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SPT FOR LIQUEFACTION RESISTANCE EVALUATIONS — STATE-OF-THE-ART AND FUTURE REQUIREMENTS

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16. ABSTRACT
The purpose of this report is to review SPT (standard penetration test) studies and their implications to successful usage of SPT for liquefaction resistance evaluations. Future requirements for further studies of SPT variability and correlations are identified. Recommendations for future standardization refinements are discussed.

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by

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Research and Laboratory Services Division
Denver Office
Denver, Colorado

SI METRIC

June 1989

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

This report was presented to the U.S.-Japan Panel on Wind and Seismic Effects Workshop Entitled "In Situ Testing Methods for Evaluation of Soil Liquefaction Susceptibility," August 1985, San Francisco, California.

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INTRODUCTION

The purpose of this report is to review standard penetration test (SPT) studies and the implications for successful usage of SPT for liquefaction resistance evaluations. Future requirements for further studies of SPT variability and correlations are identified. Recommendations for future standardization refinements are discussed.

With development of geotechnical engineering, penetration resistance tests were performed since they are practical, logical methods for evaluating suitability of ground conditions. The chronicles of SPT testing, whose inception is attributed to Charles R. Gow in the early 1920's, are many [1].* With the evolution of drilling methods and SPT testing, standardization of test techniques progressed, but in many cases, haphazardly. The SPT test has now gained widespread usage in the United States and many other countries throughout the world. The test is filled with pitfalls and variations that frustrate engineers as more detailed and refined design methodologies are developed. This is the case for liquefaction evaluations where potentially large-scale damage events are to be predicted with uncertain factors of safety.

A useful review of the history of SPT testing in the United States was developed by Fletcher in the early 1960's as part of an ASCE task committee report on static and dynamic penetration test methods [2, 3]. Important early developments include an early Harvard University publication by Mohr in 1937 [4] and inclusion in classical publications of *Subsurface Exploration and Sampling* by Hvorslev [1] and *Soil Mechanics in Engineering Practice* by Terzaghi and Peck [5]. In April 1958, standardization was initiated by American Society for Testing and Materials (ASTM) when a tentative method was published. The ASTM test method was finally adopted as a standard method in 1967.

Early in the development of SPT testing, practitioners identified potential variabilities of the testing method. In the past 20 to 30 years, considerable discussion has occurred about problems with the lack of standardization in the "standard" test. Among these discussions are the works of DeMello [6] and Ireland et al. [7]. The primary concern with the test was the variability of equipment and drilling techniques. In the 1970's, studies focused on energy measurements that now have been used to quantify test variability due to equipment and procedural techniques.

The procedures and practices of SPT testing among the international community were best described in the First European Symposium on Penetration Testing [8]. An excellent review of

* Numbers in brackets refer to entries in bibliography.

the findings of this symposium has been prepared by Thorburn et al. [4], for the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) Technical Committee on Penetration Testing. Of particular interest in these reviews is the variability of testing as performed in the United States. An early survey on SPT practice was performed by Ireland et al. [2]. With the increase in SPT energy studies, an additional practice survey was prepared by Kovacs [9], who found significant differences in practice. In Japan, Muromachi et al. [10], and Yoshimi and Tokimatsu [11] have also prepared practice surveys of great importance since Japanese data constitute a considerable amount of the liquefaction resistance data base. As a result of the above studies, the current state of SPT practice is well known.

With the evolution of SPT testing, the test was found to be a fairly good indicator of engineering parameters for sands. Early correlations were developed with relative density and friction angle of sands. Successful application of such correlations implied potential correlations with liquefaction occurrence. As shown in table 1, the many factors that affect liquefaction resistance would also affect penetration resistance [12].

The early correlations in Japan with studies of the Niigata earthquake have been extended in the last 20 years to develop an extensive data base. However, studies of test variability raised concerns as to the compatibility of the data base and accuracy of the method. Results of recent energy studies have been used to improve the data base and existing correlations. A major issue with SPT is the measures which can be taken to improve reliability or reproducibility. Also, identifying the areas of research that would quantify effects of the test and its correlation to liquefaction resistance is important.

Table 1. – Factors affecting cyclic mobility or soil liquefaction characteristics and penetration resistance (from Seed [12]).

Factor (1)	Effect on stress ratio required to cause cyclic mobility (2)	Effect on penetration resistance (3)
Increased relative density	Increases stress ratio for cyclic mobility or liquefaction	Increases penetration resistance
Increased stability of structure	Increases stress ratio for cyclic mobility or liquefaction	Increases penetration resistance
Increase in time under pressure	Increases stress ratio for cyclic mobility or liquefaction	Probably increases penetration resistance
Increase in K_o	Increases stress ratio for cyclic mobility or liquefaction	Increases penetration resistance
Prior seismic strains	Increases stress ratio for cyclic mobility or liquefaction	Probably increases penetration resistance

STANDARD PENETRATION TEST FOR ESTIMATION OF ENGINEERING PARAMETERS

Lessons Learned from Early Correlations

For the primary need of estimating the strength and compressibility of sands, the initial laboratory-controlled tank studies of SPT testing were conducted to correlate with relative density [13]. These studies considered vertical pressure levels of up to 2.8 ton/ft^2 [268 kPa] and were extended to consider effects of particle size, rod length, rod type, and saturation. Since that time, additional studies of SPT and relative density have been presented by other researchers [14, 15, 16]. The Gibbs and Holtz relationship generally found considerable favor; and their results were summarized in a relative density chart by Coffman [17], as shown on figure 1. The Gibbs and Holtz criteria were found to be reasonably conservative for most sands. To estimate engineering parameters, an estimate of relative density was first made; then estimates of strengths or compressibility were made, based on controlled laboratory studies. The determination of relative density itself was subject to variation as different methods were used by different researchers. In 1971, DeMello pointed out that correlation through an intermediate parameter was poor engineering practice as that could compound errors. As a result, he advocated direct correlations to friction angle [6].

The difficulties associated with determination of relative density of sands are best discussed in an ASTM symposium on evaluation of relative density [18]. In this symposium, many studies pointed out difficulties in applying the Gibbs and Holtz correlation. The errors associated with evaluation of relative density were also discussed. Results from Bell and Singh indicated the standard deviation of relative density predicted by the SPT test could approach 20 percent. Studies by Leary and Woodward pointed out difficulties with SPT prediction of relative density in construction control due to higher horizontal stress levels associated with densification of sands [18].

A most recent series of laboratory-controlled tank studies was performed by the Corps of Engineers [19, 20]. These studies were initiated to investigate the use of SPT for evaluation of liquefaction potential and included the evaluation of cyclic strengths by laboratory testing. Some limited studies were performed on overconsolidated sands, and the studies also focused on the correction factor to normalize the SPT N value to a 1-ton/ft^2 [95.8 kPa] effective vertical stress level. The studies pointed out the invalidity of the use of a simplified family of curves correlating SPT N values and overburden pressure to relative density for all cohesionless soils under all conditions. Although these studies indicated areas of poor agreement with the Gibbs and Holtz data, the level of agreement was sufficient to estimate "loose," "medium dense," and "dense" conditions.

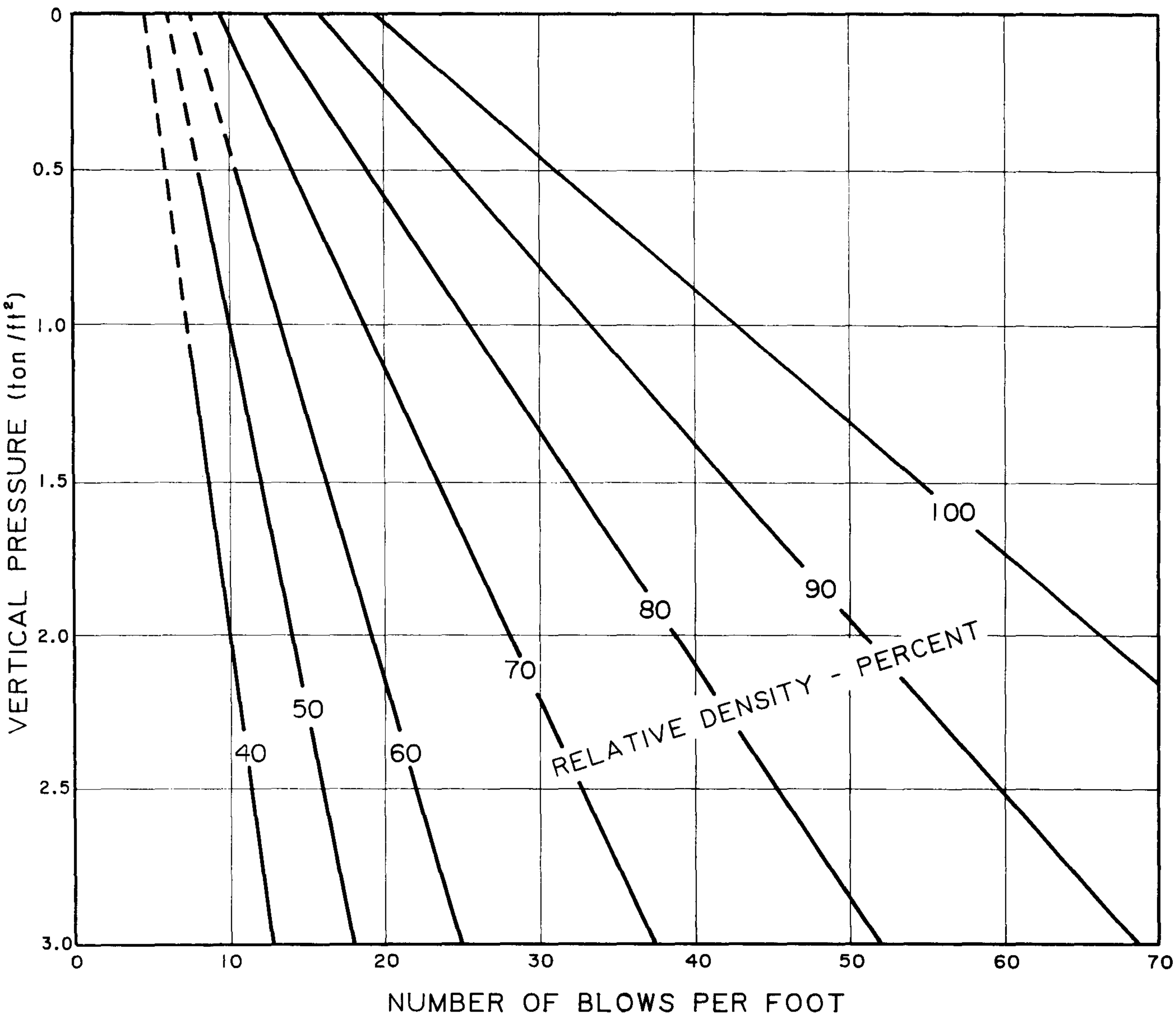


Figure 1. — Number of blows per foot from standard penetration test (140-lb hammer, 30-inch drop [63.5-kg hammer, 0.762-m drop]). To convert from ton/ft^2 to kPa, multiply by 95.76.

As Gibbs and Holtz have pointed out in discussions of the studies on SPT, the test was never meant to provide accurate predictions for specific materials but was useful as an indicator of the degree of relative density. The implications of laboratory control studies with respect to liquefaction resistance evaluations is that, even with refinement of the test, the SPT will still be nothing more than an indicator of liquefaction resistance.

Development of SPT Methods to Evaluate Liquefaction Resistance

After the Alaska and Niigata earthquake events in 1964, engineers began associating SPT data with liquefaction resistance evaluations. Relationships between critical *N* values versus depth for ground conditions in Niigata were developed in Japan [21, 22, 23]. These relationships are shown on figure 2. To compensate for site conditions different than those in Niigata, the concept of cyclic stress ratio was developed by Seed and co-workers. With some additional data on liquefied site conditions, a relationship between cyclic stress ratio and relative density was presented by Seed and Peacock [25], as shown on figure 3.

Over the next 10 years, both additional laboratory and field studies progressed with many interesting findings. Of significant note were extensive laboratory studies to evaluate such effects as number of cycles of shaking, multidirectional shaking, aging, stress level, and effects of increased horizontal stress levels. After culmination of large-scale shaking table tests, Seed managed to correlate various laboratory results to penetration resistance data; and use of relative density was dropped [12]. The results of these studies are shown on figure 4.

In the same time period, the Japanese researchers performed comprehensive studies on liquefied and nonliquefied sites by obtaining undrained cyclic shear strength of laboratory test specimens. The liquefaction resistances of soils with varying grain-size distributions were correlated to SPT N values, and a methodology was developed to evaluate liquefaction [26].

This method was of special interest to the author at the time since it could address the effects of fines content. A comparison of both methods for a range of loading conditions is shown on figure 5. Although there are some differences in cleaner sands, the methods were in good agreement considering variations in resistance for fines content and differences in the methods at high and low ranges of cyclic loadings. These differences were first addressed by Tatsuoka et al. [27], with a detailed comparison of methods.

Based on a need to extend the N_1 method to evaluate silty sands (SM), an adjustment factor of N_1, equivalent to 7.5 blows, was proposed by Seed et al. [28]. Additional field data, which contained information on silty sands, were incorporated into this study. In Corps of Engineers studies [29] and Bureau of Reclamation publications [30], the adjustment of 7.5 in N_1 was evident when N_1 values were grouped into general soil categories of silty sands (SM) and poorly graded sands (SP, SP-SM).

A review of differences between Japanese and N_1 simplified methods was presented by Tokimatsu and Yoshimi [31]. The N_1 method tended to underestimate resistance to liquefaction at small N values in silty sands while the Japanese method tended to underestimate resistance for large N values. Recently, Tokimatsu and Yoshimi [32] reevaluated the empirical data base and recognized limiting N_1 values based on limiting shear strain potentials in dense deposits at higher cyclic

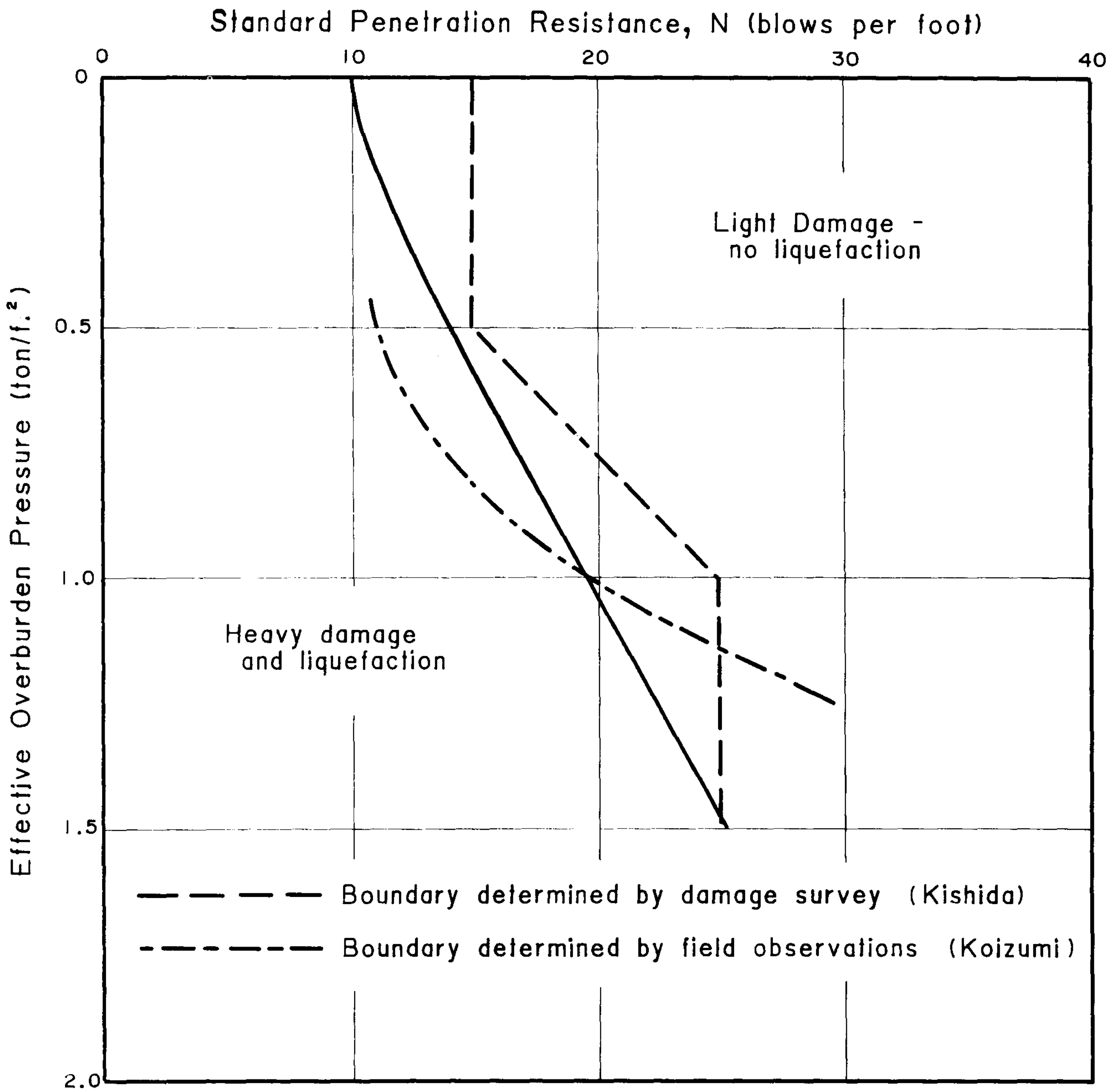


Figure 2. — Analysis of liquefaction potential at Niigata for the earthquake of June 16, 1964 [21, 22, 23, 24]. To convert from ton/ft^2 to kPa, multiply by 95.76.

stress ratios. Results of this study were in good agreement with Seed when energy differences were considered [28]. Seed, Tokimatsu et al. [33], reevaluated the world data base with respect to energy differences.

Limitations and Needs of Simplified Methods

The empirical data base, which provides the evidence of a correlation between SPT and liquefaction potential, is typically associated with level ground events. These data are usually associated

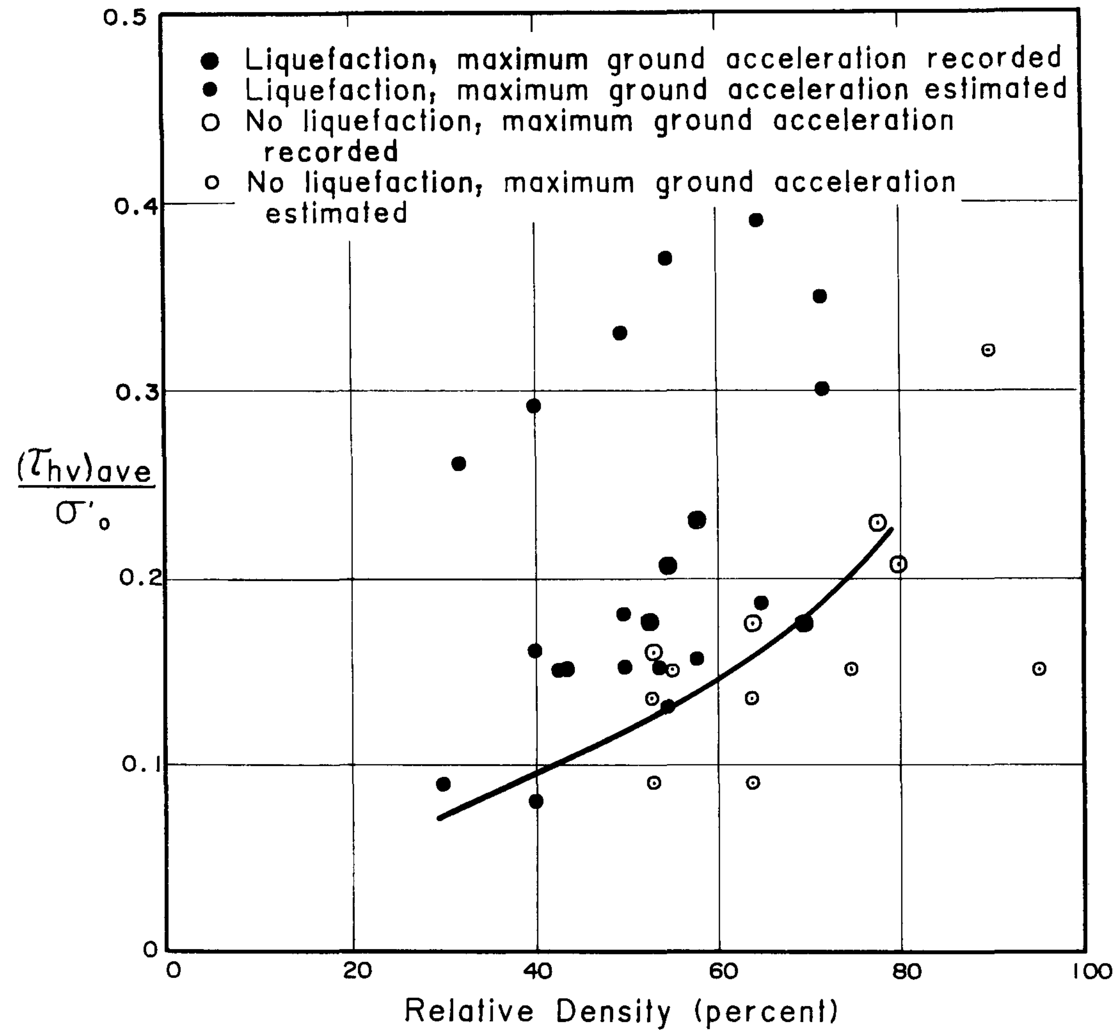


Figure 3. — Relationship between $(\tau_{hv})_{ave}/\sigma_o'$ and relative density for known cases of liquefaction and nonliquefaction [25].

with young sandy alluviums most often under normally consolidated conditions. In the data base, criteria for liquefaction are usually evidence of sand boils or excessive settlements. In the case of medium dense sands subject to confinement by less permeable surface layers, sand boils may occur in moderate events resulting in settlements in excess of those measured in the laboratory due to loss in material via sand boil ejections. In the case of structural loading of such a deposit where measures have been taken to control pore-pressure relief, the material may not be a problem. As a result, simplified methods may be conservative in denser deposits. This point is coupled with the concept of limiting shear strain potentials as discussed by Seed [12]. The SPT methods simply predict whether a deposit will reach a pore-pressure ratio of 100 percent. Both laboratory studies and limited field data indicate that resulting shear strains in dense deposits are significantly reduced. It is very difficult in practible applications to estimate tolerable shear strain levels and to accept N_1 values lower than those required by the simplified

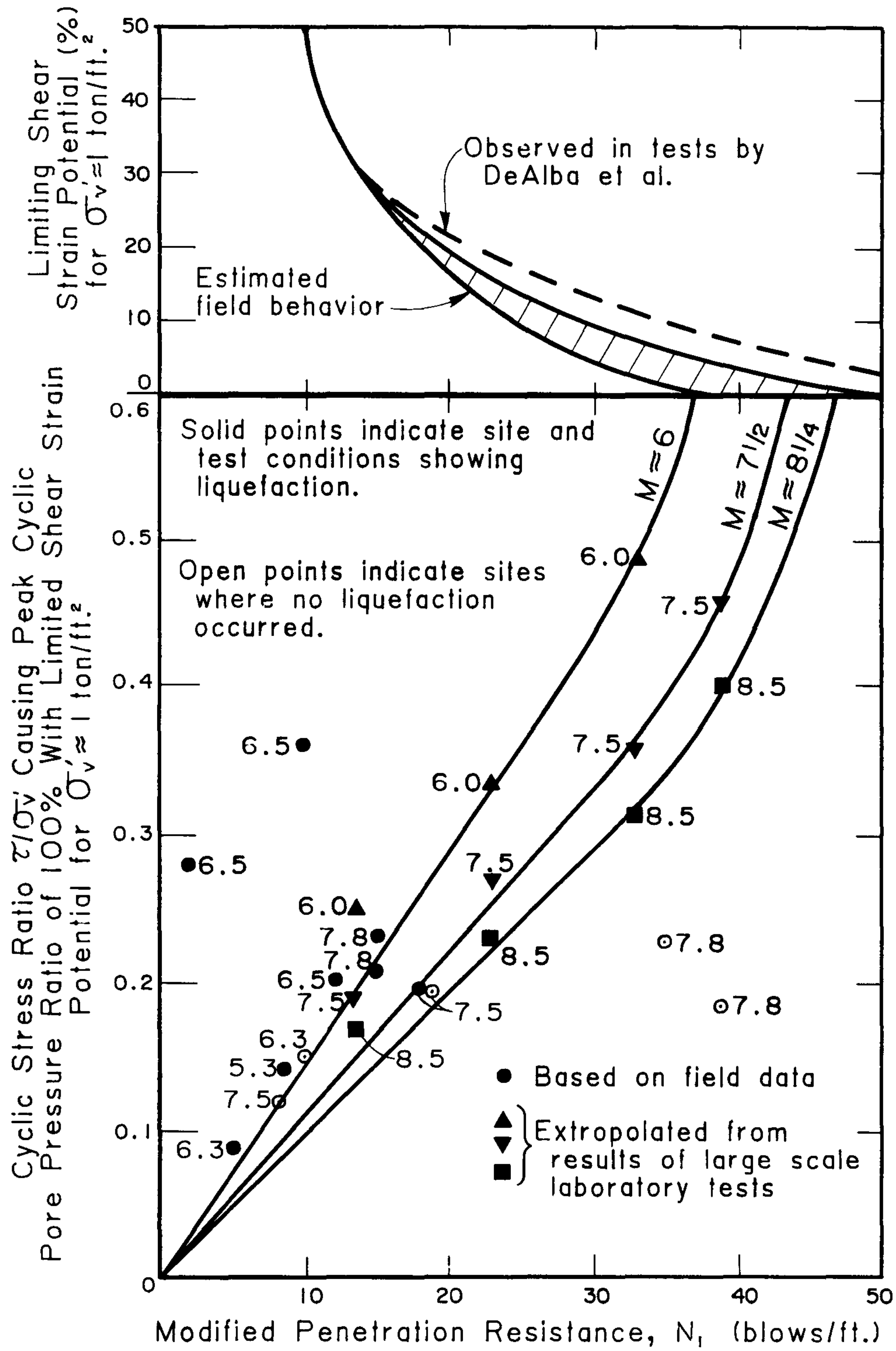


Figure 4. — Correlation between field liquefaction behavior of sands for level ground conditions and penetration resistance (supplemented by data from large-scale tests) [12]. To convert from ton/ft² to kPa, multiply by 95.76.

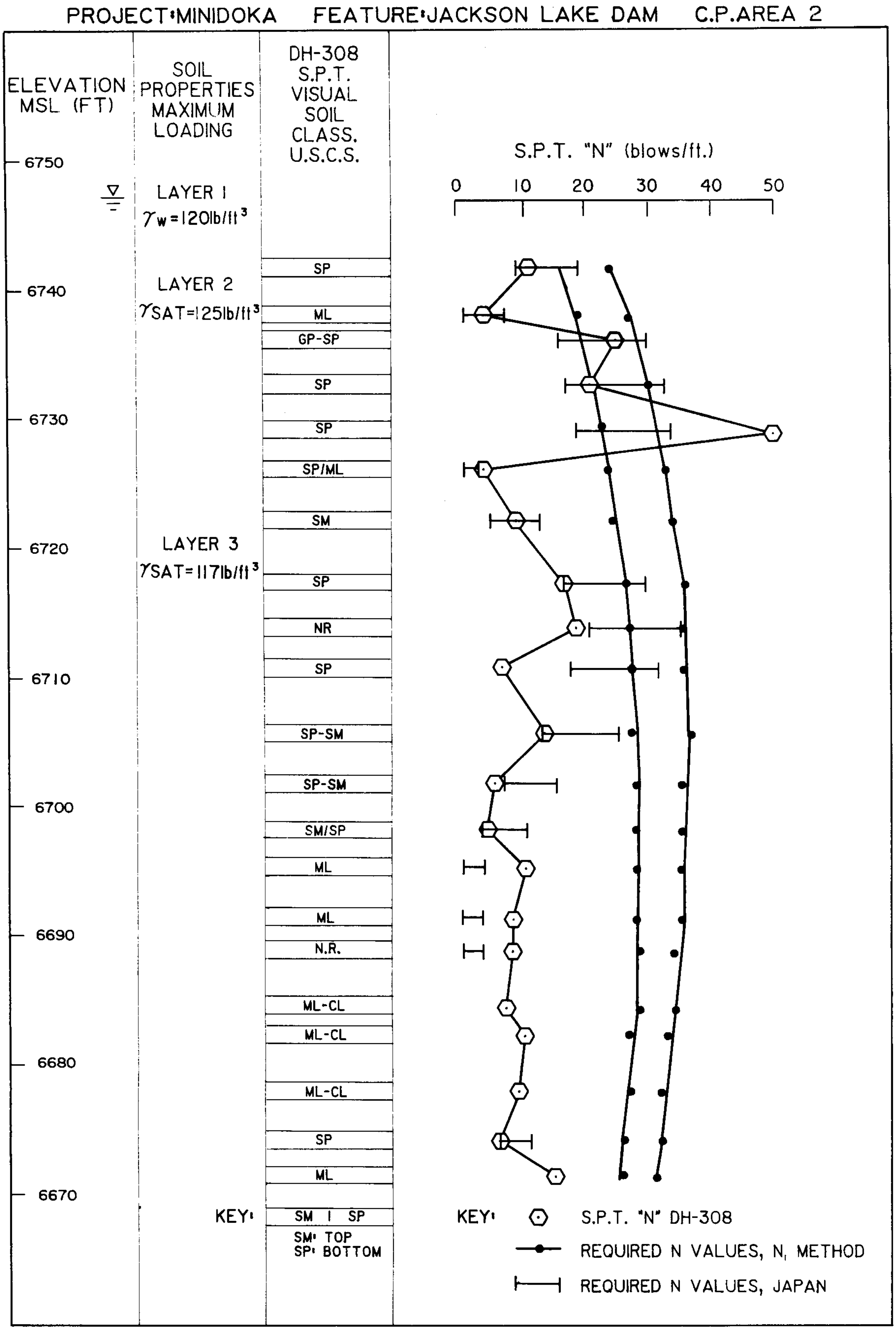


Figure 5. — Comparison of SPT liquefaction resistance evaluations using methods by Tatsuoka et al. [26], and Seed et al. [28].

methods. There is a definite need for additional field data on shear strain development in dense and medium dense deposits at higher cyclic stress ratios.

In most cases, the engineer needs to use SPT data to evaluate stability of structure foundations and embankments and not level ground conditions. Modifications of the level ground relationships are required to correct for anisotropic conditions and higher confining pressure levels. Such modifications were proposed by Seed [34]. The resistance to liquefaction as determined by the N_1 method is increased by a factor K_α (fig. 6) with increase in the ratio of shear stress to confining pressure. For confining pressure levels greater than 1.5 ton/ft^2 [144 kPa], resistance to liquefaction is reduced by a factor K_σ (fig. 7). By comparing dynamic loading conditions to resistances measured by SPT, one can predict development of 100 percent pore-pressure ratio. If a pore-pressure ratio of 100 percent develops, further studies are required to evaluate the degree of cyclic mobility that will occur.

Related to questions of superimposed structural loadings and cyclic mobility are concerns with loose, contractive soils that are subject to low levels of cyclic loadings. Poulos et al. [35] have

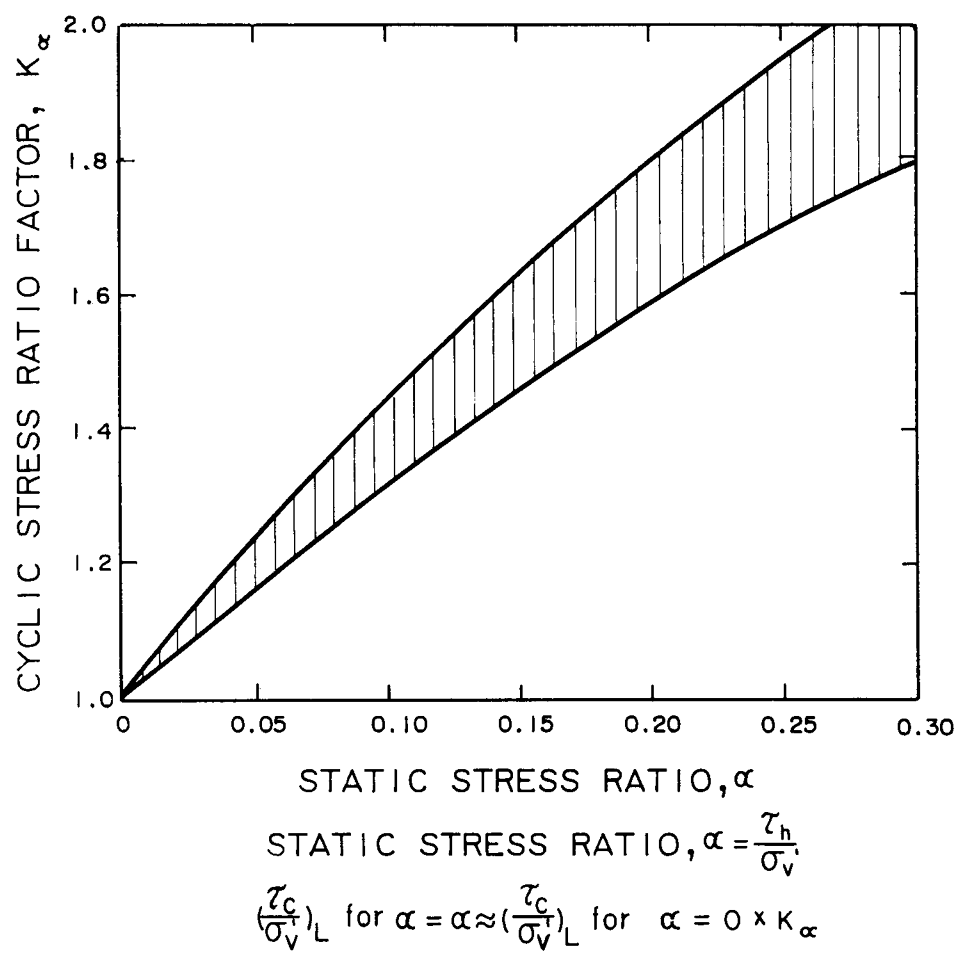


Figure 6. — Typical chart for evaluating the effect of initial cyclic loading resistance of sands [28].

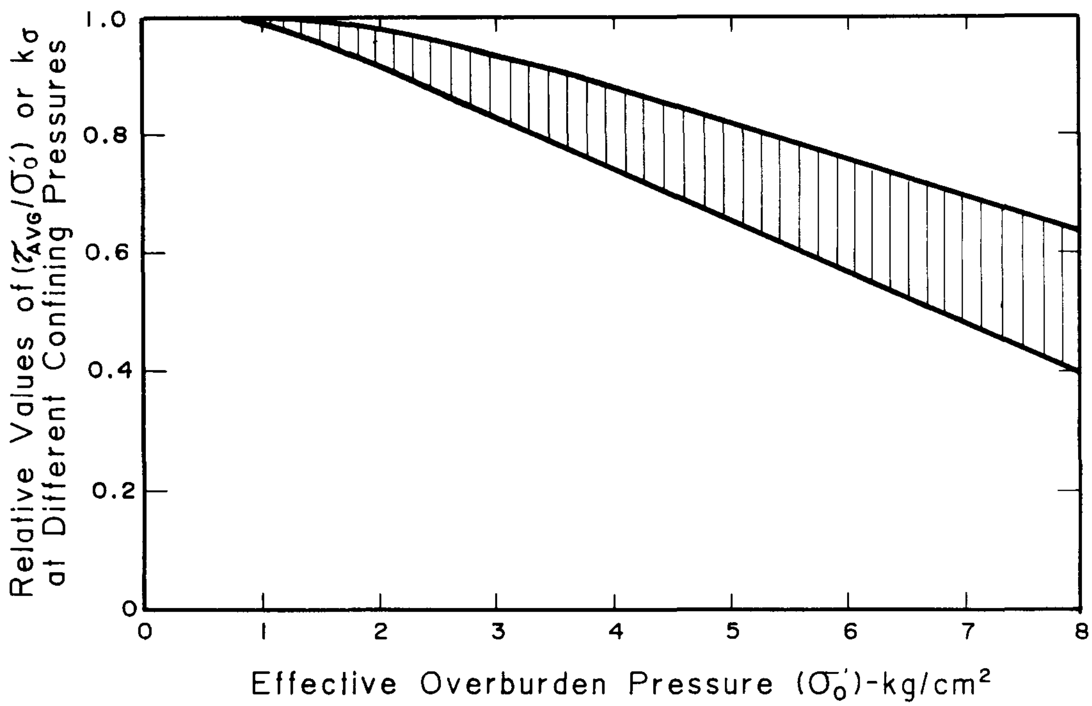
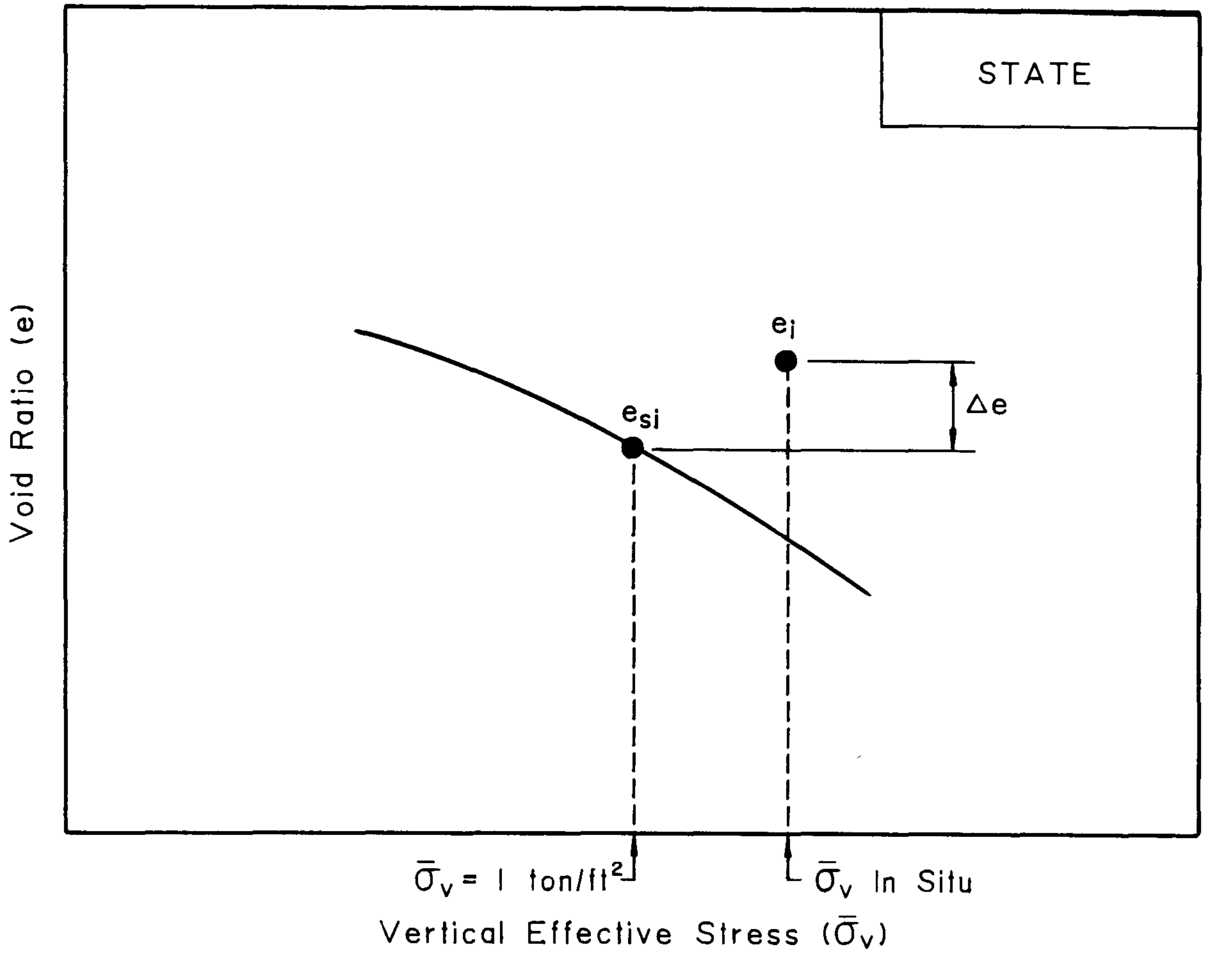


Figure 7. — Typical reduction in cyclic stress causing liquefaction with increase in initial confining pressure [28].

shown that contractive soils can be subject to levels of static shear stresses such that minor earthquake shaking (or even no shaking at all) can trigger flow conditions. The boundary between liquefaction or nonliquefaction for low N_1 values and cyclic stress ratios less than 0.1 is still subject to debate, and additional field data and experience are required to properly evaluate such conditions.

Some New SPT Correlations

Studies by Poulos et al. [35] have focused on prediction of flow slide conditions using the steady-state approach. The possibility of reaching a flow condition is associated with whether a soil is contractive under in situ stress conditions. In studies performed for the Bureau of Reclamation, Poulos et al. developed a preliminary correlation between SPT N_1 values and a parameter defined as the dilativeness index [36]. On figure 8, the definition of the dilativeness index is given. Negative values of dilativeness index imply a contractive condition. The results of this study are shown on figure 9 for silty fine sands at Jackson Lake damsite. In this study, both natural soils (untreated) and soils treated by compaction pile densification were evaluated. Scatter among results is considerable and can be attributed to variations in grain-size distributions, difficulties in determining in situ void ratios, and difficulties in assigning N_1 values to respective laboratory specimens. Such a correlation could be considerably refined in controlled laboratory studies.



$$D_i = \frac{e_{si} - e_i}{1 + e_{si}} = \frac{\Delta e}{1 + e_{si}}$$

Figure 8. — Definition of dilativeness index.

An interesting implication of figure 9 is that, with increased K_o conditions, the N_1 value to remain dilative in situ is increased. This can be attributed to the increased horizontal stress effect on penetration resistance as void ratio remains constant. The typical correction factor C_N, used to correct N values to N_1 values, is assumed to be derived for $K_o = 0.5$ conditions. If it is assumed that the N value is dependent on mean normal stress conditions, it is anticipated that N_1 values required to remain dilative under $K_o = 0.5$ conditions can be made equivalent to N_1, values at higher K_o conditions with knowledge of horizontal stress levels. Further laboratory studies would be required to confirm these relationships.

STUDIES ON SPT VARIABILITY

In early development of SPT testing, many smaller field studies were performed to evaluate changes in both drilling technique and equipment. Many organizations using the test developed

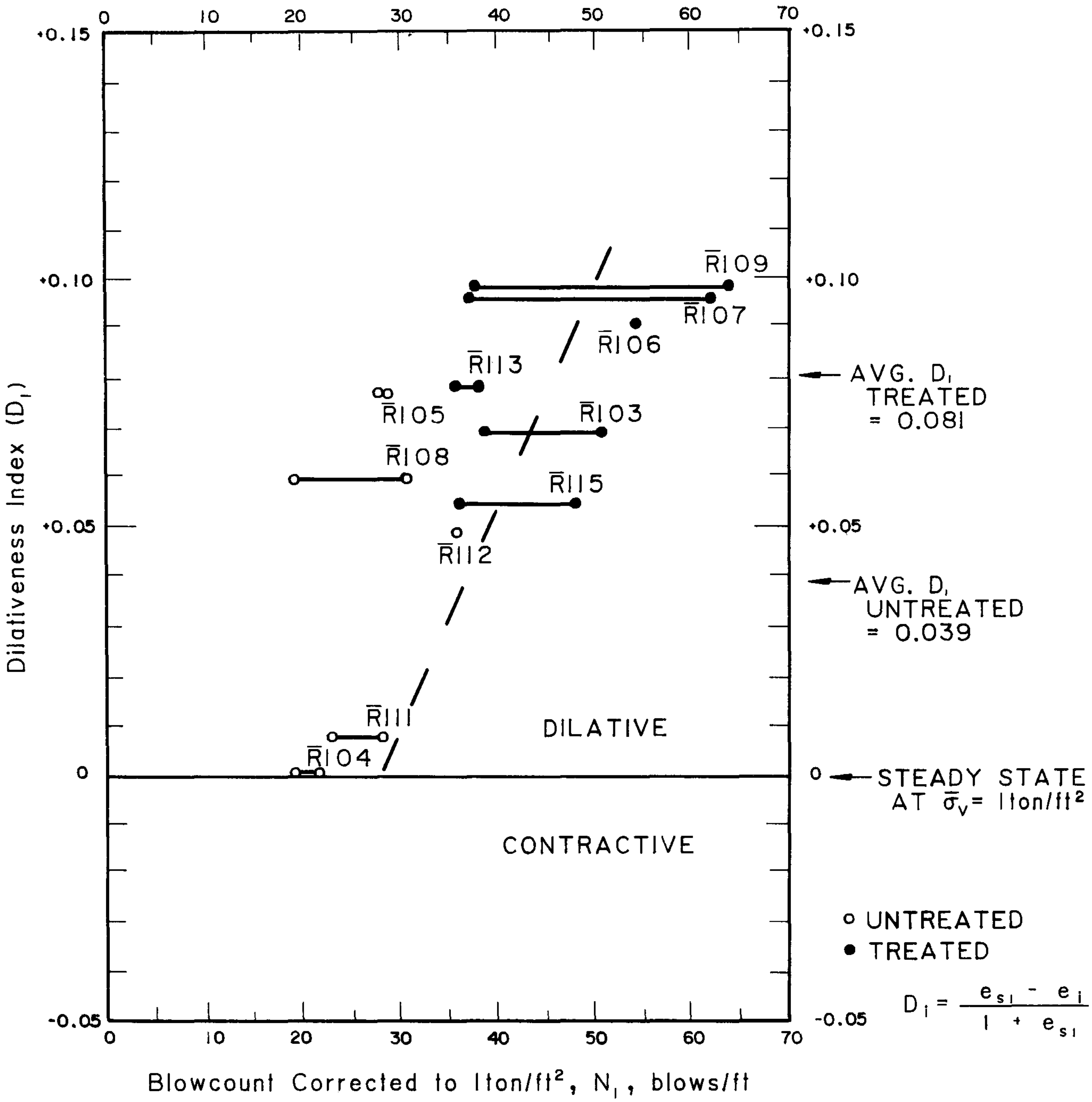


Figure 9. — Corrected blow count versus dilativeness index, silty fine sand, test site A.

their own correlations to engineering parameters, which were specific to their methodologies used in performing the test. The development of a standard methodology was initiated by ASTM. With final consideration of the test procedure as a standard method, several studies were published pointing out the variabilities due to drilling procedures and differing equipment configurations. The adoption of a standard method significantly lessened variability of the test, yet more recent studies have shown that further standardization is still desired.

Drilling Technique or Drilling Procedures

The effects of drilling technique are difficult to evaluate in laboratory controlled conditions. Most of the important studies on such variables as borehole diameter, boring method, and the use of drilling fluids have been conducted in the field. Differences in SPT data obtained at fairly homogeneous sites by different drilling contractors have been discussed by Parsons [37], Casagrande and Casagrande [38], and Sanglerat and Sanglerat [39]. Parsons showed that borings in coarse to medium sands where drilling mud or water was used produced different SPT values by a factor of up to 2-1/2, with drilling muds providing the least disturbance. In the studies by Casagrande and Casagrande, it was apparent that a cable drop-hammer system resulted in energy loss and higher SPT values. Sanglerat and Sanglerat identified poor drilling techniques causing borehole disturbance. Drilling methods such as rotary drilling, hollow or solid auger drilling, and wash boring methods, when applied properly, have all been found to provide reliable SPT data under specific conditions. Rotary drilling methods, which utilize drill muds, have been the most successful when applied to loose, saturated sand liquefaction studies.

Drilling disturbances from many factors such as improper bit design, high-bit pressure, casing and auger influence zones, rotary (r/min) effects, and other effects may never be readily quantifiable for field conditions as the drilling method combines with geological effects to develop varying conditions. An example of this is the effect of boring diameters in loose sands under imbalanced water-level conditions. It would be very unlikely that a method could be developed to predict the in situ condition of a sand once it has heaved into the bottom of the borehole. Undoubtedly, a controlled study of this effect would result in a qualitative recommendation to minimize hole diameters.

The most reliable methods for reducing drilling disturbance effects are by training of drilling crews, field inspections, and applications of good judgment. The author's experience indicates that SPT borings are typically poorly inspected. In a majority of borings, the personnel who will be utilizing the SPT data never see the data being collected in the field. Field personnel who are not trained with respect to techniques for minimizing disturbances may continue to collect unreliable data that seem adequate. Inspection of drilling methods early in a program can resolve many problems. Another point the author finds is that personnel consistently fail to check the weight of the hammer!

Development of Energy Measurement Methods

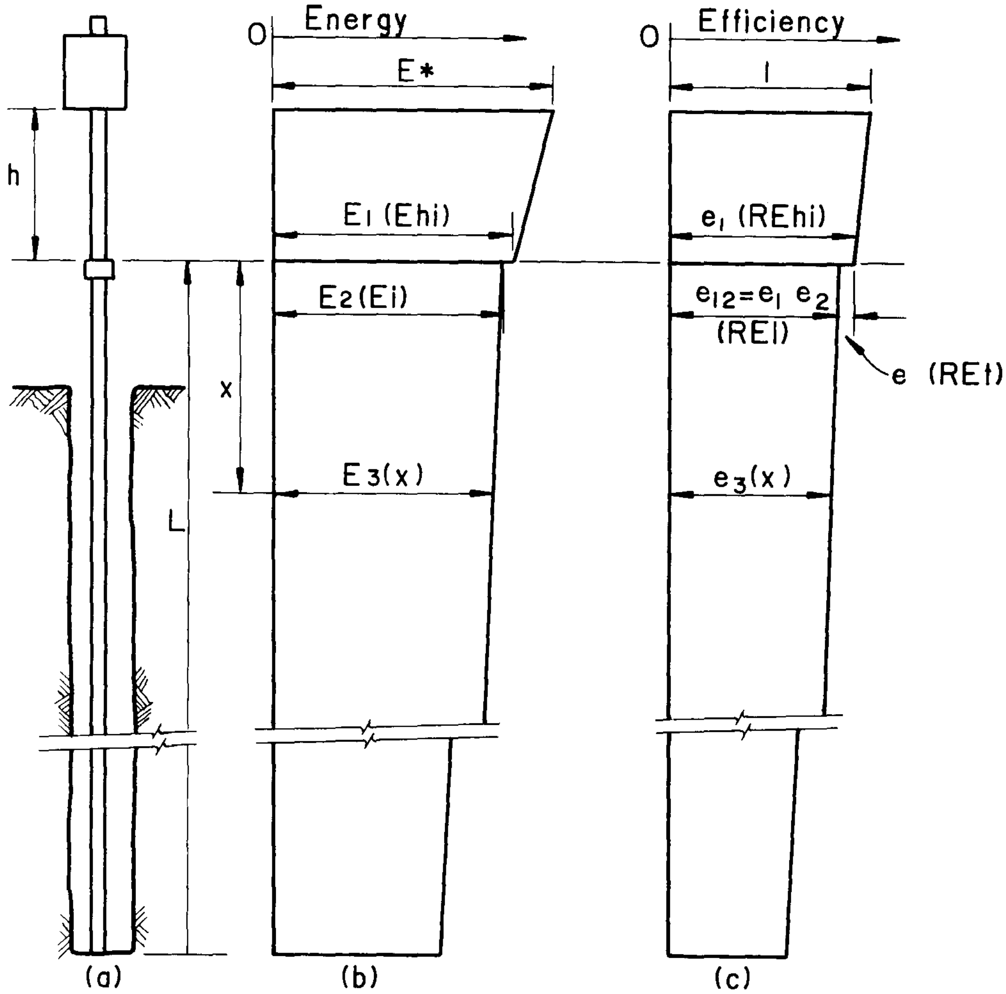
The mechanical variables of SPT testing are more easily studied than those from drilling technique. The energy dynamics of SPT testing are now being studied by use of wave mechanics. The framework for such studies is by use of elementary one-dimensional wave equation theory. Wave equation theory with lumped-mass spring models was applied to pile-driving problems by Smith [40]. In-depth application of such modeling to SPT testing was performed by McLean et al. [41]. Attempts to physically measure stress wave energies began in the early 1970's when rope and drum methods and free-fall methods of SPT were compared in Japan [42]. Dahlberg and Bergdahl [8] utilized stress wave measurements to design hammer-anvil systems for the automatic ram sounding test. Studies on hammer-fall velocity during SPT testing were performed by Kovacs et al. [43], and Goble and Ruchti [44]. The studies of hammer impact velocities showed significant losses of energy with the rope and cathead method when additional wraps were added to the cathead.

Palacios [45] developed a method of measuring stress wave energy in drilling rods at a location immediately below the anvil shown as the drill rod energy ratio E_i on figure 10. The results of the research showed that the majority of energy for sampler penetration was delivered in the first energy pulse down the rods. Stress wave F-t (force-time) histories were first measured at locations just below the anvil and just above the sampler. After confirmation of theoretical aspects, the method was simplified to measure the energy content in the first compression wave measured just below the anvil. The method was especially attractive as additional energy losses from the hammer anvil configurations could be studied. The study considered differences in hammers and drill rods to depths of 74 feet. The study had a pronounced influence on SPT testing in the United States. Based on results of this study, Schmertmann [46] cautioned users of SPT testing for liquefaction resistance evaluations of possible wide variations in SPT testing. Kovacs et al. [47] continued drill rod energy studies in the United States to eventually compile data on 56 drilling rigs under field conditions. In Japan, efficiency studies [42] focused on hammer-anvil impact behavior in addition to friction (e_1), impact (e_2), striking (e_{1-2}), and propagation (e_3) efficiencies (fig. 10). With increasing concern about compatibility of the SPT liquefaction data base, Kovacs and Salomone [48] participated in a joint U.S.-Japan cooperative research program in Japan to accumulate drill rod energy ratio data on 19 drilling rigs under field conditions.

The significant findings of studies on mechanical features of SPT testing will be summarized below under various equipment variables present in the test.

Effect of Drill Rod Length

Losses in stress wave energy due to attenuation can be attributed to internal friction, rod joints, and friction between the drill rod and borehole. Little information is available on attenuation losses caused by rod joints and external friction, but those losses are felt to be very minor.



Note : Terms in parentheses are those used in the United States.

Figure 10. — Energy ratio definitions in the SPT (Thorburn et al. [4]).

Losses due to internal friction were estimated by Palacios [45] to be on the order of 1 percent per 10 feet [3 m] of rod length. These losses, which were fairly small, were also found to be offset to depths of up to 70 feet [21 m] by increased hammer-anvil contact time with depth. Internal friction losses, on the order of those determined by Palacios, were measured on a horizontal rod-striking test by Uto and Fuyuki [42] and by Matsumoto and Matsubara in field test conditions [49]. Wang and Lu [42] pointed out that in China, it is accepted practice to correct for rod energy loss (Shi-Ming [50]). These corrections seem considerably larger than those that can be attributed to internal friction losses and are meant to incorporate rod buckling, joint losses, and increased momentum of heavier drill strings. Based on detailed studies by Palacios, it is not necessary to consider energy losses for depths less than 75 feet [23 m].

There is a definite need to study the combined effects of energy losses and increased static weight of the rods at depths exceeding 100 feet [30 m]. The author is aware of several liquefaction studies of existing embankment dams where drill strings of 200 to 300 feet [61 to 91 m] were utilized under high effective stress conditions (crest drilling) and low effective stress conditions (barge drilling). The results of wave equation studies by McLean et al. [41], point out that the effects of rod length become significant in materials with low resistances. Schmertmann [46] estimated that *N* values are increased by approximately 10 percent when drill rod lengths exceed 100 feet [30 m]. If the penetration resistance of materials are moderate, it is thought that static weight effects are minor. Corrections can then be made assuming internal friction losses of 1 percent per 10 feet [3 m] of depth when depths exceed 100 feet [30 m].

With shallow depths of drilling, Palacios found that energy transfer for penetration was impeded by quick return of the reflected tensile wave to the hammer-anvil contact, resulting in shortening of the duration of the initial compressive wave pulse [45]. Figure 11 shows that energy transmission to the SPT sampler is less effective at shallow depths. This figure shows that the theoretical maximum amount of energy (free-fall) that could possibly enter the drill rods before the loss of hammer-anvil contact. Energy transfer can increase to 100 percent at depths of about 40 feet [12 m]. The measured data indicate that the increase in energy is less pronounced in practice; but for depths of less than 10 feet [3 m], it should be considered. As a result of these findings, Seed [34] recommended that SPT *N* values be reduced by a factor of 0.75 for depths less than 10 feet [3 m].

Effect of Drill Rod Diameter

When penetration testing first utilized 1-inch [2.54 cm] pipe for drill rods, engineers became concerned with energy losses of slender drill rods due to buckling and also sidewall frictions. Early studies by Cummings with 1-inch rods indicated energy loss in buckling was a very small proportion of total energy [3]. Field studies by Clark [51], Degodoy [52], and Brown [53] indicated no significant differences in *N* values due to rod diameters. The results of field studies are subject to question since soil variability masks possible differences. Wave equation studies by Adam [54] indicated minor effects of varying stiffness on SPT *N* values, while McLean et al. [41], found "slight" differences in A and N rods using different hammer systems. Studies by Matsumoto and Matsubara quantified stress wave energies measured in three different diameter drill rods in field studies [49]. These studies showed that the smaller rods would transfer similar peak energy pulses over slightly longer durations for the first compression wave. These results, if applied to findings by Palacios [45], would indicate smaller rods are slightly more efficient in developing sampler penetration due to the longer duration of the pulse. The increased efficiency of smaller rods is also in agreement with the wave equation studies by McLean et al. [41], which predicted that N rods will give slightly higher penetration resistance values. Schmertmann

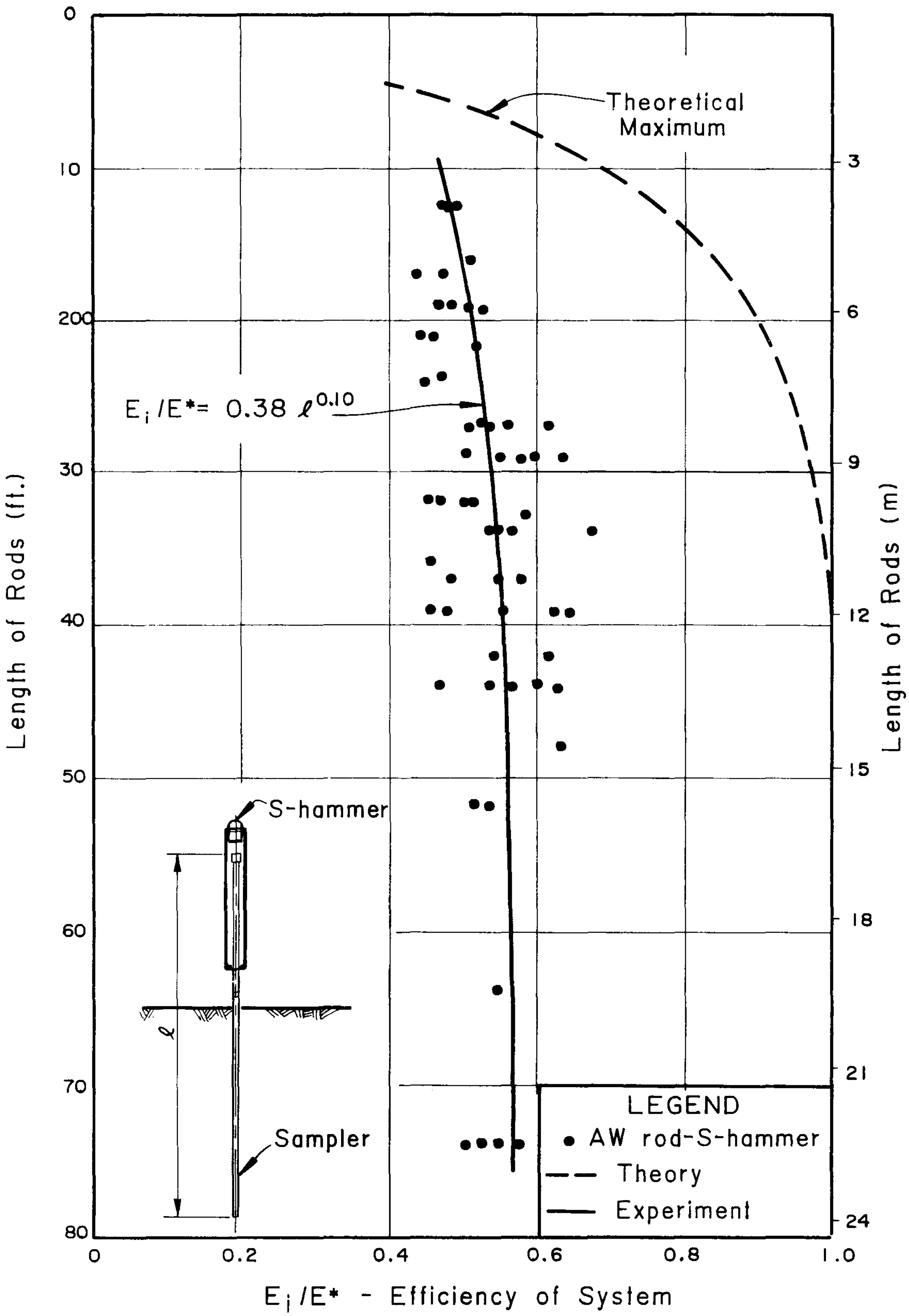


Figure 11. — Variation of E_i/E^* with rod length for AW rod-S-hammer combination (Palacios [45]).

[46] estimated that the differences in penetration resistance when using A or NW rods would be on the order of 10 percent.

Donut (Cylindrical Weight) Hammers

The donut hammer design, as shown on figure 12, is frequently used in many countries. This type of hammer can be operated by either the rope and cathead method or mechanical tripping methods, which will be discussed later. Kovacs et al. [43] showed that use of cathead wraps greater than the nominal two wraps will significantly affect energy transmission. If the hammer variation is isolated with respect to two nominal wraps, the energy variability will be primarily a function of hammer-anvil geometry with more massive anvils providing less efficiency. On figure 13, results from Kovacs in the United States indicate a mean drill rod energy ratio (RE_i) of 48 percent with a standard deviation of ±17 percent. In contrast, data collected in Japan by Uto and Fuyuki [42], showed a range of RE_i of 0.63 to 0.72. These findings were confirmed by Kovacs and Salomone [48] as shown on figure 14. These data indicate median RE_i of 67 percent. The higher mean RE_i for Japanese donut hammers can be attributed to the smaller anvil (knocking head). The standard deviation in RE_i for Japanese data is significantly better than the 17 percent from United States practice since geometry is fixed. Single operator RE_i standard deviation in U.S. practice was as high as ±12.6 percent, but typically ranged from ±6 to 8 percent.

Safety Hammers

Internal anvil safety hammers, shown on figure 12, are used more frequently in the United States than donut hammers. The safety hammer is operated by the rope and cathead method. Figure 15 from Kovacs et al. [47] shows that the mean RE_i for drilling rigs using safety hammers was 61 percent with a standard deviation of 13.5 percent. The standard deviation of RE_i is better than that of donut hammers due to restricted geometry inherent in the design of the safety hammer. Single-operator RE_i standard deviation under varying field conditions was as high as 15 percent, but generally was ±5 to 6 percent or better.

Automatic Mechanical Triphammers

Automatic mechanical triphammers are typically donut hammers lifted by a rope and gripping mechanism which trips and releases the hammer at 30 inches [0.76 m]. These hammer systems find frequent use in the United Kingdom and China. Limited RE_i information is available for these hammers. A study by Kovacs [55] of hammer-impact velocity of a Borros AB trip hammer found its fall velocity to be dependent on the rate of blows applied. The dependence was due

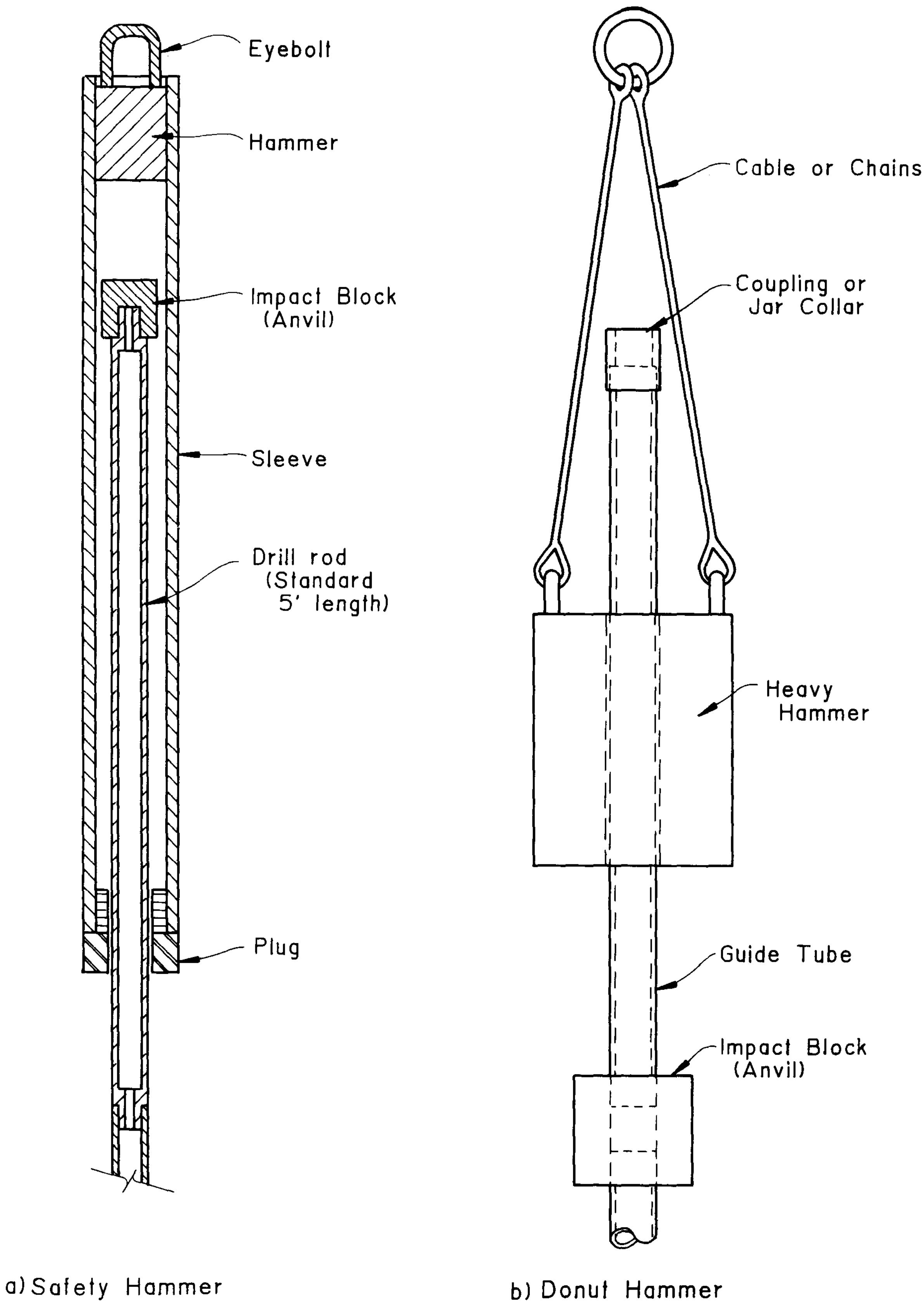


Figure 12. — Configuration of SPT hammers (Thorburn et al., [4]).

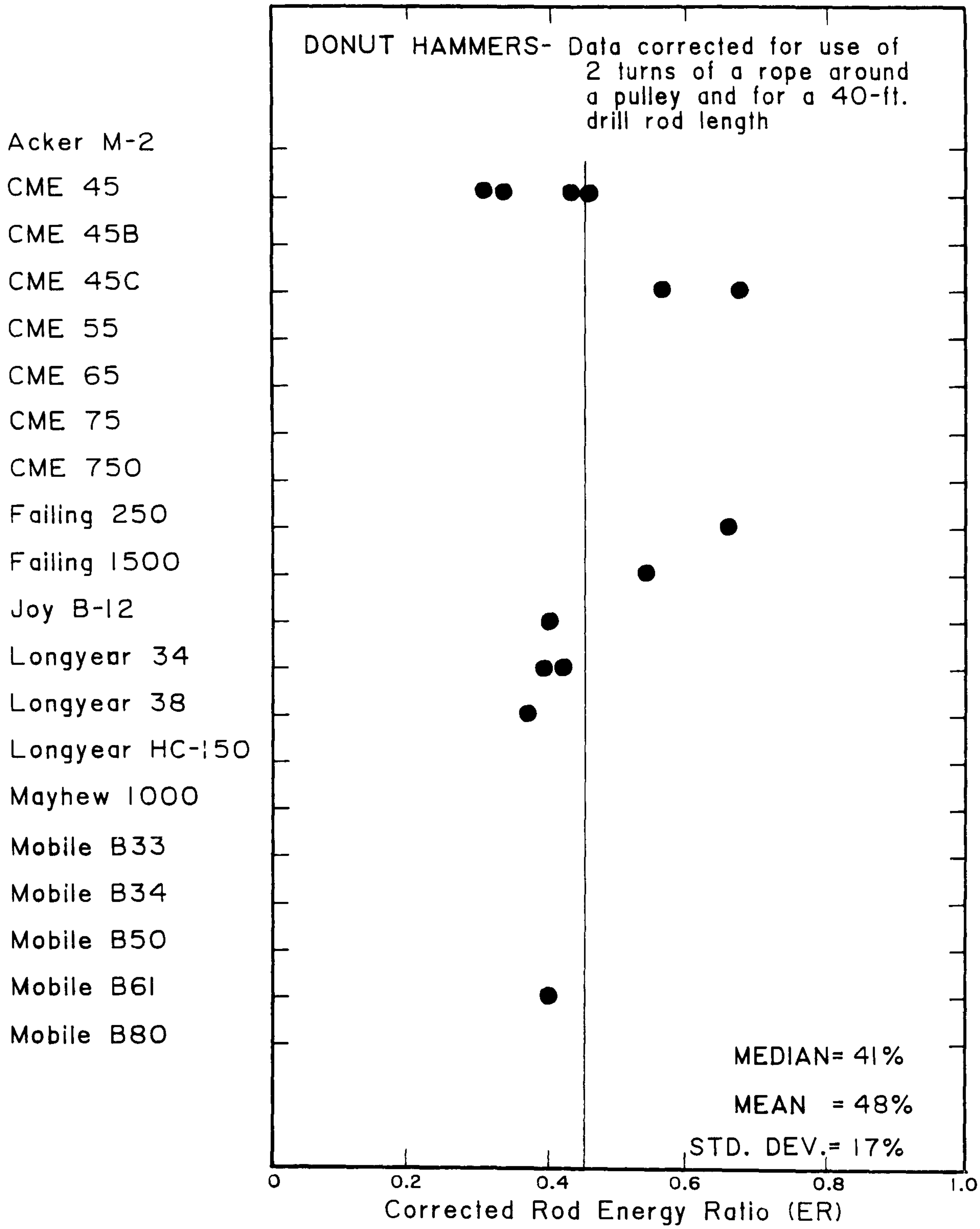


Figure 13. — Summary of energy ratio data for donut hammers (modified from Kovacs et al. [47]).

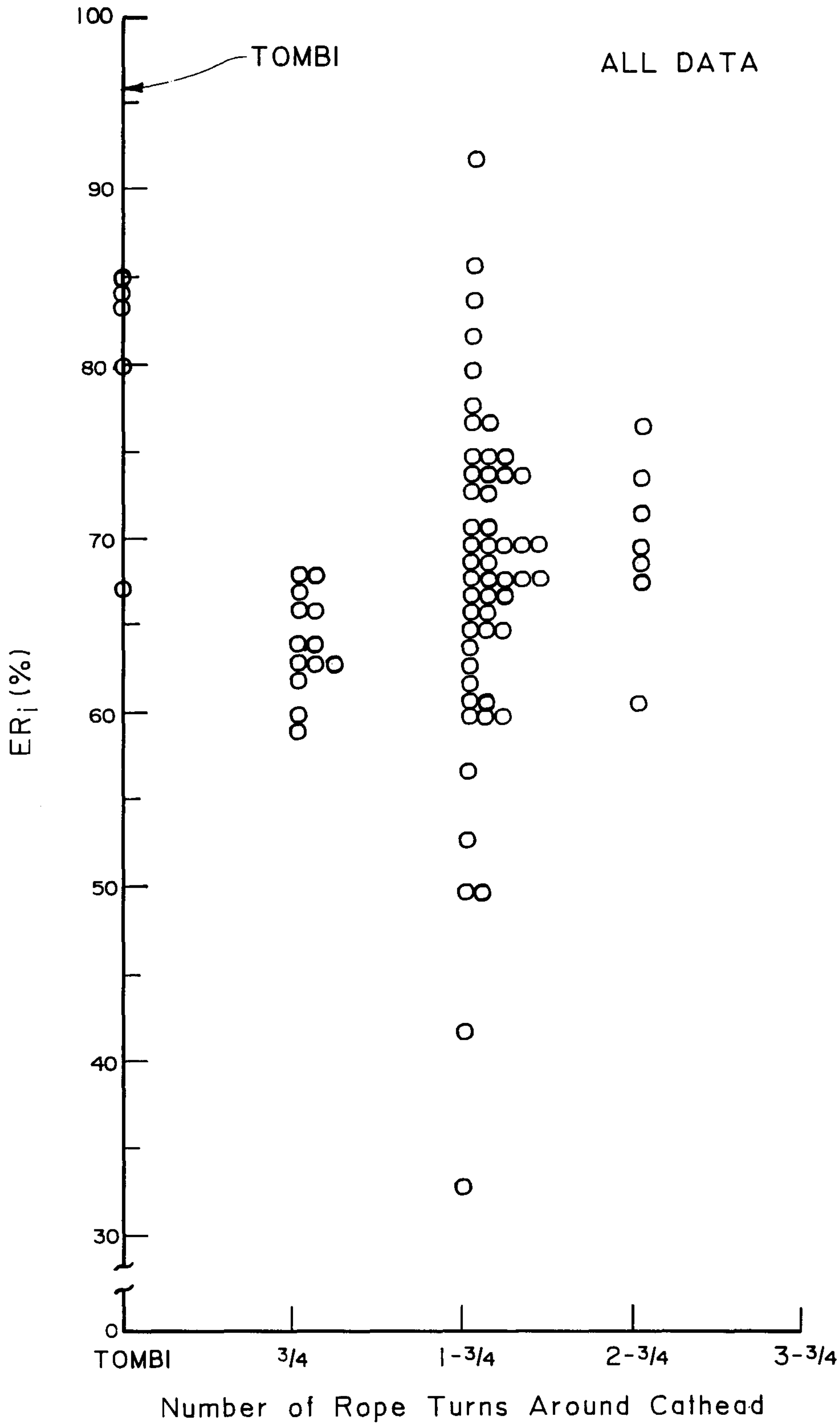


Figure 14. — The ER_i versus number of rope turns around the cathead from a joint U.S.-Japan study (Kovacs and Salomone [48]).

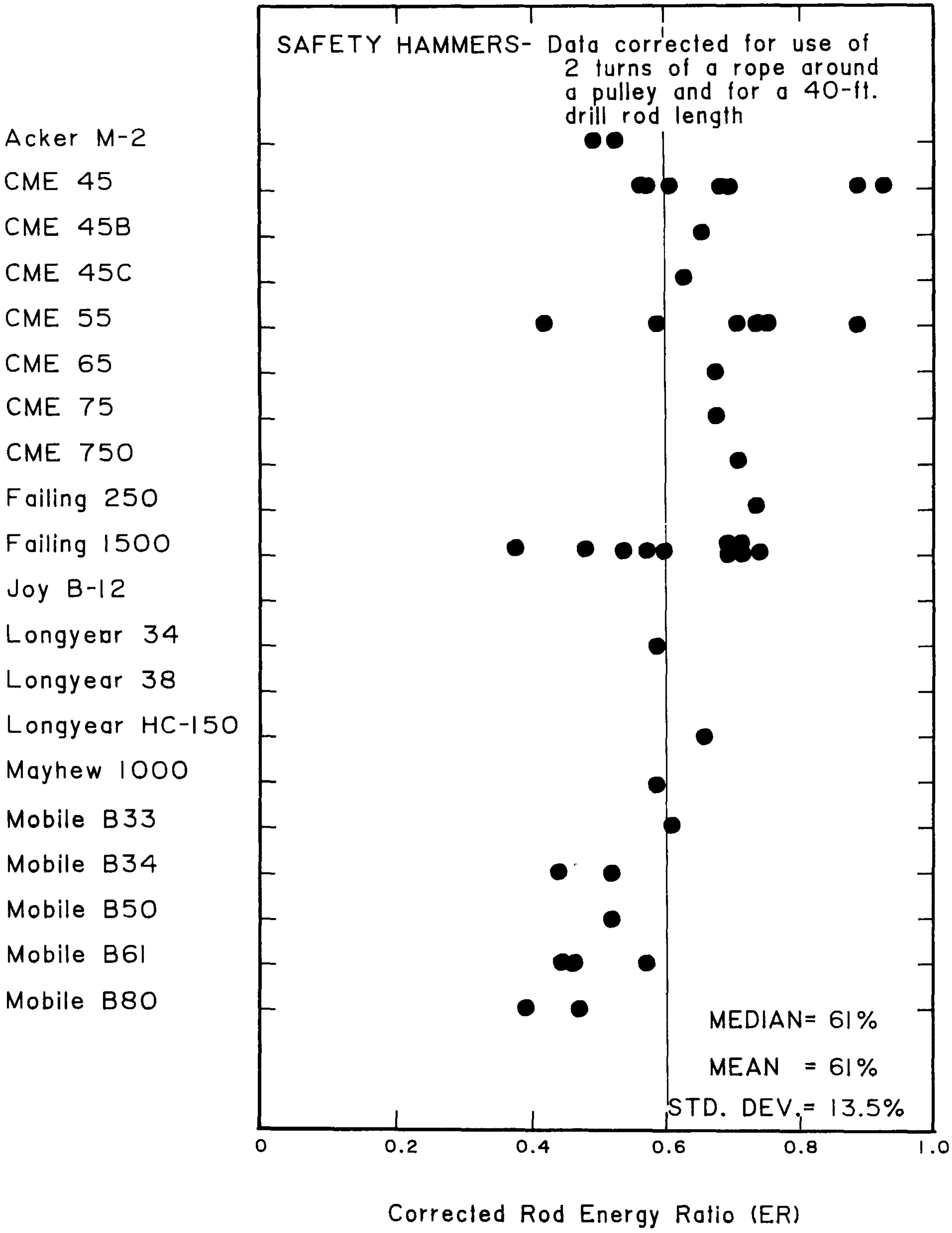


Figure 15. — Summary of energy ratio data for safety hammers (modified from Kovacs et al. [47]).

to the hammer overshooting the 30-inch [0.76-m] trip point when pulled up quickly. The velocity measurements indicated this hammer was much more consistent in energy delivery and, therefore, was a desirable replacement to hammers operated by the rope and cathead method.

Drill rod energy ratio, RE_i, was evaluated for the Pilcon triphammer by Liang [56], Douglas and Strutznksy [57], and Decker et al. [55]. The values of RE_i ranged from 55 to 62 percent with the lower than anticipated values being attributed to a large anvil. During a field liquefaction study, a Chinese automatic mechanical trip hammer was compared to a Pilcon trip hammer by Douglas [59]. The field study compared SPT data of the two hammer systems with no significant differences found. As noted by Shi-Ming [50], four different designs of hammers are in use in China; and, therefore, there could be variations in RE_i.

The author has not had an opportunity to review typical standard deviations of RE_i for such systems; but it is anticipated that, by removing drill rig and operator effects, such systems will greatly improve reliability of SPT testing.

Automatic Hammer Systems

Automatic hammer systems are employed less frequently for SPT testing since they are more costly and more complicated to operate. The Corps of Engineers [29] has employed automatic systems in field studies and in their laboratory study on relative density [19, 20]. Unfortunately, the rod energy ratios, RE_i, of such systems have not been published. Riggs et al. [60] published data on a CME automatic hammer system which indicated an energy ratio, RE_i, of 80 to 91 percent. The standard deviation of RE_i delivered in individual trials was typically on the order of ± 1 percent, which shows the great advantage of automatic systems.

Effect of Inner Barrel Diameters

Concern has arisen with respect to varying United States practice on use of constant 1-3/8-inch, [3.5-cm] inner-barrel diameters. A study by Kovacs [9] showed that approximately 40 percent of those responding utilized a 1-1/2-inch, [3.8-cm] inner-diameter barrel. Schmertmann [61], in his study of statics of SPT, predicted differences in SPT N values due to a loss of interior friction which seemed to agree with limited field data. In the Japan study, Kovacs and Salomone [48] obtained SPT N values with and without liners along with rod energy measurements. Results of this study are shown on figure 16. From this figure, it is seen that use of inner barrel diameters larger than the inside diameter of the cutting shoe results in SPT values about 10 to 30 percent lower than those with barrels having the same inside diameter as the cutting shoe. Data from

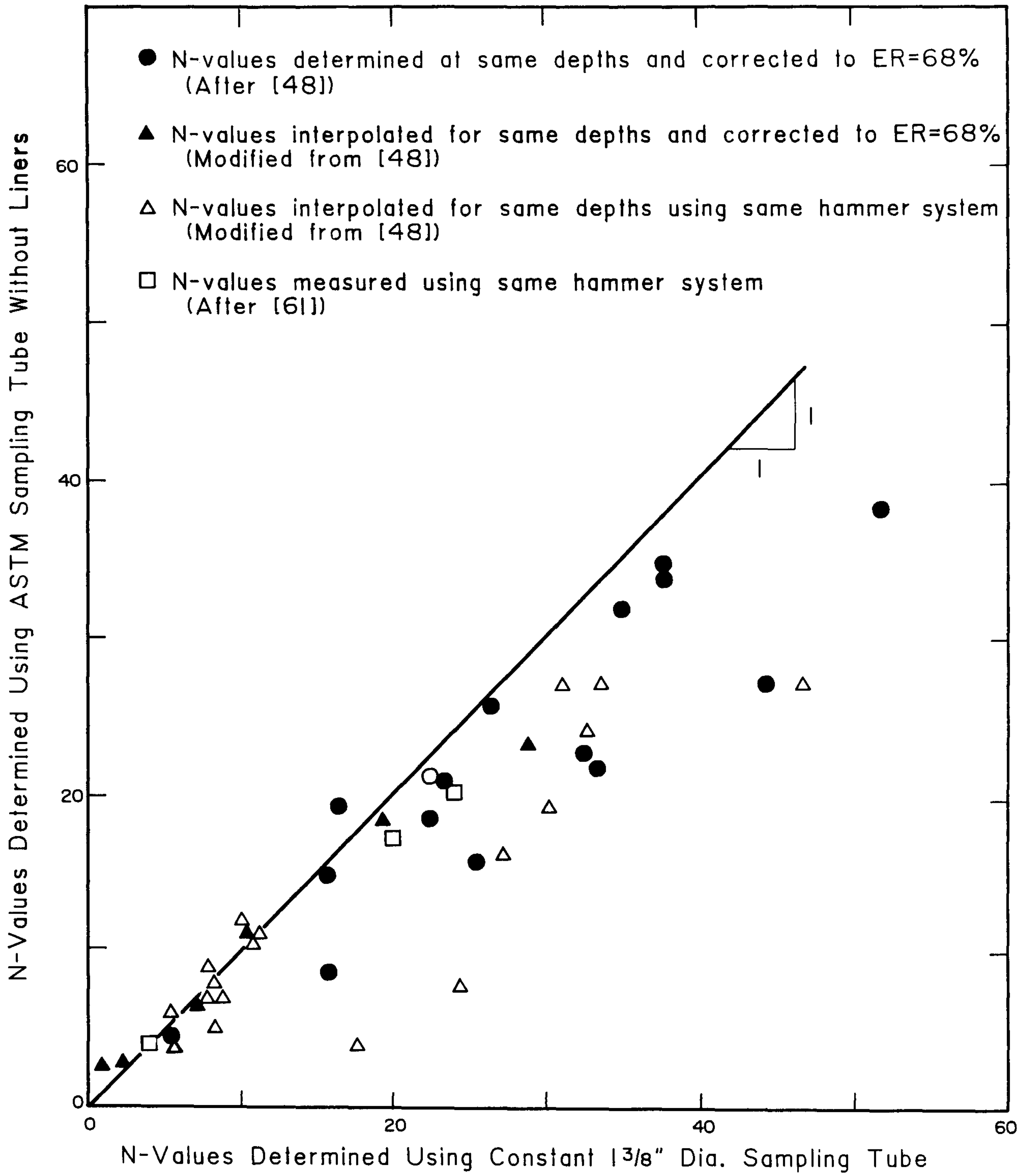


Figure 16. — Effect of type of sampling tube on *N*-values (Seed et al. [33]).

this field study are subject to some scatter and require laboratory-controlled studies for better definition and separation of effects for cohesive and cohesionless soils.

Difficulties in Obtaining Reliable Energy Measurements

The methodology developed by Palacios [45] for measuring the drill rod energy ratio, RE_i, has been applied successfully in many cases. In searching for methods of measurement, strain gauge load cells rather than accelerometers were selected for testing. In several cases, load cells were damaged during testing. In the Palacios study, several F-t histories were checked with wave equation studies; and all of the F-t records were recorded.

After the testing by Palacios and Schmertmann, a "black box" system was developed by Hall [62] to measure F-t histories and resulting rod energy ratios electronically. The system was of great assistance in providing information on SPT variability in the United States. However, in some cases, the integration times and nature of the F-t signal were not checked. Kovacs et al. [47] routinely collected F-t histories and checked the "black-box" values indicating very good agreement. A problem with reflective compressive waves was identified where the black box would erroneously calculate RE_i. This occurrence is shown on figure 17. Also, problems with load-cell shorting were identified, as shown on figure 18. In both cases, the black box calibrator would not sense the true integration time, so it was necessary to monitor integration time and compare to theoretical 2 L/c values.

These potential errors raise concern over contributions to the RE_i data base where signal quality was not monitored. An example of this is published data by Riggs [63] that were affected by compressive wave reflections (Seed et al. [33]). It should also be noted that the data compiled by Kovacs et al. [47] contains contributions by several other researchers. It is recommended that, in all future studies of rod energy ratios, RE_i, the signal quality and integration times be documented.

Additional problem areas have developed in the energy measurement methods. Recently, strain gauge load cells have been replaced with piezoelectric load cells, which provide considerably better durability over the strain gauge design. It is felt that, when both gauges are functioning properly, they will provide the same response but there has been no systematic study to prove this. The piezoelectric cells may provide better transient response. Also, there has been a tendency to correct RE_i data for compressive wave travel times which differ from theoretical values [47]. It is the author's opinion that this correction should not be used until phenomena causing it are understood.

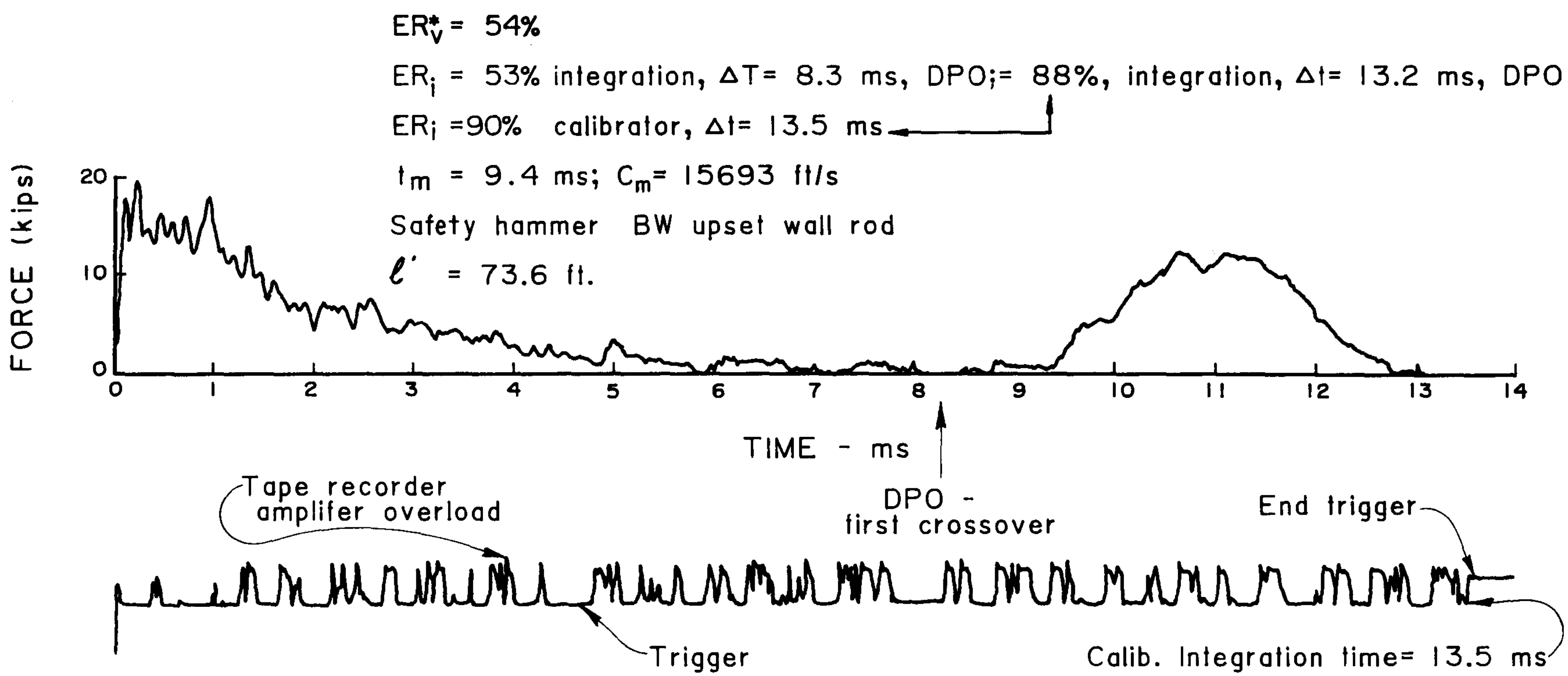


Figure 17. — Illustration of compressive wave return force-time history and trigger (duration) time (Kovacs et al. [47]).

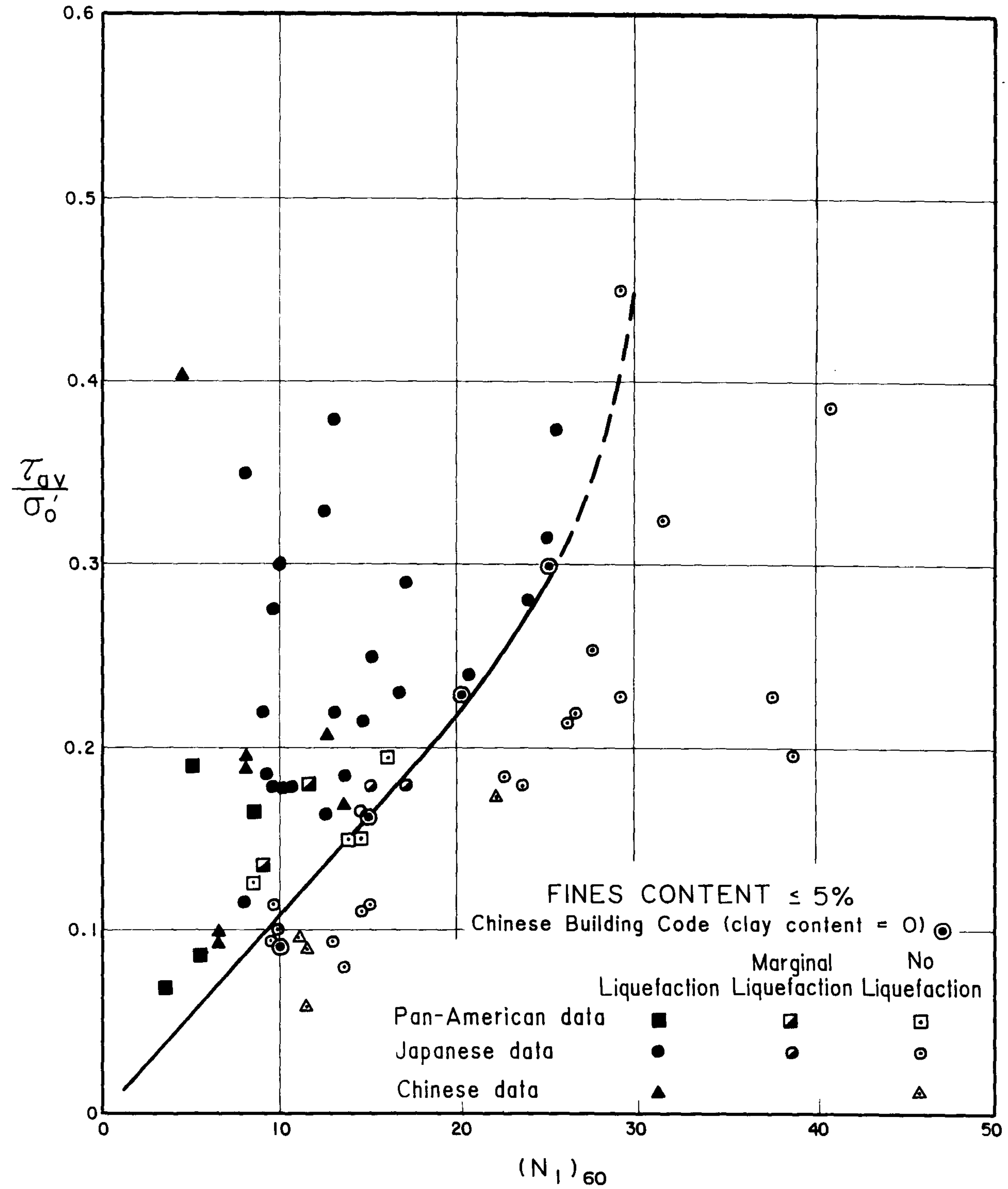


Figure 19. — Relationship between stress ratios causing liquefaction and N_1 values for clean sands for M = 7-1/2 earthquakes [33].

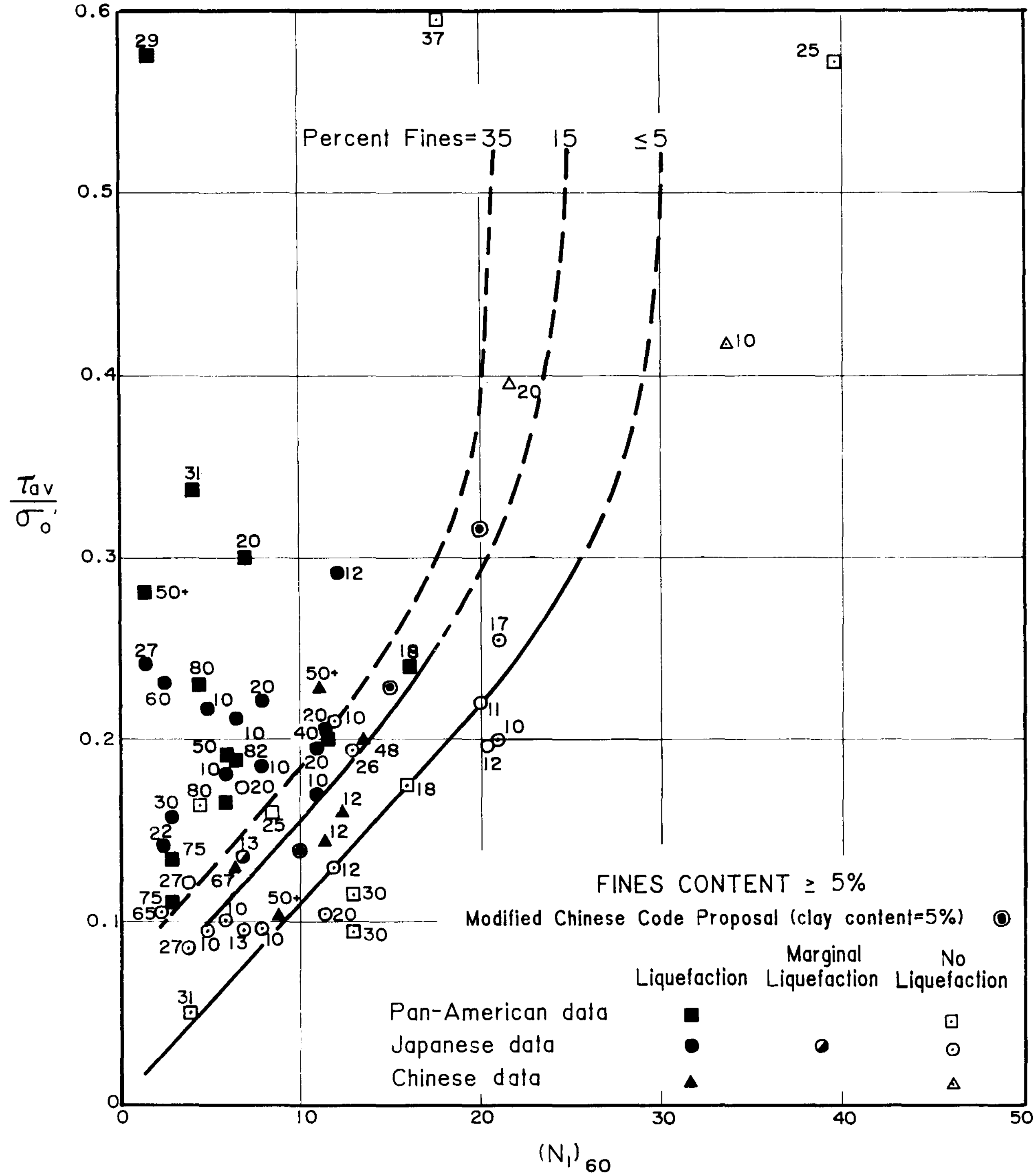


Figure 20. — Relationships between stress ratio causing liquefaction and N_1 values for silty sands for M = 7-1/2 earthquakes [33].

Also in the report, recommended SPT procedures to be used for liquefaction resistance evaluations are given. These procedures, as shown in table 3, require that an energy ratio delivered to drill rods is approximately 60 percent of theoretical maximum. For U.S. practice, it is implied that safety hammers should be used as they deliver this amount of energy on the average. For other methods, in other countries, adjustments to N_1 values can be made using estimates in this report or by obtaining energy measurements.

STANDARDIZATION

For proper execution of SPT testing for liquefaction evaluations, the use of procedures given in table 3 is recommended. Several entities are currently working on standards to refine SPT testing. The ASTM debated the inclusion of energy measurements to the current SPT test procedure, but met with resistance. As a result, the standard method was reissued in only a slightly improved format. The method allows for any type of hammer system that meets general requirements and also allows for variable inside barrel diameters. Work is underway to develop an energy standard for use in penetration resistance testing.

Work on standardization is also underway within the ISSMFE by a working group on SPT headed by Thorburn [4]. A four-part document presenting recommendations of the committee was discussed in the 11th ISSMFE Conference on August 11-15, 1985. The document contains practice reviews and a proposed SPT reference test procedure. The test procedure incorporates

Table 3. - Summary of energy ratios for SPT procedures [65].

Country	Hammer type	Hammer release	Estimated rod energy (%)	Correction factor for 60% rod energy
Japan[1]	Donut	Free-fall	78	78/60 = 1.30
	Donut[2]	Rope and pulley with special throw release	67	67/60 = 1.12
United States	Safety[2]	Rope and pulley	60	60/60 = 1.00
	Donut	Rope and pulley	45	45/60 = 0.75
Argentina	Donut[2]	Rope and pulley	45	45/60 = 0.75
China	Donut[2]	Free-fall[3]	60	60/60 = 1.00
	Donut	Rope and pulley	50	50/60 = 0.83

[1] Japanese SPT results have additional correction for borehole diameter and frequency effects.
[2] Prevalent method in this country today.
[3] Pilcon-type hammers develop an energy ratio of about 60 percent.

requirements for a sampler with constant inside diameter, free-fall hammer, and energy measurements when it is necessary to make "comparisons" of SPT data. A proposed test procedure for energy measurement methods and a section on theory and technical notes are provided which, in general, are well written and significantly contribute toward standardizing energy measurement methods.

The requirement for a "free-fall" hammer will have to be modified since it is impractical for widespread test usage. Currently, automatic hammer systems at best allow the hammer element to fall within a cyclindrical enclosure without center hole guide rods. It would be more desirable to specify a reference rod energy ratio and allow the use of both automatic and automatic mechanical triphammers with documented energy ratios. The most desirable reference rod energy ratio would be 60 percent as proposed by Seed et al. [33]. Use of the rope and cathead methods is rightfully not included within the method, as energy variations are large.

As stated earlier, energy measurements are difficult and require skilled personnel to perform them. In the ISSMFE document, problems identified earlier concerning F-t traces are discussed; and the procedure requires supplying examples of F-t traces in documentation of results similar to Schmertmann's example calibration [46]. The author concurs with these requirements to assure the reliability of such measurements. The requirements for field energy measurements would be significantly lessened if manufacturers of hammers would document typical energy level and variation with production of hammer systems.

For those who are performing SPT for analysis of liquefaction, there are now few alternatives to knowing the energy level and variations of the systems used. Although the use of the rope and cathead is undesirable, it may have to be tolerated until acceptable automatic mechanical triphammers can be designed. Until that time, it is not feasible to perform energy measurements for all data collected. For the time being, it would be simple enough to determine performance of the hammer-rope-cathead systems for general energy level. In the meantime, work should be undertaken to remove variables inherent with the rope and cathead systems. The current problems with most triphammer systems are their lack of safety features (exposed hammer-anvil contact) and some problems with overstroke, which need to be resolved.

CONCLUSIONS

1. The SPT, as currently performed, has been shown to provide suitable estimates of engineering parameters for design purposes. The test results are subject to considerable variations due to combinations of drilling techniques, geological, and mechanical effects. The mechanical effects

have been studied and are now fairly well understood. However, with control of mechanical effects, there will still be significant variations due to drilling techniques and the nature of the deposits being tested such that evaluation of engineering parameters will never be clearcut to the point where the method will provide exact values.

2. The data base of SPT data correlated to liquefaction is now sufficient to make reasonable estimates of liquefaction potential as long as data are carefully applied. Development of SPT liquefaction resistance evaluation methods in several countries has progressed to a point of mutual agreement. The SPT liquefaction data have been reevaluated and adjusted to account for variations in test procedures. Methods are now available to adjust data when using different procedures which improve liquefaction resistance estimates. Further refinements are needed to evaluate nonlevel ground applications of such methods. Future studies can be performed to evaluate the boundaries dividing full flow and limited shear strain conditions. Additional information is needed in both denser deposits at higher cyclic stress ratios and in looser deposits at smaller cyclic stress ratios.

3. The studies of mechanical and procedural variabilities in SPT testing have contributed significantly to SPT testing. The fact that SPT *N* values can vary over wide ranges have made the geotechnical engineering community pay considerably more attention to testing procedures. Efforts to further refine mechanical variabilities should be undertaken by developing alternatives to rope and cathead operations. The methods for energy measurement should be further studied and refined resulting in application as a standard test method for quantifying mechanical variability. As mechanical and automatic triphammer systems are developed to improve the test, it will be simpler to document the energy ratio of the design such that routine cumbersome measurements in the field will not be required.

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Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.