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In-situ Determination of the Shell Correction Factor in Carbonate Sands

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ABSTRACT

Carbonate sands are characterized by cone resistances lower than those of predominantly siliceous sands at comparable relative densities due to their more compressible grain structure. On the other hand, liquefaction potential of a sand deposit during an earthquake is typically estimated using charts that are developed based on liquefaction case histories from sites with predominantly siliceous sands. Therefore current liquefaction assessment methods are only valid for siliceous sand sites. In the absence of a sufficient database on carbonate sand sites, the “shell correction factor” (SCF) is often utilized to adjust the charts for siliceous sands to be applicable for the carbonate sands. The determination of such shell correction factors is usually made through time consuming and expensive calibration chamber tests in the laboratory. In this paper, it is proposed to establish the shell correction factor derived from cone penetration tests and shear wave velocity measurements in the field.

Introduction

Carbonate sands are mainly composed of the skeletal remains of marine organisms and are abundantly present in the offshore environment. These sands are characterized by cone resistances lower than those of predominantly siliceous sands at comparable relative densities but they are also known to exhibit a relatively high resistance to liquefaction. In the first section of this paper, we describe (1) the specific properties of carbonate sands in terms of cone resistance and liquefaction resistance and (2) the traditional methods used to determine the safety factor against liquefaction during an earthquake with emphasis on the advantages and drawbacks of these methods. In the second part, we present an alternative method to evaluate the liquefaction resistance of carbonate sands. This method utilizes a site-specific shell correction factor (SCF) based on the comparison of cone resistances and shear wave velocities measured in the field.

Liquefaction Resistance of Carbonate Sands

General Properties of Carbonate Sands

Carbonate sands exhibit cone tip resistances that are lower than the ones measured in predominantly siliceous sands at comparable relative densities. They also exhibit lower friction ratios, such as 0.1 to 0.3% as compared to 0.3 to 0.8% for siliceous sands. This phenomenon was described by Debats and Sims (1997) at the time of the large vibrocompaction works required for the construction of the new Hong Kong airport: (1) by nature, these sands have low densities and

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the shell particles tend to break when the cone tip penetrates them, leading to cone penetration resistances much lower than when dealing with normal silica sands; (2) the situation was experienced in some zones of the Hong Kong site where shelly materials with initial q_c values ranging from 2 to 4 MPa associated with extremely low friction ratios were encountered, and where the cone penetration resistances after compaction tended to remain in the range 4-8 MPa even though adequate compaction was achieved; and (3) it confirmed the conclusions by Jamiolkowski and Pasqualini (1992): the ratios between tip resistances in silica sands and in calcareous sands can be as high as 1.5 for relative densities in the range 50-70% and as high as 2.0 for relative densities of the order of 90%.

Common Methods for the Assessment of Liquefaction Resistance in Sands

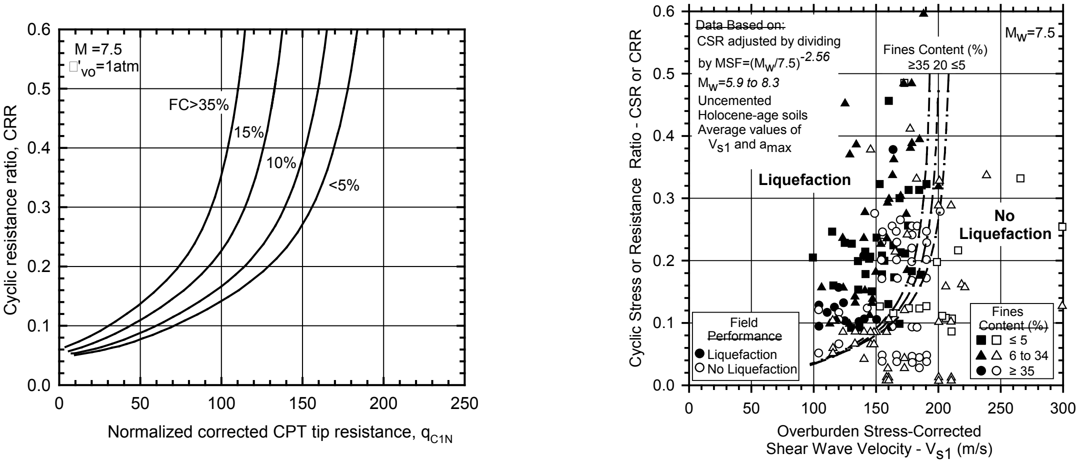
Methods Based on CPT or Shear Wave Velocity

The assessment of liquefaction potential from cone resistance is usually based on charts that are valid only for predominantly siliceous sands as can be found in Youd et al. (2001) or Idriss and Boulanger (2008); see Figure 1 (a). In this method, fines content of the sandy soil is considered using a correction to the cone tip resistance to account for the lower tip resistances measured in sands with fines. However such a correction factor is not available for carbonate content which has a similar influence on tip resistance, much like fines content. The use of the charts and correlations in the current liquefaction assessment methods is inherently overconservative since cone resistances in sands with large carbonate contents are significantly lower than the ones measured in predominantly siliceous sands. Furthermore because the friction ratios are also lower, the fines contents of the carbonate sands can be underestimated, leading to an even more conservative assessment of liquefaction resistance.

On the contrary, several researchers have shown that carbonate sands tend to exhibit a higher resistance to liquefaction than siliceous sands at the same relative density (Olgun et al. 2009, Morioka and Nicholson 2000, Sandoval and Pando 2012). Based on laboratory tests performed using the Playa Santa sand from Puerto Rico, a poorly graded calcareous clean beach sand composed of angular particles with large intra-granular voids, Olgun et al. (2009) demonstrated that this sand was less susceptible to liquefaction than quartzitic sands at the same relative density remolded and tested under similar conditions. This indicates that, the dynamic behavior of calcareous sands is different in comparison to quartzitic sands.

Consequently again, CPT based liquefaction evaluation charts cannot directly apply to carbonate sands in the absence of a correction factor to the measured cone resistance. On the other hand, as stated by Youd et al. (2001), "Andrus and Stokoe (1997, 2000) developed liquefaction resistance criteria from field measurements of shear wave velocity V_s. The use of V_s as a field index of liquefaction resistance is soundly based, because both V_s and CRR are similarly, but not proportionally, influenced by void ratio, effective confining stresses, stress history, and geologic age." This indicates that V_s can be a parameter to collectively capture soil behavior during an earthquake and its use can overcome the discrepancies mentioned above for carbonate sands. The main advantages of using V_s in direct relation to calcareous sands include: (1) V_s measurements can be performed in soils that are difficult to penetrate with CPT and SPT; (2) V_s is a basic mechanical property of soils and it is directly related to small-strain shear modulus; and (3) the small-strain shear modulus is a parameter that can be directly used in numerical and analytical procedures to evaluate dynamic soil response and soil-structure interaction (Youd et al. 2001).

Such an approach leads to liquefaction resistance charts as shown in Figure 1 (b) from Andrus and Stokoe (2000) without the need to take carbonate content into consideration because V_s is a direct soil parameter without the need for interpretation required by cone resistance.



(a) (b)

Figure 1. (a) CPT relationships for cohesionless soils with various fractions of nonplastic fines (b) Curves recommended for calculation of CRR fromV_{s1} measurements in sands and gravels

Methods Based on the Shell Correction Factor (SCF)

In such methods, cone resistance is multiplied by an adjustment factor before the application of the charts derived for predominantly siliceous sands. This correction factor is a function of the sand density and the carbonate content such that, the higher the soil density and the larger the carbonate content, the larger the correction to be applied. Al-Homoud and Wehr (2006) describe the method that was applied at various sites for the Dubai Palm Islands which were constructed using hydraulically filled carbonate sands and they present the obtained results. In this study, calibration chamber tests were performed on samples from the site in comparison to the results quoted by Jamiolkowski and Pasqualini (1992): Equation 1 presents the shell correction factor developed for the Dubai carbonate sands with 75% carbonate content.

$$SCF = 0.0046 \times D_r\,[\%] + 1.3629 \quad (SCF = 1.66 \text{ for } 65\% \text{ relative density}) \qquad (1)$$

Comments on the Calibration Tests Used to Determine the Shell Correction Factor for a Specific Site

The assessment of the shell correction factor for a specific sand formation at a project site is a difficult and costly task. Typically, calibration chamber tests can be performed but this has significant drawbacks: (1) calibration chamber tests require large amounts of sand to be transported to the laboratory (typically around one ton of sand per investigated relative density); (2) only a few relative densities can usually be tested in the calibration chamber; (3) the corrections to the measurements made in a calibration chamber (i.e. boundary effect correction factors) can be an important source of errors or uncertainties; and (4) the tests are quite expensive (typically around USD 50,000 for two relative densities tested) and they can by no means be fully representative of the variability of the site.

Proposed Method for the Assessment of the Shell Correction Factor

In this paper, a new method is proposed to assess the shell correction factor (SCF) required for the proper evaluation of the liquefaction potential in carbonate sands using the existing design charts established for predominantly siliceous sands. This method is based on the comparison of cone penetration tests results and measurements of shear wave velocities in the field. This assessment needs to be performed at the beginning of the ground improvement project in agreement with the Client's Engineer. What follows is a description of the SCF methodology and the results obtained in an important vibrocompaction site in Tangiers, Morocco, for the construction of a new container terminal platform.

Site Conditions

Vibrocompaction at the Tangiers site included nearly 5 million cubic meters of hydraulic sand fill. The treatment depth ranged from 5 to some 18 meters. The sand was dredged from the seabed several nautical miles away and placed in the reclamation area by hydraulic filling. Typical pre-compaction CPT sounding and grain size distribution curves are shown in Figure 2.

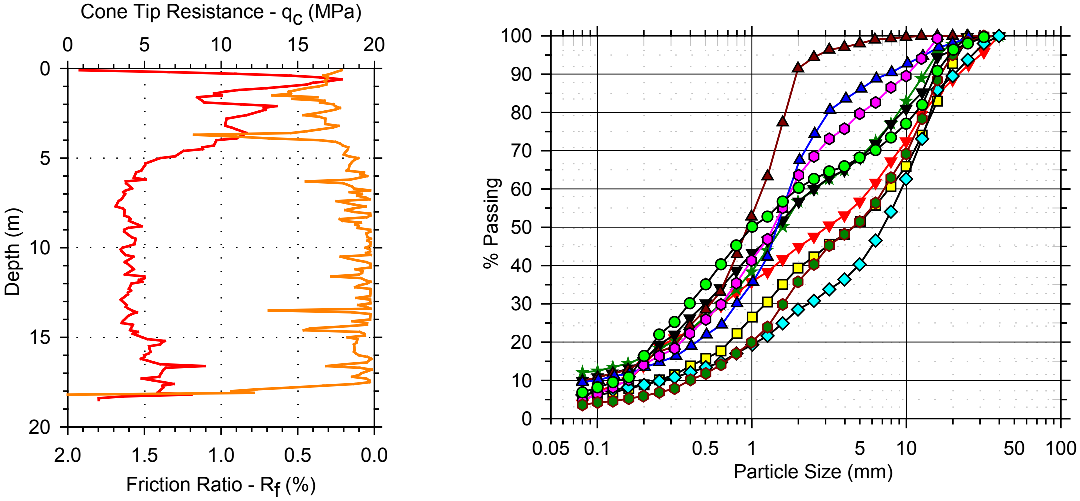
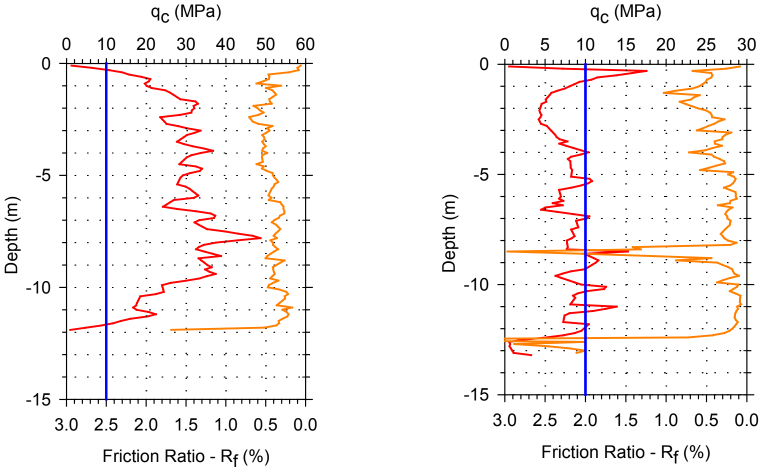


Figure 2. Typical pre-compaction CPT and particle size distribution in the reclamation

The low friction ratios, typically between 0.1 and 0.3%, are an indication of the high carbonate content of the sand. Laboratory tests confirmed that the carbonate content ranged from 75 to 95%, made of up to 20 or 30% of large size shells or carbonated algae with the rest of the carbonates ranging across the whole particle sizes as fragments of shells or algae mixed with grains of quartz, mica or heavy minerals. Ground conditions were quite variable across the site.

Vibrocompaction Specifications and Densification Results

Compaction was required to achieve a post-densification cone resistance of 10MPa over the full treatment depth in order to reach a safety factor of 1.25 against the risk of liquefaction under the following two seismic scenarios: (1) 0.24g peak ground acceleration associated with a magnitude of 4.7; and (2) 0.093g peak ground acceleration associated with a magnitude of 8.5. The compaction of the main part of the profile was carried out with Vibro Services GmbH V48 vibrators suspended from crawler cranes while the upper 2 to 3 meters were compacted with a Landpac impact roller. Although the acceptance line was generally met in the compaction, the results could sometimes prove quite variable, as can be seen on the two post-treatment CPTs presented in Figure 3. This type of problems was particularly the case at sections of the site with high carbonate content.



(a)

(b)

Figure 3. Post-vibrocompaction CPTs in (a) moderately carbonated sand and (b) highly carbonated sand

In this unique example, there are large differences in the cone resistances even though the compaction procedure was exactly the same for two sections of the site. Three times the acceptance line is achieved in the first case as seen in the left figure (shown in red) and this is compared to the observed 80% of the acceptance line in second case shown in the right figure. The basic explanation of such a stark difference is related to the larger carbonate content of the second case as shown by the lower low friction ratios. This discrepancy in achieving post-densification CPTs even though significant densification was achieved underlines the necessity to utilize a shell correction factor.

Evaluation of the Shell Correction Factor and Assessment of Liquefaction Risk

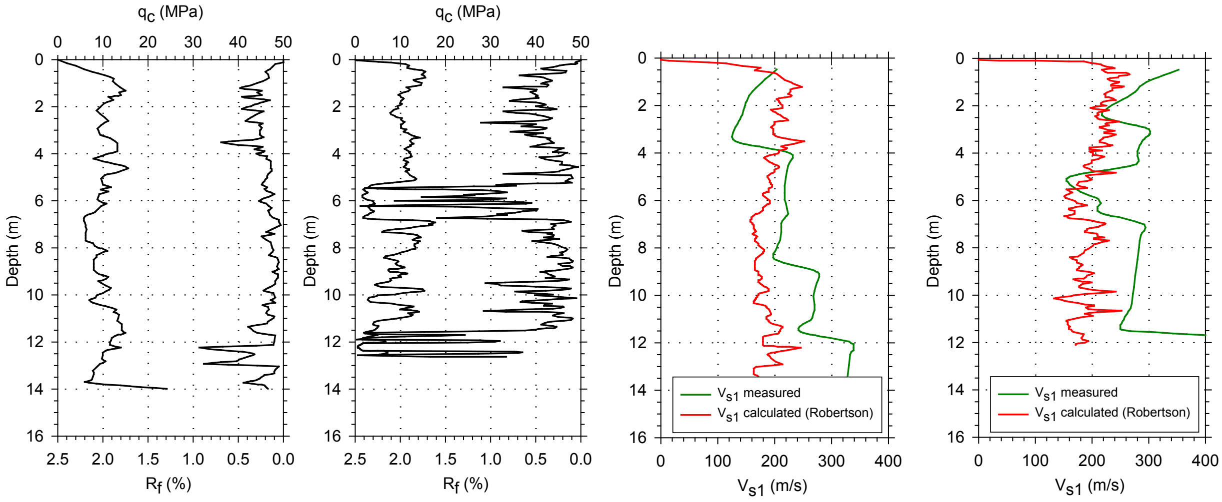
The method used to determine the shell correction factor as a function of the soil conditions can be described as follows: (1) perform cone penetration tests and shear wave velocity V_s measurements within the same zone of the site, leading to cone resistance and shear wave velocity profiles that can be compared; (2) empirically derive the V_s profile utilizing the correlation proposed by Robertson (2009) using the measured cone resistance q_c profile; (3) determine the shell correction factors (SCF) along the profile required to match the predicted V_s values with the measured V_s at each elevation in the CPT profile; (4) plot the calculated SCF as a function of the friction ratio R_f; (5) derive the correlation for SCF/R_f; (6) apply the SCF to the CPTs of the site; and (7) determine whether the mitigation of liquefaction under seismic conditions is ensured or not, using either the corrected CPT profiles in charts like in Figure 1 (a) or the V_s profiles in charts like in Figure 1 (b).

Application to the Tangiers Site

CPT and V_s Profiles

CPT profiles were obtained with a traditional 20 ton truck-mounted cone penetration rig and V_s profiles were obtained adjacent to the CPT profiles with the down-hole method. A description of the method can be found in ASTM D 7400 - 08. Measured q_c profiles for two post-treatment CPTs are shown in Figure 4 (a). Each graph details the variations of (1) cone resistance q_c (MPa); and (2) friction ratio R_f (%). In what follows the normalized shear wave velocity is defined by Equation 2:

$$V_{s1} = V_s \left(\frac{p_a}{\sigma'_{v0}}\right)^{0.25} \qquad (2)$$



Post CPT E10.1 Post CPT E12.2bis Post CPT E10.1 Post CPT E12.2bis

(a) (b)

Figure 4. (a) Comparisons Post-CPT / normalized shear wave propagation velocities V_{s1}
(b) Comparisons V_{s1} measured / V_{s1} calculated

Prediction of the Shear Wave Velocity V_{s1} Would the Sand be Siliceous

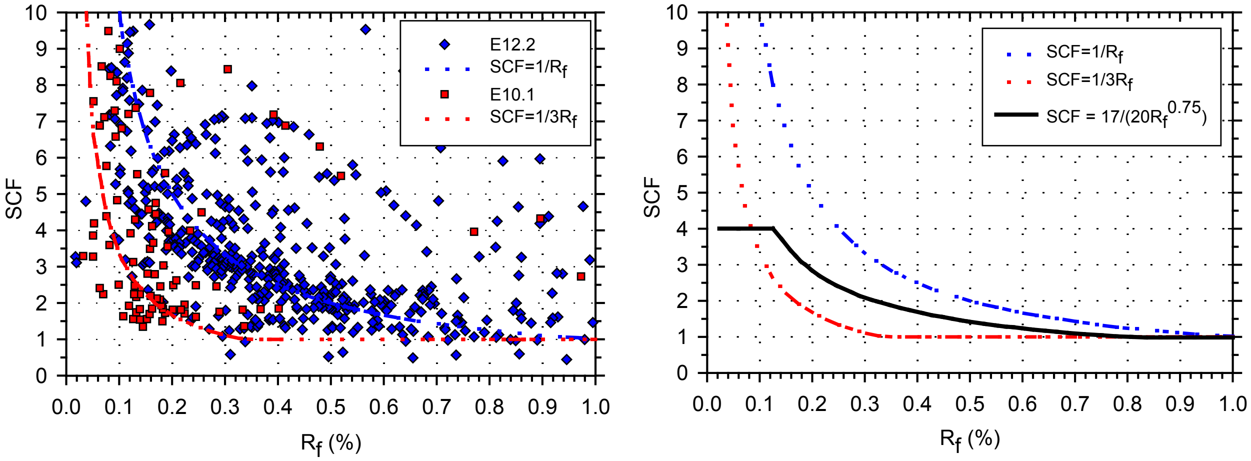
Robertson (2009) established a relation between the normalized shear wave propagation velocity V_{s1} and the normalized cone resistance q_{c1N} (Equation 3):

$$V_{s1} = \left[10^{(0.55Ic+1.68)} q_{c1N}\right]^{0.5} \quad (3)$$

This relation applies to predominantly siliceous sands. The reliability of this equation in the assessment of shear wave velocities has been validated at the LNG Terminal project in Dunkirk, France. Figure 4 (b) is the comparison of the normalized shear wave velocity (V_{s1}) profiles derived from the measured cone resistances using the Robertson correlation (Equation 3) and the V_{s1} (m/s) defined by Equation 2 from the shear wave velocities measured in the field (red and green lines, respectively). It should be noted that the measured shear wave velocities are larger than the velocities derived from the cone resistances using the Robertson (2009). This confirms that the cone resistance measured in the carbonate sands are lower than what would be reached in silica sands.

Determination of the Shell Correction Factor SCF

This determination is carried out at every elevation in the soil profile and can be summarized as follows: (1) at a depth z, we have a pair of values (q_c ; R_f); (2) iteration 1, with SCF taken equal to an arbitrarily chosen value : $q_{c\text{-corrected}}$ = SCF x q_c; (3) $V_{s1\text{-calculated}}$ = f ($q_{c\text{-corrected}}$), from Robertson (2009); and (4) iteration on SCF until $V_{s1\text{-calculated}} = V_{s1\text{-measured}}$. This provides us with a profile of SCF as a function of depth. SCF is thus confirmed to depend on the friction ratio. Figure 5 (a) gives the distribution of the pairs (SCF : R_f) for two specific CPTs.



(a) (b)

Figure 5. (a) Distribution of SCF and R_f pairs; (b) Average relation SCF = f (R_f)

The scatter of the calculated relationship between SCF and R_f from the two CPTs confirm the variability of the site conditions. However as seen, the variation of SCF as a function of R_f can be considered as bounded by the two curves SCF = 1/R_f and SCF = 1/(3R_f). Even though there is not a unique correlation between SCF and R_f, we can establish upper and lower bounds and the median trend by judgment. Figure 5 (b) shows the interpretation of these observations with indication of an approximate average line and the equation for the average line is given below.

For $R_f \leq 0.13$ % $\quad SCF = 4$

For $0.13\% \leq R_f \leq 0.8$ % $\quad SCF = \dfrac{17}{20Rf^{0.75}} \quad (4)$

For 0.8 % $\leq R_f$ $\quad SCF = 1$

Applying the set of Equations 4 to the cone resistances measured in the field and calculating the normalized shear wave velocities using Robertson's correlation to the corrected cone resistances provides us with Figure 6, where the derived normalized shear wave velocities (red curves) can be compared to the ones measured (green curves). The fact that the red and green curves are now in fairly good agreement demonstrates the adequacy of the method.

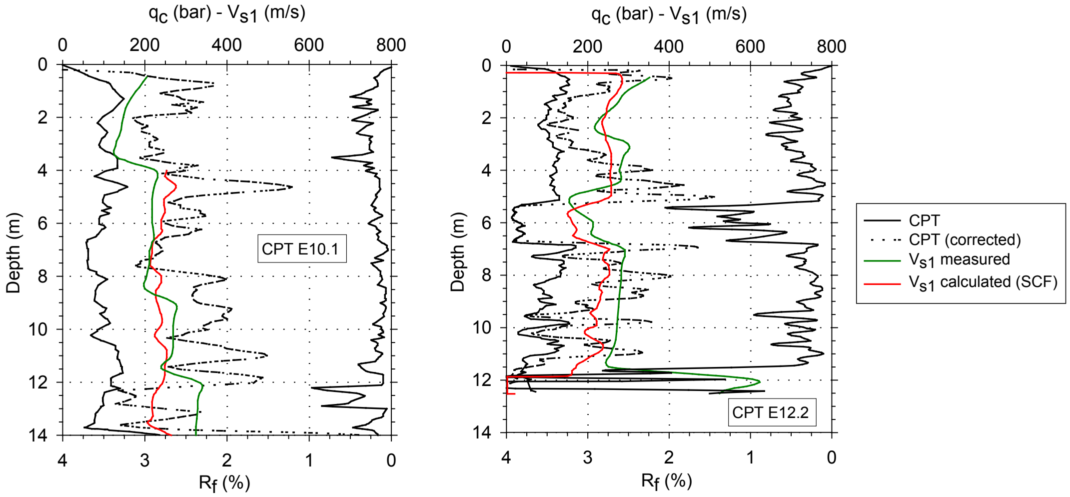


Figure 6. Application of the correlation SCF = f (R_f) on CPT E10.1 and CPT E12.2

Conclusions

The method proposed to determine the shell correction factor required to correctly assess the liquefaction resistance of carbonate sands using CPT soundings is relatively simple to implement once the SCF/R_f correlation is established for the site or for a specific zone of the site. This procedure can be checked/approved with CPTs corrected accordingly. In this method, local variations in site conditions are automatically taken into account. The only additional cost is the one linked to the shear wave velocity measurements needed to establish the SCF vs R_f relation at the beginning of the site and, possibly, whenever site conditions change.

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