US Army Corps
of Engineers



GEOTECHNICAL LABORATORY

MISCELLANEOUS PAPER GL-87-24

# LIQUEFACTION SUSCEPTIBILITY OF FINE-GRAINED SOILS PRELIMINARY STUDY REPORT

by

Nien-Yin Chang

Department of Civil and Urban Engineering
University of Colorado at Denver
1100 Fourteenth Street
Denver, Colorado 80202

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

September 1987

Final Report



Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under CWIS Work Unit 32256
Contract No. DACW39-84-M-1230

Monitored by Geotechnical Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39180-0631

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A187 581

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY<br>2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S) | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>Miscellaneous Paper GL-87-24 |
| 6a. NAME OF PERFORMING ORGANIZATION<br>(See Reverse)<br>6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION<br>USAEWES<br>Geotechnical Laboratory |
| 6c. ADDRESS (City, State, and ZIP Code)<br>1100 Fourteenth Street<br>Denver, CO 80202 | 7b. ADDRESS (City, State, and ZIP Code)<br>PO Box 631<br>Vicksburg, MS 39180-0631 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers<br>8b. OFFICE SYMBOL (If applicable) DAEN-RD | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>Contract No. DACW39-84-M-4230 |
| 8c. ADDRESS (City, State, and ZIP Code)<br>Washington, DC 20314-1000 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. 901311 / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO. CWIS 32255 |

11. TITLE (Include Security Classification)
Liquefaction Susceptibility of Fine-Grained Soils--Preliminary Study Report

12. PERSONAL AUTHOR(S)
Chang, Nien-Yin

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final Report | FROM Sep 85 TO Mar 86 | September 1987 | 77 |

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) | |
|---|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Cycle loading resistance | Pore pressure |
| | | | Fine-grained soils | Silty sands |
| | | | Liquefaction potential | Tangshan, China, earthquake |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Soil liquefaction, a hazardous ground failure induced by strong motion earthquakes, can cause catastrophic damage to structures such as dams, bridges, power plants, and water-front structures and may involve great losses of life. Examples of liquefaction and resulting damage were observed during the Alaska (1964), Niigata, Japan (1964), and Tangshan, China (1976), earthquakes. Ground failure due to earthquake-induced soil liquefaction may manifest itself as excessive settlement, loss of bearing capacity, sand boiling, and flow slides.

The liquefaction potential of clean sands has been studied extensively for the last two decades. However, case histories revealed that liquefied sands were seldom clean. They may contain various percentages of silt or clay or both. In fact, the Chinese observation in the Tangshan earthquake indicated that some cohesive soils may have liquefied. If this indeed had happened, then structures underlain by fine-grained soils, with a marginal safety factor based on the liquefaction criteria normally applied to sands, may actually be unsafe. Thus
(Continued)

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Joseph P. Koester | 22b. TELEPHONE (Include Area Code) 601-634-2202<br>22c. OFFICE SYMBOL CEWES-GH-R |

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

6a. NAME OF PERFORMING ORGANIZATION (Continued).

Department of Civil and Urban Engineering
University of Colorado at Denver

19. ABSTRACT (Continued).

there is an urgent need for establishing new criteria for the liquefaction susceptibility of soils to include those identified as fine-grained.

The author, Professor N.Y. Chang of the University of Colorado at Denver, visited several Chinese agencies and universities in and near Beijing, China, in the summer of 1985 in an attempt to investigate and verify reported data on the liquefaction of cohesive soils during the Tangshan earthquake of 1976 and to negotiate cooperative research into the problem. This report presents the result of supportive literature review and the findings of the China trip.

## PREFACE

The preparation of this preliminary study report was sponsored by the Office, Chief of Engineers (OCE), US Army Civil Works Investigation Study, "Liquefaction Potential of Fine-Grained Soils," CWIS Work Unit 32255 through US Army Engineer Waterways Experiment Station (WES) under Contract No. DACW39-84-M-4230. The subject investigation was conducted by Professor N. Y. Chang of the University of Colorado at Denver during the period September 1985 to March 1986. The OCE Technical Monitor on this project was Mr. Richard F. Davidson.

The draft of this report was prepared by Professor Chang with the valuable assistance of Messrs. J. W. Chen and H. H. Chiang, both candidates for their Ph.D.'s in Civil Engineering from the University of Colorado at Denver. The investigation and report preparation were conducted under the general direction of Dr. William F. Marcuson III, Chief, Geotechnical Laboratory (GL), and Dr. Arley G. Franklin, Chief, Earthquake Engineering and Geophysics Division (EEGD), GL. Mr. Joseph P. Koester, EEGD, GL, was the WES Project Manager and coordinated technical editing and adapted the report for WES publication.

COL Dwayne G. Lee is the present Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

## CONVERSION FACTORS, NON-SI TO SI (METRIC)
## UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| feet | 0.3048 | metres |
| kilograms (force) per square centimeter | 98,066.50 | pascals |
| pounds (force) per square inch | 6,894.757 | pascals |
| pounds (mass) per cubic foot | 16.01846 | kilograms (mass) per cubic metre |

## LIQUEFACTION SUSCEPTIBILITY OF FINE-GRAINED SOILS--PRELIMINARY STUDY REPORT

### PART I: INTRODUCTION

1. Liquefaction, in the context of this report, is a form of ground failure induced by strong earthquakes. When a saturated sand is subjected to an extended period of severe ground shaking, the excess pore water pressure tends to increase. This generation of excess pore water pressure leads to reduction in effective stress and shear strength and eventually causes the ground to liquefy and fail. Earthquake-induced liquefaction ground failure generally takes one or more the following forms: excessive settlement, loss of bearing capacity, sand boils or blows, and flow slides. Liquefaction of foundation soils can cause catastrophic damage to structures like embankment dams, mill or mine tailings dams, nuclear power plants, water-front structures, bridge supports, and various off-shore structures.

2. Case histories of earthquake-induced liquefaction indicate that soils other than uniform clean sands can also liquefy. Several sources report serious liquefaction ground failures caused by the 1976 Tangshan Earthquake in the People's Republic of China (PRC) (Fang, et al. 1981, 1982, 1983; Fu and Tatsuota, 1984; Lee, 1984; Lin et al., 1983; Wang 1979, 1979, 1981, 1981; Wei, et al., 1981; Zhou, 1980, 1981 et al.). Iwasaki, et al. (1981) and Kuribayashi and Tatsuoka (1977) examined six major Japanese earthquakes, namely the Nobi (1891), Tonankai (1944), Fukui (1948), Niigata (1964), Tokachi-Oki (1968) and Miyagi-Ken-Oki (1978) earthquakes and developed procedures for evaluating soil liquefaction potential. Seed and his coworkers were able to piece together evidence and present the probable conditions surrounding the failure of Sheffield Dam in 1925 (Seed, 1968) and the near-failure of the Lower San Fernando Dam in 1971 (Seed, et al., 1973). The seismic failures of South American mine tailings dams in the Chilean Earthquake of 1960 were reported by Dobry and Alvarez (1967). The Alaska and Niigata earthquake-induced liquefaction ground failures were reported by many researchers (Seed and Wilson, 1967; Coulter and Migliaccio, 1966; Kishida, 1966; Koizumi, 1966; Ohsaki, 1966; Seed and Idriss, 1967; Seed, 1968; Donovan and Singh, 1978). It is interesting to note that at all of the above mentioned sites, but for rare

exceptions in Japan, the soils which liquefied contained varying amounts of cohesive or cohesionless silt-and-finer material. Because of the above finding, the liquefaction potential of silty sand and sandy silt was carefully assessed in the following projects: Patoka Dam in Indiana (Marcuson and Gilbert, 1972); water-front structures at Coronado, California (Forrest, Ferritto and Wu, 1981); water-front structures in Canada (Thompson and Emery, 1976); and the Trans-Alaska Pipeline (Donovan and Singh, 1978). The seismic stability of mill tailings dams has also received much attention. Typical mill tailings usually contain substantial amounts of loosely deposited fines and are susceptible to earthquake-induced liquefaction (Dobry, et al., 1967; Ishihara, et al., 1981). Robinson (1977) reported an interesting case study of a tailings dam founded on sandy silts deposited by a previous failure and flow slide. When concern was expressed over the stability of the seafloor off Alaska in the Yukon Prodelta of the Bering Sea, an investigation of the liquefaction potential of ocean floor soils was conducted. All borings recovered silty sands (Clukey, et al., 1980).

3. The geotechnical earthquake engineering profession has devoted a great deal of research effort in the previous two decades to bettering our understanding of the liquefaction characteristics of natural soil deposits and our ability to predict the nature and extent of earthquake-induced liquefaction. Most research efforts have, however, focused on uniform, clean sands or gravels containing little or no fines. Case studies revealed that most liquefied soils contained some fines, whether cohesive or cohesionless. Uniform, clean sands are rarely encountered in natural soil deposits. Soils at previous liquefaction sites were found to have a wide range of gradation characteristics and contain different percentages of fine-grained soils like silts and clays.

4. Chinese observations during the 1976 Tangshan earthquake indicated that some fine-grained and even cohesive soils had in fact liquefied. Should this be true, critical structures, such as embankment dams and nuclear power plants, founded on fine-grained/cohesive soils which were judged safe based on contemporary liquefaction susceptibility criteria may become unsafe under a strong motion earthquake. It becomes obvious, therefore that there is an urgent need for investigating the validity of current liquefaction criteria and establishing a new one, if necessary. The author visited several Chinese agencies and universities in and near Beijing, PRC in the summer of 1985 in an

attempt to investigate and verify reported data on the liquefaction of cohesive soils during the 1976 Tangshan earthquake and to negotiate cooperative research into the problem. This report summarizes the results of a preliminary literature review and the findings from the China visit by the principal investigator, and outlines recommendations for future research into the liquefaction susceptibility of fine-grained or cohesive soils. Correspondence detailing the China visit itinerary and the response of one geotechnical agency to the proposal for cooperative research is included in Appendix A.

## PART II: FACTORS AFFECTING LIQUEFACTION POTENTIAL

5. Factors affecting liquefaction potential have been studied extensively over the past two decades. These factors include density, consolidation pressure, initial stress condition, strain history, sample disturbance, overconsolidation, and grain and gradation characteristics. Seed and Lee (1967) first reported the important effect of the relative density of sand on its liquefaction potential. Seed and Idriss (1971) assumed a linear relationship between relative density and the stress ratio causing initial liquefaction for relative densities below 80 percent. The stress ratio decreases with decreasing density. Peacock and Seed (1968) and Mulilis, et al. (1978) also presented their study results on the density effect.

6. Field observations during the 1964 Niigata earthquake showed that the liquefied zones were usually located at fairly shallow depths (generally less than 50 to 60 feet*) where consolidation pressures were less than 2 $Kg/cm^2$ (Kishida, 1969). Finn, et al. (1971) compiled the results of earlier studies by Lee and Seed (1966, 1967) on the consolidation pressure effect. Peak cyclic pulsating deviatoric stress causing liquefaction was found to increase with increasing confining pressures. Mulilis (1975) and Castro and Poulos (1976) indicated that the pulsating deviatoric stress ratio required to cause liquefaction decreased with increasing confining pressures and the magnitude of decrease was dependent on relative density.

7. Seed, et al. (1975) investigated the effect of the coefficient of lateral earth pressure at rest, $K_o$, defined as the ratio of horizontal stress to vertical stress in situ, and found that the pulsating deviatoric stress causing liquefaction increased with increasing $K_o$. Anisotropic consolidation stress ratio, $K_c$, defined as the ratio of minor principal stress to major principal stress, was investigated by Castro and Poulos (1976), who found that at a higher $K_c$, a specimen actually required a smaller cyclic stress to cause liquefaction. Others have all but discounted anisotropy as an important environmental factor in view of the dominance exhibited by major principal consolidation stress alone (Vaid and Finn, 1979).

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

8. The effect of overconsolidation ratio was investigated by Seed and Peacock (1971) and Ishihara, et al. (1978). They concluded that the liquefaction resistance increased with increasing overconsolidation ratio.

9. The effect of previous cyclic strain history was examined by Finn, et al. (1970), who concluded from their research using a simple shear device that, with previous strain history and without liquefaction, a specimen gained liquefaction resistance at a subsequent cyclic stress level. Conversely, a previously liquefied soil became more susceptible to liquefaction when again subjected to a cyclic test. Seed, et al. (1977) also drew similar conclusions from their studies.

10. Aging tends to increase the liquefaction resistance of a soil deposit. This increase can, at least partially, be attributed to the increase in grain-to-grain contacts and cementation. This may explain why a younger deposit is generally more susceptible to liquefaction than an older one (Youd and Hoose, 1977).

11. The effect of remolding was investigated by Marcuson and Townsend (1976). The shell material from the Fort Peck Dam was tested in this study. It was found that, depending upon sampling methods and specimen reconstruction procedures used, undisturbed samples were as much as 80 percent stronger than reconstituted ones. Silver (1978) studied the Shirano River sand that severely liquefied during 1964 Niigata earthquake and drew a similar conclusion.

# PART III: LIQUEFACTION OF SOILS CONTAINING FINES

## Previous U.S. Research on Gradation and Fine Content Effects

### Gradation Effects

12. In their study on the liquefaction susceptibility, Lee and Fitton (1969) tested uniform clean sands with mean grain size ranging from 0.1 to 13.4 mm and a uniformity coefficient (Cu) of around 1.5. Some silty soils were also tested. The gradations of these soils are shown in Figure 1. Results shown in Figure 2 indicate that uniform fine sands are most vulnerable to liquefaction and the dynamic strength (or liquefaction resistance) increases as the mean grain size increases. Silty and clayey soils also were found to possess higher dynamic strength than uniform fine sands. It should be noted, however, the membrane penetration effects were not accounted for in this study. Vrymoed (1971) studied the dynamic strength of standard Ottawa sand (C-190) mixed with controlled amounts of added silt. Marcuson and Gilbert (1972) as well as Toan and Blakely (1980) assessed the dynamic strength of soils ranging from sandy silts to sands at Patoka Dam and Patea Dam sites respectively. Wong, et al. (1974) examined the liquefaction potential of gravelly soils. Results indicated as the mean grain size increased from about 0.1 mm to 30 mm, the stress required to cause 10 percent axial strain increased about 60 percent, and well-graded soils were somewhat weaker than uniform soils. In their attempt to assess to the seismic safety of waterfront structures, Forrest, Ferrito and Wu (1981) tested fine silty sands with at least 10 percent silt and with the uniformity coefficient of about 4. In the study of a proposed nuclear power station site, Espana, et al. (1981) tested gravelly silty sands with average silt content of approximately 16 percent and mean grain size of 0.37 mm.

13. A systematic study on the effect of gradation on the liquefaction potential of granular soils was carried out by Yeh (1981). Results were included in a final report to the National Science Foundation on "Effects of Grain Size Distribution on Dynamic Properties and Liquefaction Potential of Granular Soils," prepared by Chang and Ko (1982). The mean grain size and the uniformity coefficient of the soil samples tested ranged from 0.149 to 1.68 mm

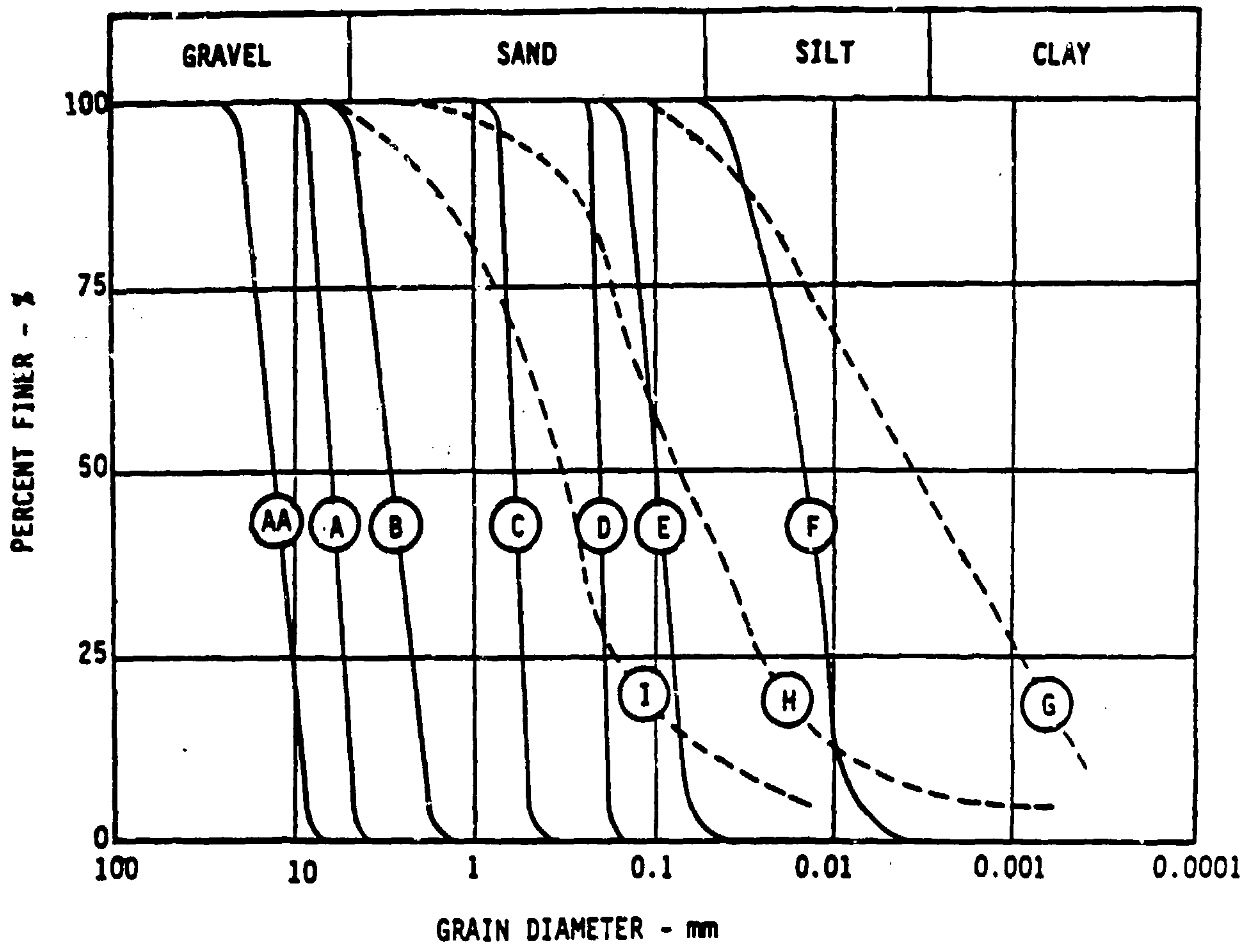



Figure 1. Gradations of soils tested by Lee and Fitton (1969). Copyright ASTM--reprinted with permission

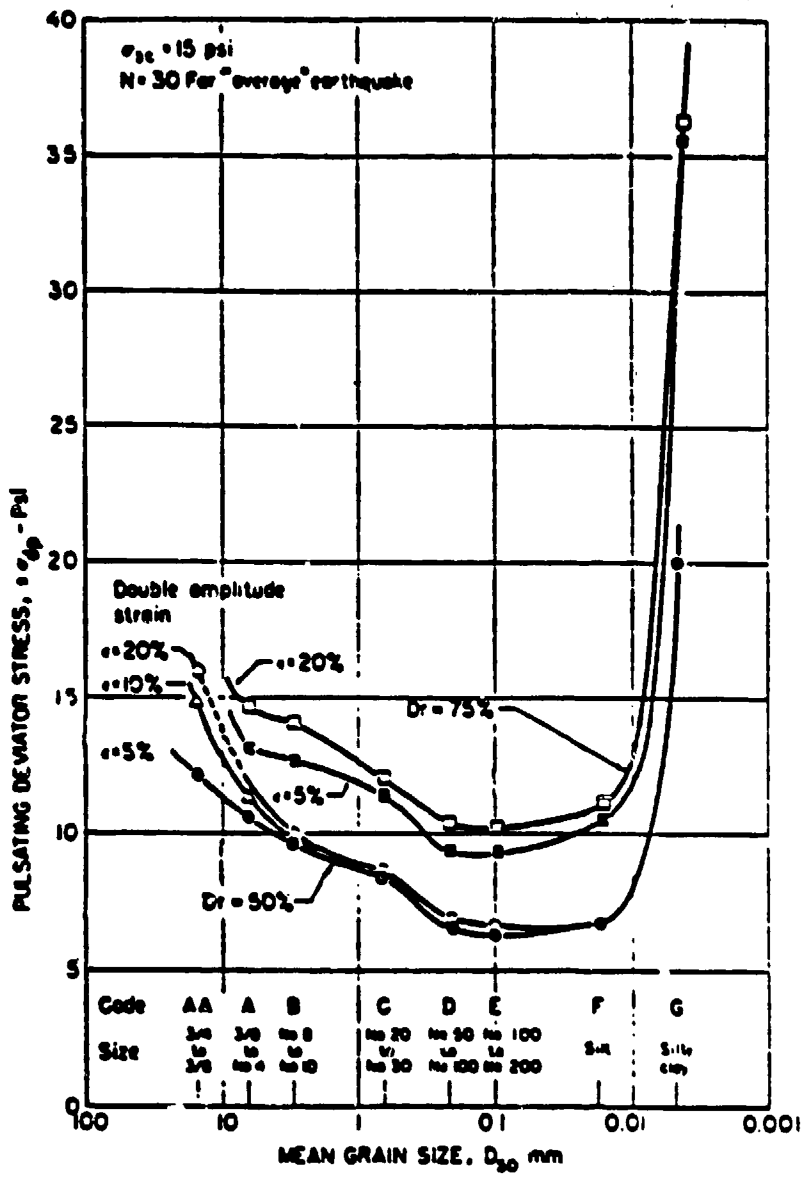



Figure 2. Comparisons of pulsating loading strengths of different grain size soils (after Lee and Fitton 1969). Copyright ASTM--reprinted with permission

and 2 to 16, respectively. Gradation curves of samples tested are shown in Figure 3. Densities and gradation characteristics are summarized in Table 1.

14. A minimum of four cyclic triaxial tests were conducted from each of the twenty-four parent soil types to investigate gradation effects on the liquefaction potential of clean- to near-clean sand. Extreme care was exercised during sample preparation to assure good quality samples. A preweighed dry sand was mixed and lowered into a zero-height-raining device seated to the base pedestal inside a sample preparation mold. After the raining device was filled with sand, it was slowly raised to allow sand particles to rain through the metal screen of a desired opening size attached to the bottom end of the raining device. The process continued until all sand particles rained through the device and deposited in the mold. The initial relative density of each sample was targeted at 50 percent.

15. The specimens were saturated following specimen placement and assembly of the triaxial chamber. De-aired water was first allowed to percolate upward through the specimen, pushing air bubbles up and out of the soil skeleton, after which the air remaining in the soil pores was forced to dissolve into the pore water by gradually increasing the back pressure while maintaining a 5 $lb/in.^2$ effective confining pressure. For most soil specimens tested, back pressures near 60 $lb/in.^2$ were sufficient to produce a desired degree of saturation, as measured by Skempton's "B" parameter. A minimum acceptable value of $B = 0.95$ was achieved before beginning consolidation. Specimens were consolidated to an effective confining pressure of 30 $lb/in.^2$ in two equal stages. Throughout consolidation and saturation stages, specimen height and volume changes were monitored by means of a dial indicator and a volume burette, respectively. After the completion of consolidation, the MTS electrohydraulic closed-loop loading machine was used to conduct cyclic triaxial tests. A minimum of four tests were conducted at each gradation. A total of 123 tests were performed to determine the effect of gradation characteristics on liquefaction potential. Mean diameter ($D_{50}$) and uniformity coefficient were used to characterize the gradation of each soil.

16. Figure 4 shows the disparity between liquefaction potential curves for soils with different mean grain sizes and approximately the same uniformity coefficient. Cyclic stress ratios causing initial liquefaction in 10 cycles of loading were plotted against mean grain sizes in Figure 5. The 10-cycle and 30-cycle curves were plotted in Figure 6. The figures show a

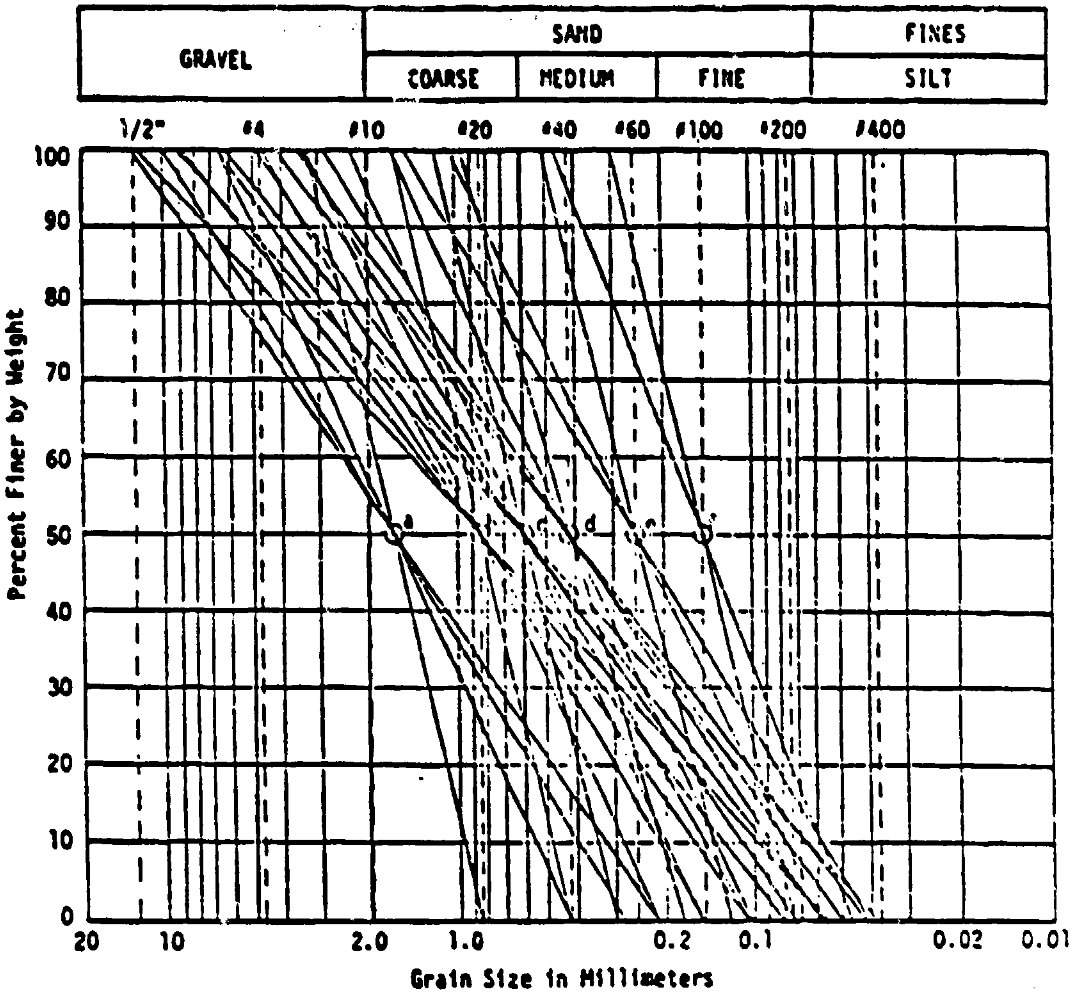



Figure 3. Gradations of Denver sand samples (after Yeh 1981)

Table 1

Index Properties of Test Samples for Gradation Effects

| Sample No.* | Max. Density (pcf) | Min. Density (pcf) | $e_{max}$ | $e_{min}$ | $D_{50}$ (mm) | Uniformity Coefficient |
|---|---|---|---|---|---|---|
| DC-$a_2$ | 104.89 | 87.03 | 0.91 | 0.58 | 1.50 | 1.89 |
| DC-$b_2$ | 104.78 | 88.51 | 0.87 | 0.58 | 0.82 | 2.17 |
| DM-$c_2$ | 105.74 | 87.03 | 0.91 | 0.57 | 0.53 | 2.16 |
| DM-$d_2$ | 106.08 | 85.05 | 0.95 | 0.56 | 0.38 | 2.20 |
| DM-$e_2$ | 106.38 | 82.67 | 1.01 | 0.56 | 0.24 | 2.88 |
| DF-$f_2$ | 102.95 | 79.60 | 1.09 | 0.61 | 0.15 | 2.70 |
| DC-$a_4$ | 114.80 | 94.46 | 0.76 | 0.45 | 1.44 | 3.73 |
| DC-$b_4$ | 116.00 | 95.45 | 0.74 | 0.43 | 0.68 | 3.71 |
| DM-$c_4$ | 118.36 | 93.96 | 0.77 | 0.40 | 0.51 | 4.31 |
| DM-$d_4$ | 115.75 | 91.98 | 0.80 | 0.43 | 0.37 | 4.93 |
| DM-$e_4$ | 116.92 | 90.50 | 0.77 | 0.42 | 0.23 | 5.15 |
| DF-$f_3$ | 108.87 | 84.06 | 0.97 | 0.52 | 0.14 | 3.40 |
| DC-$a_6$ | 121.24 | 98.91 | 0.68 | 0.37 | 1.17 | 5.50 |
| DC-$b_6$ | 121.33 | 99.41 | 0.67 | 0.37 | 0.62 | 5.72 |
| DM-$c_6$ | 122.59 | 99.40 | 0.67 | 0.35 | 0.48 | 7.20 |
| DM-$d_6$ | 121.78 | 96.93 | 0.71 | 0.36 | 0.40 | 7.00 |
| DM-$e_6$ | 119.67 | 94.55 | 0.76 | 0.39 | 0.25 | 7.50 |
| DC-$b_8$ | 123.96 | 102.38 | 0.62 | 0.34 | 0.69 | 9.50 |
| DM-$c_8$ | 125.64 | 101.39 | 0.64 | 0.32 | 0.52 | 9.00 |
| DM-$d_8$ | 123.35 | 98.91 | 0.68 | 0.35 | 0.37 | 9.70 |
| DC-$b_{10}$ | 126.23 | 103.86 | 0.60 | 0.31 | 0.62 | 10.30 |
| DM-$c_{12}$ | 127.41 | 103.47 | 0.60 | 0.30 | 0.57 | 11.30 |
| DM-$d_{10}$ | 125.94 | 101.88 | 0.63 | 0.32 | 0.37 | 12.00 |
| DM-$c_{15}$ | 129.21 | 105.35 | 0.58 | 0.28 | 0.35 | 16.00 |

* Sample No. provides information on the gradation characteristics. For instance, $a_2$ denotes sample with median grain size of "a" (1.50 mm) and a designed uniformity coefficient of 2. Specific gravity is 2.66.

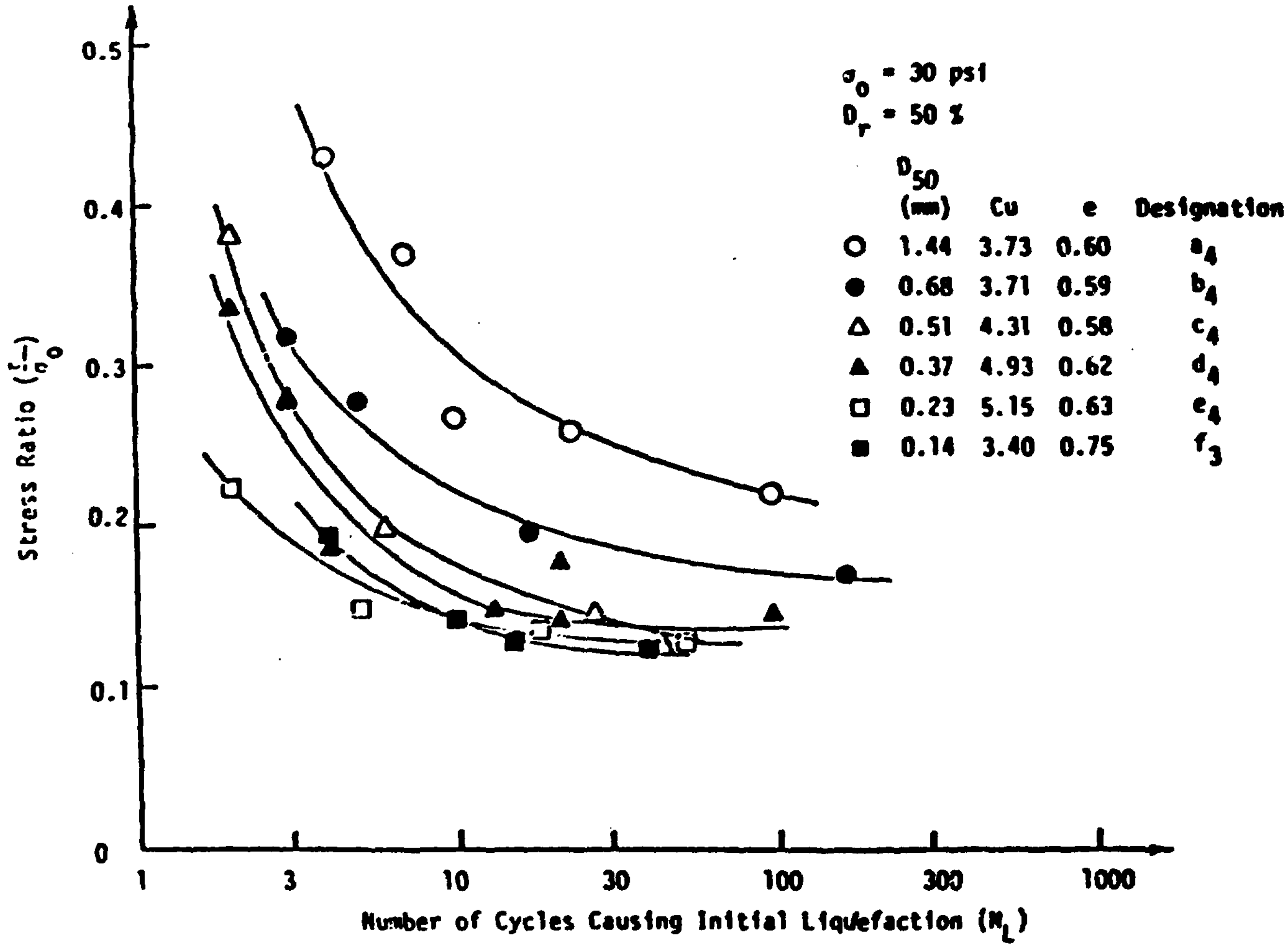



Figure 4. Effect of mean grain size on initial liquefaction, or 100 percent pore pressure response (after Yeh 1981)

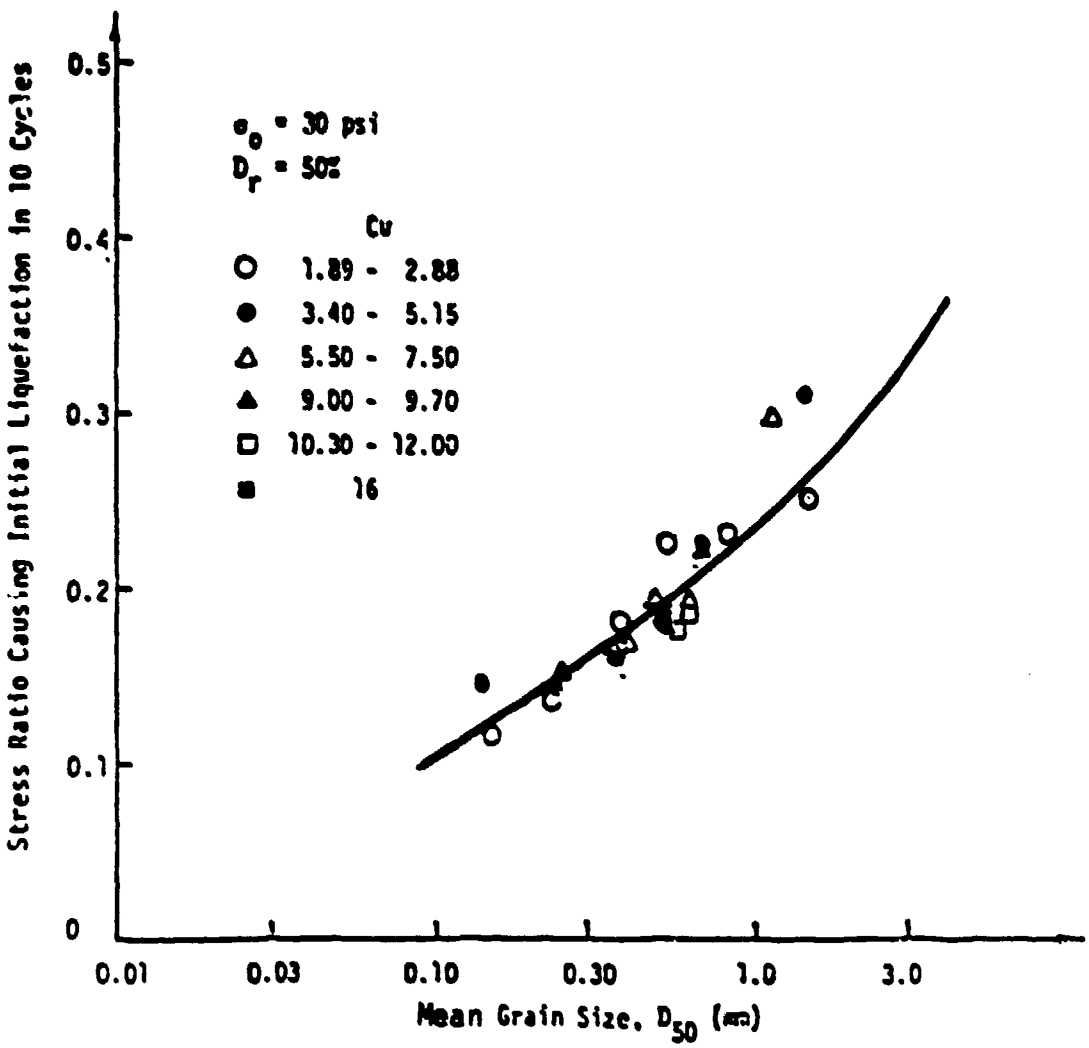



Figure 5. Effect of mean grain size on stress ratio causing initial liquefaction, or 100 percent pore pressure response, in 10 cycles (after Yeh 1981)

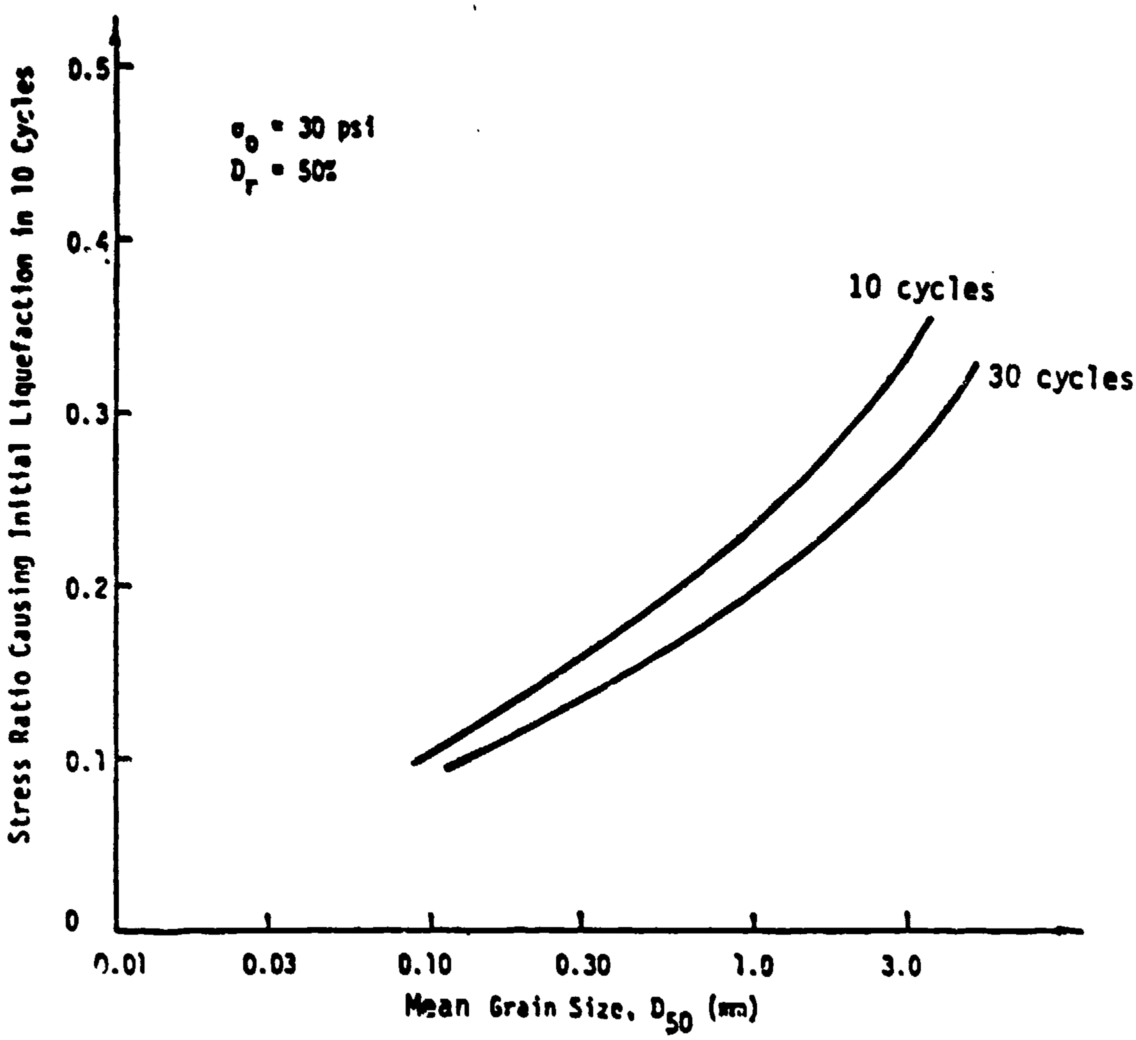



Figure 6. Effect of mean grain size on stress ratio causing initial liquefaction, or 100 percent pore pressure response, in 10 and 30 cycles (after Yeh 1981)

definite trend of liquefaction resistance to increase significantly with increasing mean grain sizes. A typical set of liquefaction potential curves is shown in Figure 7 for samples of similar mean grain diameters. Cyclic stress ratios required to cause initial liquefaction in 10 cycles are plotted against uniformity coefficient in Figure 8, which reveals no significant effect, of uniformity coefficient on the liquefaction resistance of soils. The resistance to liquefaction for the soil with mean grain diameter greater than 0.37 mm decreases with the uniformity coefficient while the resistance of the soil with mean grain diameter smaller than 0.23 mm increases slightly with the uniformity coefficient. The effect was not observed at $C_u$ greater than 8 in either case. The effect of $C_u$ was found to be much less than that of $D_{50}$. It must be noted, however, that the above data were not corrected for the membrane penetration effect, which tends to give a higher than true resistance of soils to liquefaction. The membrane penetration effect is more significant for coarse-grained and uniform sands than fine-grained and well-graded sands.

17. Chang and Ko (1982) concluded that the liquefaction potential of clean sands is strongly affected by their gradation characteristics, and the mean grain size imposes a much stronger effect than the uniformity coefficient. The resistance to liquefaction decreases with decreasing mean grain size. Uniform fine sands were found to be most vulnerable to liquefaction. Clean, medium to coarse soils are subject to potentially serious membrane penetration effects and the liquefaction resistance of these soils may be overestimated if the membrane penetration effect is not accounted for. It is thus extremely important to investigate the effect of membrane penetration on the liquefaction resistance of granular soils.

Silt Content Effects

18. Effects of silt contents were investigated by Kaufman (1981) and reported by Chang, Yeh, and Kaufman (1981). In this study, four clean granular soils were selected for gradation effects testing and mixed with 10, 30, and 60 percent of Bonny silt from a fossil deposit near Bonny Dam in eastern Colorado. Index properties of these four samples ($DC-b_2$, $DC-b_8$, $DM-d_2$ and $DM-d_6$) are shown in Table 1. Their physical properties are shown in Table 2. The Bonny silt is a low-plasticity soil with physical properties as shown in Table 3. The gradations of the samples prepared for these investigation are presented in Figure 9. An attempt was made to maintain the same void ratio at 50 percent relative density as their parent clean sand samples. As indicated

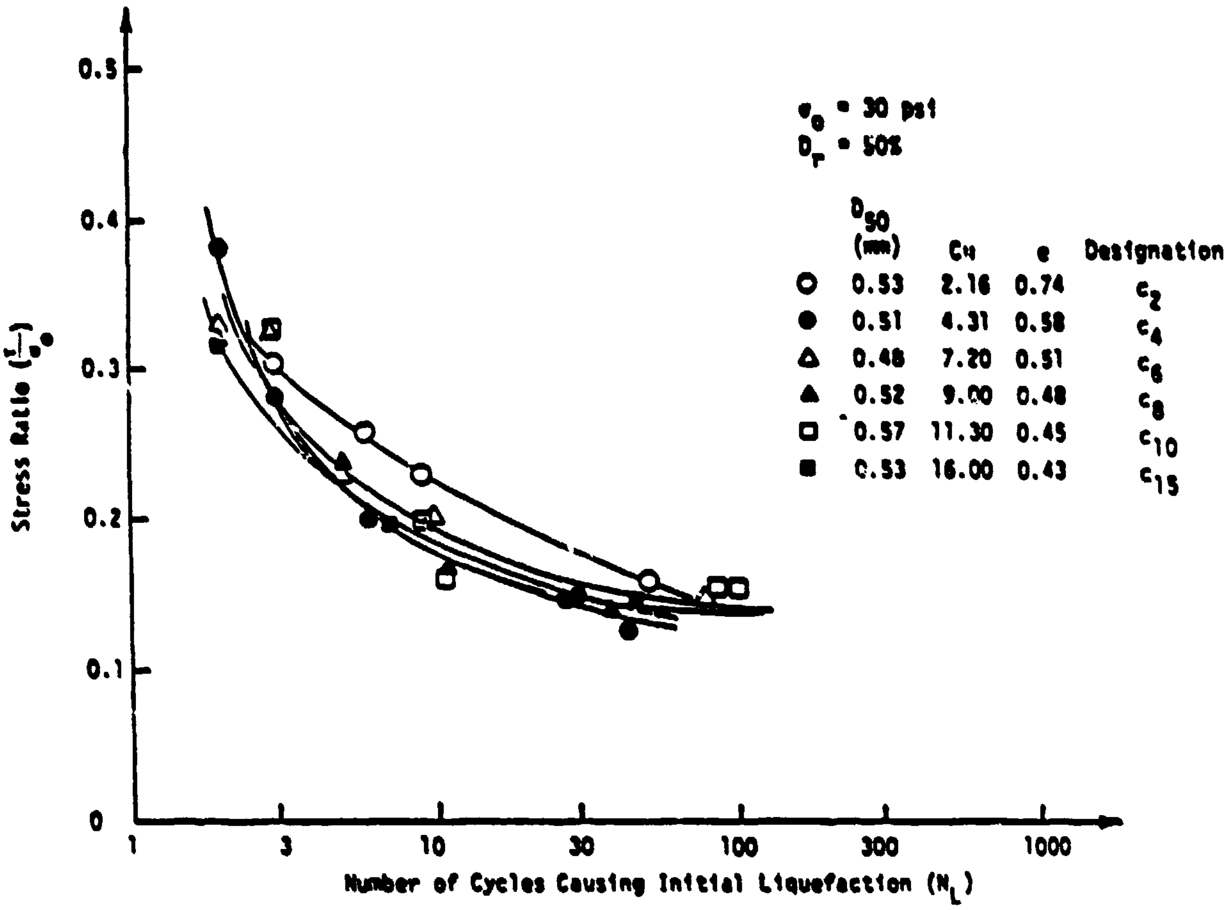



Figure 7. Effect of uniformity coefficient on liquefaction (after Yeh 1981)

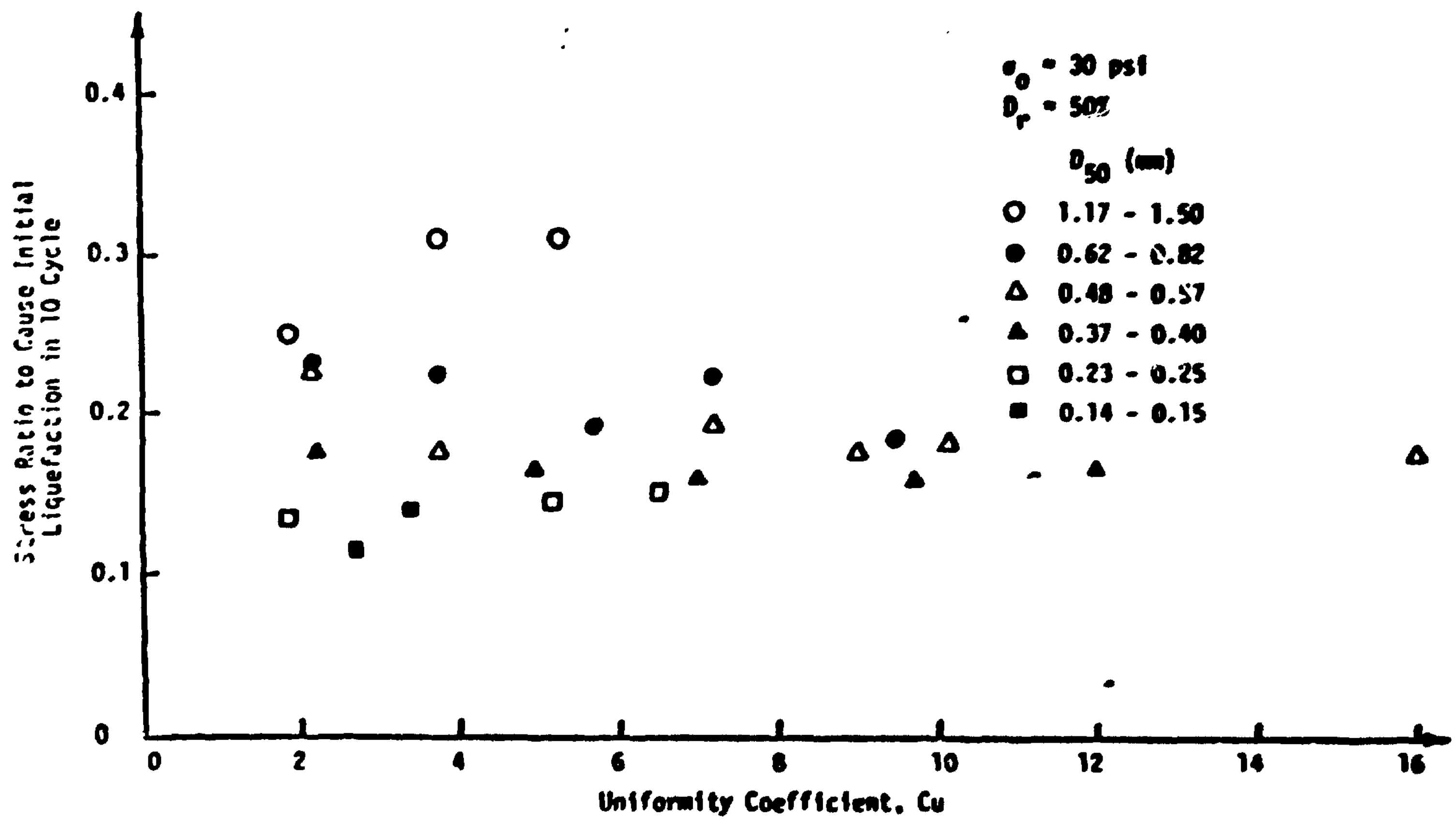



Figure 8. Effect of uniformity coefficient on stress ratio causing initial liquefaction, or 100 percent pore pressure response, in 10 cycles (after Yeh 1981)

Table 2

Physical Properties of Sands $b_2$, $b_8$, $d_2$, and $d_6$

| Property | Sand $b_2$ | Sand $b_8$ | Sand $d_2$ | Sand $d_6$ |
|---|---|---|---|---|
| $D_{50}$(mm) | 0.85 | 0.85 | 0.42 | 0.42 |
| $\gamma_d$ max(lb/ft$^3$) | 104.8 | 124.0 | 106.1 | 121.8 |
| $e_{min}$ | 0.57 | 0.32 | 0.55 | 0.35 |
| $\gamma_d$ min(lb/ft$^3$) | 88.5 | 102.4 | 85.0 | 96.9 |
| $e_{max}$ | 0.86 | 0.60 | 0.93 | 0.69 |
| $\gamma_{d_{50}}$*(lb/ft$^3$) | 96.0 | 112.2 | 94.4 | 107.9 |
| $e_{50}$** | 0.71 | 0.46 | 0.74 | 0.52 |
| $G_s$ | 2.63 | 2.63 | 2.63 | 2.63 |

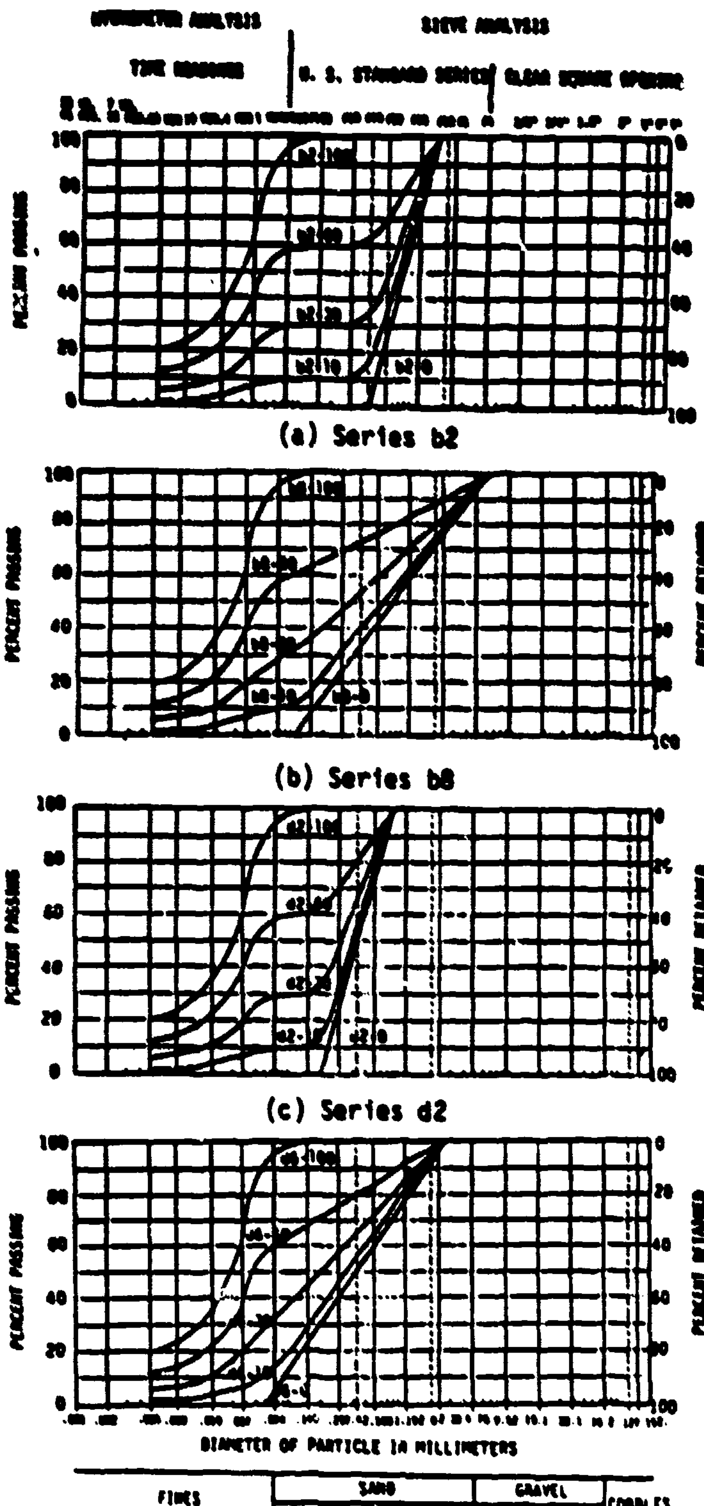
*$\gamma_{d_{50}}$ denotes the dry density corresponding to the condition of 50% relative density.

**$e_{50}$ denotes the void ratio corresponding to the condition of 50% relative density

Table 3

Physical Properties of Test Silt (Bonny Loess)

| | |
|---|---|
| Liquid Limit (LL) | 28% |
| Plastic Limit (PL) | 23% |
| Plasticity Index (PI) | 5% |
| Proctor Maximum Dry Density | 104 lb/ft$^3$ |
| Optimum Water Content | 16.5% |
| Specific Gravity ($G_s$) | 2.67 |




(a) Series b2

(b) Series b8

(c) Series d2



(d) Series d6

Figure 9. Gradations of samples tested (after Kaufman 1981)

in Table 4 for samples with 30 and 60 percent silt and with a uniform gradation (designated by a subscript of 2), it was very difficult, in fact impossible, to maintain the required density during the saturation and consolidation process. A specimen was densified during the saturation process because of the migration of silt particles in the soil mass. The electro-pneumatic cyclic loader designed by C. K. Chan (CKC) at the University of California at Berkeley was used in testing silty sand and sandy silt. An excitation load with a sinusoidal wave form was used in all tests. The excitation frequency chosen was 0.05 Hertz.

19. Sixty-eight samples were tested to assess the effect of silt content on the cyclic shear resistance and liquefaction potential of silty sand and sandy silt. The pore water pressure, axial deformation and load amplitude were monitored and recorded throughout the test. These strip chart records were analyzed in conjunction with the consolidation data recorded prior to cyclic testing to produce the initial plots sampled in figures 10 and 11 for samples $b_2$-0 and $b_2$-30, respectively. It can be seen from these figures that there is little difference in the number of cycles required to cause ±2.5, 5, 10 percent strains. Thus, a single curve of the stress ratio versus number of cycles to cause 5 percent single amplitude strain was plotted for each group. It was apparent from the same figures that there is significant difference in the trend of pore pressure development for clean sands as compared to soils containing fines.

20. Sample plots of the stress ratio required to cause 5 percent strain versus number of loading cycles are shown in Figures 12 and 13, in which the curves for the clean sands were corrected for the effect of membrane curves, compliance using the method described by Martin, et al. (1978) at N = 30 cycles. A 51 percent correction was applied to the sand $b_2$-0 and $b_8$-0 curves, and a 35 percent correction to the strength of the sand, $d_2$-0 and $d_6$-0.

21. The magnitude of the above correction is a function of $d_{50}$. It should be cautioned that this correction is highly qualitative. Without further research, it is not possible to apply this correction to clean sands with confidence. It appears from these plots that the specimens containing 30 percent silty fines show some strength increase over those containing 10 percent silt. The corrected strength curves for the clean sands lie in a comparable range with the curves for the sands containing 10 and 30 percent silt. The samples containing 60 percent fines demonstrate a greater strength gain, and,

Table 4

State of Compaction of Specimens Tested for Silt Content Effects

| Sample | Average Dry Density $\gamma_{dc}$ (lb/ft$^3$) | Maximum Dry Density $\gamma_{d_{max}}$ (lb/ft$^3$) | Average Percent Compaction $\frac{\gamma_{dc}}{\gamma_{d_{max}}}$ x 100 (%) | Attempted Void Ratio | Void Ratio After Consolidation |
|---|---|---|---|---|---|
| $b_2$-10 | 98.1 | 116 | 85 | 0.71 | 0.686 |
| $b_2$-30 | 112.0 | 123 | 91 | 0.71 | 0.475 |
| $b_2$-60 | 110.0 | 125 | 88 | 0.71 | 0.517 |
| $b_2$-100 | 96.9 | 104 | 93 | 0.71 | 0.72 |
| $b_8$-10 | 117.0 | 126 | 93 | 0.46 | 0.41 |
| $b_8$-30 | 119.0 | 126 | 94 | 0.46 | 0.39 |
| $b_8$-60 | 111.0 | 119 | 93 | 0.46 | 0.48 |
| b8-100 | 110.0 | 104 | 106 | 0.46 | 0.51 |
| $d_2$-10 | 97.6 | 111 | 88 | 0.74 | 0.69 |
| $d_2$-30 | 103.0 | 122 | 84 | 0.74 | 0.61 |
| $d_2$-60 | 107.0 | 118 | 91 | 0.74 | 0.55 |
| $d_2$-100 | 95.6 | 104 | 92 | 0.74 | 0.75 |
| $d_6$-10 | 113.0 | 121 | 93 | 0.52 | 0.46 |
| $d_6$-30 | 113.0 | 123 | 92 | 0.52 | 0.46 |
| $d_6$-60 | 109.0 | 115 | 95 | 0.52 | 0.52 |
| $d_6$-100 | 107.0 | 104 | 103 | 0.52 | 0.55 |

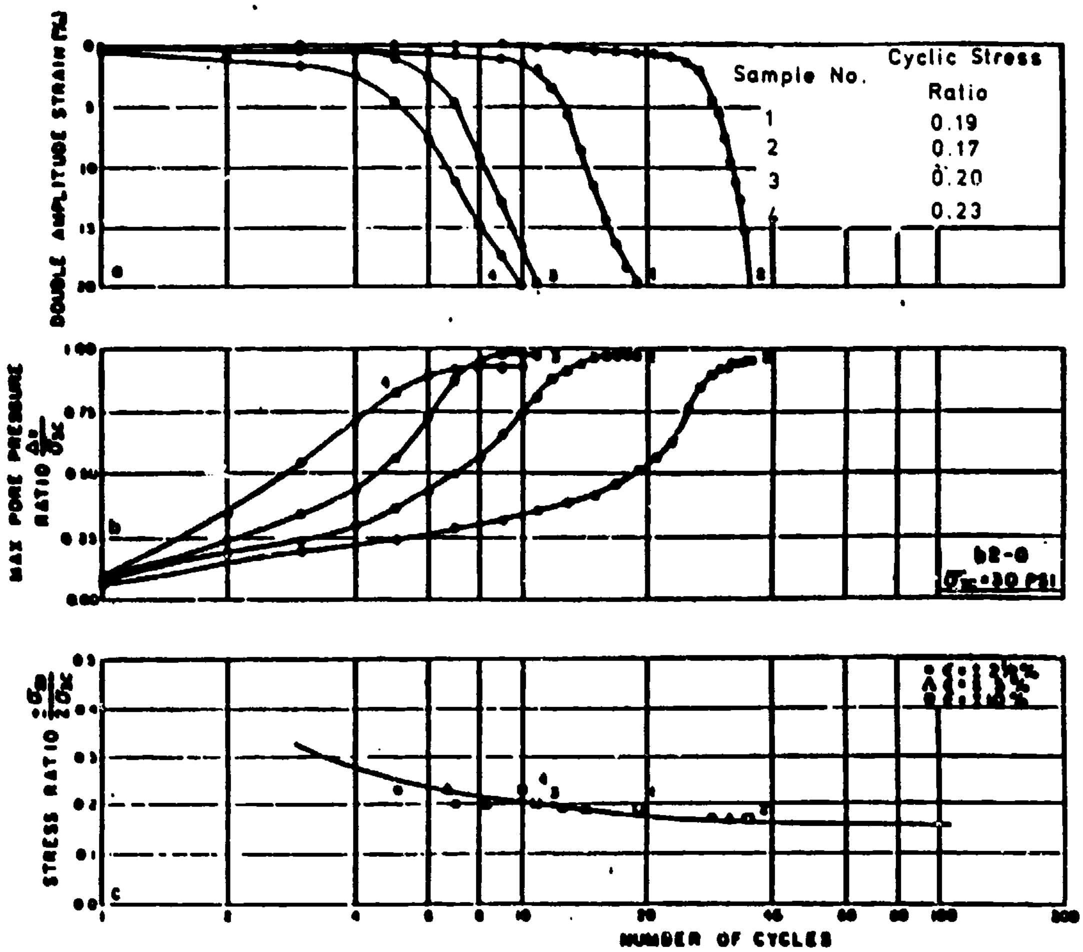



Figure 10. Cyclic triaxial test results of sample b2-0 (after Kaufman 1981)

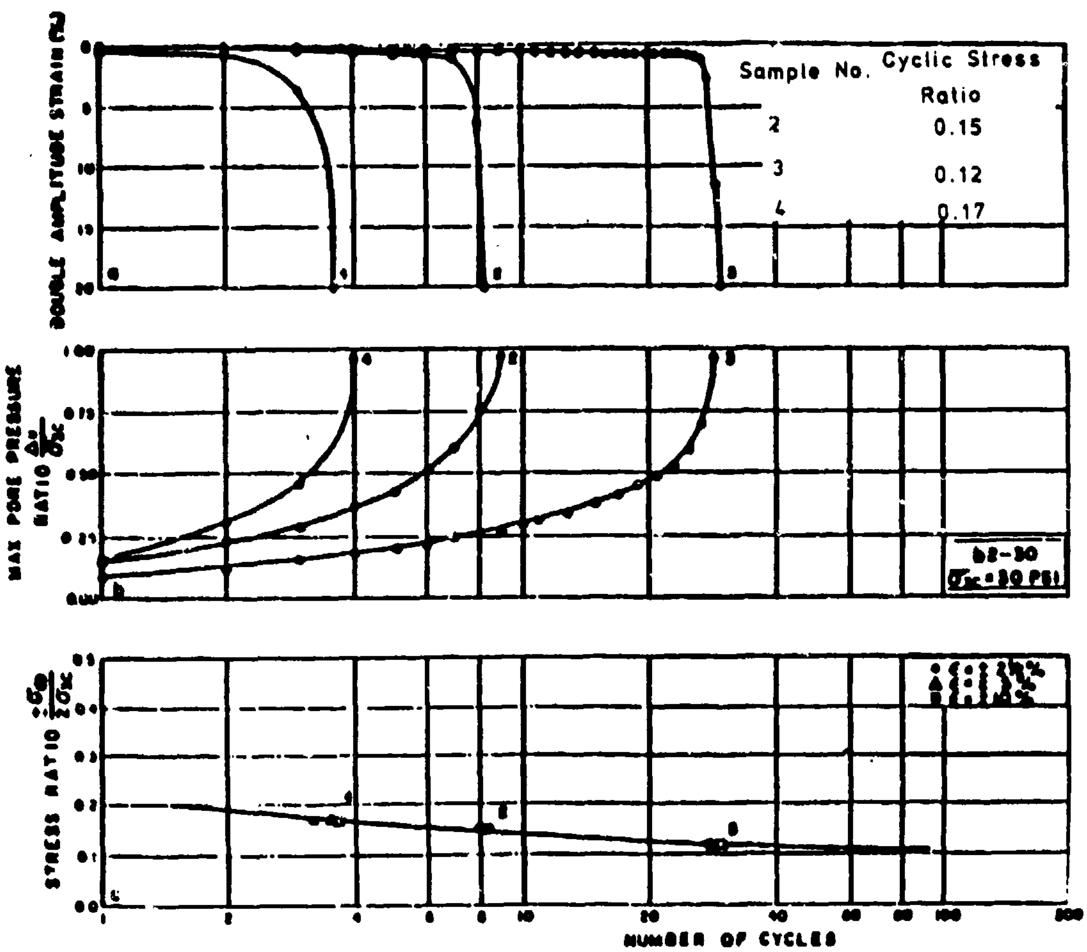



Figure 11. Cyclic triaxial strength test results of sample b2-30 (after Kaufman 1981)

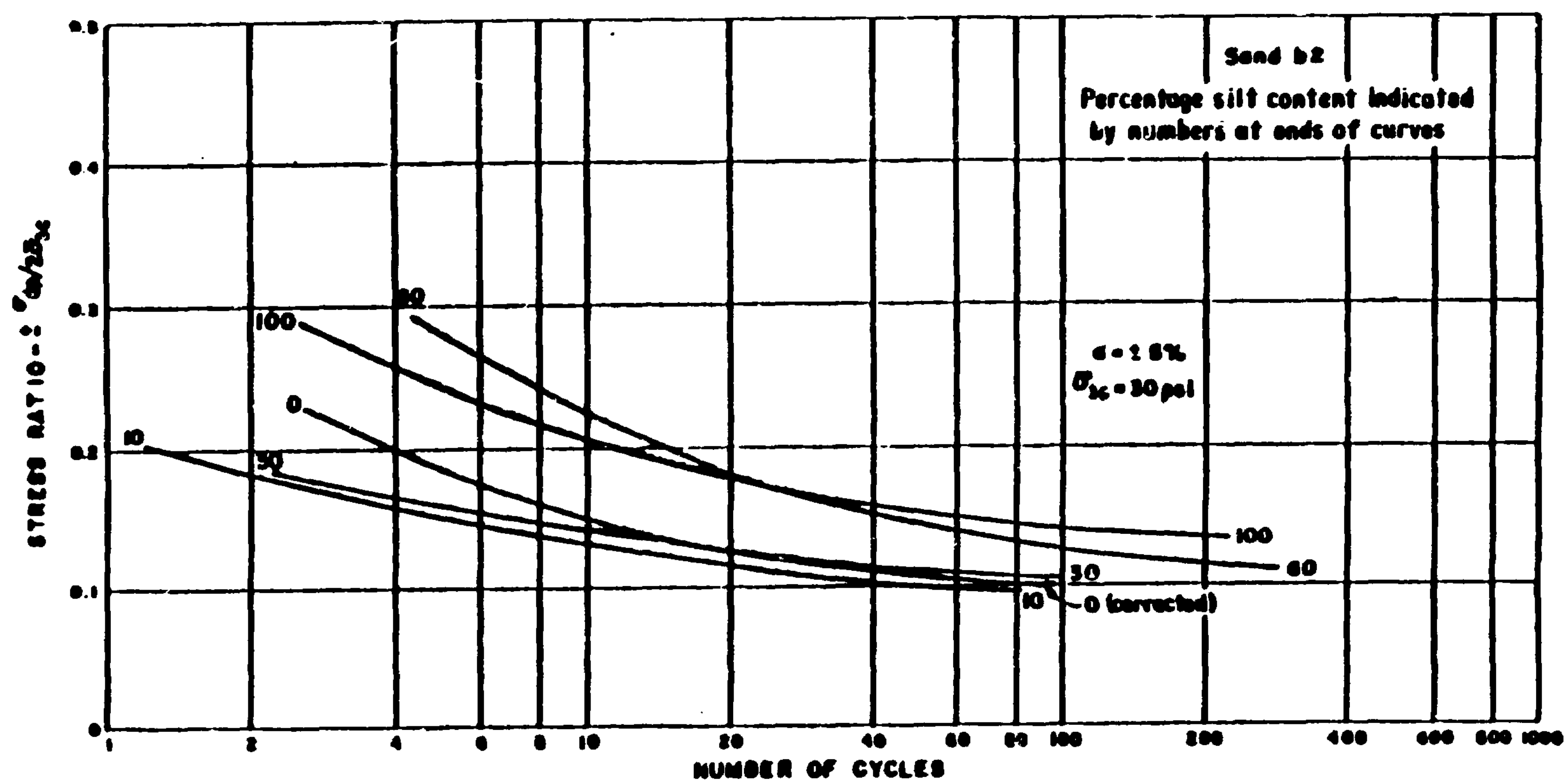



Figure 12. Cyclic strength of b2 samples--clean sand specimens corrected for membrane compliance (after Kaufman 1981)

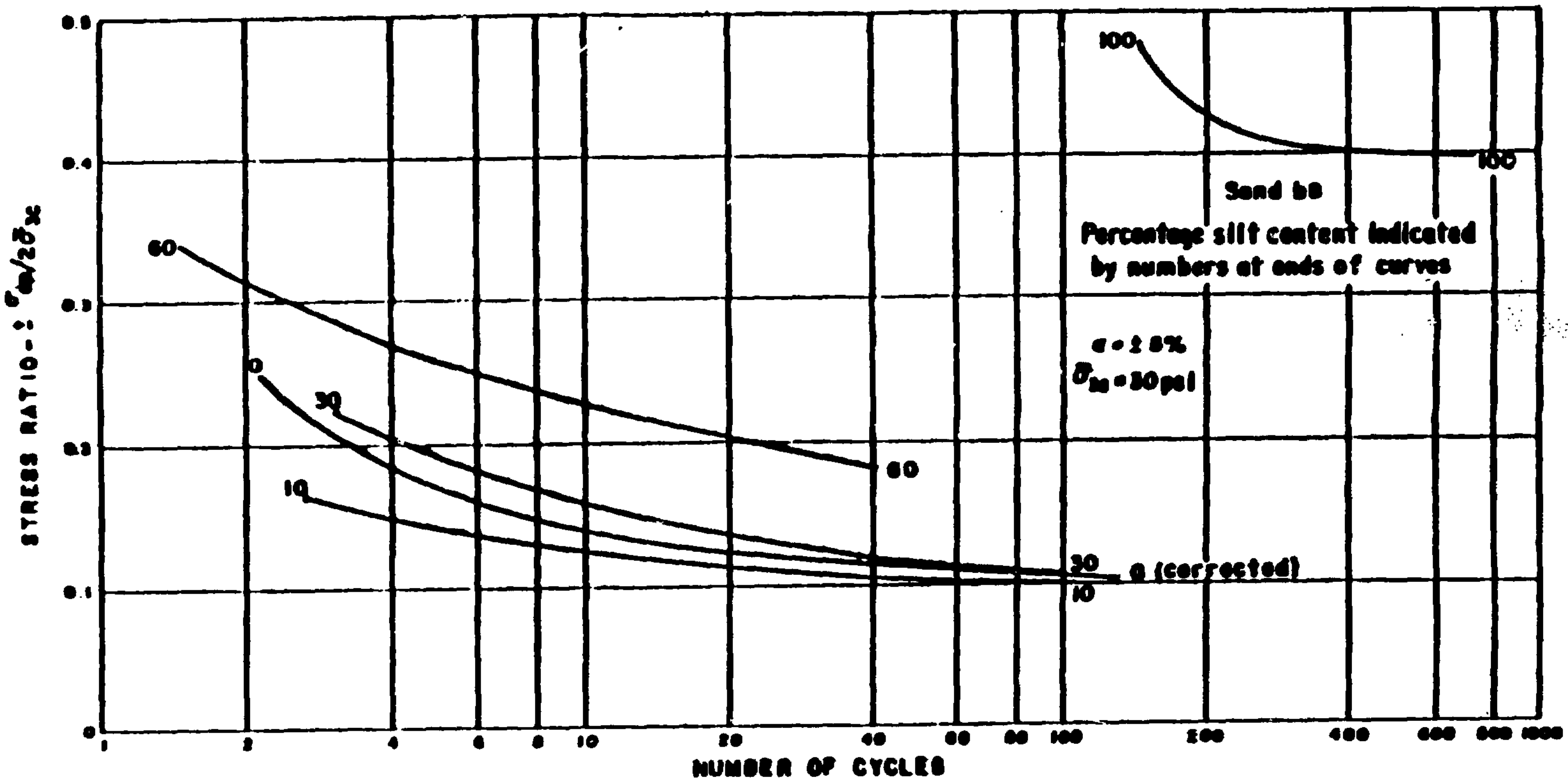



Figure 13. Cyclic strength of b8 samples--clean sand specimens corrected for membrane compliance (after Kaufman 1981)

for samples $b_2$ and $d_2$, the pure silt specimens are nearly indistinguishable in strength from the 60 percent silt specimens. In the $b_8$ and $d_6$ series, however, the increase in strength for the 100 percent silt specimens is very large.

22. Results of a density testing program involving Proctor compaction and relative density tests are shown in Table 4. From this table it can be seen that specimens in series $b_8$-100 and $d_6$-100 were in a very dense state, which resulted in a very high cyclic strength. It is likely that this is due to the relatively narrow range of void ratio that a silt might have. Sands, however, of various gradations and various amounts of fines might have a much wider range of possible void ratios.

23. Figure 14 shows the ratio required to cause ±5 percent strain as a function of the number of loading cycles for all samples containing 10 percent silty fines. This suggests that as the number of cycles increases, the mean grain diameter and the uniformity coefficient of the parent sand samples have a decreasing effect on the cyclic strengths of the silty samples, as long as corrections were applied to compensate for the membrane compliance effect.

24. Experimental results revealing the silt content effect on liquefaction resistance are summarized in Figure 15. This figure shows the effect of the added percentage of silt on the cyclic shear resistance to ±5 percent strain in 10 and 30 cycles of loading. From this plot, it appears unclear what effect the addition of 10 percent silty fines has on the cyclic shear resistance of a clean sand. This may result from the qualitative nature of the membrane penetration effect applied to the clean sand samples. With the addition of 30 percent fines an increase in cyclic shear resistance is approximately 18 percent. The greatest increase in cyclic shear strength takes place in the area between 30 percent and 60 percent fines contents. At silt contents higher than 60 percent the strength increase appears to level off.

25. Qualitatively, this trend seems to be sensible. At a very low silt content the soil structure is dominated by the sand grains. Even at 10 percent silt content there is still considerable sand-grain-to-sand-grain contact, and the behavior of the soil is still largely governed by the sand structure. The cyclic strength is thus not greatly different from that of clean sands. However, with the introduction of more than 30 percent silty fines, sand particles are increasingly surrounded by silt with far decreased sand-grain-to-sand-grain contact and the silty fines begin to increasingly dominate the

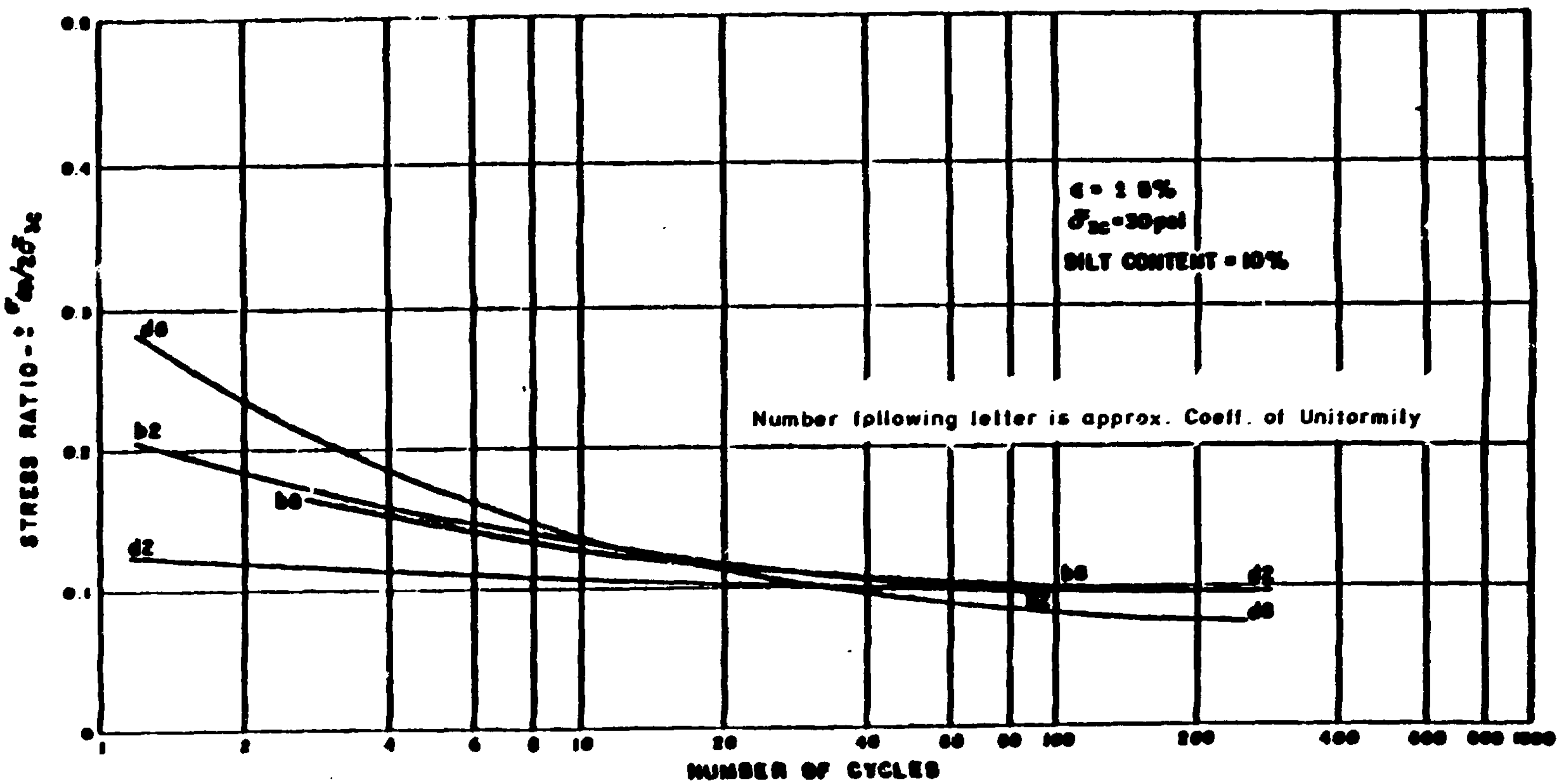



Figure 14. Cyclic strength of samples containing 10 percent silty fines (after Kaufman 1981)

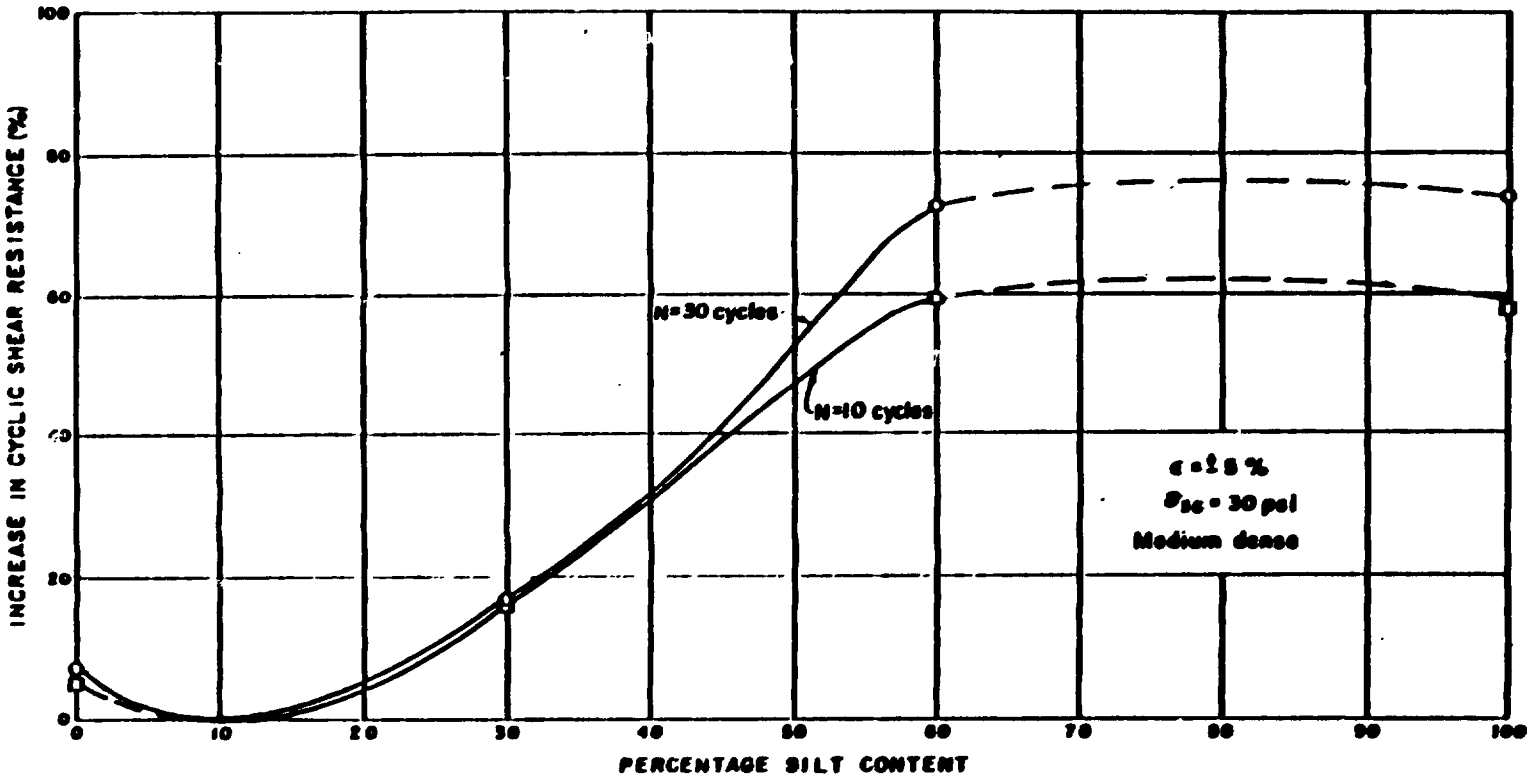



Figure 15. Average effect of silt content on cyclic shear resistance (after Kaufman 1981)

strength of soils. By the time the silt content reaches 60 percent or more, the soil fabric becomes one of sand grains embedded in silt with practically very few sand-grain-to-sand-grain contacts, and the specimen behavior is almost totally determined by the silty fines. Thus, the strength increases with the increase in silt content as summarized in Table 5.

Table 5

Average Effect of Silt Content on Cyclic Strength of Sands

| Silt Content (%) | Strength Gain at N=10 Cycles (%) | Strength Gain at N=30 Cycles (%) |
|---|---|---|
| 0 | 9.0 | 5.6 |
| 10 | --* | --* |
| 30 | 17.0 | 16.0 |
| 60 | 73.0 | 60.0 |
| 100 | 74.0** | 58.0** |

* Used as a datum level.

** Computed using only soils $b_2$-100 and $d_2$-100.

26. In summary, the research on the silt content effect indicated that the cyclic shear resistance increases over that of the parent sand as the silt content increases. The rate of this strength increase is greatly reduced as the silt content increases beyond 60 percent. The difference in permeabilities and fabric of soils containing various amounts of fines leads to vastly different pore pressure generation characteristics. The mean grain size and the uniformity coefficient of the parent sands appeared to have decreasing effect, as the number of cycles increases, on the cyclic shear resistance of the silty samples.

## Previous Japanese Research on Gradation and Fine Content Effects

27. Japan has been very active in earthquake hazard mitigation research. A large research fund is budgeted in that nation for research in earthquake engineering. Excellent research accomplishments are evidenced in various earthquake engineering publications. Japanese research on the effects

of gradation and silt content on the liquefaction resistance of soils is briefly summarized in the next paragraph.

28. Some samples recovered from borings around Tokyo revealed high silt contents of 12 to 60 percent. (Ishihara, et al. 1978; Ohsaki, 1966) Ishihara et al. tested reconstituted samples of silty sands and sandy silts from the Tokyo Bay area. Percentages of silt content were varied systematically and samples were tested for their cyclic strength using cyclic triaxial tests. The primary objective of the study however, was to investigate the effects of overconsolidation on the strength of these soils. The research concluded that the cyclic shear strength increased with overconsolidation and the gain in cyclic shear strength increased with increasing fines contents. Ishihara, et al. (1981) also investigated the cyclic strength of mill tailings. Typically, ores are crushed and ground to sand and silt sizes during mineral recovery processes. Mill tailings are then transported to a disposal site and deposited in mill tailings ponds. In tailings ponds, solid materials are loosely sedimented and naturally are very susceptible to earthquake-induced liquefaction like any other hydraulically-filled soils. Tailings also contain various percentages of fines. Iwasaki, et al. (1981), Ohsaki (1966), and Tokimatsu and Yoshimi (1981) tested silty sands and sandy silts. Their objectives, however, were to improve the correlations between dynamic shear strength and penetration resistance of these soils.

## PART IV: LIQUEFACTION OF SOILS DURING THE TANGSHAN EARTHQUAKE OF 1976

### Tangshan Earthquake and Associated Faulting System

29. Tangshan is an industrial and heavily populated city in northern China. It is located approximately 150 Km of the capital city, Beijing, as shown in Figure 16. In 1976, a strong earthquake of Richter scale magnitude 7.8, subsequently named the Tangshan earthquake, struck the city at 3:42 am on July 28 (Wang, 1977). In early evening, a strong aftershock of magnitude 7.1 followed. The earthquake struck without any obvious foreshocks or other clear precursory phenomena. The epicentral intensity was XI on the New Chinese Seismic Intensity Scale. The city was nearly destroyed and upwards of one-half million people perished. The meizoseismal area (Richter, 1958) with intensity XI was of oval shape and encompassed about 47 $Km^2$. Within this meizoseismal area, the building destruction was near 100 percent. Within the isoseismal area (370 $Km^2$) with intensity X, 80 percent of residential housing and 50 percent of industrial structures were destroyed. The area that experienced the most serious destruction has a thick overburden. Liquefaction ground failures generally took place in the southeast area of Tangshan where the recent alluvial fan of the Ruan river is located. The ground shaking intensity in this area attenuated to between VII and VIII. The intensity contours are shown in Figure 17.

30. The Tangshan area has an intensive faulting system. Major faults running through Tangshan area are the Yuan-San, Nin-Chun, and Han-San faults running in the northeast to southwest direction; Lu-Shia, Luan-Luo, and Ji canal faults running perpendicular to the previous ones; and the Lu-Luan fault intersects almost all other faults as shown in Figure 17. In the last two decades, northern China has been a very active seismic region. Since the 1966 Xingtai earthquake (425 Km southwest of Tangshan), there have been several events greater than magnitude 6, such as the 1967 Hejian earthquake (225 Km southwest of Tangshan, M=7.4), the 1975 Haicheng earthquake (400 Km east of Tangshan, M=7.3), the 1976 Horinger earthquake (550 Km west of Tangshan, M=6.3) and finally the 1976 Tangshan earthquake with the magnitude 7.8.

31. The Tangshan earthquake, besides causing building destruction, caused various forms of ground failures: subsidence, slope failure, and liquefaction. This report presents results of a preliminary study on the

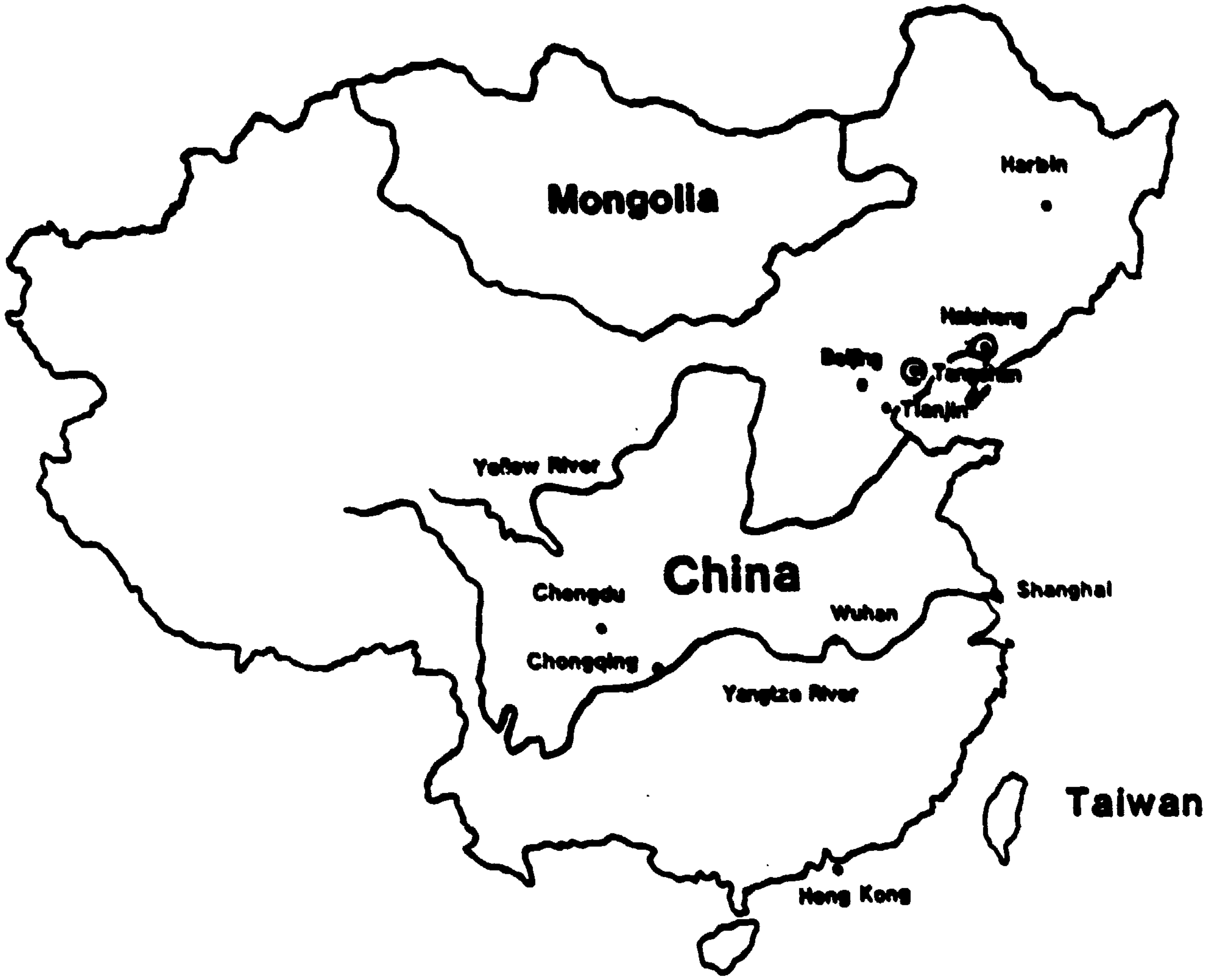



Figure 16. Epicenters of the Tangshan and Haicheng earthquakes

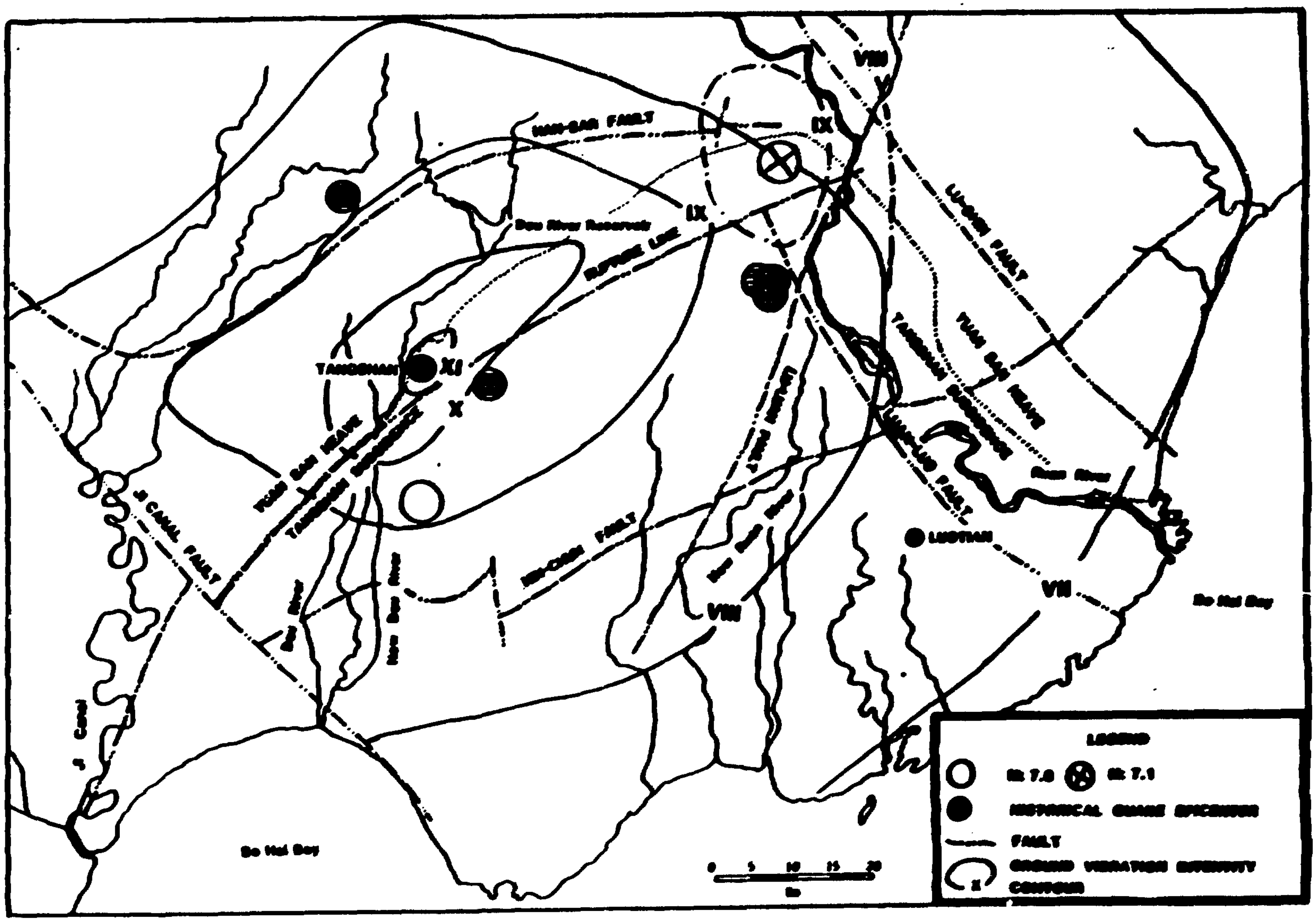



Figure 17. Fault and epicenter distribution in the Tangshan Plain

liquefaction of cohesive soils during Tangshan earthquake.

## Geologic Characteristics of Liquefied Zone

32. Liquefaction ground failure resulting from the Tangshan earthquake was observed to be most severe in the recent alluvial fan of the Ruan river. As shown in Figure 17, a major fault running in the approximately east-west direction serves as the boundary of the Yuan-San heave and the Tangshan subsidence. To its north the ground is hilly and mountainous and continues to uplift while the ground to its south, peneplain and coastal plain areas, continues to subside. Because of this heave-subside process, the Ruan river has been moving southeastward and has changed its course many times with three major ones as shown in Figure 18. The ground slope in the plain changes from 1/200 in the front range to 1/8000 in the coastal plain area. The depth to ground water table also continues to decrease toward the coastal plain and alluvial deposits become thicker. In some cases, the ground water table is shallower than one meter.

33. There are three major alluvial fans: I, II, and III as shown in Figure 18. Because of aging and prestraining during previous earthquakes, the alluvial deposit in the early alluvial fan (I) has gained liquefaction resistance in the past. No liquefaction ground failures were observed there during the Tangshan earthquake, although ground excavation revealed the evidence of some severe old liquefaction that resulted from strong historical earthquakes. Alluvial deposits in the intermediate alluvial fan (II) experienced more severe liquefaction problems than those in the early fan. The recent fan suffered the most catastrophic liquefaction ground failure because of the collective effects of the following characteristics:

- Young deposit with very little or no aging,
- Young deposit with less prestraining from previous earthquakes,
- Loose alluvial deposits,
- Shallow ground water; and
- Long ground shaking duration

In the coastal plain area near the Bo Hai Bay, because of the thick alluvial sand deposits being overlain by a thick soft marine clay deposit, the major form of ground failure was ground subsidence. However, being very soft and sensitive, the thick marine clay deposit might have undergone remolding. The

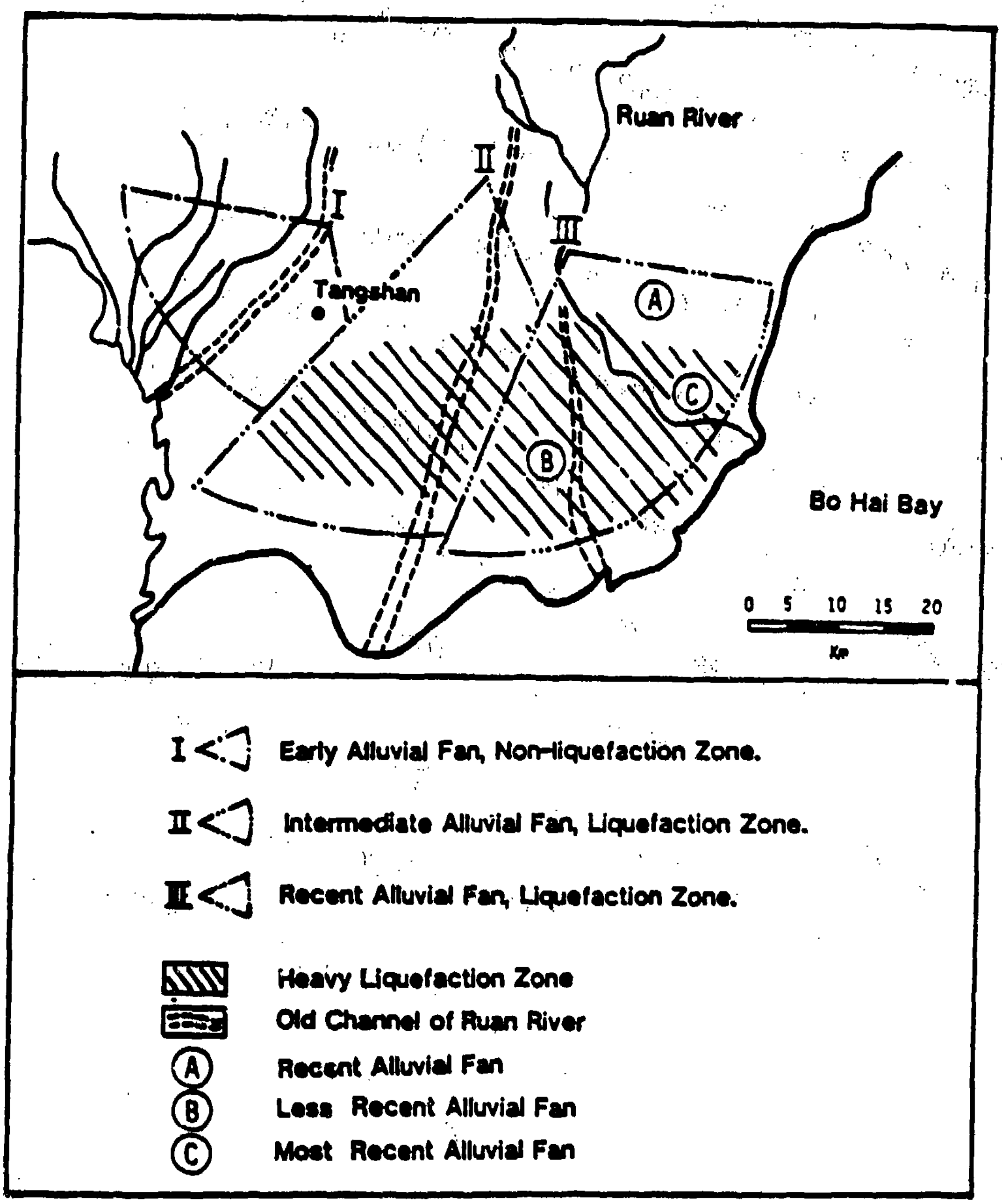



Figure 18. Migration and deposits of the Ruan River

severe regional subsidence might thus be attributed to the collective effect of the liquefaction of the underlying sand deposit and the remolding of the sensitive marine clays.

34. During the Tangshan earthquake, liquefaction ground failures occurred within a vast area of 20,000 $Km^2$, with the most recent alluvial deposit being the hardest hit. Historically, because of the continual southeastward migration of Ruan river, the severe liquefaction front also continues to move with it. The alluvial fan III-C consists of loosely deposited alluvial soils with a very shallow water table. Being the youngest among all alluvial fans, it has experienced very little aging and prestraining effects. The shaking duration was rather long, nearly one minute. The overall condition of the III-C alluvial deposit thus was very favorable to liquefaction, and, naturally, it was subjected to the most severe liquefaction ground failure associated with the Tangshan earthquake.

35. Ground shaking intensity is not the sole influence factor of liquefaction. Tangshan was in a meizoseismic zone with the ground shaking intensity of XI. Very few liquefaction ground failures were observed in the meizoseismic zone, however, even within the area with a shaking intensity of X. In fact, the severest liquefaction phenomena were observed in areas with the shaking intensities of VIII and IX. Even the area with intensity VII experienced liquefaction. The severe liquefaction in Zone III-C near the Luotian and Luanan areas shown in Figure 19 was evidently the result of the collective effects of ground shaking intensity and duration, sedimentation characteristics of alluvial deposits, topographical and geomorphic conditions, and hydrogeological conditions. The epicentral distance to this area is approximately 60 to 80 kilometers.

## Modes and Distribution of Ground Failures

36. The Tangshan earthquake produced various forms of ground failures including sand boiling, subsidence (or settlement), slope instability, and ground fracture (Fang, et al., 1981). These ground failures covered a vast area of 20,000 $Km^2$ and were caused directly or indirectly by the liquefaction of soils. Figure 19 shows the extent and the distribution of each mode of ground failures. The ground fracture was caused by the liquefaction-induced ground subsidence, slope instability, and hydraulic fracturing of ground

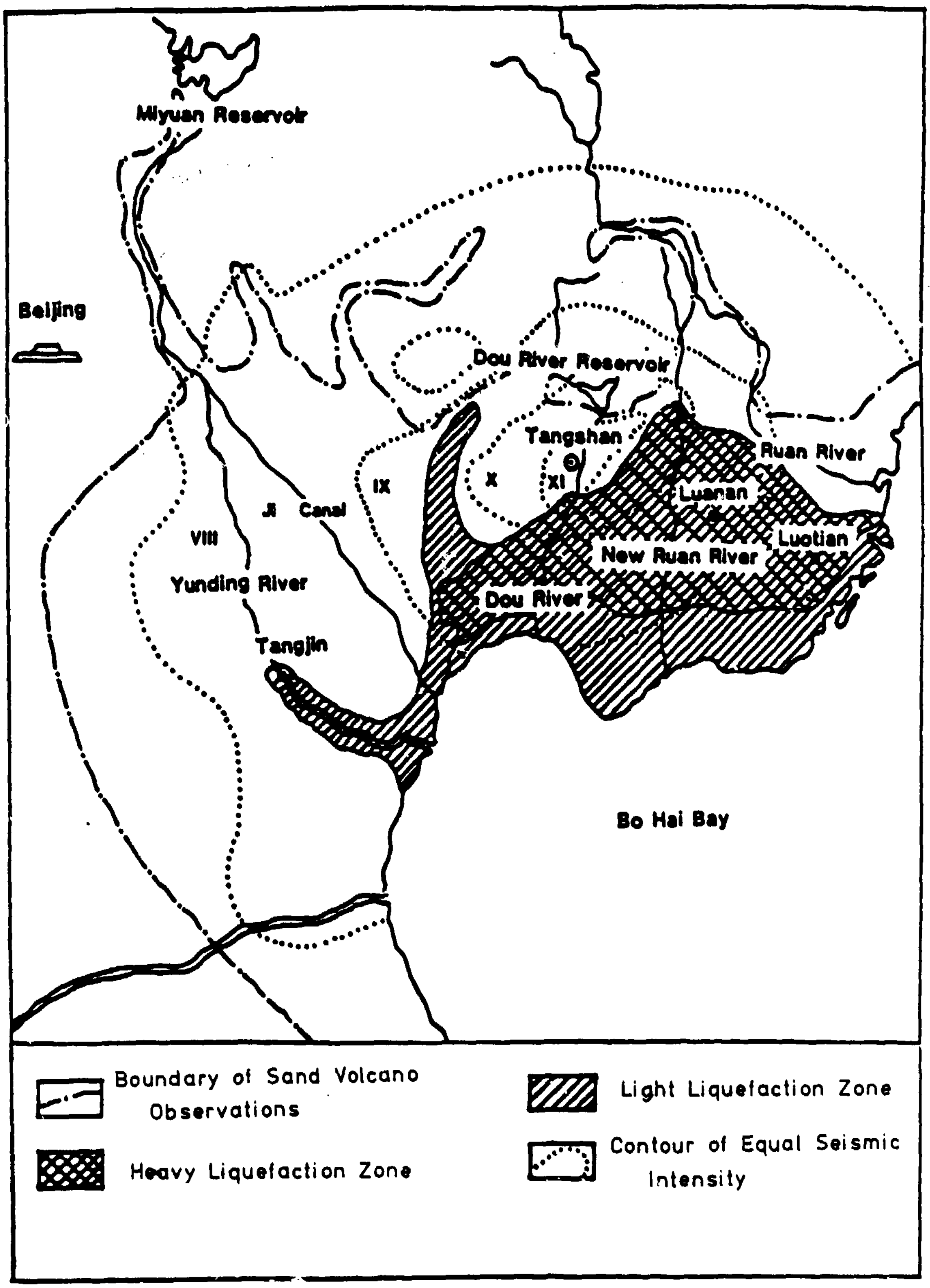



Figure 19. Liquefaction distribution map--Tangshan earthquake of 1976

resulted from the excess pore water pressure generated during seismic ground shaking.

37. The slope instability was caused by the combined effect of cyclic shear strength reduction and the additional destabilizing shear stress imparted to a slope during seismic shaking. It is interesting to observe that the slope instability was concentrated in current and/or abandoned river banks or channels. This river bank instability most likely resulted from the liquefaction of river bank soils or the soils underlying the bank. Figure 20 shows that the serious river bank instability was observed along the following waterways: Ruan, New Ruan, Sha, New Dou, and Dou Rivers, and the Ji Canal.

38. Ground subsidence was found in the southern region of the Tangshan earthquake affected area. As shown in Figure 20, the area is near the Bo Hai Bay. Large-scale ground subsidences were observed in the area with a thick, soft, marine clay deposits. The clay is soft and sensitive and is underlain by a thick alluvial deposit. The subsidence of this clay deposit might have been effected by a great extent by the liquefaction of its underlying sand deposit. Another possible cause for settlement be the failure of this sensitive clay due to the continual remolding during strong seismic ground shaking. To the north of this regional subsidence is the area of local subsidence. This is located in the transitional area from the regional subsidence to the liquefaction area. In the subsidence area, less surface evidences of ground liquefaction were observed. If the underlying sand deposit were liquefied, the surface evidence such as sand boiling of liquefaction could have been partially suppressed by the thick overlying marine clay deposit.

39. The most extensive form of ground failure caused by the Tangshan earthquake is liquefaction with surface expression of sand boiling (sand volcanoes or sand blows). Even some cohesive soils were found to have liquefied. The severity of liquefaction increases southeastward and it is most serious in the recent Ruan river alluvial fan. The degrees of liquefaction ground failures were divided into light liquefaction, moderate liquefaction and heavy liquefaction. As shown in Figure 20, liquefaction ground failures were light to the west of Dou river, most serious to the east of New Ruan river, and moderate in the area between Sha and New Ruan rivers. Ground water in the area to the east of the New Ruan river is very shallow. The alluvial deposits in this area are loose and have been subjected to the least aging and prestraining effects and are, therefore, most vulnerable to earthquake-induced

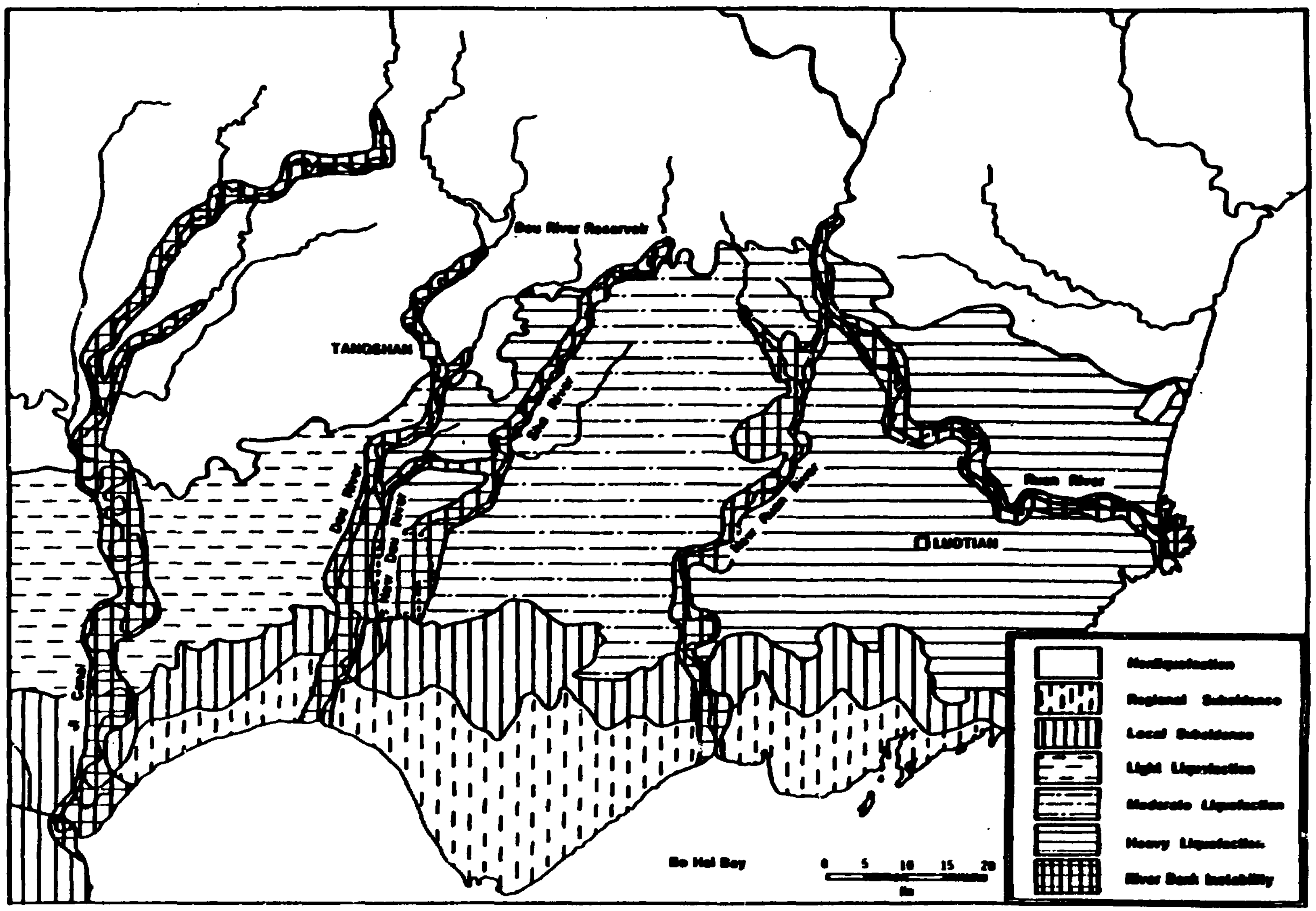



Figure 20. Earthquake-induced liquefaction and other ground failures in the Tangshan Plain

liquefaction ground failure. The ground surface evidence of liquefaction is found predominantly in the form of sand boiling. Sands from liquefaction-induced sand boiling were deposited around their surface exits as sand mounds. The size and spacing of sand mounds were found to be dependent on the intensity and duration of ground shaking, burial depth of liquefiable soils, depth of ground water table, and the index and engineering properties of the soils involved. The size and spacing of mounds increased with the intensity and duration of ground shaking, and the depth of the ground water table. These mounds are sparsely distributed in some areas and densely distributed in others. Sand mounds overlapped in densely-distributed areas and formed various network, whirling, and strip patterns (Fang, et al., 1981), coincident with shallow ground water and burial depth. Examples of these patterns are shown in Figure 21. Dimensions of sand mounds range from 10 to 50 meters and their spacings range from small to as large as 100 meters.

## Liquefied Soils in 1975 Haicheng and 1976 Tangshan Earthquakes

40. Fine-grained soils with some plasticity are no longer considered to be immune from earthquake-induced liquefaction. Among numerous recently reported cases of earthquake-induced liquefaction, almost none involved only clean sand. Most liquefied soils contained some percentages of fine particles (silt, or clay, or both). Several cohesive soils were reported to have liquefied during the 1975 Haicheng and 1976 Tangshan earthquakes (Wang, 1979; Wang, et al., 1979; Shi and Yu, 1981; Wang, 1981; Zhou, 1981; Fu and Tatsuoka, 1984). Seed and Idriss (1982) revised their liquefaction assessment criteria as follows to include information made available by the Tangshan experience:

a. For soils with $D_{50} > 0.25$mm, use the standard correlation charts.

b. For silty sands and silts plotting below the A-line in the plasticity chart and $D_{50} < 0.15$mm, let $N_1 = (N_1)$ measured + 7.5 and use the standard correlation charts for sands.

c. If the water content of any clayey soil is less than 0.9 times the liquid limit, consider the soil non-liquefiable.

Wang (1979) indicated that certain types of clayey soils may be vulnerable to severe strength loss as a result of earthquake shaking and these soils have the following characteristics:

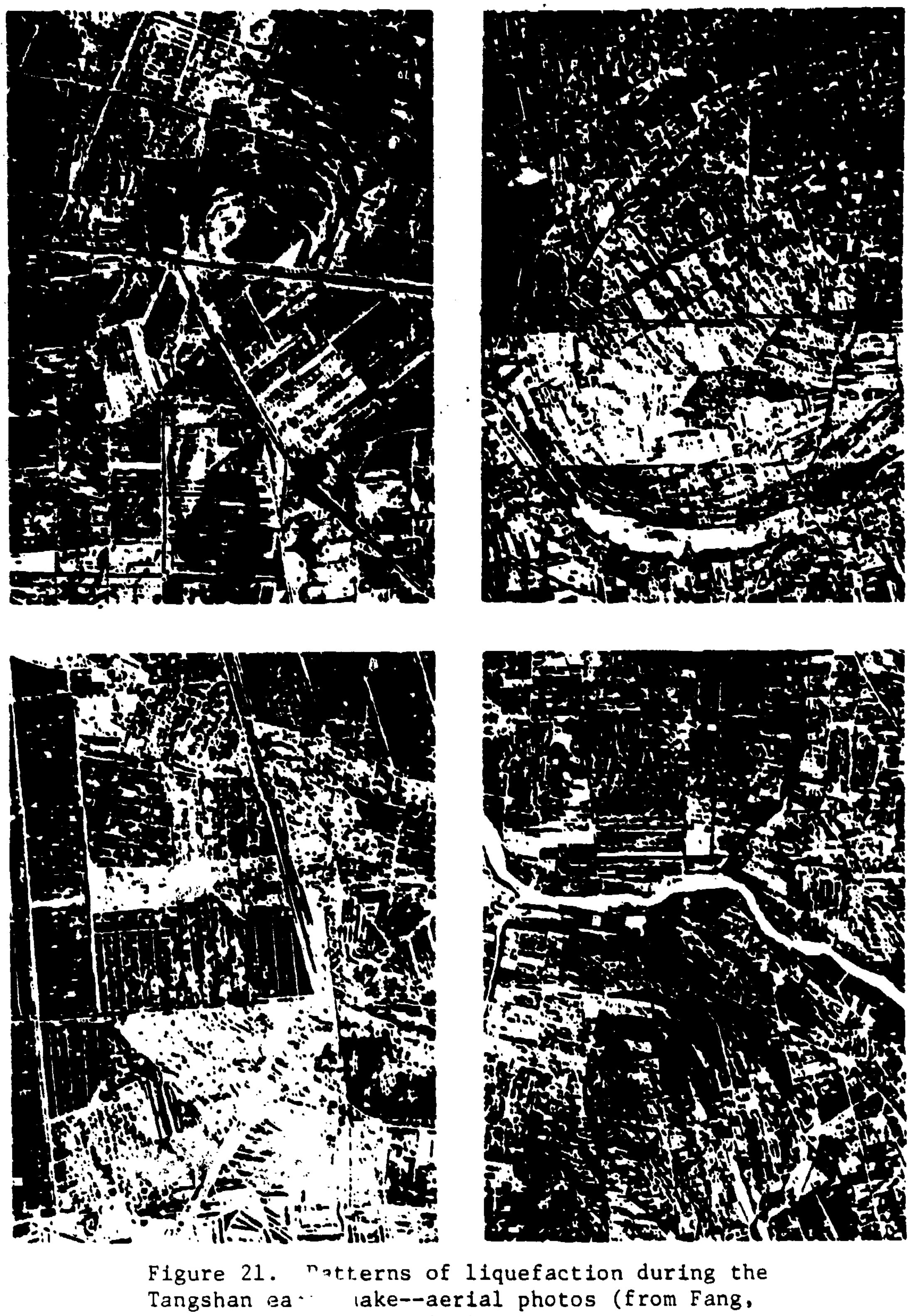


Figure 21. Patterns of liquefaction during the Tangshan earthquake--aerial photos (from Fang, et al. 1981)

percent finer than 0.005mm < 15%

Liquid limit < 35%

Water content > 0.9 x liquid limit.

Seed and Idriss (1982) also indicated that for soils plotting above the A-line on the Casagrande plasticity chart, laboratory tests should be conducted to determine their liquefaction potential (type of laboratory test unspecified). Wang, et al., (1979) attempted to formulate a functional relationship to determine the liquefaction susceptibility of soils. Ten independent factors were considered and the following five were retained in the equation: Peak ground acceleration, depth of suspect stratum, SPT blow counts, depth of ground water table, and cohesive soils content. Jennings (1980) reported, with the main information source being the Institute of Engineering Mechanics at Harbin, China, that the equation for critical blow counts given in the Chinese seismic Design Code for Industrial and Domestic Buildings was unable to predict the liquefaction of soils containing fines. The equation is intended mainly for clean, sandy soils. The clayey soils observed to have liquefied typically contained less than 10 percent of clay particles (d < 0.005mm). Shi and Yu (1981) reported from their observations of soils liquefied in 1975 Haicheng and 1976 Tangshan earthquakes that the formula used in the modified Chinese Aseismic Design Code (1979) for identifying liquefiable sands is invalid for clayey silts or clayey sands containing (unspecified) small amounts of clay size particles (d < 0.005mm). When the clay content was sufficiently large, soils were not liquefied. Thus, clay content significantly affects the liquefaction susceptibility of soils. Wang (1979) reported that saturated sands and "somewhat cohesive" silty soils are both vulnerable to liquefaction. Field observation indicated that soils liquefied during 1975 Haicheng and 1976 Tangshan earthquakes contained as much as 20% of clay size particles (d < 0.005mm) and 80% of fine particles (d < 0.005mm) as shown in Figure 22. The plasticity index of liquefied clayey soils averaged about 10 but ranged from 3 to 15 as shown in Figure 23. Figure 24 shows the natural water content of liquefied "somewhat cohesive" soils. Some coarse-grained soils, such as gravelly sands and sandy gravels, were also observed to liquefy.

41. Soils from the bank of the Manggou River with about 25 percent gravel size particles (d > 2mm) were observed to have liquefied during 1975 Haicheng earthquake. A large portion of the submerged portion of the sandy

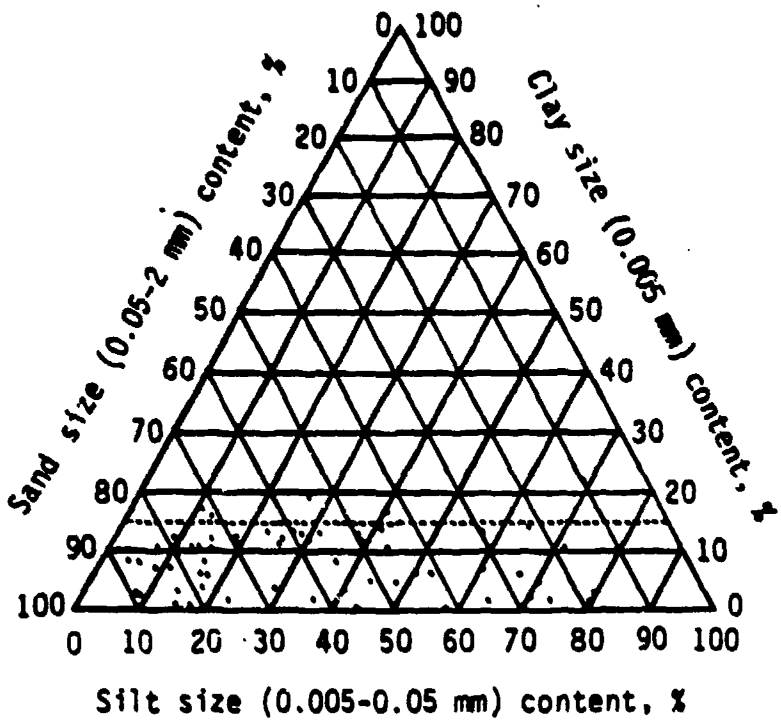



Figure 22. Grain size distributions of liquefied soils in China during strong earthquakes (VII-IX, MM intensity) (from Wang 1979)

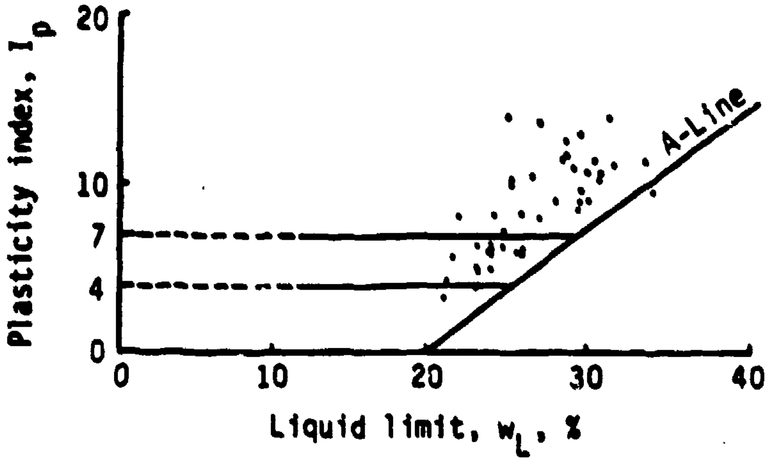



Figure 23. Plasticity chart for liquefied "somewhat cohesive" silty soils in China during strong earthquakes (VII-IX MM intensity) (after Wang 1979)

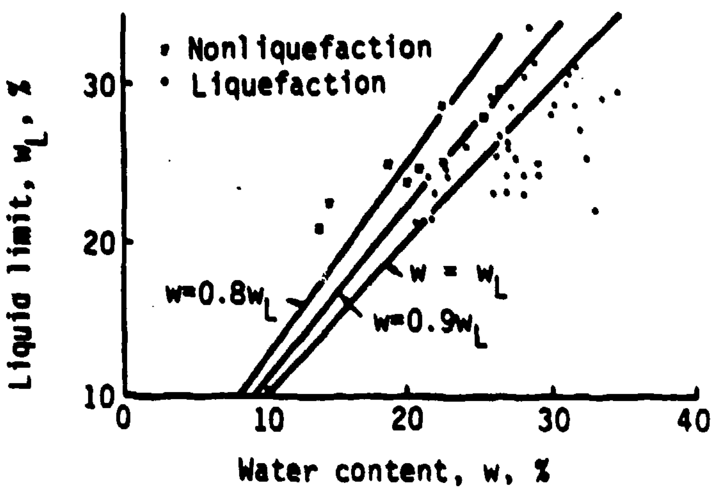



Figure 24. Water content versus liquid limit of liquefied and non-liquefied "somewhat cohesive" silty soils in China during strong earthquakes (VII-IX MM intensity) (from Wang 1979)

gravel upstream slope of Baihe Main Dam slid into the Miyuan Reservoir during the 1976 Tangshan earthquake. The liquefaction susceptibility of sandy gravel is governed by its fines content when its coarse portion (d > 2mm) is less than 60 percent. Fine-grained clayey, or "somewhat cohesive" soils liquefied during 1975 and 1976 earthquakes were found to have natural water contents of greater than 90 to 100 percent of their liquid limit and liquidity indexes greater than 0.75 to 1.0. Fang, et al. (1981, 1982, 1983) gave an extensive discussion on the liquefaction ground failures that took place during the 1976 Tangshan earthquake. Zhou (1981) reported a study on the effect of fines contents on the cone penetration resistance, in which the critical cone penetration resistance ($P_{scr}$) was formulated as a function of epicentral distance (D), depth of ground water (Hw), thickness of overburden ($H_o$), the mean depth of sand layer (H), and $L_{cr}$, a linear discrimination parameter selected to correspond with a desired probability of liquefaction (the study did not specify a value):

$$P_{scr} = \exp\,(L_{cr} - 0.0215D - 0.0766H_w - 0.0645H_o + 0.0017H).$$

The cone data from the Tangshan area were used in the formulation. The liquefied soils in the Tangshan area were mainly clean sands. The equation was used successfully in identifying liquefiable soils in the Haicheng District, northeast of Tangshan. The equation, however, was ineffective in performing the same task in the Lutai District, 48 Km southwest of Tangshan. This was attributed to the difference in fines contents of the soils from the Lutai area and the Tangshan area as shown in Table 6.

Table 6

Fines Contents of Liquefied Soils

| Area | Mean Grain Size $D_{50}$ (mm) | Minus No. 200 Content (%) | Minus 0.005 mm Content (%) |
|---|---|---|---|
| Lutai | 0.064 - 0.078 | 50 - 65 | 7 - 18 |
| Tangshan | 0.076 - 0.61 | Small | 0 |

42. Zhou (1981) also pointed out that Seed's simplified method (1971) and the method proposed in the Modified Aseismic Design Code for Industrial

and Domestic Buildings (1979) are basically for clean sands and are not effective without modification in assessing the liquefaction resistance of soils containing substantial amount of fines (silt and/or clay). Fang, et al., (1981, 1982, 1983) reported in their studies on liquefaction ground failures induced by the 1976 Tangshan earthquake that the liquefied silty sand, fine sand, and medium sand contained 10-30, 10-20, and less than 10 percent of minus 0.074 mm particles, as shown in Figure 25. Mean grain sizes of liquefied soils from Tangshan and its vicinity (peneplain), the inclined plain, and coastal plain are summarized in Table 7. Generally speaking, the mean grain size decreases and the content of minus 0.074mm size particles increases from the peneplain and inclined plain to the coastal plain. Some statistics on soils liquefied during the Tangshan earthquake are given in Table 8. Relative densities appeared to be too high for the corrected blow counts shown in the table and are estimated to more likely values in parentheses. The above adjustment was made based on the penetration resistance versus relative density curves, Figure 26, of Gibbs and Holtz (1957). The overburden pressure effect was taken into consideration.

43. In summary, the 1975 Haicheng earthquake and the 1976 Tangshan earthquake provided a wealth of information on earthquake-induced ground liquefaction. Data were, however, scattered in various Chinese engineering agencies. Gradation characteristics and fines contents were found from the available data to greatly affect the liquefaction resistance of soils. Chinese and Japanese experiences indicated that the presence of fines, either cohesive or noncohesive, does not in itself render a deposit invulnerable to earthquake-induced liquefaction, and current methodologies for assessing liquefaction potential may indicate, inappropriately, the contrary. A systematic analysis of data containing information on liquefaction of soils containing cohesive or cohesionless fines should yield important and useful information on the liquefaction susceptibility of such soils. However, any deviation from U.S. standards in the conduct of various foreign laboratory and field tests must be noticed, investigated, and a correlation developed before any further analysis of data from foreign countries is performed.

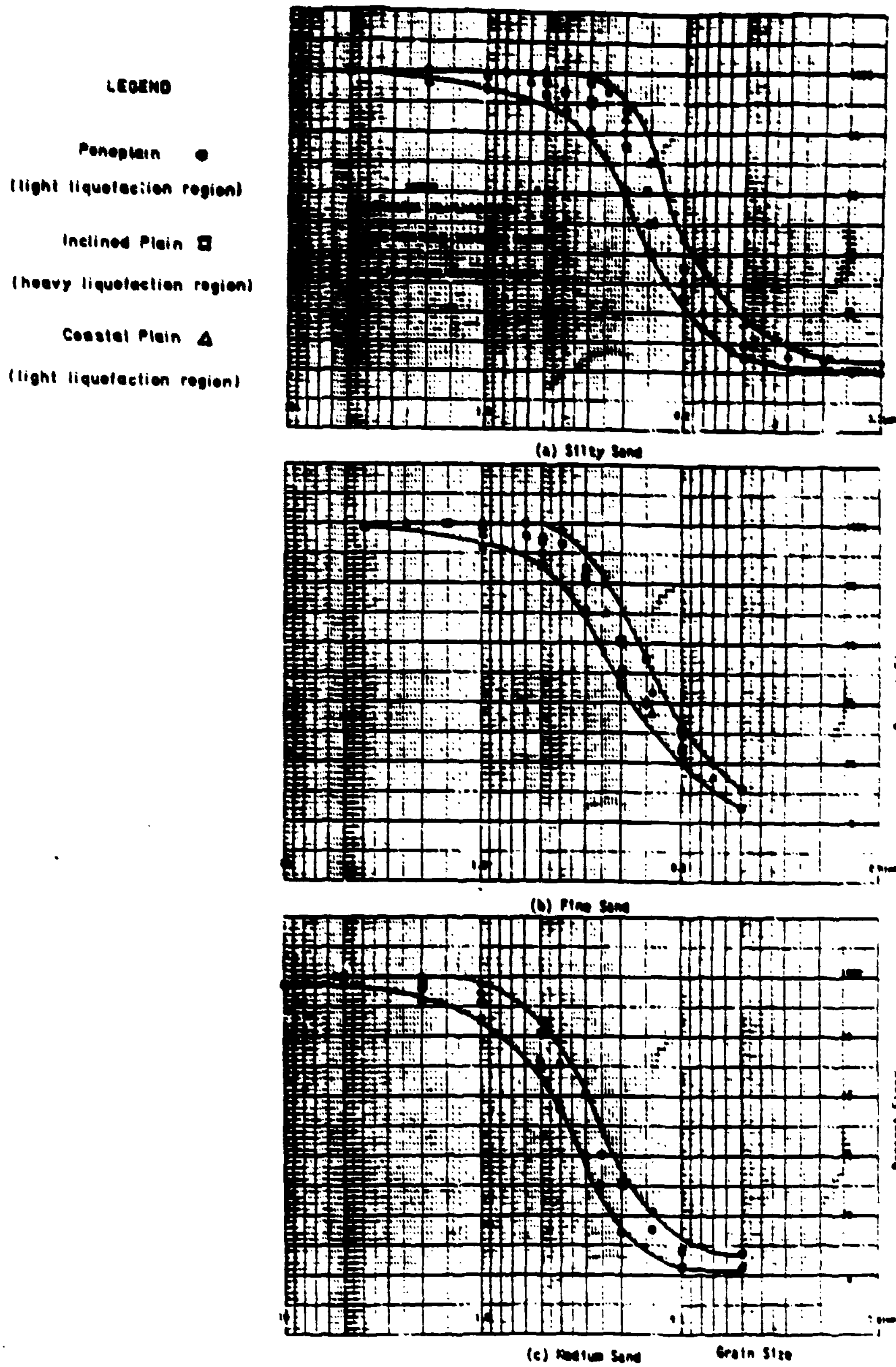



Figure 25. Gradations of liquefied soils--Tangshan earthquake

Table 7

Mean Grain Size of Liquefied Soils, mm

| Region | Light Liquefaction | Heavy Liquefaction | Liquefaction Induced Subsidence |
|---|---|---|---|
| Soil Type | Tangshan and Vicinity (Coarse)<------------- | Inclined Plain ------------- | Coastal Plain ------------->(Fine) |
| Silty Sand | 0.14 - 0.17 | 0.135 - 0.14 | 0.105 - 0.14 |
| Fine Sand | 0.18 - 0.22 | 0.165 - 0.19 | 0.16 - 0.19 |
| Medium Sand | 0.28 - 0.36 | 0.30 - 0.36 | - |

Table 8

Statistics of Liquefied Soils from Tangshan Earthquake

| Region | Soil Description | Depth of Saturated Sand (H(m) | Relative Density Dr (%) | Depth of G.W.T. h(m) | Mean Grain Size $D_{50}$ (mm) | Coefficient of Uniformity $C_u$ | Corrected Blow Counts | Effective Overburden Pressure $\sigma_v'$ (Kg/cm$^2$) | Intensity | Epicentral Distance (Km) | Duration (Sec) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chienjain | Layered Deposit with bedded clay and sand Fine sand predominant | 1.0 | 70 - 80 (80) | 1 | Silty 0.15<br>Fine 0.18<br>Medium 0.29 | 2.0<br>2.0<br>2.2 | 15-20 | 1.0-1.5 | 10 | 20 | 110 |
| Luanan | Layered Deposit with Interbedded Clay & Sand Silty sand predominant | 0.8 | 77 (65) | 0.8 | Silty 0.18<br>Fine 0.16<br>Medium 0.33 | 2.8<br>2.6<br>2.5 | 20-25 | 1.0 | 9 | 42 | 100 |
| Luotian | Layered Deposit with Interbedded Clay & Sand Fine silty sand predominant | 0.5 | 80 (80) | 0.5 | Silty 0.13<br>Fine 0.18<br>Medium 0.19 | 2.2<br>1.9<br>2.7 | 20-25 | 0.5 | 8 | 63 | 100 |
| Coastal | Clay Layers Interbedded with Thin Layer of Silty Sand | 5-15 | < 75 (< 55) | 0 | Silty 0.12<br>Fine 0.18<br>Medium 0.29 | 2.8<br>1.1<br>2.3 | <15 | 1.5 | 7-8 | 84 | 60 |

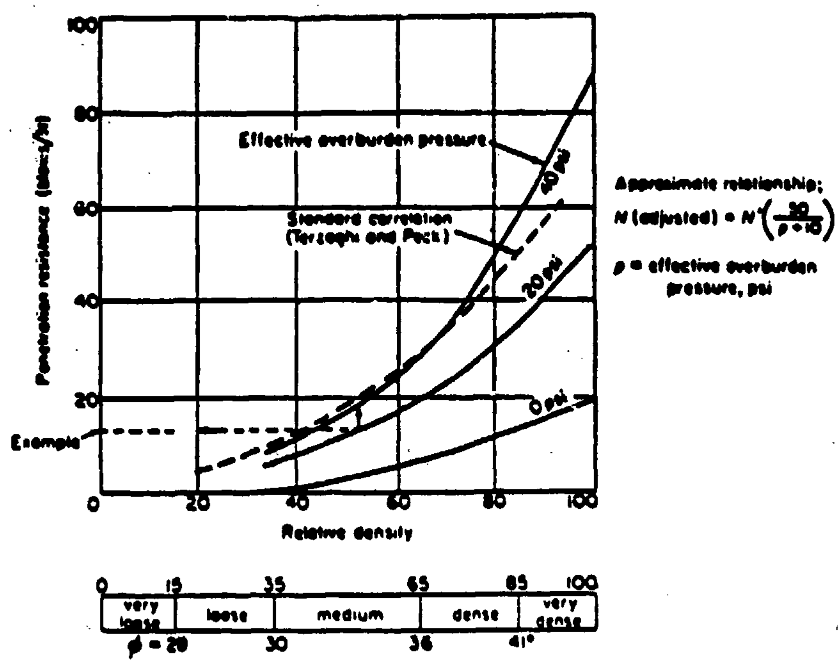


Figure 26. Relationship between standard penetration resistance and relative density of sand (after Gibbs and Holtz 1957)

## PART V: FUTURE RESEARCH NEEDS ON FINES CONTENT EFFECTS

44. Urgent needs exist to develop criteria and procedures for evaluating the liquefaction susceptibility of soils containing fines. Field observations from the United States, People's Republic of China, and Japan indicated that cohesive soils are not immune from earthquake-induced liquefaction ground failures. In fact, Chinese data indicate liquefaction of cohesive soils and soils containing substantial amount of fines (minus 0.074mm). These soils would have been judged "safe" based on the current criteria for assessing the liquefaction susceptibility of clean sands. Chinese data also demonstrated the ineffectiveness of the Modified Aseismic Design Code for Industrial and Domestic buildings (1979) in the evaluation of liquefaction susceptibility of soils containing fines, because the liquefaction criteria in design code was established based on the experience in clean sands.

45. The inability of current procedures to assess the liquefaction susceptibility of soils warrants immediate research into the liquefaction susceptibility of soils containing fines, cohesive and/or noncohesive.

46. The above research can serve as a vehicle for developing the world data bank for the earthquake-induced liquefaction of soils containing fines. Three of the countries which are currently actively conducting research in earthquake-induced ground liquefaction are the United States, Japan, and People's Republic of China (PRC). Thus, data from the above countries and others, if applicable, should be collected. The above data collection should include both laboratory and field data.

47. Laboratory tests on undisturbed and artificially-prepared soils should be conducted to expand our knowledge in this particular area. Laboratory tests on undisturbed samples can be used to confirm field observations. The characteristics of undisturbed soils are, however, extremely variable and a great number of tests are required to form a good statistical base for assessing the effects of various factors. Current sampling techniques are still not quite capable of securing undisturbed samples and test results from specimens so obtained may not represent the response expected in-situ. Laboratory tests give researchers the advantage of being to exercise control over various influencing factors. Factors can be systematically varied to obtain a desired statistical database, which can in turn be used in formulating proper criteria and assessment procedures for liquefaction susceptibility of soils.

48. The author and his colleagues at the University of Colorado at Denver have designed, fabricated, and tested a laboratory test chamber adaptable to monotonic or cyclic loading of hollow cylindrical soil specimens. Upon acquisition of a suitable loading machine, the author intends to develop a cyclic axial-torsional testing program to assess the cyclic response of various soils to a wide variation of stress histories. Such a device could be well-employed to produce laboratory stress excursions in annular representations of insitu soils that closely replicate insitu static and cyclic stress conditions considered appropriate for earthquake loading. A companion series of cyclic triaxial tests could be used to generate a database for response of the same soils to this simple and more conventionally applied liquefaction resistance test, and the result of both programs would provide valuable data toward the formulation of relationships for converting results of cyclic triaxial tests on fine-grained soils into the form best suited to earthquake-induced liquefaction susceptibility analysis, namely those results anticipated for simple shear loading. Such relationships have been established for clean sands and similar efforts are currently under investigation for well-graded soil mixtures, and the subject research would attempt to fill a gap in the state-of-the-art.

49. Field tests are also recommended in the future research. Standard penetration tests (SPT) and Cone Penetration Tests (CPT), especially the former, are the most popular field strength tests currently used. The SPT test enjoys the advantage of wide acceptance in the geotechnical and earthquake engineering professions for assessing field strength of soils. It, therefore, has a large database. It can be easily performed and also produces disturbed samples which may be used for index classification. Its drawback, however, lies in the lack of consistent international practice standard. The CPT test is capable of detecting subsoil conditions to a greater detail than the SPT test. It, however, can not recover any specimens and has a much smaller database than its counterpart.

## REFERENCES


American Society for Testing and Materials (Annual). "Standard Method of Penetration Test and Split-Barrel Sampling of Soils," Designation D1586-67, ASTM Book of Standards.

ASCE Geotechnical Division Committee on Soil Dynamics. 1978. "Definition of Terms Related to Liquefaction," Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT9, pp. 1197-1200.

Banerjee, N. B., Seed, H. B., and Chan, C. K. 1978. "Cyclic Behavior of Dense Coarse-Grained Materials in Relation to the Seismic Stability of Dams," Report No. UCB/EERC-79-13, University of California, Berkeley, California.

Casagrande, A. 1940. "Characteristics of Cohesionless Soils Affecting the Stability of Slopes and Earth Fills," Journal of Boston Society of Civil Engineers, January 1936; reprinted in Contributions to Soil Mechanics, 1925-1940, Boston Society of Civil Engineers, October.

Casagrande, A. 1938. "The Shearing Resistance of Soils in Relation to the Stability of Earth Dams," Proceedings, Soils and Foundations Conference of the U.S. Engineering Department.

Casagrande, A. 1975. "Liquefaction and Cyclic Deformations of Sands - A Critical Review," Proceedings of the Fifth Pan American Conference on Soil Mechanics and Foundation Engineering, Buenos Aires.

Castro, G. 1969. "Liquefaction of Sands," Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

Castro, G. 1969. "Investigation of Undisturbed Samples of Sand from Tarbela Dam," Report prepared for Tippetts-Abbett-MacCarthy-Stratton, July.

Castro, G., and Poulos, S. J. 1976. "Factors Affecting Liquefaction and Cyclic Mobility," ASCE Annual Convention and Exposition, Preprint 2752, Liquefaction Problems in Civil Engineering, pp. 105-137.

Castro, G., and Poulos, S. J. 1977. "Factors Affecting Liquefaction and Cyclic Mobility," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT6, pp. 501-506.

Castro, G., Poulos, S. J., France, J. W., and Enos, J. L. 1982. "Liquefaction Induced by Cyclic loading," Report by Geotechnical Engineers, Inc., to the National Science Foundation, Washington, D.C., March, pp. 1-80.

Chang, N. Y., and Ko, H. Y. 1982. "Dynamic Properties of Clays Under General Three-Dimensional Stresses," Final Report to the National Science Foundation under Grant No. PRF 79-00718.

Chang, N. Y., and Makarechi, H. 1982. "Dependence of Shear Modulus of Denver Sands on Gradation Characteristics," Proceedings of the Third International Conference on Earthquakes Microzonation, Seattle, Washington, June, pp. 945-956.

Chang, N. Y., Hsieh, N. P., Samuelson, D. L. and Horita, M. 1982. "Behavior of Monterey No. 0 Sand Under Cyclic Loads," Proceedings of the Third International Conference on Earthquake Microzonation, Seattle, Washington, June, pp. 1017-1032.

Clukey, E., Cacchione, D. A., and Nelson, C. H. 1980. "Liquefaction Potential of the Yukon Prodelta, Bering Sea," Proceedings, Twelfth Annual Offshore Technology Conference, Houston, Texas, Vol. 2, pp. 315-525.

Cooper, S. S., and Franklin, A. G. 1982. "The PQS Probe: Simultaneous Measurement of Penetration Resistance and Pore Pressure," Technical Report GL-82-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Coulter, H. W., and Migliaccio, R. R. 1966. "Effects of the Earthquake of March 27, 1964, at Valdez, Alaska," U.S. Geological Survey Professional Paper 542-C, U.S. Department of the Interior.

DeAlba, P., Chan, C. K., and Seed, H. B. 1975. "Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests," Report No. EERC 74-14, University of California, Earthquake Engineering Research Center, Berkeley, California.

Department of the Army. 1970. Laboratory Soils Testing, Engineer Manual EM 1110-2-1906, 1980 Revision, Office, Chief of Engineers, Washington, D.C.

Department of the Army. 1979. Geophysical Exploration, Engineer Manual EM 1110-1-1802, Office, Chief of Engineers, Washington, D.C.

Dobry, R., and Alvarez, L. 1967. "Seismic Failures of Chilean Tailings Dams," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM6, November, pp. 237-260.

Dobry, R., Stokoe, K. H., Ladd, R. S., and Youd, T. L. 1981. "Liquefaction Susceptibility from S-Wave Velocity," In-Situ Testing to Evaluate Liquefaction Susceptibility, Session No. 24, Preprint No. 81-544, ASCE National Convention, St. Louis, Missouri.

Dobry, R., Ladd, R. S., Chung, R. M., and Powell, D. 1982. "Prediction of Pore Water Pressure Buildup and Liquefaction of Sands During Earthquakes by the Cyclic Strain Method," National Bureau of Standards, Building Science Series No. 138, Washington, D.C., 1982.

Donaghe, R. T., and Gilbert, P. A. 1983. "Cyclic Rotation of Principal Planes to Investigate Liquefaction of Sands," Miscellaneous Paper GL-83-24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Donovan, N. C., and Singh, S. 1978. "Liquefaction Criteria for the Trans-Alaska Pipeline," Journal of the Geotechnical Engineering Division, Vol. 104, No. GT4, April, pp. 447-462.

Douglas, B. J., Olsen, R. S., and Martin, G. R. 1981. "Evaluation of the Cone Penetrometer Test for SPT-Liquefaction Assessment," In-Situ Testing to Evaluate Liquefaction Susceptibility, Section No. 24, Preprint No. 81-544, ASCE National Convention, St. Louis, Missouri.

Drenvich, V. P., and Richart, F. E., Jr. 1970. "Dynamic Prestraining of Dry Sand," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM2, pp. 453-469.

Erchul, R. A., and Gularte, R. C., 1982. "Electrical Resistivity Used to Measure Liquefaction of Sand," Journal of the Geotechnical Engineering Division, ASCE, Vol. 108, No. GT5, pp. 778-782.

Espana, G., Chaney, R. C., and Duffy, D. "Cyclic Strengths Compared for Two Sampling Techniques," Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. GT5, pp. 536-576.

Fairless, G. J. 1984. "Liquefaction Case Histories in New Zealand," Research Report 84/18, University of Canterbury, Christchurch, New Zealand.

Fang, H. Q., Zhoa, S. T., and Huang, Z. L. 1982. "Collateral Effects and Basic Patterns of Seismic Liquefaction," Proceedings of the 4th International Congress of the International Association of Engineering Geology, New Delhi, India.

Fang, H. Q., Wang, Z. Q., Zhoa, S. T., Huang, Z. L., and Mrall, I. C. 1981. "Approach to Tangshan Earthquake Engineering Geological Problems," Report of Chinese Academy of Building Research, Beijing, China.

Fang, H. Q., Zhoa, S. T., and Huang, Z. L. 1982. "Assessment of Effects of Geological Characteristics on Tangshan Earthquake-Induced Ground Liquefaction," Geotechnical Engineering Investigation Journal, (in Chinese), pp. 4-9.

Fang, H. Q., Zhoa, S. T., and Huang, Z. L. 1983. "Effects of Geomorphic Characteristics on Liquefaction of Soils," Geotechnical Engineering Investigation Journal, (in Chinese), pp. 11-15.

Fardia, M. N., and Veneziano, D. 1982. "Probabilistic Analysis of Deposit Liquefaction," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT3, pp. 395-417.

Federal Highway Administration. 1978. "Guidelines for Cone Penetration Test Performance and Design," Report No. FHWA-TS-78-209, Prepared for the U.S. Department of Transportation by Dr. John H. Schmertmann, University of Florida.

Finn, W. D. L. 1982(a). "Dynamic Analysis and Liquefaction - Emerging Trends," Proceedings of the Third International Earthquake Microzonation Conference, Seattle, Washington, Vol. II, pp. 909-929.

Finn, W. D. L. 1982(b). "Fundamental Aspects of Response of Tailings Dams to Earthquakes," Dynamic Stability of Tailings Dams, Preprint No. 82-539, ASCE National Convention, New Orleans, Louisiana.

Finn, W. D. L. 1982(c). "Soil Liquefaction Studies in the People's Republic of China," Soil Mechanics - Transient and Cyclic Loads, John Wiley and Sons, Ltd.

Finn, W. D. L., Bransby, P. L., and Pickering, D. J. 1970. "Effect of Straing History on Liquefaction of Sand," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, SM6, Proc. Paper 7670, pp. 1917-1934.

Finn, W. D. L., Lee, K. W., and Martin, G. R. 1977. "An Effective Stress Model for Liquefaction," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT5, Proc. Paper 13008, pp. 517-533.

Finn, W. D. L., and Martin, G. R. 1975. "Fundamentals of Liquefaction Under Cyclic Loading," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT5, pp. 81-92.

Finn, W. D. L., Pickering, D. J., and Bransby, P. L. 1971. "Sand Liquefaction in Triaxial and Simple Shear Tests," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM4, pp. 639-660.

Forrest, J. B., Ferritto, J. M. and Wu, G. 1981. "Site Analysis for Seismic Soil Liquefaction Potential," Proceedings International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 155-160.

Fu, S. C., and Tatsuoka, F. 1984. "Soil Liquefaction During the Haicheng and Tangshan Earthquakes in China: A Review," Soils and Foundation, Vol. 24, No. 4, pp. 11-29.

Gibbs, H. J., and Holtz, W. G. 1957. "Research on Determining the Density of Sands by Spoon Penetration Testing," Proceedings of the Fourth International Conference on Soil Mechanics and Foundation Engineering, London, England, pp. 35-39.

Haldar, A., and Tang, W. 1979. "A Probabilistic Evaluation of Liquefaction Potential," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, Proc. Paper 14374, pp. 145-163.

Horita, M. 1985. "Modeling of Cyclic Behavior of Saturated Monterey No. 0.30 Sand," Ph.D. Thesis, University of Colorado at Denver, 394 pp.

Hsieh, N. P. 1981. "Behavior of Saturated Monterey No. 0 Sand Under Cyclic Loads," M.S. Thesis, University of Colorado at Denver.

Huang, X. L. 1981. "Observations and Analysis on Building Settlement Due to the Tangshan Earthquake," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 517-522.

Ishihara, K. 1972. "Liquefaction of Subsurface Soil During Earthquakes," Technocrat, Fuji Marketing Research Company, Ltd., Tokyo, Japan.

Ishihara, K., Sodekawa, M., and Tanaka, Y. 1978. "Effects of Overconsolidation on Liquefaction Characteristics of Sand Containing Fines," Dynamic Geotechnical Testing, ASTM STP 654, pp. 246-264.

Ishihara, K., Yasuda, S., and Yokata, K. 1981. "Cyclic Strength of Undisturbed Mine Tailings," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 53-58.

Iwasaki, T., Tokida, K., and Tatsuoka, F. 1980. "Soil Liquefaction Potential Evaluation With Use of the Simplified Procedure," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 209-214.

Jennings, P. C. 1980. "Earthquake Engineering and Hazards Reduction in China," A Trip Report of the American Delegation, pp. 25-27.

Kaufman, L. P. 1981. "Percentage Silt Content in Sands and its Effect on Liquefaction Potential," M.S. Thesis, University of Colorado at Denver.

Kaufman, L. P., and Chang, N. Y. 1982. "Percentage Silt Content in Sands and its Effect on Liquefaction Potential," Proceedings, International Conference on Computational Methods and Experimental Measurements, Washington, D. C., June.

Kishida, H. 1966. "Damage to Reinforced Concrete Buildings in Niigata City with Special Reference to Foundation Engineering," Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. III, No. 1, Tokyo, Japan.

Kishida, H. 1966. "Characteristics of Liquefaction Sands During Mino-Owari, Tohnanki, and Fukui Earthquakes, "Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. III, No. 2, Tokyo, Japan.

Koester, J. P., and Franklin, A. G. 1985. "Current Methodologies for Assessing the Potential for Earthquake-Induced Liquefaction in Soils," Research Report No. NUREG/CR-4430 prepared by Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station for the U.S. Nuclear Regulatory Commission, 58 pp.

Kovacs, W. D., Salomone, L. A., and Yokel, F. Y. 1981. "Energy Measurement in the Standard Penetration Test," NBS Building Science Series 135, National Bureau of Standards, Washington, D.C.

Kuribayashi, E., an Tatsuoka, F. 1975. "Brief Review of Liquefaction During Earthquakes in Japan," Soils and Foundations, Vol. 15, No. 4, pp. 81-92.

Lee, K. L., and Fitton, J. A. 1969. "Factors Affecting the Cyclic Loading Strength of Soil," Vibration Effects of Earthquakes on Soils and Foundations, ASTM STP 450.

Lee, K. L., and Seed, H. B. 1966. "Strength of Anisotropically Consolidated Samples of Saturated Sand Under Pulsating Loading Conditions," Report No. TE-66-3, Department of Civil Engineering, University of California, Berkeley, California, July.

Lee, K. L. and Seed, H. B. 1967. "Cyclic Stress Conditions Causing Liquefaction of Sand," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM1, Proc. Paper 5058, January.

Lee, K. S. 1984. "Assessment of Liquefaction Potential of Soils During Tangshan Earthquake," Geotechnical Investigation Science and Technology (in Chinese), MMI, China, pp. 26-31.

Liu, L. 1983. "Re-Evaluation of Liquefaction Assessment Criteria in Chinese Aseismic Design Codes," Geotechnical Engineering Investigation Journal, pp. 47-52.

Liu, L., Li, K., and Bing, D. 1980. "Earthquake Damage of Baihe Earth Dam and Liquefaction Characteristics of Sand and Gravel Materials," Proceedings of the Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, Vol. 3, pp. 171-178.

Marcuson, W. F. III, and Bieganousky, W. A. 1977. "SPT and Relative Density in Coarse Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT11, pp. 1295-1309.

Marcuson, W. F. III, and Gilbert, P. A. 1972. "Earthquake Liquefaction Potential at Patoka Dam, Indiana, "Miscellaneous Paper S-72-42, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Marcuson, W. F. III, and Townsend, F. C. 1976. "Effects of Specimen Reconstitution on Cyclic Triaxial Test Results," Miscellaneous Paper S-76-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Marcuson, W. F. III, and Franklin, A. G. 1983. "Seismic Design, Analysis, and Remedial Measures to Improve Stability of Existing Earth Dams," Miscellaneous Paper GL-83-23, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Marcuson, W. F. III, Hadala, P. F., and Franklin, A. G. 1980. "Current Methods of Dynamic Analysis for Seismic Stability of Earth Dams," Engineering Geology, Vol. 16, Elsevier Scientific Publishing Company, Amsterdam, pp. 19-28.

Martin, G. R., Finn, W. D. L., and Seed, H. B. 1978. "Effects of System Compliance on Liquefaction Tests," Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT4, April, pp. 463-497.

McNearny, R. L. 1982. "The Influence of Grain Size Distribution on the Undrained Dynamic Properties of Saturated Sands," M.S. Thesis, University of Colorado at Denver.

Mulilis, J. P., Chan, C. K., and Seed, H. B. 1975. "The Effects of Method of Sample Preparation on the Cyclic Stress-Strain Behavior of Sands," EERC Report 75-18, College of Engineering, University of California, Berkeley, California, July.

Mulilis, J. P., Townsend, F. C. and Horz, R. C. 1978. "Triaxial Testing Techniques and Sand Liquefaction," Dynamic Geotechnical Testing, ASTM STP 654, pp. 265-279.

Norton, W. E. 1983. "In-Situ Determination of Liquefaction Potential Using the PQS Probe," Technical Report GL-83-15, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Ohsaki, Y. 1966. "Niigata Earthquakes, 1964, Building Damage and Soil Conditions," Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. VI, No. 2, pp. 14-37.

Olsen, R. S. 1984. "Liquefaction Analysis Using the Cone Penetrometer Test," Proceedings of the Eighth World Conference on Earthquake Engineering, San Francisco, California, July, pp. 1-28.

Peacock, W. H., and Seed, H. B. 1968. "Sand Liquefaction Under Cyclic Loading Simple Shear Conditions," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 94, No. SM3, pp. 689-708.

Poulos, S. J. 1983. "The Steady State of Deformation," Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. GT5, pp. 553-562.

Ramanujam, N., Holish, L. L., and Chen, W. H. 1978. "Post-Earthquake Stability Analysis of Earth Dams," Earthquake Engineering and Soil Dynamics, ASCE Geotechnical Engineering Division Specialty Conference Proceedings, Pasadena, California, Vol. 2, pp. 762-776.

Richter, C. F. 1958. Elementary Seismology, W. H. Freeman and Company, San Francisco, California.

Robinson, K. E. 1977. "Tailings Dam Constructed on Very Loose, Saturated Sandy Silt," Canadian Geotechnical Journal, Vol. 14, No. 3, August, pp. 399-407.

Roe, G. V., DeAlba, P.A., and Celikkol, B. 1981. "Acoustic Identification of Liquefaction Potential," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. 2, pp. 199-202.

Samuelson, D. L. 1981. "The Effect of Frequency on the Liquefaction Potential of Monterey No. 0 Sand," M.S. Thesis, University of Colorado at Denver.

Sangrey, D. A., Castro, G., Poulos, S. J., and France, J. M. 1978. "Cyclic Loading of Sands, Silts, and Clays," Earthquake Engineering and Soil Dynamics, ASCE Geotechnical Engineering Division Specialty Conference Proceedings, Pasadena, California, Vol. 2, pp. 836-851.

Seed, H. B. 1968. "Landslides During Earthquakes Due to Soil Liquefaction," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 94, No. SM5, September, pp. 1055-1122.

Seed, H. B., Arango, I., and Chan, C. K. 1975. "Evaluation of Soil Liquefaction Potential During Earthquakes," Report No. EERC-75-28, College of Engineering, University of California, Berkeley, California.

Seed, H. B., Arango, I., Chan, C. K., Gomez-Masso, A., and Ascoli, R. G. 1980. "Earthquake-Induced Liquefaction Near Lake Amatitlan, Guatemala," Report No. NUREG/CR-1341, U.S. Nuclear Regulatory Commission.

Seed, H. B., and Idriss, I. M. 1967. "Analysis of Soil Liquefaction: Niigata Earthquake," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM3, pp. 83-108.

Seed, H. B., and Idriss, I. M. 1971. "Simplified Procedure for Evaluating Soil Liquefaction Potential," Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 97, No. SM9, pp. 1249-1273.

Seed, H. B., Idriss, I. M. 1981. "General Procedures for Evaluation of Liquefaction Potential," In-Situ Testing to Evaluate Liquefaction Susceptibility, Session No. 24, Preprint No. 81-544, ASCE National Convention, St. Louis, Missouri.

Seed, H. B., Idriss, I. M. 1982. "Evaluation of Liquefaction Potential Using Field Performance Data," accepted for publication in Journal of Geotechnical Engineering, ASCE.

Seed, H. B., Idriss, I. M. 1982. Ground Motions and Soil Liquefaction During Earthquakes, Engineering Monographs on Earthquake Criteria, Structural Design, and Strong-Motion Records, Earthquake Engineering Research Institute, Berkeley, California.

Seed, H. B., Idriss, I. M., and Arango, I. 1983. "Evaluation of Liquefaction Potential Using Field Performance Data," Journal of Geotechnical Engineering, ASCE, Vol. 109, No. 3, Proc. Paper No. 17785, pp. 458-482.

Seed, H. B., and Lee, K. L. 1967. "Undrained Strength Characteristics of Cohesionless Soils," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM6.

Seed, H. B., Lee, K. L., Idriss, I. M., and Makdisi, F. 1973. "Analysis of the Slides in the San Fernando Dam During the Earthquake of February 9, 1971," Report No. EERC-73-2, College of Engineering, University of California, Berkeley, California.

Seed, H. B., Mori, K., and Chan, C. K. 1977. "Influence of Seismic History on Liquefaction of Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT4, Proc. Paper No. 12841, pp. 246-278.

Seed, H. B., and Peacock, W. H. 1971. "Test Procedures for Measuring Soil Liquefaction Characteristics," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM8.

Seed, H. B., Tokimatsu, K., Harder, L. F., and Chung, R. M. 1984. "The Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations," Report No. UCB/EERC-84/15, University of California, Berkeley, California.

Seed, H. B., and Wilson, S. D. 1967. "The Turnagain Heights Landslide, Anchorage, Alaska," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM4 pp. 325-353.

Shen, C. K., Vrymoed, J. ..., and Uyeno, C. K. 1977. "The Effect on Liquefaction of Sands," Proceedings of the National Conference on Soil Mechanics and Foundation, Japanese Society of Soil Mechanics and Foundation Engineering, Tokyo, Japan, Vol. II, pp. 381-386.

Shi, Z. J., and Yu, S. S. 1981. "Characteristics of Liquefaction of Changing Silt and its Field Discrimination," Proceedings of the Joint U.S. - P.R.C. Microzonation Workshop, Harbin, China, pp. 14-1 to 12.

Singh, S., Donovan, N. C., and Park, F. 1980. "A Re-examination of the Effect of Prior Loadings on the Liquefaction of Sands," Proceedings of the Seventh World Conference on Earthquake Engineering, 8-13 September, Istanbul, Turkey, Vol. 3, pp. 321-325.

Silver, M. L. 1977. "Laboratory Triaxial Testing Procedures to Determine the Cyclic Strength of Soils," NUREG-0031, NRC-6, National Technical Information Service, Springfield, Virginia.

Silver, M. L. 1978. "Comparison Between the Strengths of Undisturbed and Reconstituted Sands from Niigata, Japan," Technical Report S-78-9, Department of Materials Engineering, University of Illinois, Chicago.

Silver, M. L., and Park, T. K. 1976. "Liquefaction Potential Evaluated from Cyclic Strain-Controlled Properties Tests on Sands," Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 16, No. 3, pp. 51-66.

Silver, M. L., and Seed, H. B. 1969. "The Behavior of Sands Under Seismic Loading Conditions," Earthquake Engineering Research Center Report No. 69-16, University of California, Berkeley, California.

Thompson, C. D., and Emery, J. J. 1976. "Geotechnical Design Aspects for Large Gravity Retaining Structures Under Seismic Loading," Canadian Geotechnical Journal, Vol. 13, No. 3, August, pp. 231-242.

Tianjin Earthquake Engineering Research Center, Ministry of Metallurgical Industry, 1983. "Liquefaction-Induced Damages to Foundations and Typical Insitu Analysis," Geotechnical Engineering Investigation Journal (in Chinese), pp. 1-15.

Toun, R. V., and Blakeley, J. P. 1980. "The Behavior of Compacted Tertiary Siltstone Under Cyclic Loading," Proceedings, Third Australia-New Zealand Conference on Geomechanics, Vol. 6, New Zealand Institute of Engineering, pp. 1.177-1.183.

Tokimatsu, K. and Yoshimi, Y. 1981. "Field Correlation of Soil Liquefaction with SPT and Grain Size," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 203-208.

Tokimatsu, K. and Yoshimi, Y. 1983. "Empirical Correlation of Soil Liquefaction Based on SPT N-value and Fine Content," Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 15, No. 4, pp. 31-92.

Townsend, F. C. 1978. "A Review of Factors Affecting Cyclic Triaxial Tests," Dynamic Geotechnical Testing, ASTM STP 654, pp. 356-383.

Vaid, Y. P., and Finn, W. D. L. 1979. "Static Shear and Liquefaction Potential," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT10, October.

Viksne, A. 1976. "Evaluation of In-Situ Shear-Wave Measurement Techniques," REC-ERC-76-6, April, U.S. Bureau of Reclamation, Department of the Interior, Engineering and Research Center, Denver, Colorado.

Vrymoed, J. L. 1971. "Liquefaction Characteristics of Sandy Soil with Fines Under Cyclic Loading," M.S. Thesis, University of California, Davis, California.

Wang, Y. Q., Luan, F., Han, Q. G., and Li, G. X. 1979. "Formulae for Predicting Liquefaction Potential of Clayey Silt and Sand as Derived from a Statistical Method," Research Report, General Research Institute of Building and Construction, MMI, China.

Wang, W. S. 1979. "Some Findings in Soil Liquefaction," Research Institute of Water Conservancy and Hydroelectric Power, Beijing, China.

Wang, W. S. 1981. "Mechanism of Soil Liquefaction," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 221-226.

Wang, Z. Q. 1981. "Macroscopic Approach to Soil Liquefaction," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 179-185.

Wei, R. L., Guo, T. L., and Zuo, Y. M. 1981. "Pore Pressure in Silty Sand Under Cyclic Shear," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 59-64.

Wong, R. T., Seed, H. B., and Chan, C. K. 1974. "Liquefaction of Gravelly Soils Under Cyclic Loading Conditions," Earthquake Engineering Research Center Report No. 74-11, University of California, Berkeley, California.

Xie, J. 1979. "Empirical Criteria for Sand Liquefaction," Proceedings, Second U.S. National Conference on Earthquake Engineering, Stanford, University, August.

Yeh, S. H. 1981. "The Effect of Grain Size Distribution on the Liquefaction Potential of Granular Soils," M.S. Thesis, University of Colorado at Denver.

Youd, T. L., "Compaction of Sands by Repeated Shear Straining," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM7, pp. 709-725.

Youd, T. L., and Bennett, M. J. 1981. "Liquefaction Site Studies Following the 1979 Imperial Valley Earthquake," In-Situ Testing to Evaluate Liquefaction Susceptibility, Session No. 24, Preprint No. 81-544, ASCE National Convention, St. Louis, Missouri.

Youd, T. L., and Hoose, S. N. 1977. "Liquefaction Susceptibility and Geologic Setting," Proceedings of Sixth World Conference on Earthquake Engineering, New Delhi, India, Vol. 6, pp. 37-42.

Youd, T. L., and Perkins, D. M. 1978. "Mapping Liquefaction-Induced Ground Failure Potential," Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT4, Proc. Paper No. 13659, pp. 533-546.

Zhou, S. G. 1980. "Evaluation of the Liquefaction of Sand by Static Cone Penetration Test," Proceedings of the Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, pp. 156-162.

Zhou, S. G. 1981. "Influence of Fines on Evaluating Liquefaction of Sand by CPT," Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. I, pp. 167-172.

Zhu, S. L., and Toan, J. C. 1982. "Stepwise Regression Analysis of Liquefaction Potential of Cohesive Soils," Geotechnical Engineering Investigation Journal (in Chinese), pp. 12-16.

APPENDIX A

CORRESPONDENCE

IGHP

INSTITUTE OF GEOTECHNICS, HYDROGEOLOGY & PHOTOGRAMMETRY, MMI.
81, DONGFENG AVENUE, BAODING, HEBEI

PHONE, BAODING 7935
CABLE, BAODING 4430

Mr. Nien-yin Chang
University of Colorado at Denver
Department of Civil Engineering
1100 Fourteenth Street
Denver, Colorado 80202

Dear Mr. Nien-yin Chang, September 9, 1985

Thanks for your visiting to this Institute and the lectures and helps given. Through the mutual understanding, I think our cooperation in the future is not only possible, and will certainly have a very good prospect.

As a preliminary idea, I propose the following two items, please consider if it can be an item of cooperative research, and I suppose you may make application for American National Science Foundation.

(1) Liquefaction study of sand with silty and/or clayey content.

(2) Study of soil deformation and bearing capacity of pier (belled or unbelled ) type deep foundations.

For the reasons of application and some preliminary considerations, please see the appendix.

I remember we have discussed another mode possible for the cooperation , i.e. testings may be performed at both sides,

# IGHP

INSTITUTE OF GEOTECHNICS, HYDROGEOLOGY & PHOTOGRAMMETRY, MMI.
51, DONGFENG AVENUE, BAODING, HEBEI

PHONE, BAODING 7985
CABLE, BAODING 4430

China and U.S.A., under a common programme and method accepted, at a certain stage, when testing data have been accumulated enough, one or two of the scholars may visit each other's country and they will analyse the testing results, do the computing, analysis and making of the report. In this way, my Institute may make application to my country for the fund to pay the testings performed at my country.

Welcome your modifications or other proposals. We will pay due consideration to your idea.

Sincerely yours,

沈昌鲁

Shen changlu
Director of the Institute

IGHP

INSTITUTE OF GEOTECHNICS, HYDROGEOLOGY & PHOTOGRAMMETRY, MMI.
81, DONGFENG AVENUE, BAODING, HEBEI

PHONE, BAODING 7035
CABLE, BAODING 4430

Appendix

## Item Proposals and Explanations

Item 1. Liquefaction study of sand with silty and/or clayey content.

Owing to the similitude of seismic geological conditions of the China east coast with the American west coast; Owing to the fact that a series of big earthquakes occurred along the NNE structural zone of China east coast, at the cities: Hsintai, Haicheng, Tangshan, during 1966-1976, just after the Alaska earthquake of U.S.A. and the Nigata earthquake of Japan, reconnaissance report of observed earthquake damages of buildings and foundation soils are available; the liquefied layers include sands with silty and/or clayey contents; the places are suitable for sampling, testing ( lab. and/or in-situ ) of liquefaction study, that the results of analysis may be testified by the observed facts; and as you know, there are experts in this Institute in different disciplines such as, lab. testing, in-situ testing, computing and analysis, geological reconnaissance; I propose this item and guarantee that this Institute is competent in doing the following works: collecting available testing data from various sources, official and private; performing lab. testings and in-s  istings, computation and analysis.

# IGHP

INSTITUTE OF GEOTECHNICS, HYDROGEOLOGY & PHOTOGRAMMETRY, MMI.
81, DONGFENG AVENUE, BAODING, HEBEI

PHONE, BAODING 7835
CABLE, BAODING 4430

Item 2. Study of soil deformation and bearing capacity under pier ( belled and unbelled ) type deep foundations.

Owing to the similarity of the geographical position of China in northern hemisphere as that of U.S.A., there are comparable sorts of foundation soils in both countries, it is in favour of China to cooperate with U.S.A. in the bearing capacity study of foundation soils.

The pier type deep foundations may be used to penetrate different kinds of bad soils ( such as soft soil, loess soil etc.) and have a cost much lower than the ordinary piles. In many cities of China, it has been proved to be the foundation type most suitable to medium height buildings. According to the published soil mechanics literature, the soil deformation and bearing capacity under deep foundations require further study.

There are experts in this Institute, competent to perform lab. triaxial testings, in-situ pressure-meter testings, and prototype field plate-load tests. We have accumulated data of prototype testings of this kind, the loads amount to 1200 metric tons with bears area of testing 8-10 sq.m.

We are willing to cooperate with U.S.A. to complete this research item. This item will not only be beneficial to China and U.S.A., it is significant to the building construction works all over the world.

UNIVERSITY OF COLORADO AT DENVER
1100 Fourteenth Street
Denver, Colorado 80202
(303) 556-2870

College of Engineering and Applied Science

6 November 1985

Mr. Joseph P. Koester
Earthquake Engineering and
Geophysics Division
Geotechnical Engineering Laboratory
Waterways Experiment Station
U.S. Corps of Engineers
Vicksburg, Mississippi 39180

Dear Mr. Koester:

Please accept my apology for this late report on my trip to the People Republic of China. Purposes of the trip are two fold: to collect information on the liquefaction of cohesive soils during Tangshan earthquake, and to negotiate future cooperative research activities. The mission was accomplished successfully.

I arrived at Beijing, PRC on August 31, 1985. A brief itinerary is summarized for your reference:

| Visiting Period: | Activities |
|---|---|
| August 31 to September 3 | Visited the Institute of Geotechnics, Hydrogeology and Photogrammetry, Ministry of Metallurgical Industry and the Engineering Exploration Company of China Metallurgical Construction Corporation at Boading, China: gave an eight-hour lecture on liquefaction and dynamic analysis of embankment dams, listened to the briefing on their research activities including the liquefaction during Tangshan earthquake and negotiate future cooperative research activities. |
| September 4 to 6 | Visited the Tangshan Institute of Technology at Tangshan, China: gave a four-hour lecture on liquefaction and dynamic analysis of embankment dams, discussed Tangshan earthquake damages, visited the preserved damaged sites, and watched the movie about Tangshan earthquake damages. |

September 7 to 11 — Visited the Tsinghua University, The China Academy of Building Research, the Comprehensive Institute of Geotechnical Engineering and Surveying of the Ministry of Urban and Rural Construction and Environmental Protection in Beijing, China: gave lectures on liquefaction and dynamic analysis of embankment dams, discussed Tangshan earthquake damages and listened to their research briefing.

The Institute of Geotechnics, Hydrogeology and Photogrammetry (IGHP) has offered excellent cooperation for some future research activities in the area of soil liquefaction, and deep foundation performance etc. This is evidenced in the enclosed letter from the Director of IGHP. On the subject of soil liquefaction, the cooperation will include:

- Collecting available laboratory test data from various liquefied sites in previous earthquakes from government and private sources;
- Conducting further laboratory cyclic triaxial and/or simple shear tests on soils from some selected liquefied sites;
- Conducting further in situ testing at the selected liquefied sites;
- Obtaining undisturbed samples and/or bag samples for laboratory testing in U.S.A. and/or in China;
- Providing research personnel to conduct research activities including testing and data analysis;
- Exchanging research scholars during the period of cooperation, and
- Providing at least partial funding for the research activities to be conducted in China.

Liquefaction in situ data re quite massive and requires a great deal of time for analysis. The IGHP has offered to open its government files about Tangshan earthquake liquefaction data for our use. It is, therefore, proposed to send a team of two to three persons, one from WES and two from the University of Colorado to China in the coming summer to conduct the data analysis. The team will be aided by a research tem from IGHP. I will describe the next research phase in greater detail in my forthcoming research proposal to WES.

Enclosed, for your reference, is a copy of the letter of cooperation from Dr. Changlu Shen, Director of IGHP.

I combined my trip to China with the trip to India paid by the United Nations and, once I entered China, all expenses were paid by the Chinese government. Thus, the WES research dollars were not used to pay for any travel expenses, instead, they were used to pay for my time and graduate student time.

I anticipate traveling to WES to report to you the research finding around December 10, 1985. I would then submit to you the project progress report and the proposal for the next phase research. I apologize for the long delay.

While at Vicksburg, I will also report to Ms. Mary Ellen Hynes-Griffin the partial result of the dynamic analysis of the Folsom Dam. The analysis effort was concentrated on identifying the potential problem of the soil-concrete interface separation at the wrapped-around section during a strong motion earthquake. A simple report is now being drafted. I will present to her the finding from this analysis. Please kindly inform her of my plan. Thank you.

Sincerely,

Nien-Yin Chang, Professor

Enclosure
cc:file