A RECONSIDERATION OF THE INITIATION OF LIQUEFACTION IN SANDY SOILS

by

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Abstract

The Berkeley trigger criterion for evaluating the potential for earthquake-induced phenomena in sandy soils is reviewed. The historical database comprising the criterion is reconsidered using a consistent "weakest-link-in-the-chain" approach. Revised plots of average cyclic stress ratio (CSR) versus $(N_1)_{60}$ are presented using the new minimum values of $(N_1)_{60}$. Lower bound state lines, in terms of $(N_1)_{60}$, are applied to the non-liquefied data and upper bound state lines are applied to the liquefied data. It is found that these lines do not coincide, forming a single trigger line in either clean sand or sand with fines; rather, they define a zone in which liquefaction may or may not occur. An additional zone is defined in which any earthquake-induced phenomena are likely to consist of only sand boils. This supports the necessity of site-specific investigations to determine liquefaction potential. The results of this study demonstrate an effect of fines content on liquefaction potential, but not to the same extent as is found in the original interpretations of the field data.

Key words: Cyclic stress ratio, earthquake, liquefaction, sands, Standard Penetration Test, trigger.

INTRODUCTION

In earthquake design of saturated sandy soils, a fundamental issue is whether or not the design earthquake could initiate phenomena such as lateral spreading, cracking, settlement, sand boils, flow slides, buoyancy, and loss of bearing capacity. These phenomena taken together are often referred to as liquefaction. Figure 1 presents the primary source of current practice for predicting the initiation of what is called liquefaction, based on the well known work of Seed et al. (1984) who presented a catalogue of 125 case records referred to here as the Berkeley catalogue. These plots define an empirical state line between case records that were designated as having liquefied and those that did not. The case records embraced by the Berkeley catalogue are cited as being for level ground and the extension of these data to the design of sloping ground, dams and other structures has been presented by Seed (1983) and Rollins and Seed (1990). Professional and regulatory practice often adopts this work as a design method and to a significant extent, it also forms a standard against which other theories and methods of liquefaction assessment are judged.

The most significant aspect of the Berkeley catalogue is the assignment of a single Standard Penetration Test (SPT) $(N_1)_{60}$ value to describe the state of the sand for a given case record. The objective of this study was to reconsider the Berkeley catalogue selection of $(N_1)_{60}$ data. While much use has been made of the original work, many of the case records are difficult to obtain, and the raw data is not available in the original catalogue. Fear and McRoberts (1993) have recently summarized all of the original data in catalogue form, including all of the borehole logs that could be located. The objective of this paper is to summarize the major findings of this work.

This study has adopted the approach of characterizing liquefaction or non-liquefaction with a single $(N_1)_{60}$ value. However, it is argued, in agreement with general design practice that, all else being equal, the layer with the lowest $(N_1)_{60}$ would have the least resistance against liquefaction. Hence, a "weakest-link-in-the-chain" approach was consistently used in this study. This is, in general, a different approach than was used in the original work and is considered to be a justifiable method for reconsidering the data. This study primarily restricts itself to a reconsideration of the $(N_1)_{60}$ data component of the case records. The state of the sand, as measured by the $(N_1)_{60}$ value, is, of course, not the only factor affecting liquefaction potential. Clearly, the magnitude and acceleration of the earthquake, depth of the weak layer and depth of the groundwater table, as embraced by the average cyclic stress ratio (CSR) are key parameters. This study adopts the original methodology for calculating this ratio, but reassigns the CSR and fines content data as appropriate for the new selection of $(N_1)_{60}$ representing the weakest state of the sand. Case records in clean sands (percent passing the No. 200 sieve ≤ 5%) and those in silty sands are kept separate as they were in the original work.

As discussed in the National Research Council (NRC, 1985) summary, there are many other factors which also influence the response of a particular site to ground motion. Site topography can be a factor and, while the original catalogue was for level ground, there are cases where some modest slopes or additional loading were present. Site drainage and, in particular, the influence exerted by impedance of seepage, potentially further complicated by both hydraulic fracturing and density changes (water content redistribution), clearly exert possible influences. Other soil factors such as aging, grain size distribution, gravel content effects, in-situ stresses and so on will all exert effects as well. It might be said that there are so many other factors in addition to the triad of major factors considered here (CSR, $(N_1)_{60}$, fines content) that it is imprudent to base any consideration of liquefaction on such restricted grounds. Certainly the experienced designer will not rely solely on such a simplistic approach, but the predictions offered can be useful at a screening level. While some of the other factors that influence liquefaction may have been subjectively considered in the Berkeley work, there are no records available to indicate what may have been done.

This study finds that, in many cases, the Berkeley catalogue did not select a minimum value of $(N_1)_{60}$. From a design perspective, this can be a particularly significant issue as practice tends to focus on identifying the loosest zone and then applying the Seed et al. (1984) criterion to this layer. A conservatively-biased criterion that is accepted in practice makes it exceptionally difficult to introduce alternative technologies and design methodologies, especially in terms of regulatory opinions and design precedents in high risk design environments. It can be argued, given the implications of liquefaction failure and the variety of difficulties and unknowns associated with the case records, that a conservative assessment is justified. However, it should be explicitly understood that this is the case. In many other situations, on a site specific basis, more economical designs justified by investigation and testing may be appropriate.

METHODOLOGY

The approach of the Berkeley catalogue was simple and straightforward in that either there were or were not surface manifestations during or after an earthquake and, hence, it was concluded that liquefaction either had or had not occurred. It is recognized, following the concerns that were first raised by Casagrande (1976) and were recently reviewed by McRoberts and Sladen (1992), Robertson (1993), Ishihara (1993) and Youd (1993), that definitions of what does or does not constitute liquefaction is being actively discussed in the geotechnical community. This study adopted the original definitions of liquefaction used by the Berkeley catalogue. If surface features such as sand boils, cracking, lateral spreading or settlement were seen, the case record was classified as "liquefied" (indicated by the solid symbols in Figure 1). However, if no surface features were visible, either during or after the earthquake, the case record was classified as "non-liquefied" (indicated by the open symbols in Figure 1). In addition, a few case records in the Berkeley catalogue were classified as having "marginal liquefaction" (indicated by the cross symbols in Figure 1). Another category entitled "pressure relief" was added in this study for case records for which sand boils were the only surface feature observed at the site. This "pressure relief" category was added in order to explore the possible differences between sand boils and other liquefaction responses to seismic actions. This study used the same symbols in subsequent plots for case records that were reclassified as pressure relief and for those for which the classification was left as marginal liquefaction, as given in the Berkeley catalogue, as it was felt that they likely represented similar phenomena.

Following Ambraseys' (1988) numbering system, the Berkeley catalogue of 125 case records was expressed as 123 case records (four case records were merged into two). The reference papers cited by Seed et al. (1984) were obtained for each of these case records with a few exceptions (Cluff (1973), Dames and Moore (1975), Seed (1973), and Tsuchida (1979)). Information summary sheets and borehole logs for all of the case records and the complete reference list are contained in Fear and McRoberts (1993).

In the Berkeley catalogue, each case record was reduced to a single pair of SPT $(N_1)_{60}$ and average cyclic stress ratio (CSR), reflecting state and loading, respectively. The in-situ relative density is reflected by $(N_1)_{60}$ which is the SPT blowcount, corrected to a vertical effective stress of 100 kg/cm^2 and an applied energy ratio (ER) of 60%, as explained in Appendix II.The CSR is a measure of the amount of shear stress induced by the earthquake at a level ground site, relative to the initial vertical effective stress, and can be calculated using the formula in Appendix II.

All else being equal, the layer with the lowest $(N_1)_{60}$ will have the least resistance against liquefaction. Thus, this study focused on the selection of the minimum $(N_1)_{60}$ for each case record and the CSR was recalculated if necessary. Selection of the minimum $(N_1)_{60}$ value is open to the criticism that the lowest value may actually be a testing error. In this study, all data were accepted at face value. In addition, variations in CSR occur with depth and are further complicated by the level of the groundwater table. It would therefore seem possible to have a combination of state and loading at another depth in a borehole which might have less resistance against liquefaction than the minimum $(N_1)_{60}$ and the corresponding CSR. However, the magnitude of the CSR is dominated by the earthquake acceleration at a specific site. As a result, the variations in CSR with depth over the depths under consideration in this study (generally less than 13.0 m, the maximum depth in the Berkeley catalogue, with only 9 case records between 13.0 m and a maximum depth of 19.5 m) are relatively small compared to the large variations in $(N_1)_{60}$ with depth. Therefore, following the logic outlined by Liao and Whitman (1986) by selecting the minimum $(N_1)_{60}$ and then calculating the corresponding CSR seems to be a reasonable way of characterizing the liquefaction resistance of a particular borehole.

The basis for the selection of N in the Berkeley catalogue is not clear and, as expressed by Liao and Whitman (1986), who presented a recent summary of previous liquefaction catalogues, the methodology used in the Berkeley catalogue was not explicitly stated nor consistently followed. The only specific citation as to the methodology followed that has been located is a table in both Seed and Peacock (1971) and Seed and Idriss (1971) which presented an early version of the Berkeley catalogue and included a column labelled as the "average penetration resistance at critical depth, N". Liao and Whitman (1986) considered that a close inspection of Seed et al. (1975, 1984) shows that choosing the minimum N_1-value in each boring or profile is in most cases equivalent to the Berkeley characterization. However, this study found that the $(N_1)_{60}$ in the Berkeley catalogue was a minimum value only for some cases; for many other cases, it could be considered to be an average value over some portion of the borehole and, for a few cases, it was a high value.

The question of site characterization with more than one borehole must also be considered. As noted by Liao and Whitman (1986), sites tend to be characterized by a single value of SPT N. They also commented that how this value is selected as being representative of a single boring profile or of the entire site is often not very clear or consistent. Liao and Whitman (1986) argued that it is best to consider each individual boring as a case study and to select the minimum $(N_1)_{60}$ from each boring to represent the soil conditions for the case study. This would be preferable to either considering all of the borings in the liquefied zone of a site as one case study and the borings in the non-liquefied zone as a second case study (resulting in two case records) or considering each blowcount in each boring as a case study (resulting in numerous case records). According to Liao and Whitman (1986), the former would result in problems with site characterization and the latter would result in a lack of statistical independence between case records. This study considered each borehole as an individual case record, where possible, and, in particular, when extra boreholes were obtained from a particular site in addition to a typical log. This was the case for the Luan Nan (case record 56) and Le Ting (case record 57) sites in the original database. It appears that the study conducted by Seed et al. (1984) may have only been able to obtain typical logs for some sites.

The borehole log for each case record was reviewed, the SPT N which would yield the lowest $(N_1)_{60}$ was selected and the corresponding depth and fines content (percent passing the No. 200 sieve) of the soil were noted. No blowcounts were selected from above the groundwater table or within clay layers (selections were restricted to sands and occasionally silts), except for one case record in clayey sand (case record 55) which was considered to be potentially interbedded. No blowcounts were selected at depths of less than 2 m since SPT blow counts and the C_N correction factors at these depths were considered to be unreliable. For each case history, in order to calculate $(N_1)_{60}$, the C_N correction was determined as given in Appendix II and the specific SPT hammer energy ratio given in the Berkeley catalogue was adopted at face value.

For two case records (case records 7 and 16), the original case record was in clean sand, but was replaced by a case record in sand with fines. For seven case records (case records 1, 2, 4, 15, 17, 63 and 64) originally in clean sand in the Berkeley catalogue, each original case record was replaced by two case records in this study, consisting of the minimum $(N_1)_{60}$ in clean sand and the minimum $(N_1)_{60}$ in sand with fines. It was not clear which of the two was the critical $(N_1)_{60}$; therefore, both values were selected and used on the appropriate subsequent plots. These pairs of case records, together with the additional information from the borehole logs that were obtained for the Luan Nan and Le Ting sites, as described earlier, resulted in expanding the original Berkeley catalogue database to a total of 155 case records.

EXAMPLE CASE RECORDS

Table 1 provides statistics regarding the composition of the original database of 125 case records in the Berkeley catalogue and the changes that were made during the reconsideration in this study. Some of these statistics are primarily for interest; the effects of others will be discussed later.

The non-liquefied case records are important points for defining the liquefaction trigger line and many of them had large reductions with the new selections of representative values of $(N_1)_{60}$. However, although all case records (liquefied and non-liquefied) were re-evaluated where possible, it was felt that case records in the Berkeley catalogue that were said to have liquefied with values of $(N_1)_{60}$ greater than 15 were especially pivotal to this study. As will be presented later in the paper, it was primarily the result of moving these case records that produced significant differences with the Berkeley catalogue in terms of upper bound lines to the liquefied data. At lower values of $(N_1)_{60}$, the effects were less significant. These important case records are highlighted on Figure 1 (case records 1, 3, 4, 7, 8, 17, 56 and 87 on the clean sand plot and 55, 90 and 111 on the plot for sand with fines). Table 2 provides a summary of these case records by comparing the original interpretations with the results of this study and providing some additional comments of importance. Detailed consideration of these case records and further discussion of the relevant factors are provided in the research report by Fear and McRoberts (1993).

In subsequent plots in this paper, case record 56-L6, which was introduced in this study, and case record 90 will be assigned question marks to indicate that they can be considered as a questionable liquefied case records. Case record 56-L6 can be considered questionable because the $(N_1)_{60}$ of 21.4 is much higher than any of the other liquefied case records at the Luan Nan site (see Table 2) and the failure mode (which was unspecified) may well consist of only pressure relief phenomena. Considering all of the new Luan Nan case records, with the exception of 56-L6, the dividing line between liquefied and non-liquefied case records is at an $(N_1)_{60}$ between 12.3 and 14.0. Case record 90 can be considered questionable because of the high gravel content in the borehole and the reassessments at the other piers, as outlined in Table 2.

Although not listed in Table 2, it is of interest to note that 20 additional boreholes with sufficient information to be considered as individual case records were obtained from the Beijing Municipal Bureau of City Planning (1982) for case record 57 (Le Ting), in sand with fines. These consisted of 7 non-liquefied case records with $(N_1)_{60}$ ranging from 8.4 to 19.8 (average of 13.0) and 13 liquefied case records with $(N_1)_{60}$ ranging from 6.5 to 12.6 (average of 9.2). Thus the dividing line between liquefied and non-liquefied case records is at an $(N_1)_{60}$ between 9.2 and 13.0, less than that for the Luan Nan case records which were in clean sand.

DISCUSSION

As outlined in Table 1, for 94 of the case records, either a new assessment was made (58 case records) or this study agreed with the original Berkeley catalogue interpretation (36 case records). For the 58 case records for which a new assessment was made, the Berkeley catalogue selection appears to be often representative of the average $(N_1)_{60}$ over some portion of the borehole and in some cases was a high value. For the remaining 36 case records, the Berkeley catalogue appears to have selected the minimum $(N_1)_{60}$, thus agreeing with the results of this study.

For these 36 case records, this study produced slightly higher or lower values of $(N_1)_{60}$ than given in the Berkeley catalogue, even for sites for which this study used the same selection of raw blowcount and critical depth. This was primarily due to small differences in the calculation of the correction factors, such as C_N and r_d. For a few sites, this study did not quite agree with the level of the groundwater table or the value of N as given in the Berkeley catalogue. Table 3 presents statistics for both these case records and the 31 case records for which data were not found and the Berkeley catalogue interpretations were accepted at face value in this study. For the latter, either the reference papers cited by Seed et al. (1984) were not found or they did not contain borehole logs for the case records. In several cases, it appears that the original interpretations may have been based on data presented in tabular form or quoted as average values. All of the case records in Table 3 possess low to intermediate values of $(N_1)_{60}$ and, hence, are not crucial to the shape and location of the upper and lower bound state lines which are discussed later.

Revised plots of CSR versus $(N_1)_{60}$

Figure 2 presents the case records from this study that did not liquefy, with the $(N_1)_{60}$ axis expanded from the proportion considered in the Berkeley catalogue. The number next to each case record represents the fines content. Details of the notation are given in Appendix II. With the exception of case record 19, a lower bound state line can be established on the plot for clean sands (fines content $\leq 5\%$). When this line is superimposed on the plot for sand with fines, there are 14 case records which have fines contents greater than clean sand and plot above or to the left of the line. At the same level of earthquake intensity, as expressed by CSR, a case record in sand with fines may have a lower value of $(N_1)_{60}$ than in clean sand without liquefying. This supports the view that finer grained soils are more resistant to liquefaction for the same penetration resistance. A lower bound state line for sands with fines is also shown and can be seen to have a different shape as well as location than the lower bound state line for clean sand.

Figure 3 presents the interpretation for liquefied and pressure relief sites from this study, also with an expanded $(N_1)_{60}$ axis. The number next to each case record represents the fines content. Considering sands with fines and with the exception of case record 90 (which as previously discussed could be influenced by gravel and is questionable), an upper bound state line for liquefied case records is established. This state boundary is transferred to the clean sand plot and it can be seen that an essentially subparallel line forms a reasonable state boundary to all of the liquefied clean sand case records. Case records 56-L6 and 17 on the clean sand plot are considered to be questionable as explained above and below, respectively. This also supports the general observation that sands with fines are more resistant to liquefaction than clean sands at the same value of $(N_1)_{60}$. It is difficult to support a further discrimination based on the percentage of fines. In fact, a close inspection of the original Berkeley plot (Seed et al., 1984) also supports this conclusion.

All of the liquefied and pressure relief case records from this study are combined in Figure 4, also with an expanded $(N_1)_{60}$ axis. The two upper bound state lines from Figure 3 for liquefied case records in sand with fines and for liquefied case records in clean sands are shown on Figure 4. A conservative upper bound line is also shown, extending to a $(N_1)_{60}$ of 22 and encompassing all of the pressure relief case records as well as three questionable case records. Case records 56-L6 and 90 have been discussed earlier. Case record 17, which is presented in Table 2, had two selections for minimum values of $(N_1)_{60}$, 16.6 in clean sand and 6.5 in sand with fines. Both selections are more critical than the original Berkeley interpretation of 24.0 in clean sand. The new selection in sand with fines is probably more crucial than the new selection in clean sand. Thus, in Figure 4, of the two data points shown for case record 17, the one in clean sand with the higher $(N_1)_{60}$ can be considered to be questionable.

All of the interpretations from this study have been combined in Figure 5, for comparison with the lines from the Berkeley catalogue, and the $(N_1)_{60}$ axis has been returned to the proportion used in the original catalogue. Unlike the representation found in the Berkeley catalogue, there is no distinct line between liquefied and non-liquefied sites in either clean sands or sands with fines. The upper bound state lines from this study for liquefied case records in both clean sands (fines contents $\leq 5\%$) and sands with fines are at substantially lower values of $(N_1)_{60}$ than the trigger lines from the Berkeley catalogue interpretations, particularly at higher values of CSR. At values of CSR less than about 0.140, the upper bound state line for clean sand is similar to the Berkeley catalogue line for clean sands. At values of CSR less than about 0.18, the upper bound state line for sand with fines is similar to the Berkeley catalogue line for sands with fines contents of 15%. The lower bound state line encompassing all of the non-liquefied case records is substantially less than the upper bound state line for all liquefied case records in sand with fines. In clean sand, this is valid up to a CSR of about 0.25. Although not shown on Figure 5, it appears that there may be a horizontal cutoff for each of the upper bound lines, representing a threshold CSR required to cause liquefaction. For clean sand, this would be at a CSR of about 0.07.

Impeded Drainage

Andrus et al. (1991) and Yegian et al. (1994) have postulated that an impermeable soil cap may play a crucial role in preventing the upward dissipation of excess pore water pressure. This may influence the sand state that is or is not susceptible to liquefaction at a given $(N_1)_{60}$. The 155 case records in this study were considered in terms of the potential for open seepage versus impeded drainage, in terms of the available stratigraphic information. Fear and McRoberts (1993) classified the drainage potential as open seepage if no soil above the minimum $(N_1)_{60}$ was less permeable in terms of soil classification. However, if a layer of less permeable soil was present at some point above the minimum $(N_1)_{60}$, the drainage potential was classified as impeded drainage. It is recognized that thin impermeable layers may exist that were not observed in the investigations or reported. For 32 of the 155 case records, the drainage conditions could be considered to be open seepage. For 92 of the case records, there was some type of drainage impedance. The remaining 31 case records had drainage conditions which were unknown. Figure 6 presents a summary of the data, combining together clean sands and sands with fines and considering the three types of drainage impedance as one category.

Additional data from recent studies

Additional data from Ambraseys (1988; 1992), Kayen et al. (1992) and Kayen (1993) were also obtained and reconsidered. These 25 case records are summarized in the catalogue compiled by Fear and McRoberts (1993) and they appear to support the conclusions drawn from the reconsideration of the Berkeley database, especially in terms of the location of the upper bound state lines for liquefied case records. However, since the additional case records were predominantly cases of liquefaction, there were not enough non-liquefied case records to make any definite conclusions as to their location with respect to the location of the lower bound state lines, particularly the lower bound state line for clean sand.

Interpretation and significance of results

The Berkeley interpretations are generally more conservative than the interpretations made here, particularly at higher values of CSR and it is clear that they constitute a conservative assessment of the potential for triggering earthquake-induced phenomena in sandy soils, based on $(N_1)_{60}$, CSR and fines content. Even the conservative upper bound state line (encompassing all of the questionable liquefied case records and pressure relief case records), although similar to the Berkeley line for clean sand up to a CSR of about 0.25, is not as conservative as the Berkeley line at higher values of CSR. Furthermore, the results of this study indicate a zone in which liquefaction may or may not occur, whereas, the more conservative Berkeley plot indicates no such zone.

From a design perspective, a site located at a combination of CSR and $(N_1)_{60}$ plotting less than the lower bound state line for all non-liquefied case records would clearly be at risk for the initiation of a wide range of earthquake-induced phenomena. Some differences between clean sands and sands with fines is apparent in making such a determination. Secondly, there is a transition zone between the lower bound state boundary for non-liquefied case records and the upper bound state boundary for liquefied case records where liquefaction phenomena may or may not occur. In addition, between the upper bound and the conservatively assessed upper bound state lines for liquefied case records, there is a potential for pressure relief phenomena such as sand boils and, by inference, subsequent settlement.

The above results and discussion are based on using a "weakest-link-in-the-chain" approach, assuming that all of the case histories are level ground conditions and accepting the definition of liquefaction based on field observations as given by the Berkeley catalogue. The ideal level ground condition consists of ground that is completely level and in which an element of soil has, initially, no horizontal or vertical shear stresses acting on it. If the ground is actually sloping or if the soil in question is close to or beneath structures such as buildings or bridges, these initial driving shear stresses acting on the soil may not be equal to zero. As outlined in Table 1, if only the sites for which the conditions were known are considered, about half could be called "level ground"; the other half may have had higher initial driving shear stresses than a truly level ground condition due to their proximity to such things as building foundations, bridge piers and slopes of various kinds . In addition, it was observed that there was little difference between values of $(N_1)_{60}$ for case records in the sloping ground and structure categories and the case records which could truly be considered to be level ground. None of these case records consisted of steeply sloping ground and the trigger plots presented here are not considered to be applicable to such slopes. Case records with significant slopes are considered by Seed (1987).

Drainage conditions, as summarized in Figure 6 may exert an effect on the interpretation of the case records. It appears that the liquefied case records at higher values of $(N_1)_{60}$ tend to be classified as cases of impeded drainage. Indeed, the maximum $(N_1)_{60}$ for open drainage liquefied case records appears to be approximately 11, with the exception of one case record at 14.3. This case record was classified as open drainage based on some general borehole logs from the site, rather than the specific log for the case record. The non-liquefied data tends to be randomly distributed with the possible suggestion that there is more impeded drainage than open seepage at values of $(N_1)_{60}$ less than 10. The interpretation of this data is complicated by post-seismic effects (most site investigations were conducted some time after the earthquake) and missing stratigraphic data. There does appear to be some suggestion for support of the conclusions which were drawn by Andrus et al. (1991) and Yegian et al. (1994) and discussed earlier.

The upper bound state lines determined in this study are asymptotic to values of $(N_1)_{60}$ in the region of 13 to 15. This is consistent with observations made by Robertson et al. (1992) and McRoberts and Sladen (1992) that, for screening purposes, the state boundary between contractant and dilatant sandy material falls within this range. For earthquakes with $M<8$, Bartlett and Youd (1992) considered an $(N_1)_{60}$ of 15 to represent the dividing line as to whether or not significant lateral spreading would occur and, hence, whether or not the design analysis should include an evaluation of ground displacements. Ishihara (1993, Figure 99) suggested a boundary line for liquefaction which can be interpreted to range from an $(N_1)_{60}$ of 19 to 24, and a dividing line between flow and no flow at an average $(N_1)_{60}$ of 10. Ishihara's flow-no flow boundary line could be considered to be low compared with the results discussed above. The conservative upper bound line in Figure 5 is asymptotic to an $(N_1)_{60}$ of 22 and is consistent with Ishihara's (1993, Figure 99) boundary line for liquefaction. Ishihara is understood to define liquefaction as any earthquake-induced phenomenon or 5% double amplitude strain. Within this context, the interpretation considered in this study could be viewed as follows: the upper bound state line would describe a state boundary line for all earthquake-induced phenomena except sand boils or settlement and the conservative upper bound line would represent an upper bound to sand boil activity or substantial settlement. It is considered that limited settlement could still occur beyond the conservative upper bound line.

The upper and lower bound state lines presented in this study are meant to be envelopes which encompass all of the data. Thus, they are lines of zero exceedance based on the interpretation method used and the data available. Applying probabilistic techniques to the data, as was performed by Liao (1986) on the original Berkeley database, may prove to be useful, but is beyond the scope of this paper. In addition, there appears to be insufficient data at this time to, for example, interpolate curves of probabilities of exceedance between the upper bound state line for clean sand and the conservative upper bound state line. These data consist of 5 case records which have been classified as pressure relief/marginal liquefaction and 3 case records which are considered to be questionable. Clearly, it would be of great interest to North American practice to focus some research on the few case histories, particularly the questionable ones, which fall between the upper bound state line and the conservative upper bound state line. Limited information has been obtained regarding these eight case records, which are from Japan (7 case records) or China (1 case record). Further study may be able to help resolve whether these case records are valid or truly questionable.

The observation, in this study, of various state boundary lines and zones in which different earthquake-induced phenomena will occur appears to be consistent with the conclusions which Seed himself was beginning to make. Seed et al. (1985, Figure 8) presented a "tentative relationship between cyclic stress ratio, N_1-values and limiting strains for natural deposits of clean sand". This figure suggested that at values of $(N_1)_{60}$ lower than the most conservative liquefaction-no liquefaction boundary line for clean sand, the consequences of cyclic loading, the forms of liquefaction and the amount of strain that would occur depend on the magnitude of $(N_1)_{60}$. However, many do not make use of the strain lines that were proposed by Seed et al. (1985), but rely solely on the most conservative trigger line for liquefaction trigger analyses.

CONCLUSIONS

In general, it must be noted that this study, in itself, does not seek to produce a new design methodology for liquefaction. Rather, it offers an alternative way of considering the original database and this may be useful as a component of the overall design process. It must be cautioned that neither the present study nor the original interpretations should be used by itself as a design method. The data presented here may be complementary to other design findings, especially if these are found to be difficult to implement due to the precedents offered by the original work. The original Berkeley work permitted a clear yes/no type of choice in assessing the potential for triggering of liquefaction. This original work has unfortunately evolved into a design method which, if coupled with lower bound site data, may well be overly conservative and either embody a poor use of resource allocation for risk reduction, or unnecessary costs. Alternatively, there may well be instances where the original method, if combined with average site data in the zone of interest, may not be sufficiently conservative depending on factors that were unquantified in both the original and present studies. Resolution of these factors is clearly a matter for design. This study, by introducing a different interpretation of the case records and the wide transition zones, introduces the potential for design domains in which there is substantial scope to demonstrate possible economic benefits of more detailed site investigations and analyses, such as those reported by Byrne et al. (1993).

This study found, especially for higher $(N_1)_{60}$ liquefied case records, that a safe state line defined at a given earthquake intensity (i.e. CSR) could be established considerably lower than the original Berkeley recommendation. This upper bound line is based on minimum $(N_1)_{60}$ interpretations and is more consistent with the design practice of selecting the lowest, more critical, in-situ data. This practice is becoming increasingly prevalent as cone penetrometer testing (CPT) allows for a more detailed record of soil variations than is generally possible with SPT testing. A conservative design boundary line, which encompasses case records for which only sand boils were reported and three case records of doubtful provenance, was also established. This conservative line is similar to the original Berkeley line for clean sand at values of CSR up to about 0.25, but is significantly less than the Berkeley line at higher values of CSR. The upper bound line is therefore viewed as being transitional between all case records for which strong evidence of seismically induced phenomena, other than sand boils, is reported, and a domain, defined by the conservative design boundary line, in which only sand boils and three questionable case records are found. A transition zone, within which liquefaction may or may not occur, also clearly exists. For clean sands, this represents a range of $(N_1)_{60}$ from 5 to 13 for a CSR of 0.16. The study did not recover the unique line between the upper bound liquefied state and the lower bound non-liquefied state as represented in the Berkeley catalogue. Rather, there is a broad zone in which either state is possible. At a given earthquake intensity, as measured by the CSR, there is a lower bound state line below which liquefaction is highly probable.

Analyzing numerous case studies to produce a trigger plot for liquefaction is not a simple task. There are many variable factors which serve to complicate the process. No matter how the study is performed or how consistent one tries to be in assigning a single valued combination of $(N_1)_{60}$ and CSR to a case record, one must always exercise a certain amount of judgement. It is clear that the original Berkeley interpretations involved judgement and were directed toward a conservative assessment of the data base. In addition, $(N_1)_{60}$ and CSR are not the only factors affecting the potential for liquefaction at a particular site. Other factors such as fines content, gravel content, cementation, age, fabric, thickness of the liquefied layer, thickness or nature of any overlying non-liquefied layer, impeded seepage and topography may affect both the potential for liquefaction and the extent of the effects once liquefaction has been triggered. These factors and others likely add uncertainty to the database and may account for the transition zones that have been observed in this study. However, based on the available data, it was difficult to further distinguish between the data on the basis of any of these factors, except for fines content and possible impeded seepage. While an effect of fines content was found, the study does not support the broader range reported in the original work. Some trends have been suggested regarding the effects of impeded drainage; however, further investigation and research is needed to determine specific effects on liquefaction potential. The application of statistical techniques to the revised database using the methods and procedures followed by Liao (1986) would constitute a logical extension of this study.

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APPENDIX I. REFERENCES

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Appendix II. Notation

The following symbols are used in this paper:

a_{max} = maximum earthquake acceleration at the ground surface

ClS = clayey sand

C_N = SPT overburden correction factor

$= \frac{2}{1 + \sigma_v'}$ for $\sigma_v' < 1$ tsf or 1 kg/cm^2, after Skempton (1986)

$= (\frac{1}{\sigma_v'})^{0.56}$ for $\sigma_v' \geq 1$ tsf or 1 kg/cm^2, after Jamiolkowski et al. (1986)

N.B. $\sigma_v' = \sigma_o'$ in this study

CSR = equivalent average cyclic stress ratio for an M=7.5 earthquake

$= 0.65 \bullet (\frac{a_{max}}{g}) \bullet \frac{\sigma_o}{\sigma_o'} \bullet r_d \bullet \frac{1}{r_m}$

ER = energy ratio, in percent, for the specific SPT setup used

FC = fines content, % passing the No. 200 sieve

FS = fine sand

g = gravitational acceleration = 9.81 m/s^2

M = earthquake magnitude, on the Richter scale

N = raw SPT blowcount

N_1 = SPT blowcount corrected for overburden effects to 1 tsf or 1 kg/cm2

$(N_1)_{60}$ = SPT blowcount corrected for overburden effects and energy effects, to 1 tsf or 1 kg/cm2 and to an ER of 60%

$= C_N \times (\frac{60}{ER}) \times N$

r_m = a factor to convert between an equivalent CSR for an earthquake of magnitude 7.5 and a CSR for an earthquake of magnitude, M (Seed et al. (1984), Table 5)

r_d = a factor to account for the variation in earthquake acceleration with depth

= 1 - (0.010)(z), where z is the critical depth, in metres

S	= sand
Si	= silt
SiS	= silty sand
σ_o	= initial vertical total stress
σ_o'	= initial vertical effective stress
σ_v'	= vertical effective stress

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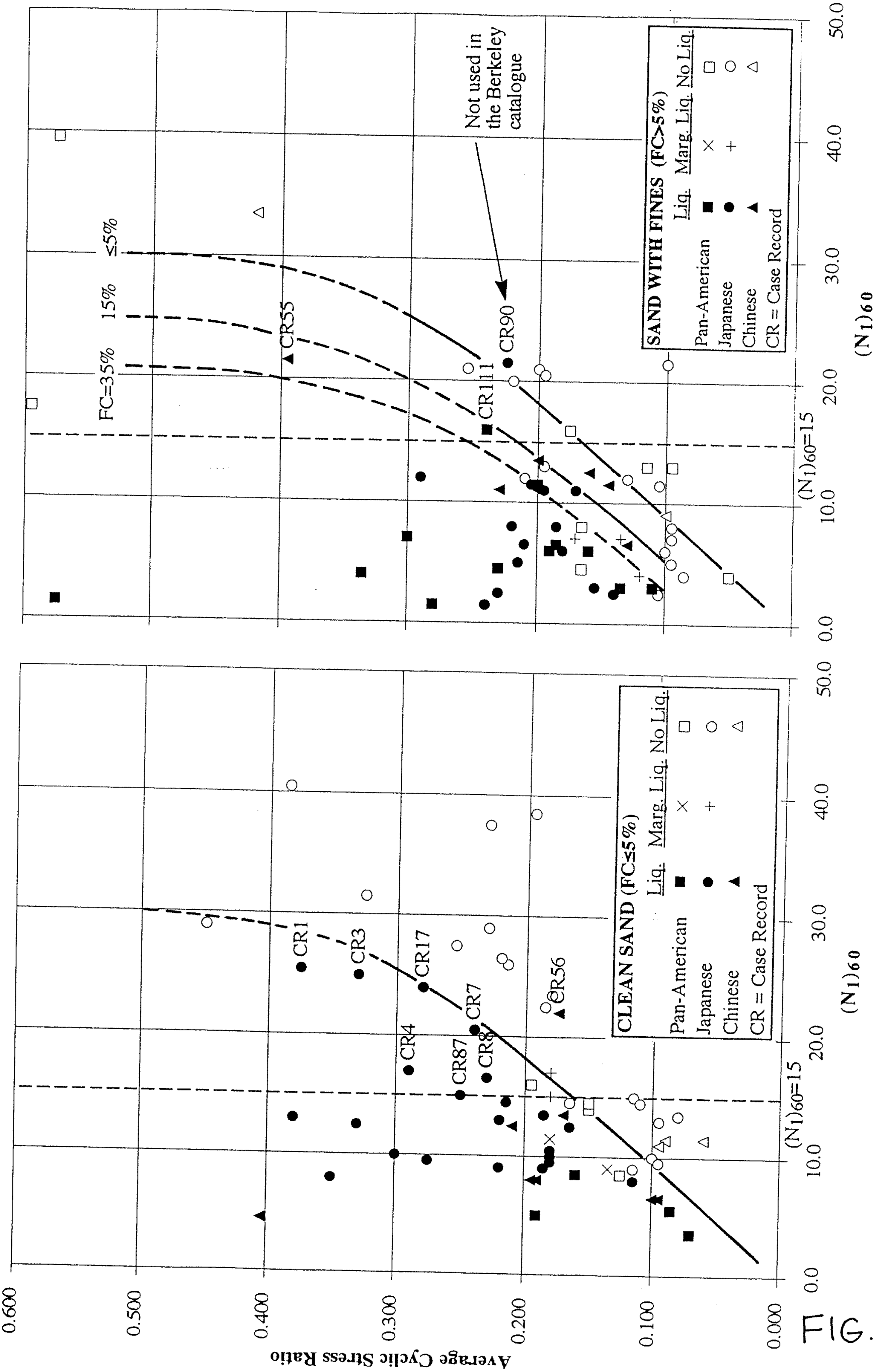

Average Cyclic Stress Ratio
0.000
0.100
0.200
0.300
0.400
0.500
0.600
$(N_1)_{60}$
0.0
10.0
20.0
30.0
40.0
50.0
$(N_1)_{60}$=15
CLEAN SAND (FC≤5%)
Liq.
Marg. Liq.
No Liq.
Pan-American
Japanese
Chinese
CR = Case Record
CR1
CR3
CR17
CR7
CR4
CR87
CR8
CR56
SAND WITH FINES (FC>5%)
FC=35%
15%
≤5%
CR55
CR111
CR90
Not used in the Berkeley catalogue

FIG. 1

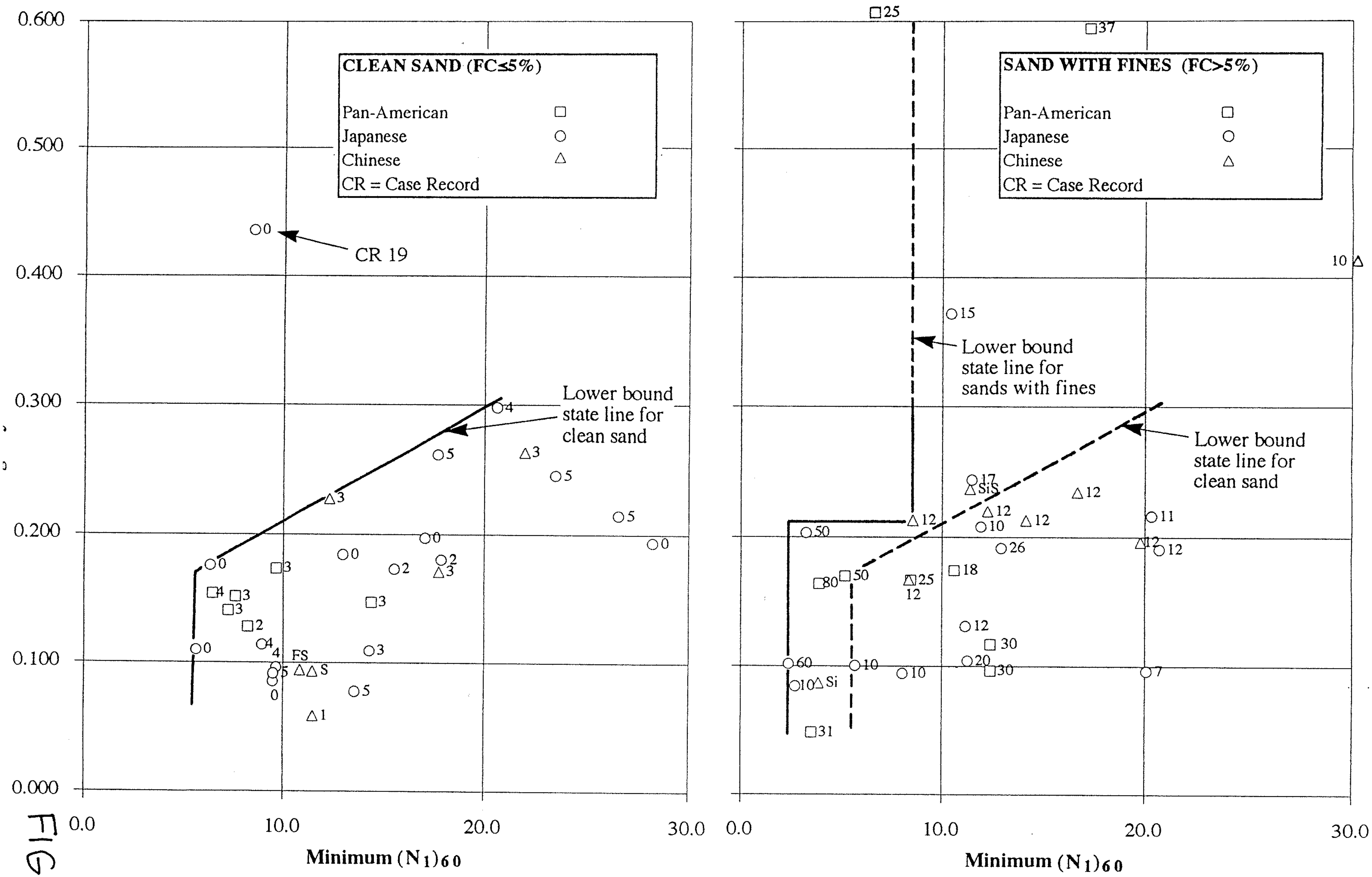
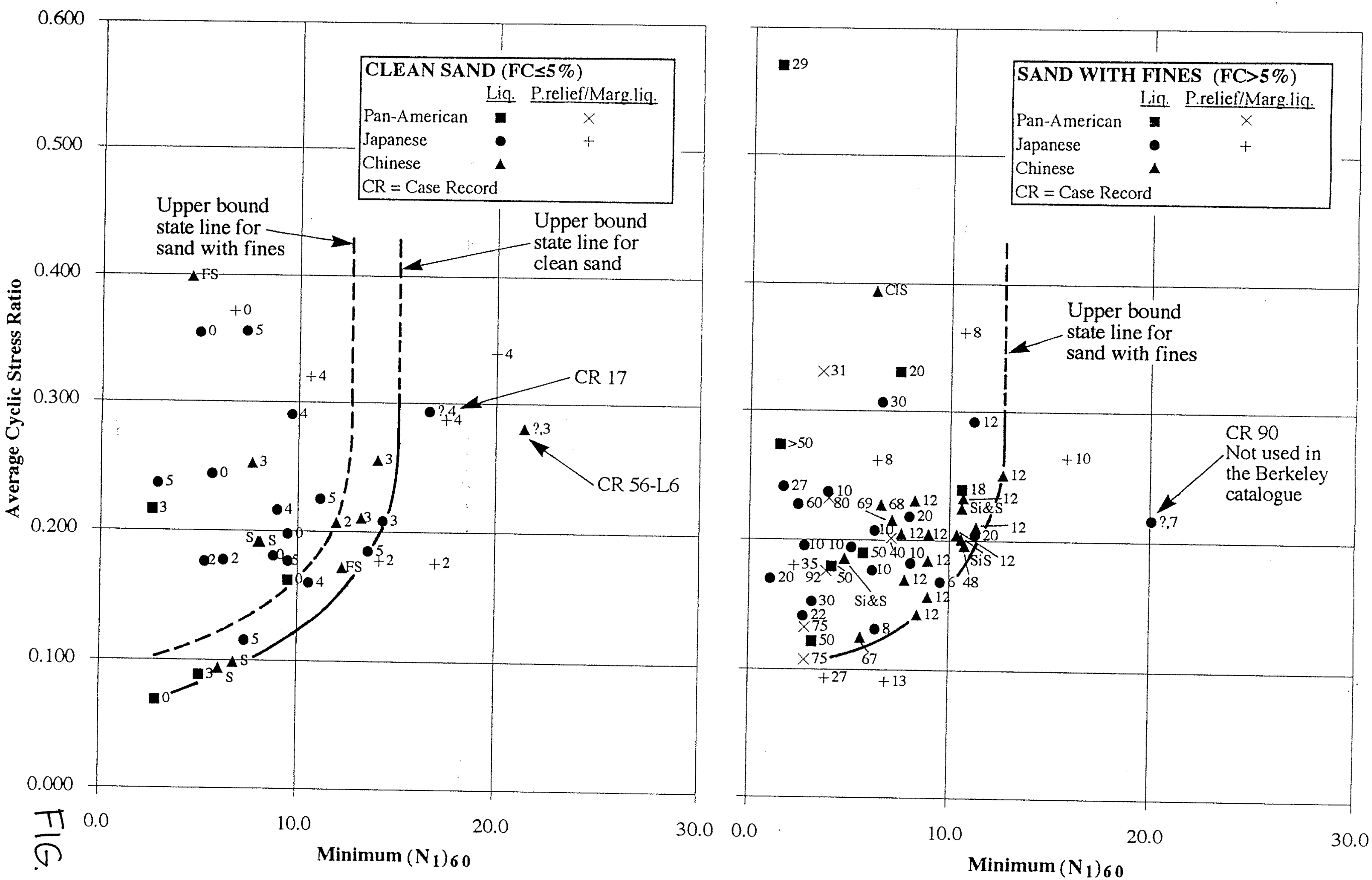
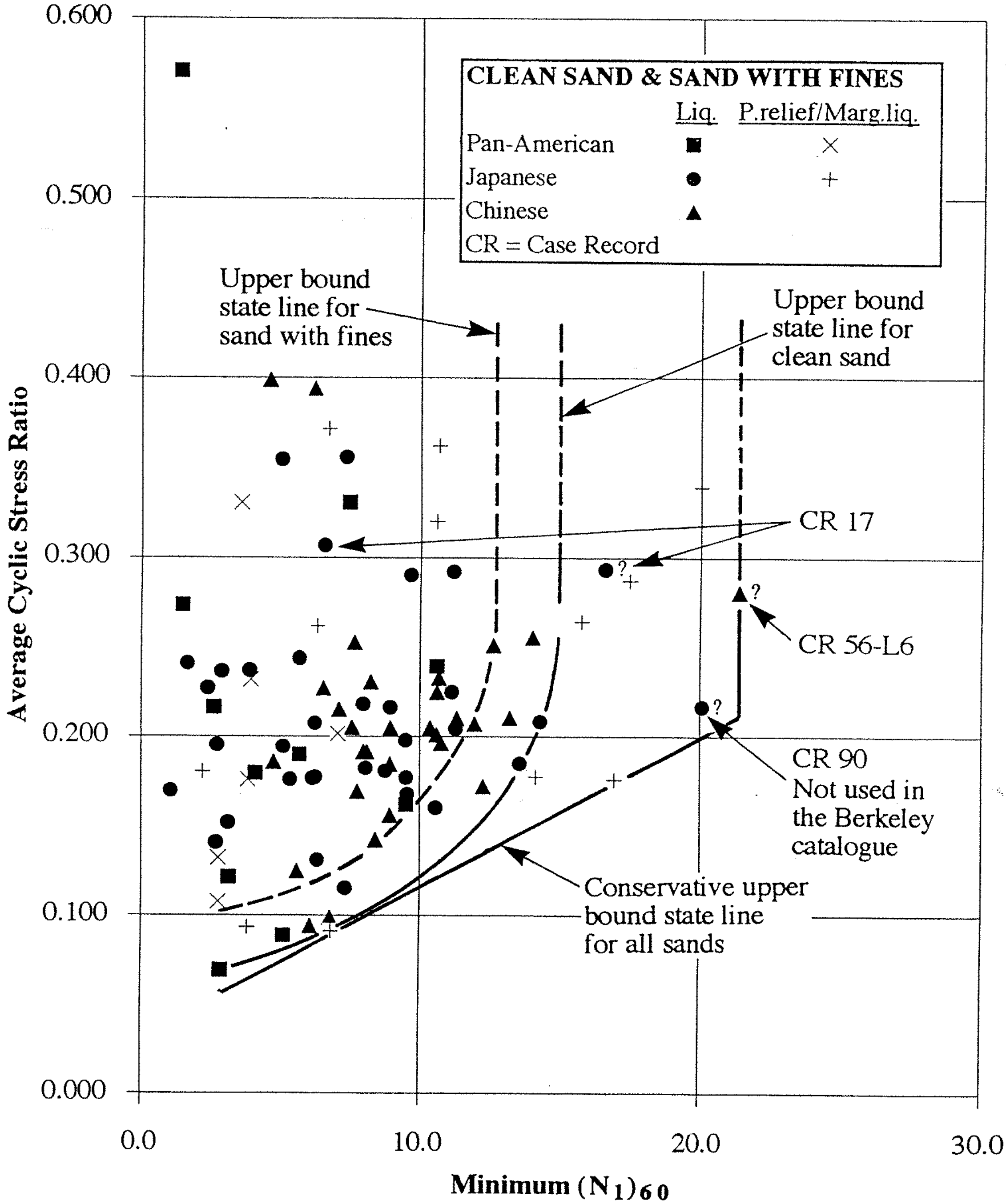

CLEAN SAND (FC≤5%)
Pan-American
Japanese
Chinese
CR = Case Record
CR 19
Lower bound state line for clean sand
Minimum (N1)60
SAND WITH FINES (FC>5%)
Pan-American
Japanese
Chinese
CR = Case Record
Lower bound state line for sands with fines
Lower bound state line for clean sand
Minimum (N1)60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.0
10.0
20.0
30.0

FIG. 2



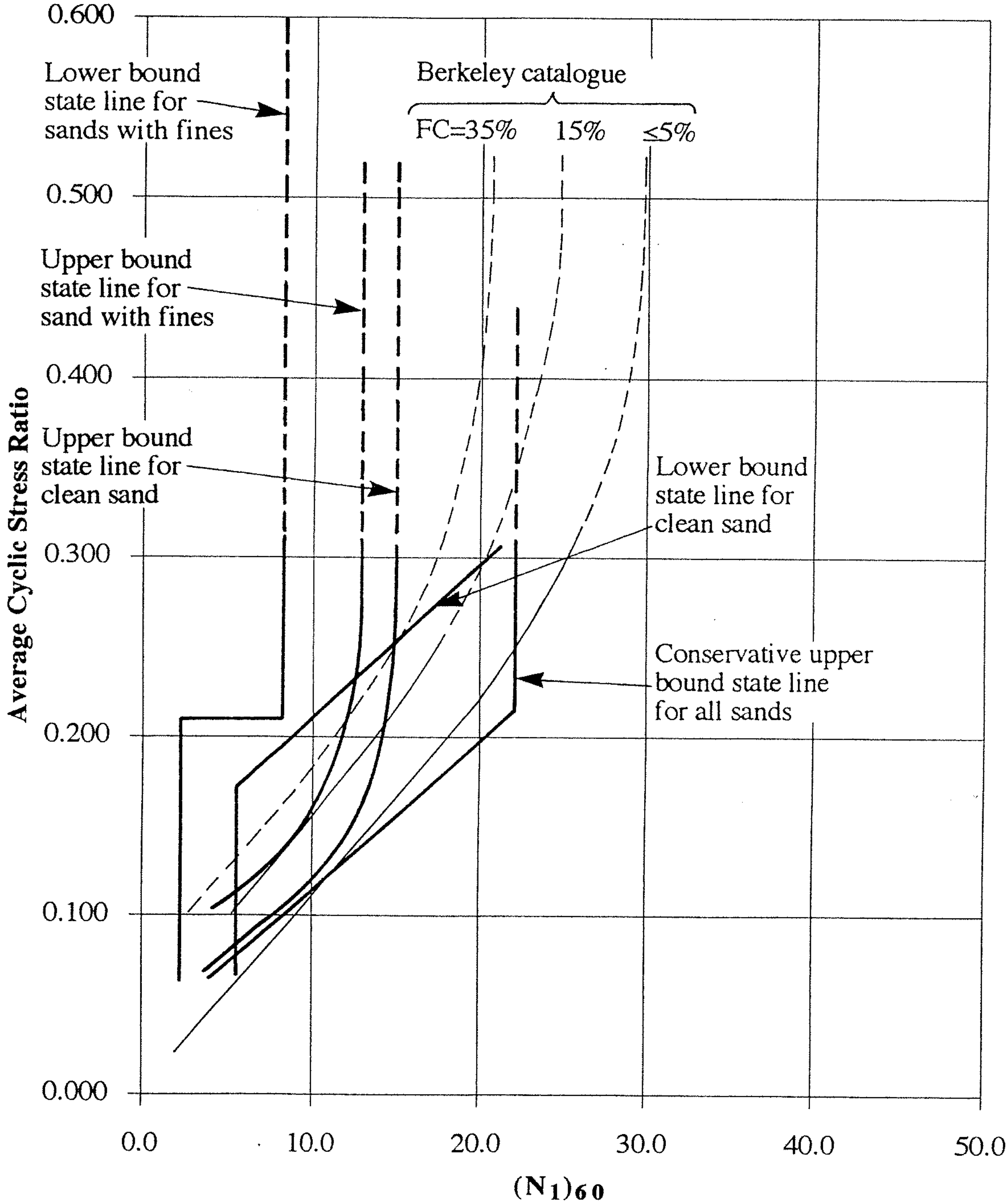
Average Cyclic Stress Ratio
Minimum (N1)60
CLEAN SAND (FC≤5%)
Liq.
P.relief/Marg.liq.
Pan-American
Japanese
Chinese
CR = Case Record
Upper bound state line for sand with fines
Upper bound state line for clean sand
CR 17
CR 56-L6
SAND WITH FINES (FC>5%)
Upper bound state line for sand with fines
CR 90 Not used in the Berkeley catalogue

FIG. 3



CLEAN SAND & SAND WITH FINES
Liq.
P.relief/Marg.liq.
Pan-American
Japanese
Chinese
CR = Case Record
Upper bound state line for sand with fines
Upper bound state line for clean sand
CR 17
CR 56-L6
CR 90 Not used in the Berkeley catalogue
Conservative upper bound state line for all sands
Average Cyclic Stress Ratio
Minimum (N1)60
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0

FIG. 4



0.600
0.500
0.400
0.300
0.200
0.100
0.000
Average Cyclic Stress Ratio
Lower bound state line for sands with fines
Upper bound state line for sand with fines
Upper bound state line for clean sand
Berkeley catalogue
FC=35%
15%
≤5%
Lower bound state line for clean sand
Conservative upper bound state line for all sands
0.0
10.0
20.0
30.0
40.0
50.0
(N1)60

FIG. 5

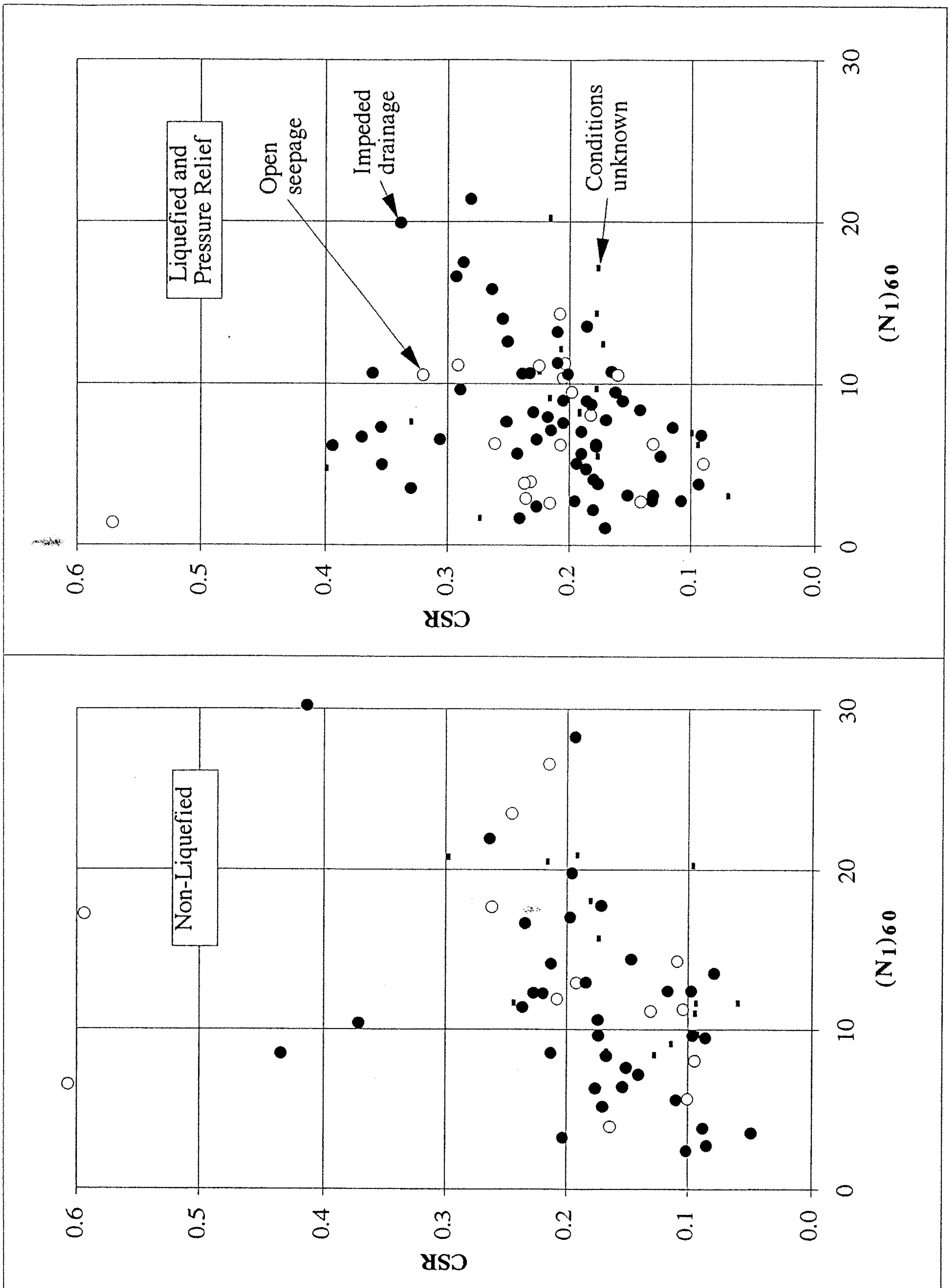

Liquefied and Pressure Relief
Open seepage
Impeded drainage
Conditions unknown
CSR
(N1)60
Non-Liquefied
CSR
(N1)60
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30

FIG. 6

	Number of Case Records
A. Classification of the Original 125 Case Records	
(i) Berkeley catalogue	
Liquefied	67
Marginal Liquefaction	7
Non-liquefied	51
(ii) This study	
Liquefied	56
Pressure relief/marginal liquefaction	15
Non-liquefied	52
Liquefied or non-liquefied depending on location at the site	2
B. Case Records repeated twice in the Database (each pair of points reflects one site investigation, but two different earthquakes, usually one which did not cause liquefaction and a larger one which did)	21
C. Availability of Reference Papers	
Original reference papers were located	112
Related papers found when original reference was not found	12
No reference paper found	1
D. Site conditions	
Level ground	49
On or near sloping ground (dyke, dam, slope, river embankment, lakeside or riverside)	25
Under or near a structure (e.g. bridge, building)	22
Site conditions unknown	29
E. Re-evaluation of case records	
(i) No re-evaluation could be made	31
Original reference paper did not contain a BH log	18
Original reference paper was not found; any alternates that were found did not contain BH logs	13
(ii) A re-evaluation was made	94
Same $(N_1)_{60}$ selected as in the Berkeley catalogue	36
Lower $(N_1)_{60}$ selected than in the Berkeley catalogue	58

TABLE 1

	Case Record				Original Data					New Data					
	No.	Name	Earthquake	Reference	Liquefied?	$(N_1)_{60}$	Depth (m)	CSR	FC (%)	Liquefied?	$(N_1)_{60}$	Depth (m)	CSR	FC (%)	Comments
Case Records Originally in Clean Sands	1	Ogaki	1891 Mino-Owari	Kishida (1969)	yes	25.5	10.05	0.375	0	pressure relief pressure relief	6.7 10.7	5.00 17.00	0.371 0.362	0 8	•sand boils only • investigated in late sixties by Kishida (1969) • area in artesian condition (artesian wells used until 1940) • "not clear whether the eruptions of water resulted from a liquefied condition or from the artesian conditions" (Kishida, 1969) • located in what appears to be the same geological environment as case records 3 and 4
	3	Unuma	1891 Mino-Owari	Kishida (1969)	yes	25.0	6.10	0.330	3	pressure relief	20.0	9.35	0.339	4	• sand boils and some cracking • investigated in late sixties by Kishida (1969) • site investigation missed a pumice layer at shallow depth which may or may not be significant since a white mixture of sand and water was observed erupting from the ground • gravel contents greater than 20% • similar concerns re: artesian conditions as for case record 1
	4	Ogase	1891 Mino-Owari	Kishida (1969)	yes	17.0	5.18	0.290	4	pressure relief pressure relief	15.8 17.5	4.00 5.18	0.264 0.287	10 4	• sand boils and some cracking • investigated in late sixties by Kishida (1969) • gravel contents greater than 20% • similar concerns re: artesian conditions as for case record 1
	7	Arakawa 21	1923 Kanto	Kodera (1964)	yes	20.5	8.23	0.240	1	yes	3.9	8.25	0.237	10	• Pier 21 of the Arakawa Bridge • Piers 7 and 12 (case records 5 and 6) of the bridge which liquefied and Pier 49 which had marginal liquefaction were in the same geological environment and were re-assigned lower values of $(N_1)_{60}$ as well • site conditions may be considered to be other than truly level ground due to bridge piers and bridge loading
	8	Arakawa 30	1923 Kanto	Kodera (1964)	yes	16.5	5.18	0.230	5	yes	11.1	5.00	0.225	5	• Pier 30 of the Arakawa Bridge • same comments apply as for case record 7
	17	Takaya 45	1948 Fukui	Kishida (1969)	yes	24.0	7.01	0.280	4	yes yes	6.5 16.6	15.00 10.00	0.306 0.293	30 4	
	56	Luan Nan	1976 Tangshan	Shengcong et al. (1983)	yes	22.0	5.36	0.175	3	yes (56-L2) yes (56-L3) yes (56-L6) yes (56-L7) no (56-L1) no (56-L4) no (56-L5)	7.7 13.2 21.4 14.0 12.3 22.0 17.8	5.30 10.30 8.30 8.30 11.30 9.30 4.30	0.252 0.210 0.281 0.255 0.228 0.264 0.171	3 3 3 3 3 3 3	• apparently interpreted in the Berkeley catalogue using a "typical log" from Shengcong et al. (1983) • this study obtained additional logs from the Beijing Municipal Bureau of City Planning (1982), both liquefied and non-liquefied • failure modes not specified in either report
	87	Yuriagekami 2	June 1978 Miyagiken-Oki	Iwasaki et al. (1978)	yes	15.0	4.27	0.250	0	yes	5.6	3.50	0.243	0	
Case Records Originally in Silty Sands	55	Qing Yin	1976 Tangshan	Shengcong et al. (1983)	yes	21.5	5.30	0.395	20	yes	6.2	11.75	0.394	clayey sand	• apparently interpreted in the Berkeley catalogue using a "typical log" from Shengcong et al. (1983) • no additional logs were obtained • clayey sand layer could be interbedded sand and clay • failure mode not specified in Shengcong et al. (1983)
	90	Yuriage Bridge 2	June 1978 Miyagiken Oki	Iwasaki et al. (1978)	yes	21.5	3.35	0.225	7	yes	20.1	3.35	0.216	7	• from the Yuriage Bridge (Iwasaki, 1978) • listed in the Berkeley catalogue, but not included in the Seed et al. (1984) plot for sand with fines, possibly because it had a gravel content > 20% • this same site did not liquefy in an smaller earlier EQ (case record 73 - also listed in the Berkeley catalogue, but not included in the plot for sand with fines) • another pier with a lower $(N_1)_{60}$ did not liquefy and lower $(N_1)_{60}$'s were found in other units which did liquefy
	111	River Park C	1979 Imperial Valley	Youd et al. (1983)	yes	16.0	4.27	0.240	18	yes	10.6	3.50	0.239	18	• soil unit C at the site was said to have liquefied • Berkeley catalogue $(N_1)_{60}$ seems to be based on the average N in soil unit C for boreholes drilled at the site

TABLE 2

Response	Number of Case Records	(N1)60		
		Mean	Standard deviation	Range
A. 36 case records for which borehole logs were found				
liquefied	14	7.4	5.1	1.4 to 13.6 (1)
pressure relief	10	5.8	4.3	2.8 to 17.0
non-liquefied	12	10.6	5.7	2.4 to 20.1
B. 31 case records for which borehole logs were not found (2,3)				
liquefied	16	8.3	3.4	1.5 to 14.5
non-liquefied	15	13.0	5.4	8.0 to 26.5

Notes:

(1) Except for case record 90 (see Table 1) which liquefied with an (N1)60 of 20.1.
(2) Case records with no borehole logs in references cited by Seed et al. (1984) = 18.
(3) 10 case records are based on 5 sites, each affected by two earthquakes.

TABLE 3