Liquefaction potential evaluation SPT based

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ABSTRACT: This article deals with the Seed Simplified Method for Liquefaction Evaluation in saturated sands, some points of which need to be discussed. The main issue to be analyzed resides in the way the $(N_1)_{60}$ parameter was determined. The method predictions are sometimes quite the opposite of real behavior, as is shown herein based on real cases. The product of (N-SPT) times E(energy), a constant, is not always followed, as in the Schmertmann equation. This is of fundamental importance. E corresponds to energy measured in-situ, in 30 centimeter intervals. Seed usually uses E average for the respective equipment and corresponding country. Thus, a true N_{60} (number of blows for 60% of maximum potential energy available) is not obtained. There is a difference between both E values. The Schmertmann equation needs E to be measured in-situ; otherwise it cannot be used. Furthermore, the $(N_1)_{60}$ value deduced is not generally adequate. If a true value of $(N_1)_{60}$ is introduced in a Seed graph, assuming that it is numerically equal to $(N_1)_{60}$ of the graph, an inexact Cyclic Resistant Ratio (CRR) is estimated. The most important fact is that for each 30 centimeters of soil interval penetrated, there corresponds a measured E (energy) for certain SPT equipment, which is also different from the average energy. The uncertainty percentage of some versions of this method is within the range of 25% to 42% regarding seismic performance data. As a conclusion, the Seed method is a good idea that is well implemented in the Site Specific Method, based on Seed´s original idea.

Keywords: liquefaction; Seed; SPT; database; evaluations

1. Introduction

The SPT based method for liquefaction potential evaluation in [1] is only a little different from [2]; these and other versions consider pore pressure generation. Seed [2] is an upgrade of [3]. Seed had previously developed two methods: [4, 5]. Their purpose is the same, to obtain a lower bound of CRR defined as $\tau/\sigma_{v'}$, in which τ is the uniform cyclic shear stress and $\sigma_{v'}$ the vertical effective stress, so CRR is the value of the previous mentioned quotient that causes soil failure (sand) in a number of uniform cycles of shear stress application for a site as a function of N (SPT blow count), whether standardized or not standardized. The standardization refers to N_{60}, or N measured at 60% of the maximum potential theoretical energy available in the hammer that strikes the bars of an SPT system, falling 76 centimeters. After Youd et al.[1], some methods based on the same idea [2], like [6, 7], and their last version [8], were developed, with only 24 cases added, showing a marginal change. The only difference between these methods and [1], resides in the database which is different but developed the same way Seed originally did. In this article we include references of different years which are necessary for the purpose of the article. The problem with all the above mentioned methods is that the parameter $(N_1)_{60}$ was approximately determined in the construction of the graphs. $(N_1)_{60}$ means that N measured in site is first standardized to N_{60} through the Eq. (1), based on [9],

$$NE = (N_{60})(0.6)E^* \quad (1)$$

and then normalized to 1k/cm^2 , Eq. (2) ,

$$(N_1)_{60} = N_{60}\,(Cn) \quad (2)$$

In the above Eq. (1), E stands for energy in-situ, for the interval of 30 centimeters, measured at the time the SPT is being performed; 0.6 is the fraction of the maximum theoretical potential energy available from the falling hammer,E*; Cn in Eq. (2) is a normalization coefficient that depends on the depth the SPT is performed at. In all the previously mentioned methods, E in Eq. (1) is not measured in situ, and an average value is selected for it instead. The use of an average value for E in Eq. (1) is different from E measured in situ and in the interval of soil where SPT is being recorded. As a result, E average bears little connection to the real value of E, and so, N_{60} is not adequately evaluated, and an inadequate database is generated. In this article we discuss the use of [1] or any other equivalent SPT based methods for sands. The exception is the Site Specific Method based on Seed´s idea, which is mentioned later.

2. Methods

A description of the above methods follows, excepting [4, 5]. This is necessary for the following dated discussion.

Seed et al., 1983, method. The evolution of the simplified procedure for the liquefaction potential assessment in saturated sands using data based on SPT tests is reviewed. Data from sites that liquefy or do not liquefy during earthquakes in USA, Japan, China and other countries are presented in order to establish a criterion regarding the assessment of the liquefaction potential of sands in earthquakes of magnitude 7,5M_w . Using a combination of site data and laboratory measurements, the above is extended to earthquakes of other magnitudes. Using a method based on site observation, specifically the performance of sands in previous earthquakes, liquefaction or no-liquefaction, related to "standardized" N of the site is the way the graph of this method was constructed. This author then describes the method of construction of the graph. This implies a method based on empirical correlations between some in-situ characteristic and an observed behavior. It has been found that a suitable parameter to express the cyclic liquefaction characteristics of sand in conditions of plain and horizontal terrain is the Cyclic Stress Ratio (CSR). According to the author of this method, the CSR in-situ induced by an earthquake, could be estimated in the following way, [3] ; Eq. (3) ,

$$CSR = \tau_h average/ \sigma_{o'} = 0.65\ (a_{max}/g)\ (\sigma o/ \sigma_{o'})\ r_d \quad (3)$$

in which, $\tau_{haverage}$ stands for uniform cyclic horizontal shear stress; a_{max} is the peak horizontal ground acceleration at the surface; σ_o is the vertical total stress related to the corresponding sand interval; $\sigma_{o'}$ is the vertical effective stress in the sand interval; r_d is a reduction factor related to the deformation of the soil column between the surface and the soil depth, its value varies between 1.0 at the surface and 0.9 at a depth of 9.0 meters; the factor 0.65 is necessary for uniformity in the cycles. The CSR values thus obtained were correlated with sites with or without liquefaction in real earthquakes, associated to parameters indicative of soil characteristics such as relative density determined based on SPT soundings or SPT with N corrected. Therefore, for the evaluation of the liquefaction resistance of a new site and for a certain level of seismic intensity, with Eq. (3), the CSR induced by the earthquake, could be correlated and compared with the CSR for liquefaction onset determined by an in-situ correlation as mentioned above; in this last case CSR corresponds to CRR(Cyclic Resistant Ratio). The in-situ properties can only be reliably evaluated through adequate in-situ testing in sand deposits, or with undisturbed samples. Due to the difficulty of this last method, the method of correlations with in-situ testing is preferred for performance evaluation. Since the SPT has been widely used in the past, most of the available data regarding on site performance are normally correlated with this index of soil characteristics. An almost complete database of many sites with the certainty of liquefaction and no-liquefaction was presented by [3] and used to determine the correlation between site CSR and the relative density of sand SPT based according to [10]. This set of site cases along with other additional data, determines correlations between parameters which induce liquefaction and resistance to SPT penetration. Thus,[3] shows a correlation between CSR and N_1. N_1 is a normalized value of N-SPT, corrected to an overburden pressure of 1 k/cm², through Eq. (4), and Cn depends on the overburden pressure, estimated at in-situ test depth,

$$N_1 = Cn\ N \quad (4)$$

This way, using [3], the graph illustrates a lower bound of CSR that induces liquefaction called CRR, cyclic resistant ratio, as a function of N_1, and compared with the CSR earthquake induced from Eq. (3), predicts liquefaction or no-liquefaction, according to the value of the safety factor SF, Eq. (5) ,

$$SF = CRR/CSR \quad (5)$$

If SF >1.0 there is no-liquefaction whereas if SF $\leq$ 1.0 liquefaction occurs. In addition, [3], presents a graph for liquefaction evaluation applied to earthquakes of other magnitudes but with the same data base.

Seed et al., 1985, method for liquefaction potential evaluation. In this reference, Seed clarifies the significance of the N-SPT values used in correlations of site observations of soils liquefaction or no-liquefaction, with values of N_1 measured in SPT tests. Site data are "reinterpreted" according to Seed, and plotted in terms of a new standard recommended, $(N_1)_{60}$, obtained from SPT tests, in which energy of penetration in the bars is 60% of the maximum potential energy available from the SPT hammer. The background for this is that energy measurements associated to N vary with different equipment. This means that the same soil interval can have different associated N, and energy E. As a consequence, to represent all data in respect to one parameter, each N is standardized to energy of 60%, through the Eq. (6) ,

$$N_{60} = (Nm)\ ERm\ /\ (0.6\ E^*) \quad (6)$$

suggested by Seed, based on [9], see Eq. (1). Nm in Eq. (6) , is the N-SPT measured in-situ (interval). Seed also prepared a table with an average correction factor for energy for different countries and equipment. The mentioned factor must be used in Eq. (6) , and is defined as, Eq. (7) ,

$$Ce = ERm/(0.6\ E^*) \quad (7)$$

The true energy for the in-situ measurement is ERm, which must be used in Eq. (6), instead of the average. On the other hand, quoting [2], for $(N_1)_{60} \leq 25$, the correlation line drawn for clean sands is close to the one proposed by [3]. That is to say, the N_1 values of this work correspond almost exactly to $(N_1)_{60}$. This will be discussed later on in the corresponding section of this article. Fig. 1, shows the superposition of the [2] graph, with the line based on [3]. In this figure, Tay stands for cyclic shear stress.

Youd et al., 2001, method. This method shows few differences regarding the preceding one. The only difference is the line that separates liquefaction from no-liquefaction (clean - sand line) for low values of $(N_1)_{60;}$ this line is almost horizontal. The new figure, which is not shown, is the base curve for clean sands using the SPT, with earthquakes of M_w 7.5, with data from liquefaction case histories. It was modified from [2]. Table 1. includes ranges of C_e , which is the fraction of the 60% maximum available potential energy; C_e is energy correction factor, as a function of the type of the SPT equipment, [1]. This last method also recommends making measurements of energy in soil intervals of 30 centimeters, in-situ, to transform to $(N_1)_{60}$. All the above mentioned will be discussed below.

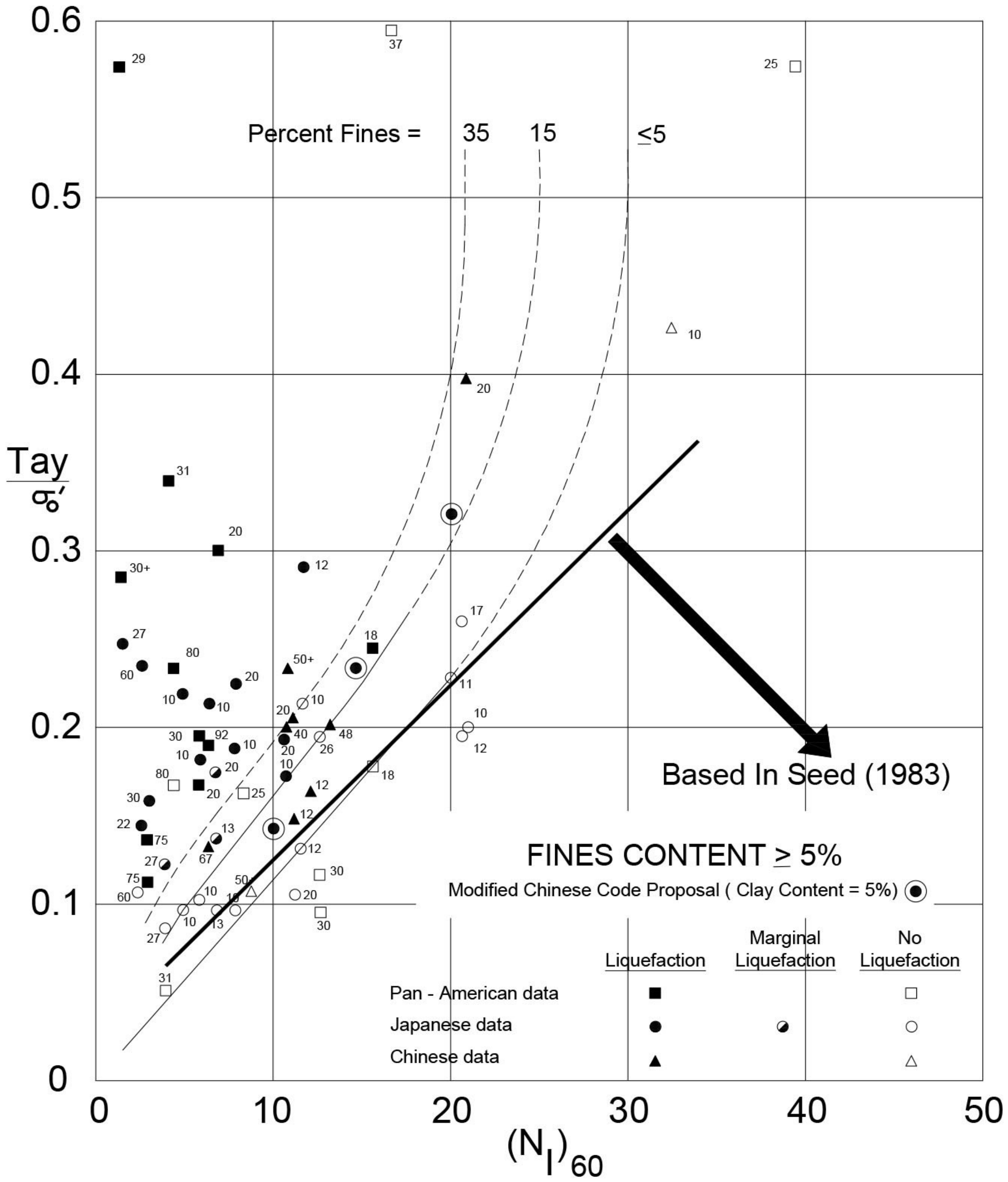

Figure 1. Clean sand base curve for SPT, for 7.5 - magnitude earthquakes with data from liquefaction case histories (modified from Seed et al. 1985). Also, line CRR-N_1 of Seed, 1983.

Table 1. Energy coefficient ranges of different SPT Hammer

SPT Hammer	Ranges of Ce
Donut	0.5 - 1.0
Safety	0.7 – 1.2
Automatic	0.8 – 1.3

Cetin et al., 2004, method [6]**.** The intention of this method is to complement the [2] data base. Data points were added or eliminated from the original graph [2] according to the following:

- eliminated 36 data points of the [2] graph
- added data points to the graph considering the [1] recommendations for energy.

The Cetin et al. data base is composed of 201 data points; in some cases there are repetitions of the same Ce value.

Idriss and Boulanger, 2010, method [7]. In December of that year a new database was published based on the [2], idea. This database consists of 495 values, with some repetitions of some values of Ce, despite different soil conditions.

3. Results

Boulanger et al. [11], and [12, 13, 14], mention many case histories of inadequacy in the liquefaction or no-liquefaction predictions with fluctuations between 25% and 42%. Castro [15] expressed concern regarding the accuracy of some aspects of the method; like any geotechnical method, there are uncertainties in its use. Thus, many experienced geotechnical engineers use more than one method for the definition of geotechnical parameters, and make analyses if they face a critical situation. Anyhow, [15] is in accordance with our criticism of the Seed method. The results can be appreciated in Table 2. , based on some versions of the Seed simplified method of Liquefaction Potential Evaluation; it includes 89 evaluations, with respect to statistical samples criteria.

Table 2. Liquefaction assessment and observed behavior

Earthquake	Evaluations	Success	Failure	Inadequacy
	(1)	(2)	(3)	(3)/(1)
Loma Prieta 1989 (USA) [11]	26	18	8	30%
Chi Chi 1999 (Taiwan) [13]	7	4	3	42%
Loma Prieta 1989 (USA) [12]	48	35	13	27%
Maule 2010 (Chile) [14]	8	6	2	25%

4. Discussion

Prior to the discussion of the above mentioned methods**,** the research conducted by [9] is briefly exposed. They found that for each N (SPT) there was energy measured in the interval of penetration of the SPT sampler (last 30 centimeters). This N value and the energy used to obtain it depend on the same variables which are the following: mainly, SPT equipment, e (void ratio), effective overburden pressure, degree of saturation and the type of soil. It is a fact that there are many types of SPT equipment, (See Table 1.) and also that each type of equipment has been applied differently, so for the same interval of sand, N and E (energy) measurements could be different. In this investigation it was also found that constant c in the same soil interval, is defined as, Eq. (8) ,

$$NE = c \tag{8}$$

This is very important since different types of equipment arrive to the same constant c. This way, this could be standardized to only one value of energy and one N representative of the soil interval so that the same graphs for liquefaction evaluation could be used despite using different equipment. Standardization goes like this, Eq. (9) ,

$$NE = c = N_{60}(\ 0.6E^*) \tag{9}$$

in which N_{60} is the number of blows with the SPT in the interval, for energy of 60 % (0.6) of the maximum theoretically available E* (the theoretical potential energy of the hammer fall during the SPT test). See Fig. 2, [9]. In this figure, Ei is the energy that enters the system of bars and E* is the maximum theoretical potential energy of the hammer. In the same figure N´ is the number of blows for advancing the sampler a fixed distance. This figure shows four series of hammer reduced drop tests, demonstrating a linear inverse relation between wave energy and number of blows. It is worthwhile mentioning that the determination coefficient r^2 is high: 0.98.

Considering its importance, the c constant was named **geotechnical identity.** Thus, it can be seen that, with energy measurements in the soil interval it is possible to transform to a standardized N, in this case N_{60}, and this way estimate the liquefaction potential, that is, CRR as a function of $(N_1)_{60}$, defined in Eq. (2). The problem with the first two above-described methods, and [5] , which is only mentioned, is that they do not take into account energy measurements, and the same interval can have many related N with different SPT equipment. As a consequence, the same interval may have opposing predictions. The last four methods described, [2, 1, 6, 7], use $(N_1)_{60}$ -based liquefaction graphs; N standardized to 60 % energy and normalized to an effective overburden pressure of 100 kpa (different Cn). In this case the $(N_1)_{60}$ values used in the construction of these graphs were not obtained from energy measurements of soil intervals, but from estimations or variation ranges for each equipment, or from average values depending on the SPT equipment used. Selecting average values of E (energy) and N (SPT) mask reality, since E and N of any strata could be different, indicating liquefaction, which could be opposite to results of average values. It can be noticed that there is a distortion of the real values of $(N_1)_{60}$, and therefore these graphs are somewhat

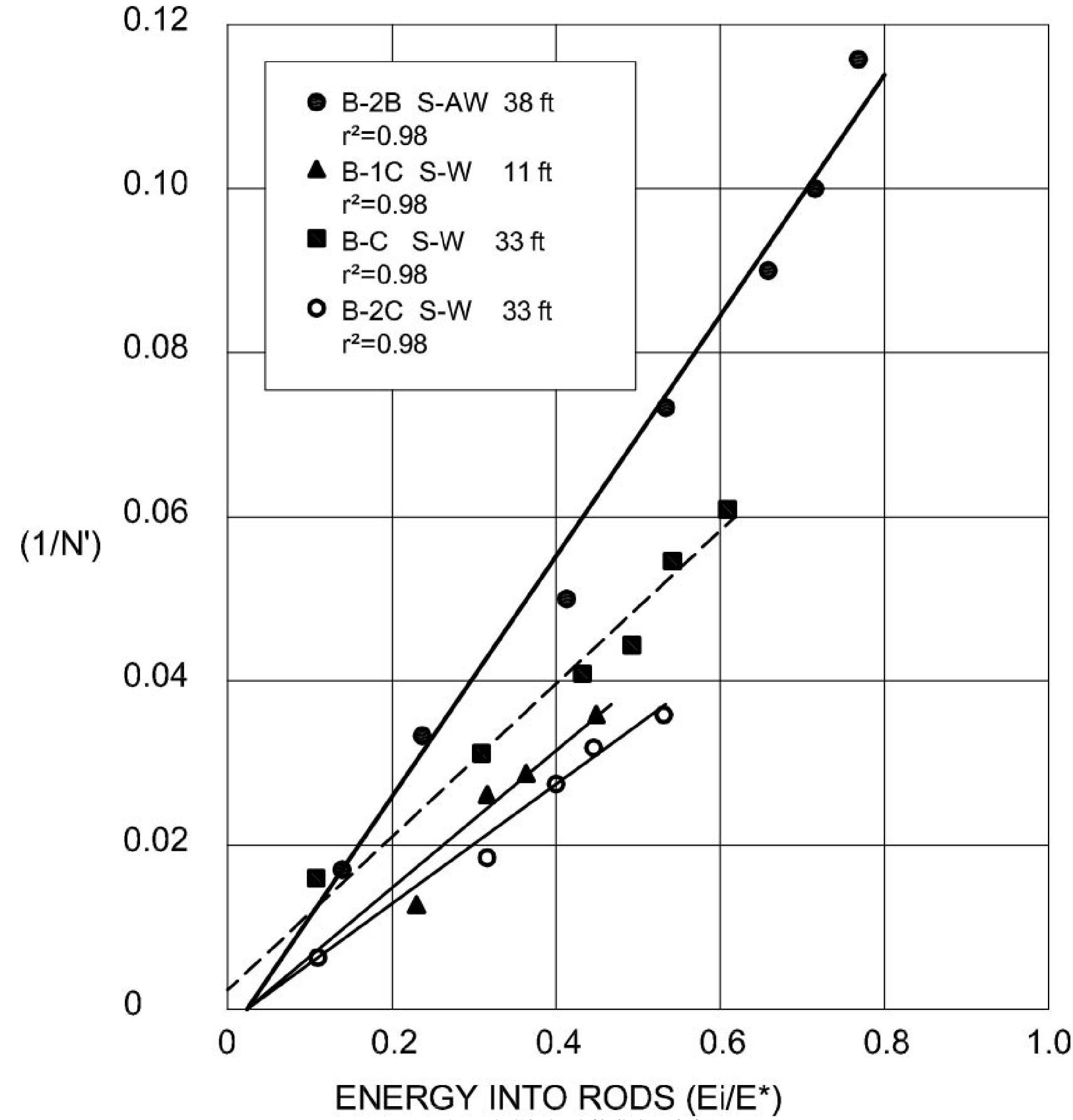

Figure 2. (1/N´) – (Ei/E*) Correlation

problematic. With regard to Seed´s statement: For values of $(N_1)_{60}$, [2], up to 25, the correlation line drawn for clean sands, Fig 1., is almost the same as the proposal of [3], pointing out that the values of N_1 used in that article correspond almost exactly to $(N_1)_{60}$. These are the comments of this author**:**
When applying [9], the following Eq. (10), is obtained:

$$(N_1)_{60}\,(0.6\,E^*) = N_1\,E_1 \quad (10)$$

in which, E_1 is the energy corresponding to N (See the definition of N_1 in Eq. (4)),
Then, Eq. (11),

$$(N_1)_{60} = N_1(E_1/0.6\,E^*) \quad (11)$$

which implies that $E_1 = 0.6$ E***;** in other words, all the Seed data points have an energy correction factor of Ce = ER%/60 = 1.0; that is $E_1 = 0.6$ E* in all the cases. Furthermore, some of the repetitions of the same coefficient of energy transformation (Ce) that the article [7] mentions are not acceptable, since different soil strata imply different Ce .
Zeevaert [16] mentions that the excess pore pressures induced by the earthquake are a function of P and S waves, as is logical; instead different versions of Seed method consider only S waves. At the ISC-4 conference held in Brazil, [17] mentioned that the N-SPT was unreliable. Additionally, [18] mentioned that the SPT should be replaced by other methods. It is also necessary

to remember that when it comes to estimating relative density as a function of N-SPT and overburden pressure, graph [10] does not consider energy, so the same interval of 30 centimeters of sand can have many different N, as a function of different equipment (different energy applied), that is to say, different relative densities. That graph is only qualitatively useful. In spite of the above-mentioned, the liquefaction potential can be estimated with accuracy by the Site Specific method, [19]. This method is based on related CRR values from undisturbed samples of saturated sands with values of $(N_1)_{60}$ determined with measurements of N-SPT and E, in positions near the spots from where samples were extracted. Maybe frozen samples are required. Seed's idea is the basis of this method.

5. Conclusions

As a general conclusion, it has been proved that the use of the SPT-based simplified method for liquefaction potential evaluation has sometimes given the expected results. The methods included in this article, for the SPT liquefaction potential assessment, based on versions of the Seed Simplified method and specifically related to the way each database was determined, are almost exhaustive. This is the first time that possible reasons are mentioned for some discordance between predictions and performance. As a consequence, these SPT-based methods should be used with caution; this is the importance of the article. Perhaps other procedures could be used for adequate predictions. Among these methodologies, the SPT-based Site Specific Method can be resorted to for accurate results, thus considering Seed´s idea.

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