CHAPTER 5

LIQUEFACTION POTENTIAL EVALUATION AND ANALYSIS

This chapter provides information to use when evaluating and analyzing the potential for failure due to liquefaction during a seismic event at an Ohio *waste containment facility*. Ohio EPA requires that the *soil units* at any *waste containment facility* be able to withstand the effects of a plausible earthquake and rule out the possibility of liquefaction. This is because it is generally expected that the engineered components of a *waste containment facility* will lose their integrity and no longer be able to function if a foundation soil layer liquefies.

> Soil liquefaction occurs in loose, *saturated* cohesionless *soil units* (sands and silts) and sensitive clays when a sudden loss of strength and loss of stiffness is experienced, sometimes resulting in large, permanent displacements of the ground. Even thin lenses of loose *saturated* silts and sands may cause an overlying sloping soil mass to slide laterally along the liquefied layer during earthquakes. Liquefaction beneath and in the vicinity of a *waste containment unit* can result in localized bearing capacity failures, lateral spreading, and excessive settlement that can have severe consequences upon the integrity of *waste containment systems*. Liquefaction-associated lateral spreading and flow failures can also affect the global stability of a *waste containment facility*.

REPORTING

This section describes the information that should be submitted to demonstrate that a facility is not susceptible to liquefaction. Ohio EPA recommends that the following information be included in its own section of a geotechnical and stability analyses report. At a minimum, the following information about the liquefaction evaluation and analysis should be reported to Ohio EPA:

> Any drawings or cross sections referred to in this policy that are already present in another part of the geotechnical and stability analyses report can be referenced rather than duplicated in each section. It is helpful if the *responsible* party ensures the referenced items are easy to locate and marked to show the appropriate information.

- A narrative and tabular summary of the findings of the liquefaction evaluation and analysis including all *soil units* evaluated.
- A detailed discussion of the liquefaction evaluation including:
    - A discussion and evaluation of the geologic age and origin, fines content, plasticity index, saturation, depth below ground surface, and soil penetration resistance of each of the *soil units* that comprise the *soil stratigraphy* of the *waste containment facility*,

- The scope, extent, and findings of the subsurface investigation as they pertain to the liquefaction potential evaluation.

- A narrative description of each potentially liquefiable layer, if any, at the facility, and

- All figures, drawings, or references relied upon during the evaluation marked to show how they relate to the facility.

! If the liquefaction evaluation identifies potentially liquefiable layers, then the following information should be included in the report:

- A narrative and tabular summary of the results of the analysis of each potentially liquefiable layer,

- Plan views of the facility that include the northings and eastings, the lateral extent of the potentially liquefiable layers, and the limits of the *waste containment unit(s)*,

- Cross sections of the facility showing *soil units*, full depictions of the potentially liquefiable layers, and the following:

  - location of engineered components of the facility,

  - material types, shear strengths, and boundaries,

  - geologic age and origin,

  - fines content and plasticity index,

  - depth below ground surface,

  - soil penetration resistance,

  - temporal high *phreatic surfaces* and *piezometric surfaces*, and

  - in situ field densities and, where applicable, the in situ *saturated* field densities.

- The scope, extent, and findings of the subsurface investigation as they pertain to the analysis of potentially liquefiable layers,

- A description of the methods used to calculate the factor of safety against liquefaction,

- Liquefaction analysis input parameters and assumptions, including a rationale for selecting the maximum expected horizontal ground acceleration,

- The actual calculations and/or computer inputs and outputs, and

- All figures, drawings, or references relied upon during the analysis marked to show how they relate to the facility.

FACTOR OF SAFETY

The following factor of safety should be used, unless superseded by rule, when demonstrating that a facility will resist failures due to liquefaction.

Liquefaction analysis: FS $\geq$ 1.00

> The number of digits after the decimal point indicates that rounding can only occur to establish the last digit. For example, 1.579 can be rounded to 1.58, but not 1.6.

The above factor of safety is appropriate, only if the design assumptions are conservative; site-specific, *higher quality data* are used; and the calculation methods chosen are shown to be valid and appropriate for the facility. It should be noted, however, that historically, occasions of liquefaction-induced instability have occurred when factors of safety using these methods and assumptions were calculated to be greater than 1.00. Therefore, the use of a factor of safety against liquefaction higher than 1.00 may be warranted whenever:

- A failure would have a catastrophic effect upon human health or the environment,
- Uncertainty exists regarding the accuracy, consistency, or validity of data, and no opportunity exists to conduct additional testing to improve or verify the quality of the data,
- Large uncertainty exists about the effects that changes to the site conditions over time may have on the stability of the facility, and no engineered controls can be carried out that will significantly reduce the uncertainty.

> Designers may want to consider increasing the required factor of safety if repairing a facility after a failure would create a hardship for the *responsible parties* or the waste disposal customers.

Using a factor of safety less than 1.00 against liquefaction is not considered a sound engineering practice. This is because a factor of safety less than 1.00 indicates failure is likely to occur. Furthermore, performing a deformation analysis to quantify the risks and damage expected to the *waste containment facility* should liquefaction occur is not considered justification for using a factor of safety less than 1.00 against liquefaction. This is because the strains allowed by deformation analysis are likely to result in decreased performance and loss of integrity in the engineering components. Thus, any failure to the *waste containment facility* due to liquefaction is likely to be substantial and very likely to increase the potential for harm to human health and the environment. If a facility has a factor of safety against liquefaction less than 1.00, mitigation of the liquefiable layers will be necessary, or another site not at risk of liquefaction will need to be used.

> If the liquefaction analysis does not result in a factor of safety of at least 1.00, consideration may be given to performing a more sophisticated liquefaction potential assessment, or to liquefaction mitigation measures such as eliminating the liquefiable layer, or choosing an alternative site.
>
> A variety of techniques exist to remediate potentially liquefiable soils and mitigate the liquefaction hazard. Liquefaction of Soils During Earthquakes (National Research Council, Committee of Earthquake Engineering, 1985) includes a table summarizing available methods for improvement of liquefiable soil foundation conditions. However, Ohio EPA approval must be obtained prior to use of any methods for mitigation of liquefiable layers.

The *responsible party* should ensure that the designs and specifications in all authorizing documents and the quality assurance and quality control (QA/QC) plans clearly require that the assumptions and specifications used in the liquefaction analysis for the facility will be followed during construction, operations, and closure. If the *responsible party* does not do this, it is likely that Ohio EPA will require the assumptions and specifications from the liquefaction analysis to be used during construction, operations, and closure of a facility through such means as are appropriate (e.g., regulatory compliance requirements, approval conditions, orders, settlement agreements).

From time to time, changes to the facility design may be needed that will alter the assumptions and specifications used in the liquefaction analysis. If this occurs, a request to change the facility design is required to be submitted for Ohio EPA approval in accordance with applicable rules. The request to change the facility design must include a new liquefaction analysis that uses assumptions and specifications appropriate for the change.

LIQUEFACTION EVALUATION

Ohio EPA requires the assessment of liquefaction potential as a key element in the seismic design of a *waste containment facility*. To determine the liquefaction potential, Ohio EPA recommends using the five screening criteria included in the U.S. EPA guidance document titled RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities, EPA/600/R-95/051, April 1995, published by the Office of Research and Development. As of the writing of this policy, the U.S. EPA guidance document is available at www.epa.gov/clhtml/pubtitle.html on the U.S. EPA Web site.

Recommended Screening Criteria for Liquefaction Potential

The following five screening criteria, from the above reference, are recommended by Ohio EPA for completing a liquefaction evaluation:

- Geologic age and origin. If a soil layer is a fluvial, lacustrine or aeolian deposit of Holocene age, a greater potential for liquefaction exists than for till, residual deposits, or older deposits.

- Fines content and plasticity index. Liquefaction potential in a soil layer increases with decreasing fines content and plasticity of the soil. Cohesionless soils having less than 15 percent (by weight) of particles smaller than 0.005 mm, a liquid limit less than 35 percent, and an in situ water content greater than 0.9 times the liquid limit may be susceptible to liquefaction (Seed and Idriss, 1982).

- Saturation. Although low water content soils have been reported to liquefy, at least 80 to 85 percent saturation is generally deemed to be a necessary condition for soil liquefaction. The highest anticipated temporal *phreatic surface* elevations should be considered when evaluating saturation.

- Depth below ground surface. If a soil layer is within 50 feet of the ground surface, it is more likely to liquefy than deeper layers.

- Soil Penetration Resistance. Seed et al, 1985, state that soil layers with a normalized SPT blowcount [$(N_1)_{60}$] less than 22 have been known to liquefy. Marcuson et al, 1990, suggest an SPT value of [$(N_1)_{60}$] less than 30 as the threshold to use for suspecting liquefaction potential. Liquefaction has also been shown to occur if the normalized CPT cone resistance (q_c) is less than 157 tsf (15 MPa) (Shibata and Taparaska, 1988).

> In some cases, it is necessary to stabilize a borehole due to heaving soils. The use of hollow-stem augers or drilling mud has been proven effective for stabilizing a borehole without affecting the blow counts from a standard penetration test. Casing off the borehole as it is advanced has also been used, but it has been found that for non-cohesive soils, such as sands, it has an adverse effect on the standard penetration test results (Edil, 2002).

If three or more of the above criteria indicate that liquefaction is not likely, the potential for liquefaction can be dismissed. Otherwise, a more rigorous analysis of the liquefaction potential at a facility is required. However, it is possible that other information, especially historical evidence of past liquefaction or *sample* testing data collected during the subsurface investigation, may raise enough of a concern that a full liquefaction analysis would be appropriate even if three or more of the liquefaction evaluation criteria indicate that liquefaction is unlikely.

LIQUEFACTION ANALYSIS

If potential exists for liquefaction at a facility, additional subsurface investigation may be necessary. Once all testing is complete, a factor of safety against liquefaction is then calculated for each *critical layer* that may liquefy.

A liquefaction analysis should, at a minimum, address the following:

- Developing a detailed understanding of site conditions, the *soil stratigraphy*, material properties and their variability, and the areal extent of potential *critical layers*. Developing simplified cross sections amenable to analysis. SPT and CPT procedures are widely used in practice to characterize the soil (field data are easier to obtain on loose cohesionless soils than trying to obtain and test undisturbed *samples*). The data needs to be corrected as necessary, for example, using the normalized SPT blowcount [$(N_1)_{60}$] or the normalized CPT. The total vertical stress (σ_o) and effective vertical stress (σ_o') in each stratum also need to be evaluated. This should take into account the changes in overburden stress across the lateral extent of each *critical layer*, and the temporal high *phreatic* and *piezometric surfaces*,

- Calculation of the force required to liquefy the critical zones, based on the characteristics of the critical zone(s) (e.g., fines content, normalized standardized blowcount, overburden stresses, level of saturation),

- Calculation of the design earthquake's effect on each potentially liquefiable layer should be performed using the site-specific in situ soil data and an understanding of the earthquake magnitude potential for the facility, and

- Computing the factor of safety against liquefaction for each liquefaction susceptible *critical layer*.

Liquefaction Potential Analysis - Example Method

The most common procedure used in practice for liquefaction potential analysis, the "Simplified Procedure," was developed by H. B. Seed & I. M. Idriss. Details of this procedure can be found in RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities (U.S.EPA, 1995). As of the publication date of this policy, the U.S. EPA guidance document was available from www.epa.gov/clhtml/pubtitle.html on the U.S. EPA Web site. Due to the expected range of ground motion in Ohio, the Simplified Procedure is applicable. However, if the expected peak horizontal ground acceleration is larger than 0.5 g, more sophisticated, truly nonlinear effective stress-based analytical approaches should be considered, for which there are computer programs available. The simplified procedure comprises the following four steps:

1. Identify the potentially liquefiable layers to be analyzed.

2. Calculate the shear stress required to cause liquefaction (resisting forces). Based on the characteristics of the potentially liquefiable layers (e.g., fines content, normalized standardized blowcount), the critical (cyclic) stress ratio (CSR_L) can be determined using the graphical methods included in the U.S. EPA guidance referenced above. Note: this determination is typically based on an earthquake of magnitude 7.5. If the design earthquake is of a different magnitude, or if the site is not level, the CSR_L will need to be corrected as follows.

$$CSR_{L(M-M)} = CSR_{L(M=7.5)} \cdot k_M \cdot k_s \cdot k_a \qquad (5.1)$$

where

$CSR_{L(M—M)}$ = corrected critical stress ratio resisting liquefaction,
$CSR_{L(M=7.5)}$ = critical stress ratio resisting liquefaction for a magnitude 7.5 earthquake,
k_M = magnitude correction factor,
$k\sigma$ = correction factor for stress levels exceeding 1 tsf, and
k_α = correction factor for the driving static shear stress if sloping ground conditions exist at the facility. Special expertise is required for evaluation of liquefaction resistance beneath ground sloping more than six percent (Youd, 2001).

The k-values are available from tabled or graphical sources in the referenced materials.

> The correction factors can be obtained from different sources, such as the 1995, U.S. EPA, Seismic Design Guidance, or the summary report from the 1996 and 1998 NCEER/NSF Liquefaction Workshops. The U.S. EPA document tends to be somewhat more conservative for earthquakes with a magnitude less than 6.5. In 1999, I.M. Idriss proposed yet a different method for calculating the empirical stress reduction factor (r_d), which was less conservative than the method included in the U.S. EPA guidance, but more conservative than the method included in the NCEER method. Designers should select correction factors based on site-specific circumstances and include documentation explaining their choices in submittals to Ohio EPA.

3. Calculation of the design earthquake's effect on the critical zone (driving force). The following equation can be used.

$$CSR_{EQ} = 0.65\left(\frac{a_{max,z}}{g}\right) r_d \left(\frac{s_0}{s_0'}\right) \qquad (5.2)$$

where
CSR_{eq} = equivalent uniform cyclic stress ratio induced by the earthquake,
σ_0 = total vertical overburden stress,
σ_0' = effective vertical overburden stress,
$a_{max,z}$ = the maximum horizontal ground acceleration, and
g = the acceleration of gravity.

Liquefaction Potential Analysis - Example Method (cont.)

$$a_{\max,z} = \left(a_{\max}\right)\left(r_d\right) \qquad (5.3)$$

where $a_{max,z}$ = the maximum horizontal ground acceleration,
a_{max} = peak ground surface acceleration, and
r_d = empirical stress reduction factor.

$$r_d = \frac{a_{\max@depth\ D}}{s_{0@depth\ D}\left(\frac{a_{\max@surface}}{g}\right)} \qquad (5.4)$$

4. <u>Calculate the factor of safety against liquefaction (resisting force divided by driving force)</u>.

$$FS_L = \frac{CSR_{L(M-M)}}{CSR_{EQ}} \geq 1.00 \qquad (5.5)$$

where FS_L = factor of safety against liquefaction,
$CSR_{L(M—M)}$ = shear stress ratio required to cause liquefaction, and
CSR_{EQ} = equivalent uniform cyclic stress ratio.

REFERENCES

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