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ADVANCES OF CONE PENETRATION TESTING IN EARTHQUAKE ENGINEERING APPLICATIONS

R. E. S. Moss, Ph.D., P.E. (1,2); and R. Moffat, Ph.D. (2,3)

1. *Professor, Cal Poly, San Luis Obipso, California, USA*
2. *LMMG Geotecnia Limitada, Santiago, Chile*
3. *Assistant Professor, Universidad Adolfo Ibañez, Santiago.*

Resumen

El ensayo de penetración de cono (CPT), ha aumentado considerablemente su uso en ingeniería sísmica en la última década su uso debido a su precisión, exactitud, y utilidad. En este trabajo se realiza un breve resumen de los recientes avances en la aplicación del CPT a la deducción del potencial de licuefacción, deformaciones post-licuefacción, falla cíclica de arcillas, estabilidad dinámica de taludes, y respuesta sísmica de sitio. En suelos granulares las mediciones continuas de resistencia de punta y fuste han sido correlacionadas con propiedades del suelo tales como densidad relativa y ángulo de fricción. En arcillas la resistencia de punta medida es directamente proporcional a la resistencia no drenada del material. Las mediciones CPT son ideales para suelos sueltos o blandos que son comúnmente encontrados cuando se observa falla sísmica del suelo. Adicionalmente el ensayo CPT es instrumentado con acelerómetros que permiten realizar mediciones de velocidades de onda de corte al mismo tiempo que se obtienen las mediciones de cono durante la penetración del suelo. Esto permite la medición de la rigidez a pequeñas deformaciones del suelo utilizadas en la modelación dinámica y análisis de la respuesta de sitio. En presas de relave y taludes, la combinación de las mediciones de penetración para estimar la resistencia del suelo y la rigidez del suelo a pequeñas deformaciones para deducir la respuesta modal, permite poseer un set completo de mediciones para el estudio de la estabilidad dinámica de los taludes. Para análisis de la respuesta de sitio, el ensayo CPT entrega la más efectiva y económica forma de caracterizar el perfil de velocidad de onda de corte de las capas de suelo que conforman el suelo de fundación. Algunos métodos recientes y proyectos son descritos en este trabajo para demostrar la utilidad del ensayo CPT en aplicaciones de ingeniería sísmica.

Abstract

The Cone Penetration Test (CPT), because of its precision, accuracy, and utility has been increasingly used in earthquake engineering applications in the last decade. This paper provides a brief survey of recent advances in applying the CPT to; liquefaction triggering, post-liquefaction deformations, cyclic failure of clays, dynamic slope stability, and seismic site response. In granular soils the continuous CPT measurements of tip and sleeve resistance are well correlated with the engineering properties of relative density and friction angle. In clay soils the CPT tip resistance is directly proportional to the undrained shear strength. CPT measurements are ideal for weak or soft soil layers, which are the primary culprits in seismic soil failure. The CPT is commonly instrumented with an accelerometer so that shear wave velocity measurements can be made concurrently with penetration measurements. This allows for the measure of the small strain stiffness of the soil for dynamic modeling and site response analysis. For tailings dams and earth slopes the combination of penetration measurements to estimate soil strength and small strain stiffness to assess the modal response provides a complete set of measurements for assessing the dynamic slope stability. For site response analysis the CPT provides the quickest and most cost effective means of layer-specific shear wave velocity imaging of the foundation conditions. A number or recent methods and projects are described in this paper to demonstrate the utility of the CPT in earthquake engineering applications.

Keywords: CPT, liquefaction, deformations, cyclic failure, site response

1 Introducion

The Cone Penetration Test (CPT) is being used more and more in geotechnical subsurface investigations. Because of the CPT's precision, accuracy, and utility has found increasing use in earthquake engineering applications. This paper provides a brief survey of recent advances in applying the CPT to;

- liquefaction triggering,
- post-liquefaction deformations,
- cyclic failure of clays,
- dynamic slope stability, and
- seismic site response.

In granular soils the continuous CPT measurements of tip and sleeve resistance are well correlated with the engineering properties of relative density and friction angle. Standard Penetration Test (SPT) blow counts are also correlated with these engineering properties but the SPT is an interval point estimate (usually at 1.5 m intervals) and lacks both precision and accuracy. In clay soils the CPT tip resistance is directly proportional to the undrained shear strength, whereas Standard Penetration Test (SPT) blow counts in clay soils are meaningless.

CPT measurements are ideal for weak or soft soil layers, which are the primary culprits in seismic soil failure. The CPT is commonly instrumented with an accelerometer so that shear wave velocity measurements can be made concurrently with penetration measurements. This allows for the measure of the small strain stiffness of the soil for dynamic modeling and site response analysis. For tailings dams and earth slopes the combination of penetration measurements to estimate soil strength and small strain stiffness to assess the modal response provides a complete set of measurements for assessing the dynamic slope stability. For site response analysis the CPT provides the quickest and most cost effective means of layer-specific shear wave velocity imaging of the foundation conditions. A number or recent methods and projects are described in this paper to demonstrate the utility of the CPT in earthquake engineering applications.

2 Liquefaction Triggering of Sandy Soils

The CPT is an ideal test for assessing triggering of liquefaction because it can measure the penetration resistance with the tip, the effects of fines content with the sleeve, the soil state (contractive or dilatant) with the pore pressure , and the small strain stiffness with the shear wave velocity. The continuous measurement of penetration is particularly sensitive to layering and bedding that can control liquefaction behavior. A number of liquefaction triggering curves based on CPT measurements are used in practice (e.g., [1] Robertson and Wride, 1998; [2] Youd et al., 2001; [3] Moss et al., 2006; [4] Idriss and Boulanger, 2006). The typical framework (Figure 1) uses existing case histories of liquefaction and non-liquefaction to develop a threshold (preferably probabilistic) to afford the prediction of liquefaction given a measure of the resistance (cone tip penetration resistance, q_c) versus load (cyclic stress ratio, *CSR*). Most calculations are performed using spreadsheets or software with the many competing methods pre-programmed for easy comparison.

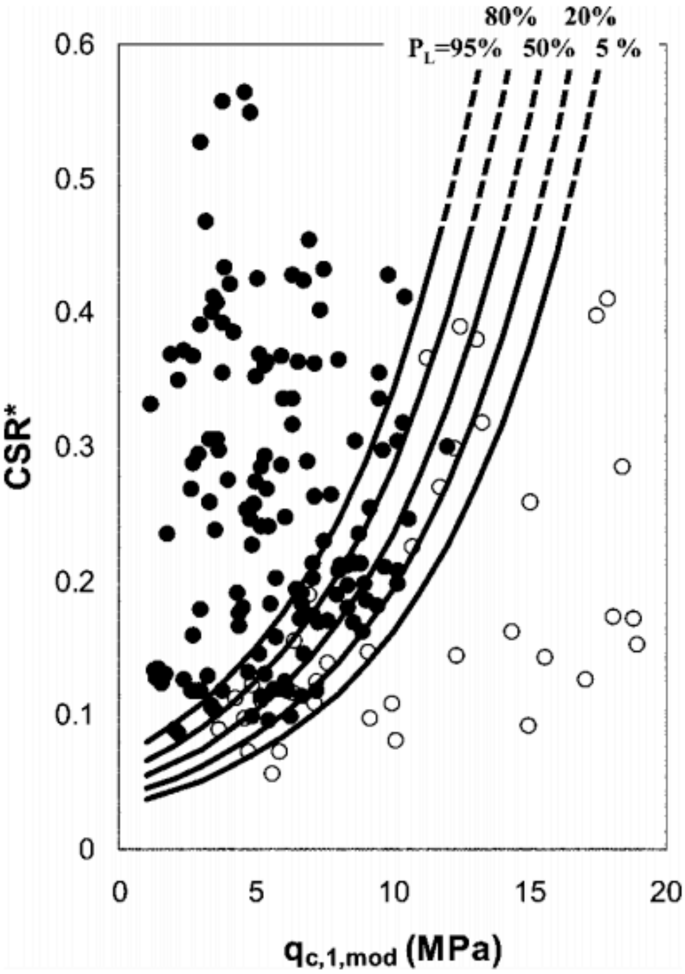

Fig. 1 – Liquefaction triggering plot from [2] Moss et al., (2006) showing corrected cone tip penetration resistance on the x-axis versus cyclic stress ratio on the y-axis. The open circles are non-liquefied case histories and the dots are liquefied case histories. The curves are contours of equal probability of liquefaction.

To provide confidence in the penetration-based triggering results the shear wave velocity (V_s) measurements, made as part of the CPT investigations, can also be used to assess triggering ([5] Andrus, Stokoe and Juang, 2004; [6] Kayen et al., 2013). Methods based on V_s are not as accurate as those based on cone tip penetration, but do capture ageing effects that are destroyed during penetration of the soil ([7] Dobry et al., 2014). The two measurements, cone tip resistance and shear wave velocity, compliment each other well and can lead to a deeper understanding of the soil response ([8] Schneider and Moss, 2011).

3 Post Liquefaction Deformations

More critical to the performance of an engineered facility are the deformations that can come about due to liquefaction. These deformations can be particularly hard to determine with accuracy and are often grouped as either deformations that are less than a meter, and deformations that are greater than a meter ([9] Seed et al., 2003). This one meter threshold can be determined by comparing the post-liquefaction residual strength (s_{ur}) to the static driving shear stresses (τ_o). When the driving stress is greater than the liquefied strength, then large deformations can be expected, when the driving stresses are not greater than the residual strength then small localized deformations are typical. Static driving shear stresses are often due to sloping ground, free-face conditions such as along a river bank, or shear stresses induced by foundation loads.

More precise deformation estimates can be achieved using nonlinear time-domain numerical modeling (e.g., FLAC). However, ensuring accuracy of this type of modeling can be a difficult task itself, and even with expertise in these types of analysis it can often take weeks of billable hours to build a reasonable numerical model. To aid in quickly assessing deformations ranges [10] Yazdi and Moss (2016) have synthesized a number of deformation studies and presented them in the form of triggering and deformation charts based on the CPT.

Figure 2 shows the typical triggering framework, penetration resistance versus cyclic loading, with respect to two triggering thresholds ([3] Moss et al, 2006; [10] Yazdi and Moss, 2016). Post-liquefaction deformation studies for level-ground conditions (i.e., minimal driving shear stresses) have been summarized on the bottom of this figure as deformation ranges of large, medium, and small as a function of the CPT tip resistance. These deformations can be refined further into volumetric strains and shear strains using Figure 3 which is a modification of lab work by [11] Ishihara and Yoshimine (1992).

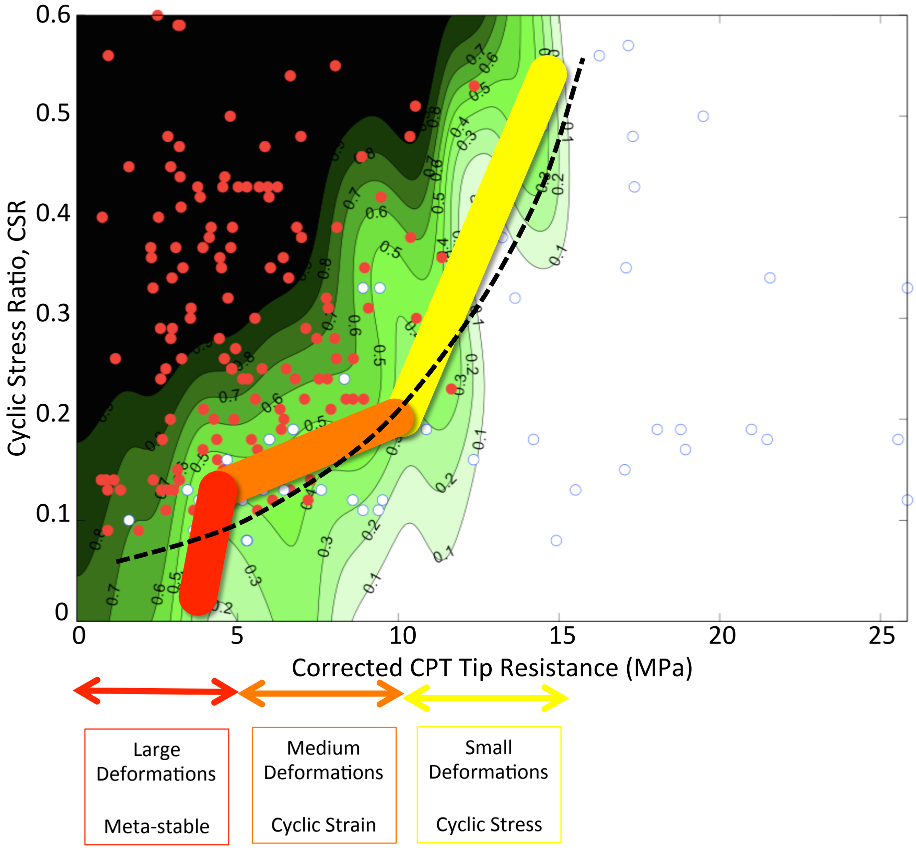

Fig. 2 – Non-parametric triggering curve (bold line after [10] Yazdi & Moss, 2016) along with probabilistic triggering curve (dotted line after [3] Moss et al., 2006) with respect to level ground post-liquefaciton deformation ranges (large, médium, small after [10] Yazdi & Moss, 2016).

When dealing with driving shear stresses and deformations greater than 1 meter, a survey of existing flow failure and lateral spreading case histories can provide bounds on the the pre-failure penetration resistance. As reported in [10] Yazdi and Moss (2016) flow failures have a median corrected tip resistance of 2.9 MPa, with an upper bound penetration resistance 6 MPa. [12] Youd et al. (2002) found that these flow failures typically occur when the slope was greater than 6%, resulting in deformations greater than 5 m. Lateral spreads were found to have more limited deformation potential, in most cases 3 m or less, and exhibited penetration resistance in the 3 MPa to 8 MPa range. Above 8 MPa sandy soils are thought to be dilatant enough to resist large post-liquefaction deformations such as lateral spreads and flow failures.

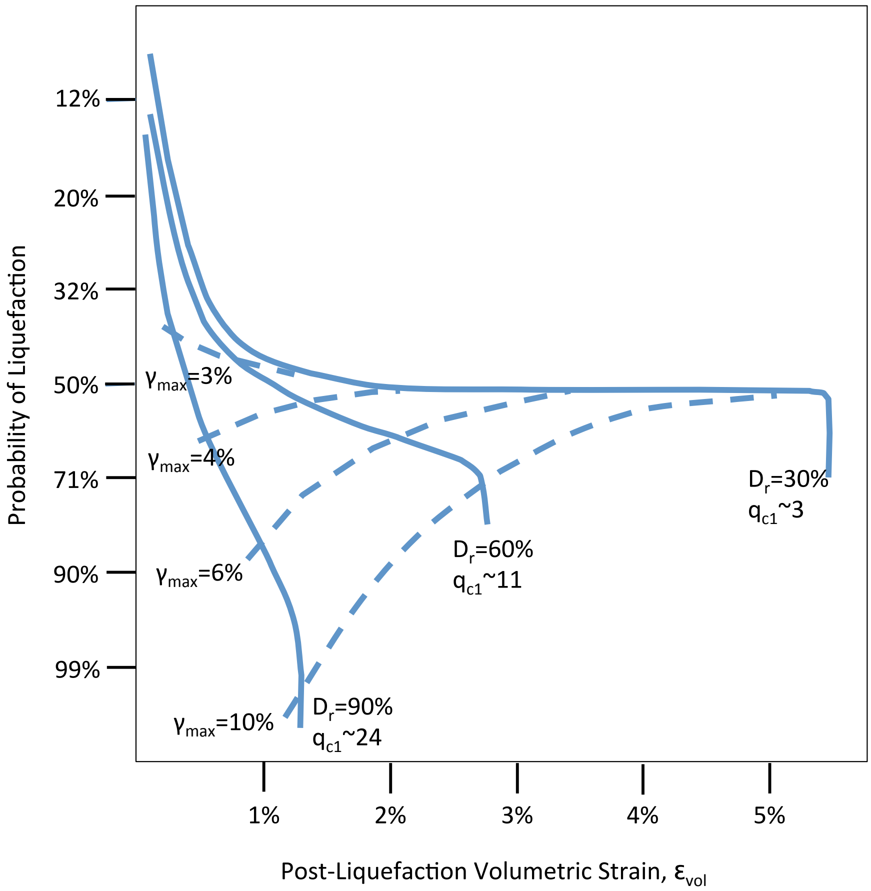

Fig. 3 – Post-liquefaction volumetric (ε_{vol}) and shear strain (γ_{max}) curves for different relative density (D_r) and correlated cone penetration resistance (q_{c1}) of the lab samples. From [10] Yazdi and Moss (2016), this figure is modified from [11] Ishihara and Yoshimine (1992) where we have transformed the y-axis into probability of liquefaction.

4 Cyclic Failure of Clay Soils

Sensitive clay soils can be susceptible to seismic failure. Whereas the deformations are not as large as those caused by liquefaction they can still cause damage to engineered features. This problem is similar to post-liquefaction deformations in that we compare the static diving shear stresses and the residual strength of the soil. There are several methods for analyzing clayey soils for cyclic failure potential as discussed in [13] Boulanger and Idriss (2004).

One common method of assessing the undrained strength (s_u) of clayey soil is using uncorrected cone penetration (q_c) resistance. A semi-theoretical relationship between the tip resistance and the undrained strength of clay is ([14] Lunne et al., 1997):

$$s_u = \frac{q_t - \sigma_{vo}}{N_k} \quad (1)$$

Where q_t is the pore pressure (u) corrected tip resistance (q_t~q_c+0.2u), σ_{vo} is the initial total vertical stress, and N_k is the cone factor. The cone factor is somewhat soil dependent and typically takes a value between 10 and 18, with 14 being a useful average ([15] Robertson, 2015). The undrained strength measured with the cone is a high strain measure of strength, but does not measure the residual strength of the soil. To do that a vane shear test (VST) is the most accurate field test. In many situations the vane shear can be performed in the same hole or directly adjacent to the cone penetration test to measure the peak ($s_{u,peak}$) versus the residual ($s_{u,residual}$) strength to get sensitivity (S_t=$s_{u,peak}$/$s_{u,residual}$). A sensitivity of 1.2 or greater indicates a sensitive soil that may be susceptible to cyclic failure ([16] Holtz, Kovaks, and Sheahan, 2010). The CPT, however, can provide an estimate the sensitivity by assuming that the sleeve (f_s) is measuring the remolded strength of the soil ([15] Robertson, 2015).

$$S_t = \frac{s_u}{f_s} \quad (2)$$

5 Dynamic Slope Stability

The seismic stability of slopes, that are not susceptible to liquefaction and/or cyclic failure, is a function of the dynamic resonance of the slide mass. This resonance, measured using the period, is a first-mode response of the slide mass to the incoming seismic ground motion and can result in co-seismic deformations. A common class of methods for estimating co-seismic slope deformations uses empirical charts; [17]Makdisis & Seed (1979), [18] Bray et al., (1995), and [19] Bray and Travasarou (2007). These methods are relatively quick and provide an "order of magnitude" deformation assessment for making engineering decisions. To use these empirical methods the resonant period (T_s) of the slide mass must be determined:

$$T_s = \frac{4H}{V_s} \quad (3)$$

Where H is the height of the slide mass and V_s is the shear wave velocity. The height of the slide mass and the shear wave velocity can often accurately and efficiently be determined using cone penetration testing. The potential slip surfaces, layering, bedding, and other slope geometry constraints are often clearly identified using penetration resistance from the CPT. The shear wave velocity measured using the cone is a highly accurate downhole measurement with a coefficient of variation (standard deviation/mean) as low as 2%, this compared to ReMi that can be as high as 15% ([20] Moss, 2008). A complete investigation of native slopes, embankments, tailings, or other slopes can often be accomplished with only the CPT as the investigative tool.

6 Seismic Site Response

The dynamic response of a soil column due to seismic shaking can results in amplification/deamplification of the ground surface as a function of layering, shear stiffness, and unit weight. For level ground conditions at low to medium strain levels an equivalent linear 1D analysis is often sufficient for assessing the dynamic response of the soil. The thickness (*h*) and shear stiffness ($G_o = \rho V_s^2$) of each layer in the profile can be quickly measured using the CPT, and the first mode (T_s) of the entire profile (*H*) can be quickly calculated using Equation 3 just as in dynamic slope stability problems. The relative accuracy, precision, and cost effectiveness of the CPT makes this the test of choice when dealing with sands that are loose to medium dense and/or clays that are soft to medium stiff. When the soils become too stiff or dense to penetrate, combining shallow CPT with deep passive surface wave measurements provides complementary measurements that can sufficiently characterize most sites.

7 CPT Measurements Example

The following figures show subsurface investigations from San Antonio, Chile. In Figure 4 is an example of CPT measurements performed at a site where liquefaction was documented during the 1985 Chilean earthquake. Cone resistance, sleeve friction and pore water pressure were taken every 5 cm to a depth of approximately 19 m.

Based on these measurements it is possible to infer the soil profile ([15] Robertson, 2015) as is shown in Figure 5. Mostly sand and silty sand are present at this site. This was confirmed by obtaining soil samples from a boring located 2m away from the CPT sounding. Based on these CPT measurements it was possible to carry out a liquefaction analysis (Figure 6). The likelihood of liquefaction is dependent on the earthquake magnitude, peak ground acceleration, fines content, depth of water table, and other parameters. Here the analysis is for some future earthquake scenario that results in liquefaction in layers from 2 to 4 m and 11 to 14 m. Also shown in this figure are estimated post-liquefaction vertical settlements. In Figure 7 are shown the coincident shear wave velocity measurements obtained during the CPT sounding.

8 Summary

This paper presets the utility of the cone penetration test (CPT) as applied to geotechnical earthquake engineering problems. The accuracy and precision of this test makes it a valuable subsurface investigation tool for most soft to medium soil conditions, the same conditions that are susceptible to the effects of strong ground shaking from an earthquake. Shown are recent techniques for dealing with liquefaction, post-liquefaction deformations, cyclic failure of clays, dynamic slope stability, and seismic site response. Example CPT measurements are provided to show how these methods have been applied at a site in San Antonio, Chile.

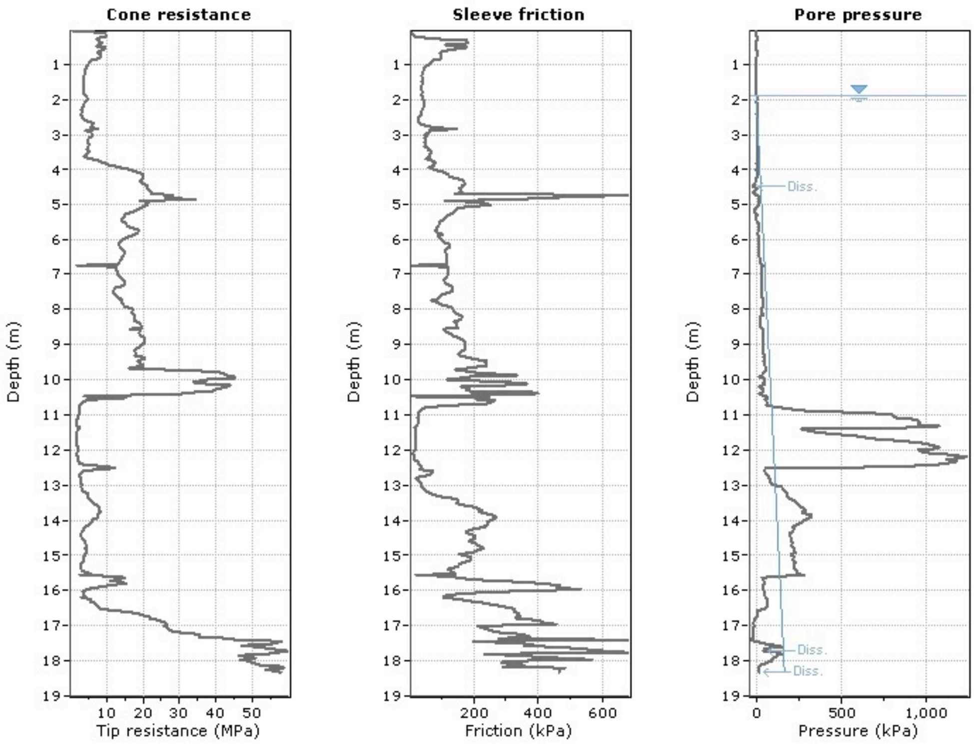

Figure 4. CPT measurements in San Antonio. Shown from left to right are cone tip resistance (MPa), sleeve friction (kPa), and pore water pressure (kPa) as a function of depth (m).

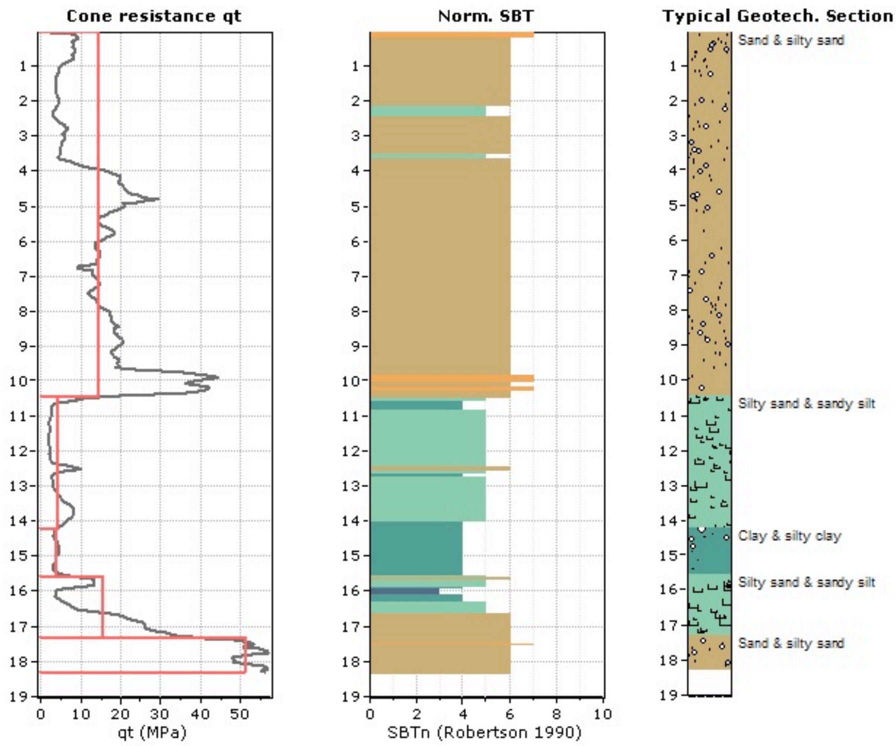

Figure 5. Soil profile based on CPT measurements. Shown is the pore pressure corrected tip resistance q_t (MPa), the soil behavior type SBT ([21] Robertson, 1990), and the accompanying geotechnical descriptions with depth (m).

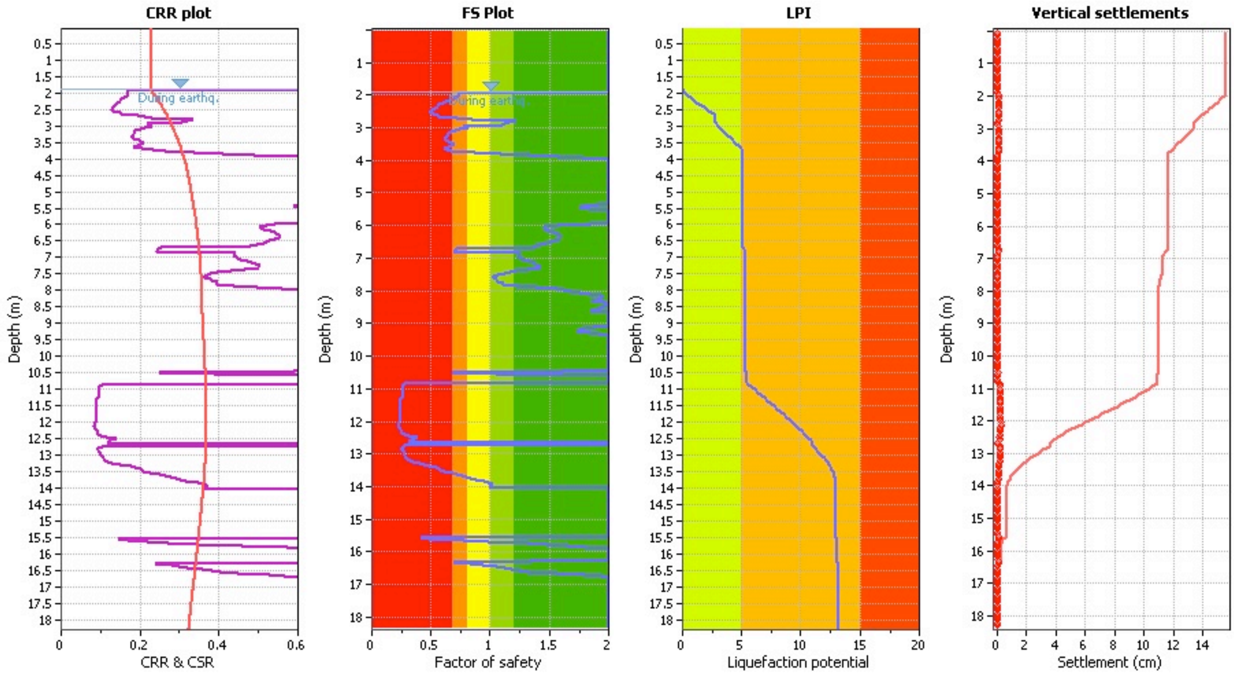

Figure 6. Example of liquefaction analysis. From left to right is the plot of CSR-CRR versus depth, the factor of safety against liquefaction FS, plot of liquefaction potential index LPI, and estimated post-liquefaction vertical settlement (cm).

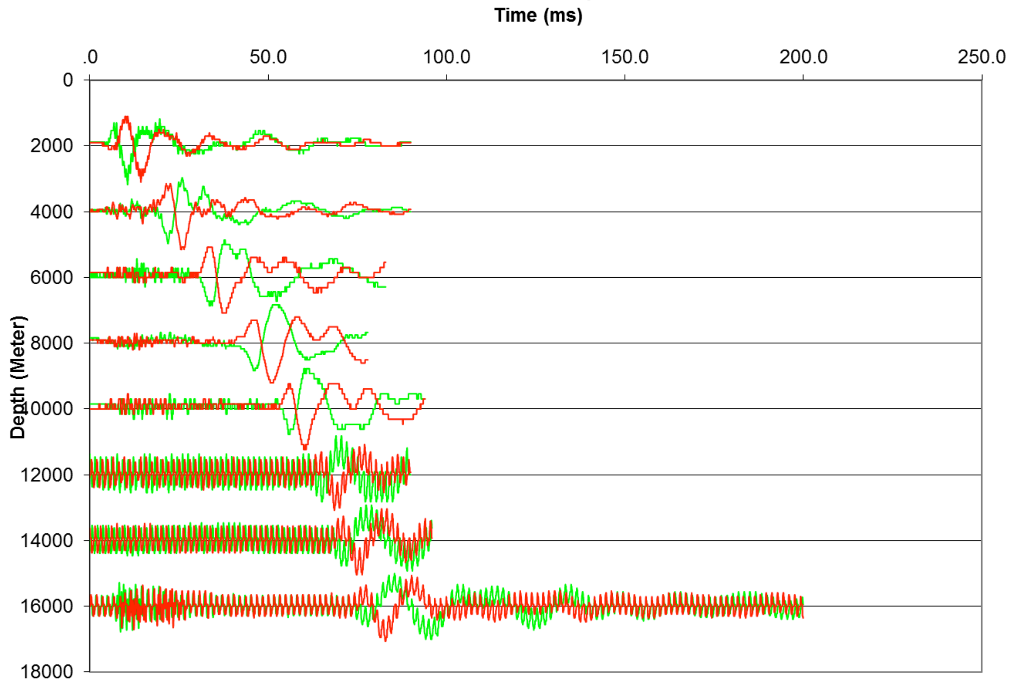

Figure 7. Shear wave velocity measurements acquired during CPT sounding. Shown is the time (ms) versus depth (m) for shear waves polarized in oppisite directions to determine first arrival.

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