Discussion of "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils" by T. L. Youd, I. M. Idriss, Ronald D. Andrus, Ignacio Arango, Gonzalo Castro, John T. Christian, Richardo Dobry, W. D. Liam Finn, Leslie F. Harder Jr., Mary Ellen Hynes, Kenji Ishihara, Joseph P. Koester, Sam S. C. Liao, William F. Marcuson III, Geoffrey R. Martin, James K. Mitchell, Yoshiharu Moriwaki, Maurice S. Power, Peter K. Robertson, Raymond B. Seed, and Kenneth H. Stokoe II

October 2001, Vol. 127, No. 10, pp. 817–833.

Robert Pyke, M.ASCE[1]

[1]Consulting Engineer, 1076 Carol Lane, Suite 136, Lafayette, CA 94549.

The writers are to be commended for their efforts in trying to forge a consensus opinion out of a large number of experts, but the resulting paper unfortunately illustrates some of the difficul-'ies of engineering by committee. While the writers' response to ome of the comments below may be that the points in question were outside the scope of the workshops convened by the writers, because this paper will be widely read and quoted as a reference, the discusser would welcome brief comment on these points in their closure.

1. It is surprising that more emphasis is not placed on the geologic setting and the type of soil deposits being considered. The authors note that the simplified procedure for evaluating the liquefaction resistance of soils that is described in the paper is applicable only to sites on level to gently sloping terrain, underlain by Holocene alluvial or fluvial sediment at depths less than 15 m, and later in the paper they also note that liquefaction resistance increases markedly with geologic age. However, many readers are likely to gloss over these limitations and a better way of stating the problem is that liquefaction with engineering consequences is largely, if not wholly, confined to hydraulic fills and very recent alluvial and fluvial deposits. Any evaluation of the potential for liquefaction should start by asking the question: is there any precedent for liquefaction of this class of deposit in this region? If the answer is no, then the potential for future occurrences is very small.

2. Likewise, the paper makes it clear that the simplified procedure described in the paper is limited to predicting the occurrence of liquefaction as defined by the observation of sand boils, fissures, or lateral spreads. In many of the case histories used there may have been no consequences to engineered structures. While evaluation of these consequences may have been outside e scope of the workshops, because the paper lacks guidance on this issue it will be subject to misuse in practice. It would be desirable to at least add simple guidance such as quoting the findings of Bartlett and Youd (1995) who found that, with few exceptions, lateral spreading from liquefaction is restricted to sediments having normalized SPT blowcounts of no more than 15, or otherwise noting that engineering consequences are likely to be minimal if the normalized SPT blowcounts exceed 15.

3. The practice of doing curve fits to uncertain empirical data "for convenience in programing speadsheets and other electronic aids" is generally to be deplored. No matter what limitations may be included in the paper or otherwise intended by the authors, this only serves to encourage the cookbook approach, which is seen with increasing frequency in practice in which questionable data are entered into a speadsheet or computer program and the numerical result is taken as gospel. Users of procedures such as those described in the paper should generally be encouraged to reduce the data by hand so that they consider every data point and, in those cases where liquefaction turns out to be a real issue, to familiarize themselves with the pertinent case histories and to use them directly in their evaluation.

4. The use of independent curve fits to a number of empirical relationships is questionable. Given the status of this field of study in 1996, it may well have been preferable to devote the available resources to adding more and better data to the catalog of case histories and processing that data in a uniform manner rather than relying on piecemeal expert opinions. Fortunately, this has now been done by Seed et al. (2001) and, in the discusser's opinion, the relationships of Seed et al. should now take precedence over those in this paper.

5. Regardless of whether one uses the relationships in this paper or the improved relationships of Seed et al., the simplified procedure has additional limitations that normally tend to make its use conservative. A notable general limitation is the assumption that penetration resistance is a good indicator of the potential for liquefaction. Seed (1979) listed five factors which were known, or could reasonably be assumed, to have a similar effect on penetration resistance and the potential for liquefaction but these were never intended to be equalities. In particular, two of these factors, overconsolidation and aging, are likely to have a much greater effect on increasing the resistance to liquefaction than they do on penetration resistance. Thus soils that are even lightly overconsolidated or more than several decades old may have a greater resistance to liquefaction than indicated by these standard relationships, which are heavily weighted by data from hydraulic fills and very recent streambed deposits. Additionally, the simplified procedure assumes that soils are horizontal stratified. In deposits such as alluvial fans where soils from successive episode of deposition tend to be lensed rather than layered, cleaner and looser sands often form a soft inclusion that is surrounded by a stiffer matrix of clayey sands. In such a deposit the strains in the potentially liquefiable material will be controlled by the deformation of the stiffer matrix and the stresses developed in the softer material will be much less than those calculated using the simplified procedure.

6. These limitations might be judged pedantic were it not for the fact that routine use of the simplified procedure is consistently

predicting liquefaction where observations do not suggest any evidence of the phenomenon. As a particular example the discusser has been called in to review a number of studies conducted in the alluvial fan deposits which surround San Francisco Bay where the simplified procedure has predicted liquefaction for levels of shaking felt in the 1989 Loma Prieta earthquake when, in fact, liquefaction was not observed. The application of the simplified procedure in these cases has been overly conservative partly because blowcounts in clayey soils are commonly included in the analysis rather than being discarded, but the two factors listed in item 5 above are likely also significant. Silva and Costantino (1999) have made similar findings in Kobe, Japan. Using relatively well constrained estimates of the peak acceleration they found that the simplified procedure predicted much more widespread liquefaction than was observed.

References

Bartlett, S. F., and Youd, T. L. (1995). "Empirical prediction of liquefaction-induced lateral spreading." *J. Geotech. Eng.*, 121(4), 316–329.

Seed, H. B. (1979). "Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes." *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.*, 105(2), 201–255.

Seed, R. B., Cetin, K. O., Moss, R. E. S., Kammerer, A. M., Wu, J., Pestana, J. M., and Riemer, M. F. (2001). "Recent advances in soil liquefaction engineering and seismic site response evaluation." *Proc., 4th Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dynamics*, San Diego, Paper No. SPL-2.

Silva, W. J., and Costantino, C. (1999). "Assessment of liquefaction potential for the 1995 Kobe Japan earthquake including finite source effects." *Report prepared for the U.S. Army Engineer Waterways Experiment Station.*

Closure to "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils" by T. L. Youd, I. M. Idriss, Ronald D. Andrus, Ignacio Arango, Gonzalo Castro, John T. Christian, Richardo Dobry, W. D. Liam Finn, Leslie F. Harder Jr., Mary Ellen Hynes, Kenji Ishihara, Joseph P. Koester, Sam S. C. Liao, William F. Marcuson III, Geoffrey R. Martin, James K. Mitchell, Yoshiharu Moriwaki, Maurice S. Power, Peter K. Robertson, Raymond B. Seed, and Kenneth H. Stokoe II

October 2001, Vol. 127, No. 10, pp. 817–833.

T. L. Youd, M.ASCE[1]; I. M. Idriss, F.ASCE[2]; Ronald D. Andrus[3]; Ignacio Arango[4]; Gonzalo Castro[5]; John T. Christian[6]; Richardo Dobry[7]; W. D. Liam Finn[8]; Leslie F. Harder Jr.[9]; Mary Ellen Hynes[10]; Kenji Ishihara[11]; Joseph P. Koester[12]; Sam S. C. Liao[13]; William F. Marcuson III[14]; Geoffrey R. Martin[15]; James K. Mitchell[16]; Yoshiharu Moriwaki[17]; Maurice S. Power[18]; Peter K. Robertson[19]; Raymond B. Seed[20]; and Kenneth H. Stokoe II[21]

[1]Professor, Brigham Young Univ., Provo, UT 84602.
[2]Professor, Univ. of California at Davis, Davis, CA 95616.
[3]Professor, Clemson Univ., Clemson, SC 29634-0911; formerly, National Institute of Standards and Technology, Gaithersburg, MD.
[4]Bechtel Corporation, San Francisco, CA 94119-3965.
[5]PhD, GEI Consultants, Inc., Winchester, MA 01890.
[6]PhD, Engineering Consultant, Waban, MA 02468-1103.
[7]Professor, Rensselaer Polytechnic Institute, Troy, NY 12180.
[8]Professor, Univ. of British Columbia, Vancouver BC, Canada.
[9]California Dept. of Water Resources, Sacramento, CA 94236-0001.
[10]U.S. Army Engineering Waterway Experiment Station, Vicksburg, MS 39180.
[11]Professor, Scientific Univ. of Tokyo, Tokyo, Japan.
[12]U.S. Army Engineering Waterway Experiment Station, Vicksburg, MS 39180.
[13]Parsons Brinckerhoff, Boston, MA 02116.
[14]PhD, U.S. Army Engineering Waterway Experiment Station, Vicksburg, MS 39180.
[15]Professor, Univ. of Southern California, Los Angeles, CA 90089-2531.
[16]Professor, Virginia Polytechnic Institute, Blacksburg, VA 24061.
[17]PhD, Principle, Geomatrix Consultants, Santa Ana, CA 94612.
[18]Geomatrix Consultants, Oakland, CA 94612.
[19]Professor, Univ. of Alberta, Edmonton AB, Canada.
[20]Professor, Univ. of California, Berkeley, CA 94720.
[21]Professor, Univ. of Texas at Austin, Austin, TX 78712.

The writers (workshop participants) wish to thank Dr. Pyke for his thoughtful comments on procedures for evaluating liquefaction resistance of soils. We generally agree with Dr. Pyke's comments, but add the following commentary to further amplify our discussions and considerations of these issues.

Geologic Setting

We agree that geologic setting and geologic criteria provide very useful information for screening or preliminary assessment of liquefaction susceptibility. However, to fully evaluate liquefaction resistance, we believe that site-specific investigations are required. A critical question is, which procedure is most reliable in instances where assessments from geologic criteria yield conclusions that differ with those arrived at from site-specific investigations. The consensus of the workshop participants is that conclusions based on site-specific analyses are more reliable. That reliability is greater in both instances whether site-specific investigations indicate that recent sediments are determined to be nonliquefiable or older sediments are determined to be liquefiable. In particular, we believe that the discusser's comment that "liquefaction with engineering consequences is largely, if not wholly, confined to hydraulic fills and very recent alluvial and fluvial deposits" is too restrictive. There are a number of important case histories of liquefaction of sediments deposited in early Holocene and late Pleistocene time. For example, many of spectacular liquefaction effects generated by the 1811–1812 New Madrid earthquakes in lowlands near the Mississippi River occurred in late Wisconsin (late Pleistocene) braided stream deposits (Obermeier 1989). Similarly, many sediments that liquefied during the 1886 Charleston, South Carolina earthquake were deposited during the Pleistocene era with dates of deposition ranging from 85,000 to 230,000 years before the present (Martin and Clough 1994). Other examples are lateral spreads that pervasively developed in gravelly sediment at the edges of alluvial fans in the Lost River Valley during the 1983 Borah Peak, Id. These sediments were also deposited during late Pleistocene time (Andrus and Youd 1987). Although nearly all of the case history data compiled by the late Professor H. B. Seed and his associates were from fills and late

Holocene sediments, and hence, the simplified procedure is most applicable to these sediments. As discussed in the paper, some consideration should be given to increase of liquefaction resistance with age for early Holocene and older deposits. Unfortunately, as we note in the paper, the influence of aging on liquefaction resistance has been proven, but not sufficiently quantified to allow numerical correction for this effect in engineering practice.

Consequences of Liquefaction

The discusser properly notes, and it is clearly stated in the paper, that the scopes of the workshops did not include consideration of ground deformation, displacement or other consequences of liquefaction. The assessment of liquefaction resistance is only a first step in assessing liquefaction hazard. A second step is an assessment of possible consequences of liquefaction, including lateral spread, flow failure, loss of bearing strength, etc. Assessing consequences requires additional information, such as ground slope, thickness and extent of the liquefiable layer, and specialized analysis procedures. Several procedures have been proposed to evaluate consequences of liquefaction, including the procedures of Bartlett and Youd (1995) and Youd et al. (2002) for estimating lateral spread displacement. Practicing geotechnical engineers should be well aware of the possible consequences of liquefaction and should be able to apply pertinent procedures for analyzing these effects. Although some unknowledgeable individuals may misuse the procedures recommended in the summary paper, we believe that such misuse in more a problem of education than of lack of comprehensive guidance in our workshop report.

Equations

The issue of approximating several curves in the procedure with equations received considerable deliveration at the 1996 Workshop. Several participants initially agreed with the discusser that providing approximate equations to quantify pertinent curves could lead to "black-box" approaches by uninformed investigators. Undoubtedly some abuse of the procedure has and will be made by such individuals. Other workshop participants argued that enterprising engineers are going to numerically approximate the existing curves anyway and that the workshop should provide expert guidance as to the best models. Another argument raised is that considerable time and tedious work is required to evaluate liquefaction resistance by hand calculation. Although such exercises may give better intuitive feeling for the simplified procedure, large amounts of penetration data, such as that provided in digitized CPT logs, require untenable amounts of time to analyze by hand calculation. If calculations could be made quickly with computer aided analyses, more time could be spent on parametric and sensitivity analyses, which in turn could provide better background for engineering judgments that must eventually be made. Such analyses may also generate better intuitive understanding than hand calculation. After considerable discussion, consensus was achieved that the workshop participants should provide the best numerical approximations possible with the current (1996) state of knowledge. Thus, equations were prepared and published as part of the workshop report. We feel that this decision was correct and is in the best interest of the profession.

Use of Workshop Time

Improving the case history data base is better done by individual investigators, who can take adequate time to research and evaluate each data point. Proposed improvements to the state of the art can be beneficially reviewed by panels of experts, as we did at the 1996 and 1998 workshops. As the discusser points out, some progress in improving the case history data set has occurred through the individual studies of Seed et al. (2001). To have attempted such improvements by committee in a two-day workshop, however, would not likely have been a productive use of our time.

Age, Overconsolidation, and Lenticular Deposition

The workshop participants generally agree with the discusser's comments. Additional research is needed to quantify effects of aging and overconsolidation and to provide correction factors for these important conditions. The workshop participants agreed in 1996 that the influence of these factors had not been adequately quantified. However, ignoring aging and overconsolidation, as is commonly done in engineering practice, is conservative; that is, ignoring these factors is not likely to lead to over estimation of liquefaction resistance. We add an additional note here that Andrus and Stokoe (2000) have introduced a correction for the influence of age as part of the shear-wave procedure. A related important issue, which was not addressed at the workshop because of the limited scope, is whether aging and overconsolidation increase postliquefaction shear resistance of soils. That issue also needs more research.

With respect to lenses of liquefiable material contained within a stiffer soil matrix, we believe that the discusser's assessment is correct. In such instances, the stiffness of surrounding soil may prevent development of sufficient shear strains in the lense to generate large excess pore water pressers and liquefaction of the enclosed sediment.

Overly Conservative Proclivity of the Simplified Procedure

Again, the workshop participants agree with the discusser's comments. Because of conservativeness built into the core procedure and the fact that local site factors strongly affect development of surface effects, the simplified procedure should be expected to overestimate observed liquefaction effects at many sites. In particular, surface effects, such as sand boils and fissures, may not be generated at level sites underlain by thin or lenticular liquefiable layers. Another case in which surface manifestations of pore pressures at depth may not be observed is when the loose soils are overlain by more pervious soils and/or the groundwater level is deep. Conversely, use of surface effects as a diagnostic measure may also be misleading. For example, the change of character and lengthening of period of recorded ground motions at the Treasure Island instrument site during the Loma Prieta earthquake has been interpreted as a clear indication that soil softening and liquefaction occurred beneath that locality. No sand boils, ground fissures, or other surface evidences of liquefaction, however, were observed within a hundred or so meters of the instrumented site. Thus, the use of surface effects as a diagnostic test for liquefaction at depth is also an imperfect measure. Again, knowledgeable engineers must understand these various nuances associated with liquefaction behavior to correctly assess liquefaction hazard.

Errata

The following errors occurred in the published paper:

1. Eq. (25), p. 827, should read $\mathrm{MSF}=(M_w/7.5)^{-3.3}$.
2. In application, $(N_1)_{60cs}$ values should be used in Eq. (4).

References

Andrus, R. D., and Stokoe, K. H. (2000). "Liquefaction resistance of soils from shear-wave velocity." *J. Geotech. Geoenviron. Eng.*, 126(11), 1015–1025.

Andrus, R. D., and Youd, T. L. (1987). "Subsurface investigation of a liquefaction induced lateral spread, Thousand Springs Valley, Idaho." *Miscellaneous Paper No. GL-87-8*, U.S. Army Corps of Engineers, 133 pp.

Bartlett, S. F., and Youd, T. L. (1995). "Empirical prediction of liquefaction-induced lateral spreading." *J. Geotech. Eng.*, 121(4), 316–329.

Martin, J. R., and Clough, G. W. (1994). "Seismic parameters from liquefaction evidence." *J. Geotech. Eng.*, 120(8), 1345–1361.

Obermeier, S. F. (1989). "The New Madrid earthquakes; An engineering–geologic interpretation of relict liquefaction features." *Professional Paper No. 1336-B*, U.S. Geological Survey, 114 pp.

Seed, R. B., Cetin, K. O., Moss, R. E. S., Kammerer, A. M., Wu, J., Pestana, J. M., and Riemer, M. F. (2001). "Recent advances in soil liquefaction engineering and seismic site response evaluation." *Proc., 4th Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dynamics, Paper No. SPL-2*, San Diego.

Youd, T. L., Hansen, C. M., and Bartlett, S. F. (2002). "Revised multilinear regression equations for prediction of lateral spread displacement." *J. Geotech. Geoenviron. Eng.*, 128(12), 1007–1017.