW, SEE
"LOG OF TEST BORINGS 1 OF 2"



PROFILE
Horiz: 1" = 5'
Vert: 1" = 10'

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FUNCTIONAL SUPERVISOR	DRAWN BY:	FIELD INVESTIGATION BY:			
NAME:	CHECKED BY:				

OGS CIVIL LOG OF TEST BORINGS SHEET

ORIGINAL SCALE IN INCHES FOR REDUCED PLANS 0 1 2 3

UNIT: 3643
PROJECT NUMBER & PHASE: 11000204891 CONTRACT NO.: 11-257151

DISREGARD PRINTS BEARING EARLIER REVISION DATES

REVISION DATES 09-19-12 10-30-12 11-13-12 SHEET X OF X

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