

Updating Assessment Procedures and Developing a Screening Guide for Liquefaction

by T. Leslie Youd,
Brigham Young University

Research Objectives

The main objectives of this research program are to provide consensus updates to standard procedures and prepare guidance documents for assessing liquefaction hazards for highway bridge sites. The scope of these studies includes evaluation of liquefaction resistance of soils with standard and cone penetration tests, shear wave velocity measurements, and Becker penetration tests. Additional issues, such as updated magnitude scaling factors, are addressed. The research findings are incorporated in unified, well-established guidelines for use by practicing engineers.

Liquefaction-induced ground and foundation displacements have been major causes of bridge damage during past earthquakes. The Great Alaskan earthquake of March 27, 1964 marked the commencement of studies to understand and mitigate liquefaction hazard (McCulloch and Bonilla, 1970; Kachadoorian, 1968; Youd, 1993). Over the past 30 years, a procedure, termed the “simplified procedure,” has evolved for evaluating the seismic liquefaction resistance of soils. This procedure has become the standard practice in North America and throughout much of the world. Seed and Idriss (1971) developed and published the basic “simplified procedure.” The procedure has been corrected and augmented periodically since that time with landmark studies by Seed (1979), Seed and Idriss (1982), and Seed et al. (1985).

In 1985, the Committee on Earthquake Engineering of the National Research Council (NRC) organized a workshop with experts from the profession and observers who thoroughly reviewed the state-of-the-art for assessing liquefaction hazard in order to evaluate and update the procedure. The workshop produced a report (NRC, 1985) that has become a widely used reference. Another workshop, held in 1996 and sponsored by MCEER, was convened to review developments and gain consensus for further augmentations to the procedure. The scope of the workshop was limited to evaluation of liquefaction resistance. The workshop proceedings provide further updates to the simplified procedure (see Youd and Idriss, 1997) and various recommendations were made on the following topics:

1. Use of the standard and cone penetration tests for evaluation of liquefaction resistance

Sponsors

MCEER Highway Project/FHWA
National Science Foundation

Related Highway Project Tasks

- *Effects of Liquefaction on Vulnerability Assessment*, **G. Martin**, University of Southern California and **T.L. Youd**, Brigham Young University
- *Liquefaction Remediation Techniques for Bridge Foundations*, **G. Martin**, University of Southern California and **J. Mitchell**, Virginia Polytechnic Institute
- *Synthesis Report: Liquefaction Vulnerability Assessment*, **G. Martin**, University of Southern California and **T.L. Youd**, Brigham Young University



Workshop Organizers

T.L. Youd, Brigham Young University

I.M. Idriss, University of California, Davis

Workshop Participants

R.D. Andrus, National Institute of Standards and Technology

I. Arango, Bechtel Corp.

G. Castro, GEI Consultants, Inc.

J.T. Christian, Consultant, Boston

R. Dobry, Rensselaer Polytechnic Institute

W.D. Liam Finn, University of British Columbia

L.F. Harder, California Department of Water Resources

M.E. Hynes, U.S. Army Engineers Waterways Experiment Station

K. Ishihara, Science University of Tokyo

J. Koester, U.S. Army Engineers Waterways Experiment Station

S. S.C. Liao, Parsons Brinckerhoff

W. Marcuson III, U.S. Army Engineers Waterways Experiment Station

G. Martin, University of Southern California

J. Mitchell, Virginia Polytechnic Institute

Y. Moriwaki, Woodward Clyde Consultants

M. Power, Geomatrix Consultants, Inc.

P. Robinson, University of Alberta, Edmonton

R. Seed, University of California, Berkeley

K. Stokoe, University of Texas, Austin

2. Use of shear wave velocity measurements for evaluation of liquefaction resistance
3. Use of Becker penetration test for gravelly soils
4. Magnitude scaling factors
5. Correction factors for large overburden pressures

In addition, a "screening guide" for assessing liquefaction hazard was developed by Youd (1998). The guide presents procedures for the systematic evaluation of liquefaction resistance and damage potential for bridge sites and guidance for the prioritization of sites for further investigation and possible remediation. The screening guide procedures are generic, and can be used to determine liquefaction hazard for a variety of other types of structures.

Evaluating Liquefaction Resistance of Soils

In general, soil liquefaction is a major concern for structures constructed on saturated sandy soils. Major earthquakes, such as the 1906 San Francisco, 1964 Alaska, 1964 Niigata, Japan, 1989 Loma Prieta, and 1995 Kobe, Japan, produced extensive damage as a consequence of liquefaction and illustrate the need for engineering procedures to assess and mitigate the hazard. Since 1964, experimental and analytical studies have been carried out to better understand this phenomenon. Much of the early work was based on laboratory testing of reconstituted samples subjected to cyclic loading by means of cyclic triaxial, cyclic simple shear, or cyclic torsional

This research developed unified procedures for the assessment of seismic hazard to highway systems as a consequence of liquefaction, and produced two significant publications. *Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*, NCEER-97-0022, provides consensus updates to standard procedures that can be used for evaluations of liquefaction susceptibility for a wide array of applications. The consensus approach to liquefaction evaluation is being referenced in many new documents for geotechnical engineers. The approach has recently been recommended by the city and county of Los Angeles, thus it is expected that geotechnical consultants in the Los Angeles area will refer to the updated "simplified procedure" described in these proceedings. The *Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites*, MCEER-98-0005, is intended for use by highway engineers with experience in geotechnical engineering practice, but not necessarily specialized in seismic hazard evaluation. It is based on well-established experimental and analytical procedures developed in the U.S. and Japan and structured for implementation by practicing engineers. The simplified procedures and the screening guide are not highway specific, i.e., they can be used for generic liquefaction evaluation purposes for a wide variety of structures.

tests. The outcome of these studies generally confirmed the fact that resistance to cyclic loading is influenced primarily by the state of the soil, the intensity and duration of the cyclic loading, and the grain characteristics of the soil. However, the results also showed that the disturbance induced by sampling and test preparation procedures so greatly affected the test results that laboratory procedures were abandoned for routine engineering practice. At that point, the laboratory procedure was replaced by a procedure based on cheaper and generally more reliable field tests, such as standard cone penetration tests, for evaluation of liquefaction resistance.

The calculation or estimation of two primary seismic variables is required to evaluate liquefaction resistance. These variables are the seismic demand placed on a soil layer, expressed in terms of cyclic stress ratio (CSR), and the capacity of a soil layer to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR).

Seed and Idriss (1971) formulated the following equation for calculating CSR:

$$CSR = (\tau_{av} / \sigma'_{vo}) = 0.65(a_{max} / g)(\sigma_{vo} / \sigma'_{vo})r_d \quad (1)$$

where a_{max} is the peak horizontal acceleration during an earthquake, g is the gravitational acceleration, σ_{vo} and σ'_{vo} are total and effective overburden stress, respectively; and r_d is a stress reduction factor. Curves showing the range and average values of r_d are plotted in Figure 1. For noncritical projects such as hazard screening, the following equations

may be used to estimate average values of r_d for use in Equation 1:

$$r_d = \begin{cases} 1.0 - 0.00765z & z \leq 9.2\text{m} \\ 1.174 - 0.0267z & 9.2 < z \leq 23\text{m} \\ 0.744 - 0.008z & 23 < z \leq 30\text{m} \\ 0.50 & z > 30\text{m} \end{cases} \quad (2)$$

where z is depth below ground surface in meters. Average values of r_d estimated from these equations are plotted on Figure 1.

Several procedures have been applied to determine CRR. As noted above, field tests have become the state-of-the-practice for routine investigations to avoid the difficulties associated with sampling and testing. Accordingly, as part of the general consensus recommendations from the 1996 workshop (see Youd and Idriss, 1997), four field tests were recommended for general use in evaluating liquefaction resistance for engineering practice. These are: (1) standard penetration test (SPT), (2) cone penetration test (CPT), (3) measurement of shear-wave velocity (V_s), and (4) Becker



Co-authors of Papers Presented

R. Boulanger, University of California, Davis

R. Kayen, U.S. Geological Survey, Menlo Park

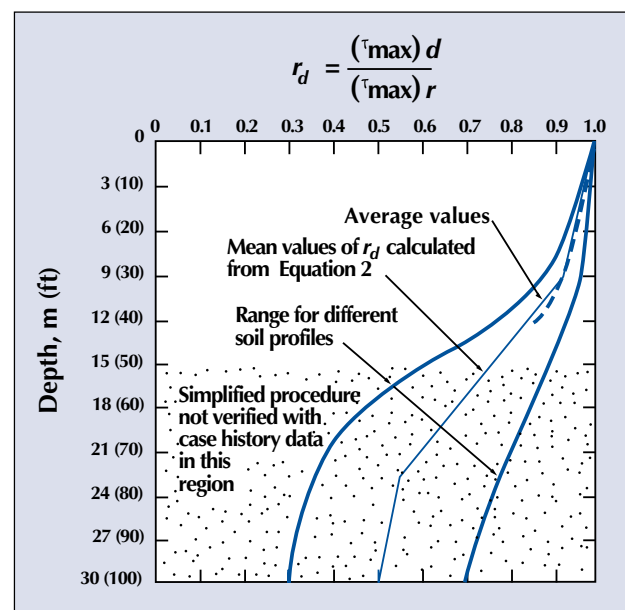
S. Noble, DOWL Engineers, Anchorage

R. Olson, U.S. Army Engineers Waterways Experiment Station

C. Wride, University of Alberta, Edmonton

Reviewers of the Workshop Proceedings

D. Anderson, CH2M-Hill
T. Blake, Fugro-West



■ Figure 1. r_d versus Depth Curves Developed by Seed and Idriss (1971) with Added Mean Value Lines from Equation 2

penetration test (BPT) for gravelly sites. The advantages and disadvantages of each test are listed in Table 1. A conscientious attempt was made to correlate liquefaction resistance criteria from various tests to provide generally consistent results, no matter which test is employed and independent of the testing conditions. Some recommendations and considerations for each test are briefly discussed in the following.

Standard Penetration Test (SPT)

Criteria for evaluating liquefaction resistance based on SPT blow counts are largely embodied in the CSR versus $(N_1)_{60}$ plot as shown in Figure 2. Conservatively drawn CRR curves separate data indicative of liquefaction from data indicative of nonliquefaction for various fines contents. The CRR curve for magnitude 7.5 earthquakes and for fines contents less than 5% is the basic

penetration criterion for a simplified procedure and is referred to as the “simplified base curve.” A recommended adjustment to this plot was to modify the trajectory of the simplified base curve at low $(N_1)_{60}$ to a projected CRR intercept of about 0.05 as shown in Figure 2. This adjustment reshapes the base curve to achieve consistency with CRR curves developed from cone penetration test (CPT) data and probabilistic analysis by Liao et al. (1988) and Youd and Noble (1997).

Cone Penetration Test (CPT)

Although not as commonly used as the SPT, the CPT is becoming a major tool for delineating soil stratigraphy and for conducting preliminary evaluations of liquefaction resistance. Criteria have been developed for calculating liquefaction resistance (CRR) directly from CPT data (see Robertson and Wride in Youd and Idriss, 1997). These criteria may be applied in practice—provided adequate samples are retrieved, preferably by the SPT procedure—to verify the soil types and liquefaction resistance assigned.

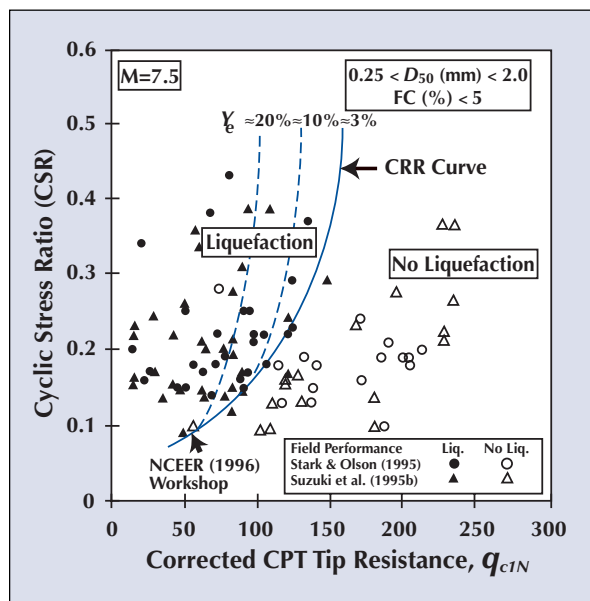
Figure 3 shows the primary chart used for determining liquefaction resistance from CPT data for clean sands. The chart shows CSR plotted against corrected and normalized CPT resistance, q_{cIN} , from sites where liquefaction was or was not observed following past earthquakes. Similarly, a CRR curve defines the boundary between liquefaction and nonliquefaction. This chart is valid for magnitude 7.5 earthquakes and clean, sandy soil. The figure also shows that cyclic shear strain and ground deformation potential at liquefiable sites decrease as penetration resistance increases (dashed curves).

■ Table 1. Comparison of Advantages and Disadvantages of Various Field Tests

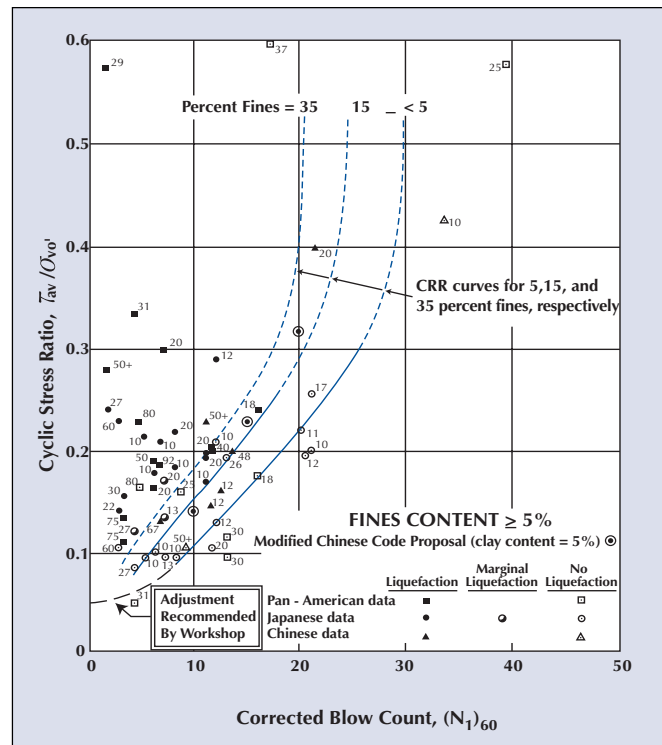
Feature	Test Type			
	CPT	SPT	V_s	BPT
Number of test measurements at liquefaction sites	Abundant	Abundant	Limited	Sparse
Type of stress-strain behavior influencing test	Drained, large strain	Partially drained, large strain	Small strain	Partially drained, large strain
Quality control and repeatability	Very good	Poor to good	Good	Poor
Detection of variability of soil deposits	Very good	Good	Fair	Fair
Soil types in which test is recommended	Non-gravel	Non-gravel	All	Primarily gravel
Test provides sample of soil	No	Yes	No	No
Test measures index or engineering property	Index	Index	Engineering property	Index

Because the CPT equipment and procedures are less variable than those for the SPT, fewer corrections are required. Nevertheless, corrections are still required for overburden pressure and grain characteristics. These corrections are discussed in detail in papers by Robertson and Wride, and Olsen, in Youd and Idriss (1997).

Finally, theoretical as well as laboratory studies indicated that cone resistance is influenced by softer or stiffer soil layers above or below the cone tip. It was observed that the CPT did not usually measure the full penetration resistance in thin sand layers sandwiched between layers of softer soils. Based on an elastic solution, Vreugdenhil et al. (1994) developed a procedure for estimating full cone penetration resistance of thin, stiff layers contained within softer strata. Robertson and Fear (1995) further suggested a correction factor for cone resistance, K_H , as a function of layer thickness as shown in Figure 4.



■ Figure 3. Recommendations for Calculating CRR and CPT Data Along with Empirical Liquefaction Data (after Youd and Idriss, 1997)



■ Figure 2. Simplified Base Curve Recommended for Calculating CRR from SPT Data Along with Empirical Liquefaction Data (after Youd and Idriss, 1997)

Shear Wave Velocity, V_s

Several simplified procedures have been proposed for the use of field measurements of small-strain shear wave velocity, V_s , to assess liquefaction resistance of granular soils. The advantages of using V_s are that (1) it can be accurately measured in-situ using a number of techniques such as crosshole and downhole seismic tests, the seismic cone penetration test, or spectral analysis of surface waves, (2) measurements are possible in soils that are difficult to penetrate with CPT and SPT, (3) measurements can be performed in small laboratory

specimens allowing direct comparison between laboratory and field behavior, and (4) it is directly related to small-strain shear modulus. Two significant limitations of using V_s in liquefaction hazard evaluations are that seismic wave velocity measurements are made at small strains whereas liquefaction is a large strain phenomenon, and seismic testing does not provide samples for classification of soils and identification of nonliquefiable soft clay-rich soils. A paper by Andrus and Stokoe (Youd and Idriss, 1997) reviews current simplified procedures for evaluating the liquefaction resistance of granular soil deposits using small-strain shear wave velocity.

Becker Penetration Tests (BPT)

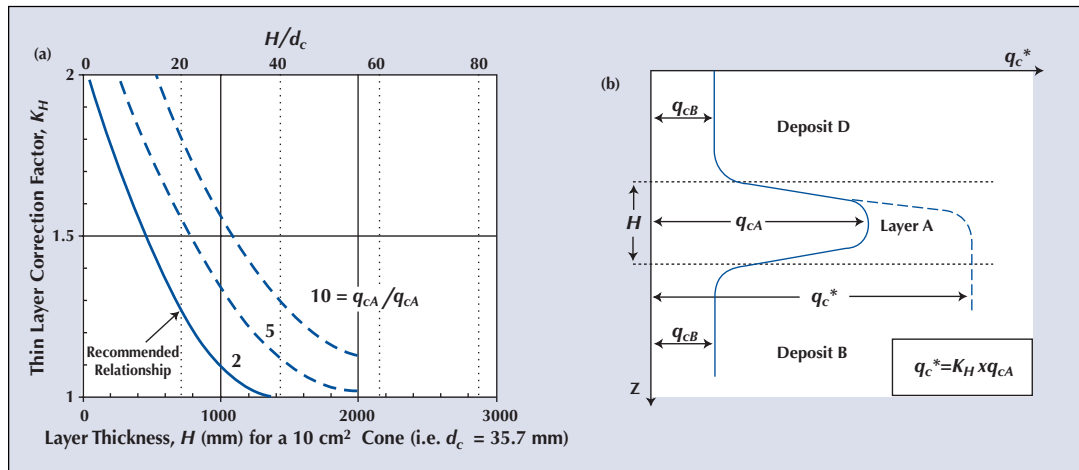
Liquefaction resistance of non-gravelly soils has been evaluated primarily through CPT, SPT and occasionally with V_s measurements. However, CPT and SPT are not generally reliable in gravelly soils as large gravel particles may interfere with the normal deformation of soil materials around the penetrometer, increasing penetration resistance. Therefore, the Becker penetration

test (BPT) has become an effective tool using large-diameter penetrometers. The BPT consists of a 3 m long double-walled casing driven into the ground with a double-acting diesel-driven pile hammer. The BPT resistance is defined as the number of blows required to drive the casing through an increment of 300 mm.

The BPT is not correlated directly with liquefaction resistance, but is used to estimate equivalent SPT blow counts through empirical correlations. The equivalent SPT blow count is then used to estimate liquefaction resistance. However, studies have shown that SPT blow counts can only be roughly estimated from BPT measurement due to deviations in hammer energy for which Harder and Seed (1986) developed an energy correction procedure based on measured bounce-chamber pressure, and friction along the driven casing and its influence on the penetration resistance.

Workshop Conclusions

In addition to discussing the various tests described above, workshop participants examined magnitude scaling factors; corrections for high



■ Figure 4. Thin-layer Correction Factor, K_H , for Determination of Equivalent Thickness-layer CPT Resistance (modified from Robertson and Fear, 1995)

overburden pressures, static shear stresses and age of deposit; seismic factors, such as magnitude and peak acceleration; and energy-based criteria and probabilistic analyses. General consensus recommendations included the following (see Youd and Idriss, 1997):

- Consensus criteria for evaluating liquefaction resistance were developed for SPT, CPT, shear wave velocity and BPT tests.
- Two or more test procedures should be applied at each site to assure both adequate definition of soil stratigraphy and consistent evaluation of liquefaction resistance is attained.
- New sets of magnitude scaling factors are recommended for engineering practice. These factors are greater than those used previously for earthquakes with magnitude less than 7.5. The new factors yield safe but less conservative estimates of liquefaction resistance.
- Evaluating liquefaction resistance beneath sloping ground or embankments is not well understood at this time.
- Moment magnitude, M_w , should be used as an estimate of earthquake size for liquefaction resistance calculations.
- The preferred procedure for estimating peak acceleration is to apply attenuation relationships consistent with soil conditions at a given site.

Developing a Screening Guide

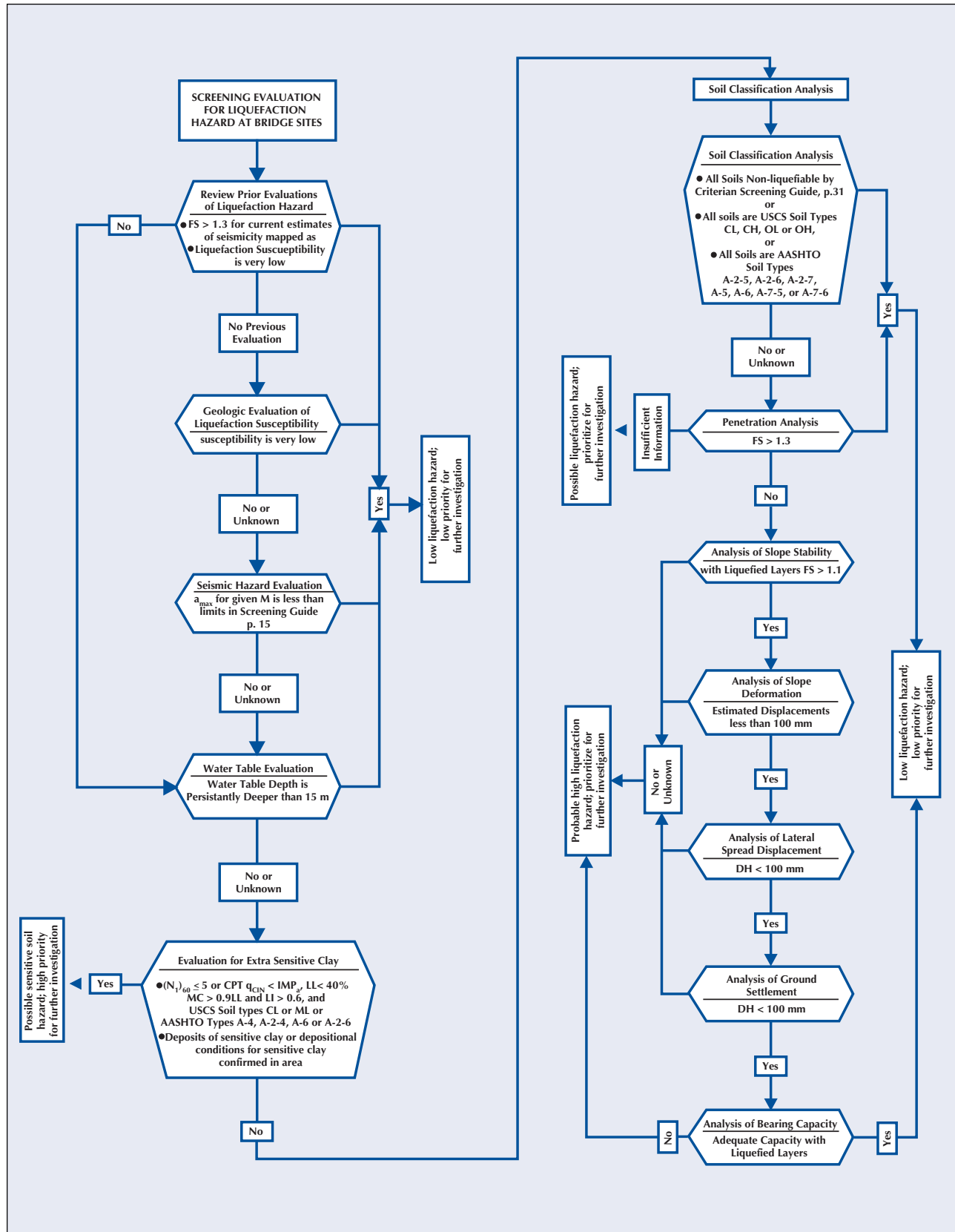
Liquefaction does not occur randomly in natural deposits but is limited to a rather narrow range of seismic, geologic, hydrologic, and soil

environments. Taking advantage of relationships between these environments and liquefaction susceptibility, a screening guide was developed which guides geotechnical engineers in conducting rapid assessments of liquefaction hazard. The guide presents a systematic application of standard criteria for assessing liquefaction susceptibility, evaluating ground displacement potential, and assessing the vulnerability of bridges to liquefaction-induced damage. The screening proceeds from least complex, time-consuming and data-intensive evaluations to the more complex, time-consuming, and rigorous analyses. Thus, many bridge sites can be evaluated and classified as low hazard with very little time and effort. Only bridge sites with significant hazard need to be evaluated with the more sophisticated and time-consuming procedures.

The screening guide is conservative—that is, at each juncture in the screening process, uncertainty is weighed on the side that liquefaction and ground failure could occur. Thus, a conclusion that liquefaction and detrimental ground displacement are very unlikely is a much more certain conclusion than the converse outcome—that liquefaction and detrimental ground displacements are possible. This conservatism leads to the corollary conclusion that additional investigation is more likely to reduce the estimated liquefaction hazard than increase it.

The principal steps and logic path for the screening procedure are listed in Figure 5. In assessing liquefaction hazard, the recommended procedure is to start at the top of the logic path, perform the required analyses for each step, and

“The simplified procedures and the screening guide are not highway specific, i.e., they can be used for generic liquefaction evaluation purposes for a wide variety of structures.”



■ Figure 5. Flow Diagram Showing Steps and Criteria for Screening of Liquefaction Hazard for Highway Bridges

proceed downward until the bridge is classified into one of four categories:

1. Confirmed high liquefaction and ground failure hazard—very high priority for further investigation and possible mitigation;
2. Confirmed liquefaction susceptibility but unknown ground failure hazard—high priority for further investigation;
3. Insufficient information to assess liquefaction susceptibility—prioritized for further investigation;
4. Low liquefaction hazard—low priority for further investigation.

If there is clear evidence that liquefaction or damaging ground displacements are very unlikely, the site is classed as “low liquefaction hazard and low priority for further investigation,” and the evaluation is complete for that site. If the available information indicates a likely hazard, or if the data are inadequate or incomplete, the site is classed as having possible liquefaction hazard, and the screening proceeds to the next step. If the available site information is insufficient to complete a liquefaction hazard analysis, then simplified seismic, topographic, geologic, and hydrologic criteria are used to prioritize the site for further investigation. The complete details of the procedure are given by Youd (1998).

Conclusions and Recommendations for Future Research

The consensus approach to liquefaction evaluation is being referenced in many new documents for geotechnical engineers throughout

the U.S. The updated “simplified procedure” has been recommended in both the city and county of Los Angeles as the preferred approach to use to assess liquefaction potential at a given site. In a companion effort, liquefaction hazard maps have been produced for southern California and the California Division of Mines and Geology will produce similar maps for northern California. Taken together, the updated maps and the updated “simplified procedure” will greatly enhance the accuracy of liquefaction hazard assessments. Accurate assessments will allow retrofit projects to be prioritized according to potential impact and new projects to be designed to accommodate potential hazards.

Finally, there are issues that should be further investigated and addressed in the liquefaction evaluation procedures. The evaluation of liquefaction resistance beneath sloping ground or embankments (slopes greater than 6%) is not well understood. Hence, such evaluations are beyond the applicability of the simplified procedure, and further studies are required to develop procedures for the evaluation of liquefaction resistance beneath sloping ground. Moreover, it is known that liquefaction resistance increases with soil plasticity. However, more research is needed in order to quantify this relationship. Recently, probabilistic methods have been used in some risk analyses, but are still outside the mainstream of standard practice. Similarly, seismic energy passing through a liquefiable layer can be potentially adopted as a liquefaction resistance criteria. This concept is relatively new and also requires further research.

“The updated ‘simplified procedure’ has been recommended in both the city and county of Los Angeles as the preferred approach to use to assess liquefaction potential at a given site.”

References

- Kachadoorian, R., (1968), *Effects of the Earthquake of March 27, 1964, on the Alaska Highway System*, U.S. Geological Survey, Professional Paper 545-C.
- Liao, S.S.C., Veneziano, D., Whitman, R.V., 1988, "Regression Models for Evaluating Liquefaction Probability," *Journal of Geotechnical Engineering*, Vol. 114, No. 4, pp. 389-411.
- McCulloch, D.S. and Bonilla, M.G., (1970), *Effects of the Earthquake of March, 1964, on the Alaska Railroad*, U.S. Geological Survey, Professional Paper 545-D.
- National Research Council (NRC), (1985), *Liquefaction of Soils During Earthquakes*, National Academy Press, Washington, D.C.
- Robertson, P.K. and Fear, C.E., (1995), "Liquefaction of Sands and Its Evaluation," *Proceedings of the First International Conference on Earthquake Geotechnical Engineering*, Keynote Lecture, Tokyo, Japan.
- Seed, H.B., (1979), "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes," *Journal of Geotechnical Engineering*, ASCE, Vol. 105, No. GT2, pp. 201-255.
- Seed, H.B. and Idriss, I.M., (1971), "Simplified Procedure for Evaluation Soil Liquefaction Potential," *Journal of the Soil Mechanics and Foundation Division*, ASCE, Vol. 97, No. SM9, pp. 1249-1273.
- Seed, H.B. and Idriss, I.M., (1982), *Ground Motions and Soil Liquefaction During Earthquakes*, Earthquake Engineering Research Institute Monograph.
- Seed, H.B., Tokimatsu, K., Harder, L.F. and Chung, R.M., (1985), "The Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations," *Journal of Geotechnical Engineering*, ASCE, Vol. 111, No. 12, pp. 1425-1445.
- Vreugdenhil, R., Davis, R. and Berrill, J., (1994), "Interpretation of Cone Penetration Results in Multilayered Soils," *International Journal for Numerical Methods in Geomechanics*, Vol. 18, pp. 585-599.
- Youd, T.L., (1993), *Liquefaction-Induced Damage to Bridges*, Transportation Research Record, No. 1411, pp. 35-41.
- Youd, T.L., (1998), *Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites*, Technical Report MCEER-98-0005, Multidisciplinary Center for Earthquake Engineering Research, Buffalo New York.
- Youd, T.L. and Idriss, I.M., eds, (1997), *Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*, Technical Report NCEER-97-0022, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, New York.
- Youd, T.L. and Noble, S.K., (1997), "Liquefaction Criteria Based on Statistical and Probabilistic Analyses," *Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*, Technical Report NCEER-97-0022, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, New York.

Continue with next chapter
