

Liquefaction Assessment Using the CPT and Accounting for Soil Aging

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Abstract – Due to its continuous data recording capability, excellent repeatability and accuracy, relatively low cost and simplicity of operation, the cone penetration test (CPT) offers enhanced liquefaction assessment over its predecessor the standard penetration test (SPT). However, soil ageing, which influences the cyclic resistance ratio (CRR), is difficult, if not impossible, to be detected by the CPT due to disturbance during the test. This situation may lead to excessively conservative estimation of CRR values which result in conservative assessment of liquefaction potential. This paper presents and discusses liquefaction assessment using the CPT and methods for accounting for soil ageing. A field study, conducted at Gillman, South Australia, is presented and the study site is assessed for liquefaction potential. This paper also explores the influence of soil ageing on the subsequent liquefaction assessment using a magnitude earthquake of up to 7.5.

Keywords - cone penetration test, liquefaction, soil aging.

Introduction

Liquefaction causes significant damages to structures (Khoshnevisan et al., 2015; Liu et al., 2016; Lu, 2016; Verdugo et al., 2015). Initially, the procedure for liquefaction evaluation based on the cone penetration test (CPT) was derived from a correlation between the CPT and the standard penetration test (SPT). However, the US National Center for Earthquake Engineering Research (NCEER) has identified CPT as a prime candidate for reconnaissance exploration and indicated that the CPT could be used to develop preliminary liquefaction resistance profiles for site investigations (Martin & Lew, 1999). This is due to main improvements since the electric CPT was introduced, namely the ability of the equipment to eliminate errors caused by friction between the inner and outer rods; longer continuous testing – up to 1 metre length with a steady rate of penetration that minimises undesirable soil movement; and more reliable measurements (Muhs, 1978 in Lunne et al., 1997). Conversely, Sladen (1989), Yu et al. (1997), Robertson & Wride (1998) and Marchetti (1999) cited by Totani et al. (2001), warned that the CPT-based liquefaction assessment might incorporate errors because the cone is not sensitive to the age of sand deposits. Furthermore, several researchers, such as Pike (2003), Leon et al. (2006) and Andrus et al. (2009), found that the ability of soil to resist liquefaction increases with age. A study by Leon et al. (2006) in sand deposits found that ignoring age effects underestimated the cyclic resistance ratio (CRR), which is a crucial parameter in liquefaction assessment, by as much as 60%.

In 2008 Hayati et al. analyzed data from over 30 sites in 5 countries and proposed an aging correction factor, KDR, to incorporate the aging effect into the CPT-based liquefaction assessment. Since then there have been no further enhancements to this method. This paper examines the results of a field study to explore the CPT-based liquefaction assessment and how it is affected by soil age. In addition, a critical state approach and the seismic hazard history of the study site are used to verify the method.

Testing Program and Liquefaction Assessment Using CPT

The in-situ testing and sampling were conducted at a site in Gillman, South Australia, on soil deposits within the St. Kilda Formation (Figure 1a), which is very susceptible to liquefaction (Poulos et al.,

1996; Mitchell & Moore, 2007; Mitchell, 2009). The layout of the in-situ testing is shown in Figure 1b which has been arranged in such a manner as to avoid the disturbance of one test to another. There is a cluster of in-situ tests within a radius of 2 meters which consist of 3 CPTs and 2 continuous sampling bores. The results of the CPTs are summarized in Figure 1c. The continuous sampling was carried out to obtain the soil profile of the study site including its state parameter. The simplified soil profile derived from this sampling is incorporated in Figure 1c. The state parameter is presented later.

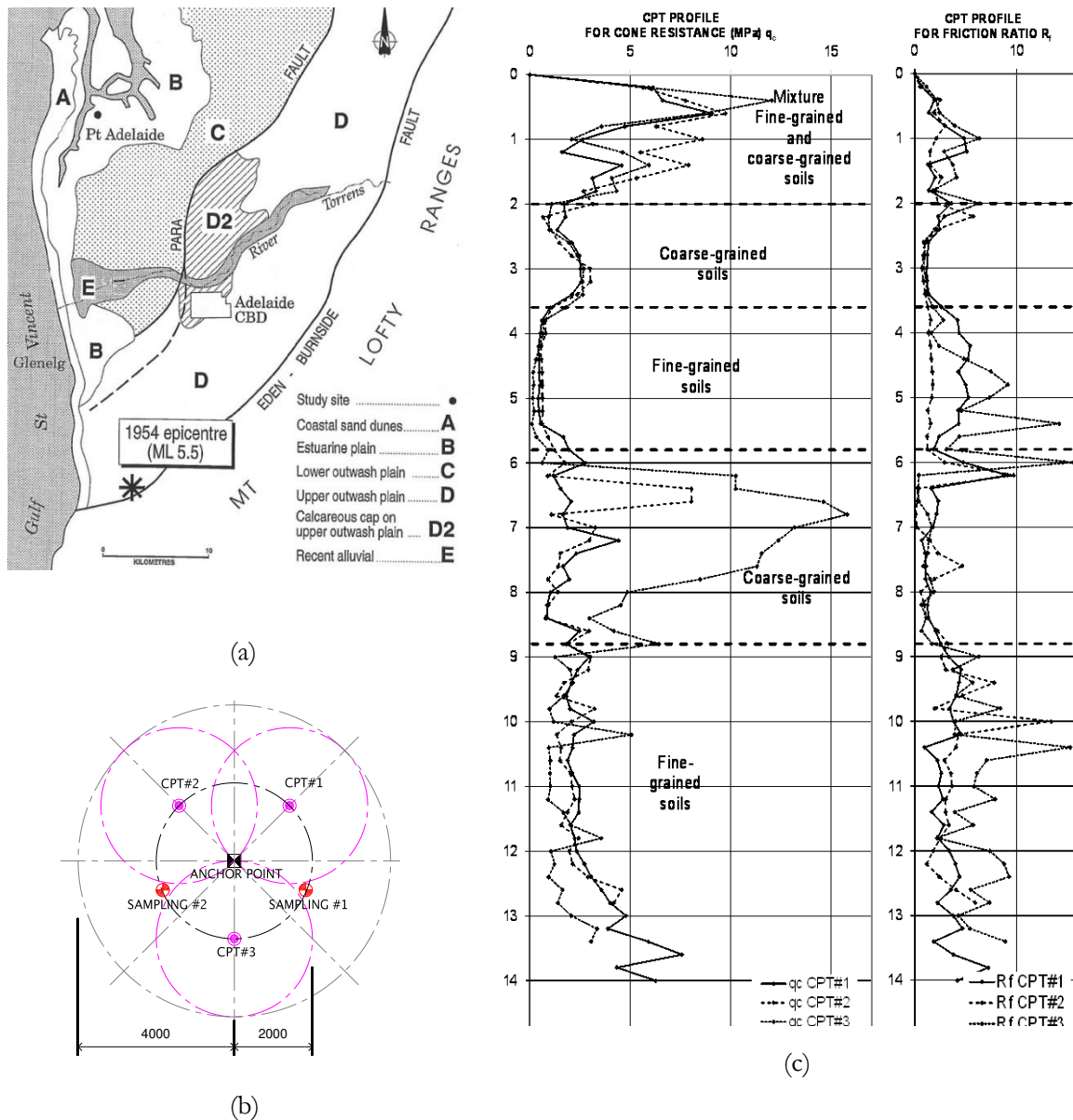


Figure 1. (a) Field study incorporating a general geological setting; (b) Layout of in-situ testing of the present study; and (c) CPT profile of the present study

Simplified Procedure Liquefaction Assessment Using the CPT

The most common procedure adopted around the world for liquefaction assessment is the "simplified procedure," originally developed by Seed & Idriss (1971). The simplified procedure requires the estimation of two primary seismic variables, namely the cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR) (Youd et al., 1998). The former can be determined using a formula developed by Seed and Idriss in 1971 (Youd et al., 1998; Andrus et al., 1999; Finn, 2001) which has since been modified by Hwang et al. (2004) and Idriss & Boulanger (2004), as follows:

$$CSR_{M=7.5}=0.65*(a_{max}/g)*(σ_{vo}/σ'_{vo})*(r_d/MSF) \quad (1)$$

where a_{max} is the peak horizontal acceleration at the ground surface generated by the earthquake; g is the acceleration due to gravity; $σ_{vo}$ and $σ'_{vo}$ are the total and effective vertical overburden stresses, respectively; r_d is a stress reduction coefficient/factor at a depth of interest; and MSF is the magnitude scaling factor for an earthquake of magnitude M (Boulanger & Idriss, 2015).

The adopted procedure to obtain the CRR using CPT data herein is consistent with the recommendations of the 1996 NCEER and 1998 NCEER/NSF Workshops. The CRR can be calculated using the following equations:

$$CRR_{7.5}=0.833[(q_{c1N})_{cs}/1,000]+0.05 \quad \text{if } (q_{c1N})_{cs} < 50 \quad (2)$$

$$CRR_{7.5}=93[(q_{c1N})_{cs}/1,000]^3+0.08 \quad \text{if } 50 < (q_{c1N})_{cs} < 160 \quad (3)$$

This method requires a normalized tip resistance to approximately 1 atm (100 kPa) and a fines content adjustment. The resulting CRR values using these approximations are shown in Figure 2 and indicated by the grey CRR curves without the effect of aging.

Accounting for Soil Ageing in Liquefaction Assessment Using the CPT

The age correction factor proposed by Hayati et al. (2008) was incorporated into the CRR values to obtain the new CPT-CRR curves including the influence of aging (*bold red curves*). The age of the soils was determined using amino-acid racemization, radiocarbon, and thermoluminescence dating by Burton (1984) and Daily et al. (1976).

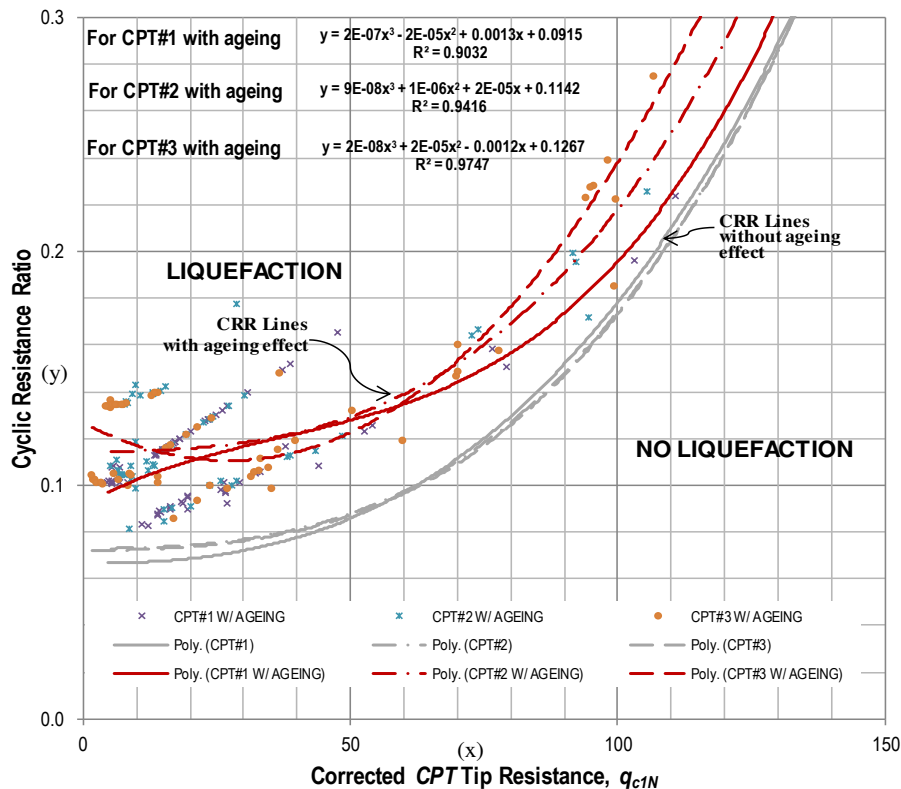


Figure 2. CPT cyclic resistance ratios with and without aging effect versus corrected tip resistance

Discussion of the Liquefaction Assessment Results

The results of the assessments presented in Figures 3 and 4 demonstrate that, as one would expect, an increase in earthquake magnitude results in an increase in the number of liquefiable soils at the

study site. The increase in earthquake magnitude will increase the intensity of cyclic loading. Therefore, an increase in the earthquake magnitude will result in further layers liquefying.

A soil type evaluation was carried out as outlined by Setiawan (2011) and it was found that there are two potential layers which may liquefy during an earthquake event at the study site. These two layers occur at approximate depths of 1.4 to 4.4 m and 6.4 to 9.0 m. A laboratory-based critical state parameter, ψ , liquefaction assessment was also undertaken, as outlined by Setiawan (2011), and this suggested that there are three, relatively thin, liquefiable layers. These occur at depths of 2.0 to 2.4 m, 4.0 to 4.6 m and 7.8 to 8.4 m and are contractive, as indicated in Figures 3 and 4. These analyses also suggest that it is unlikely that liquefaction will occur and be manifested at the ground level at the study site.

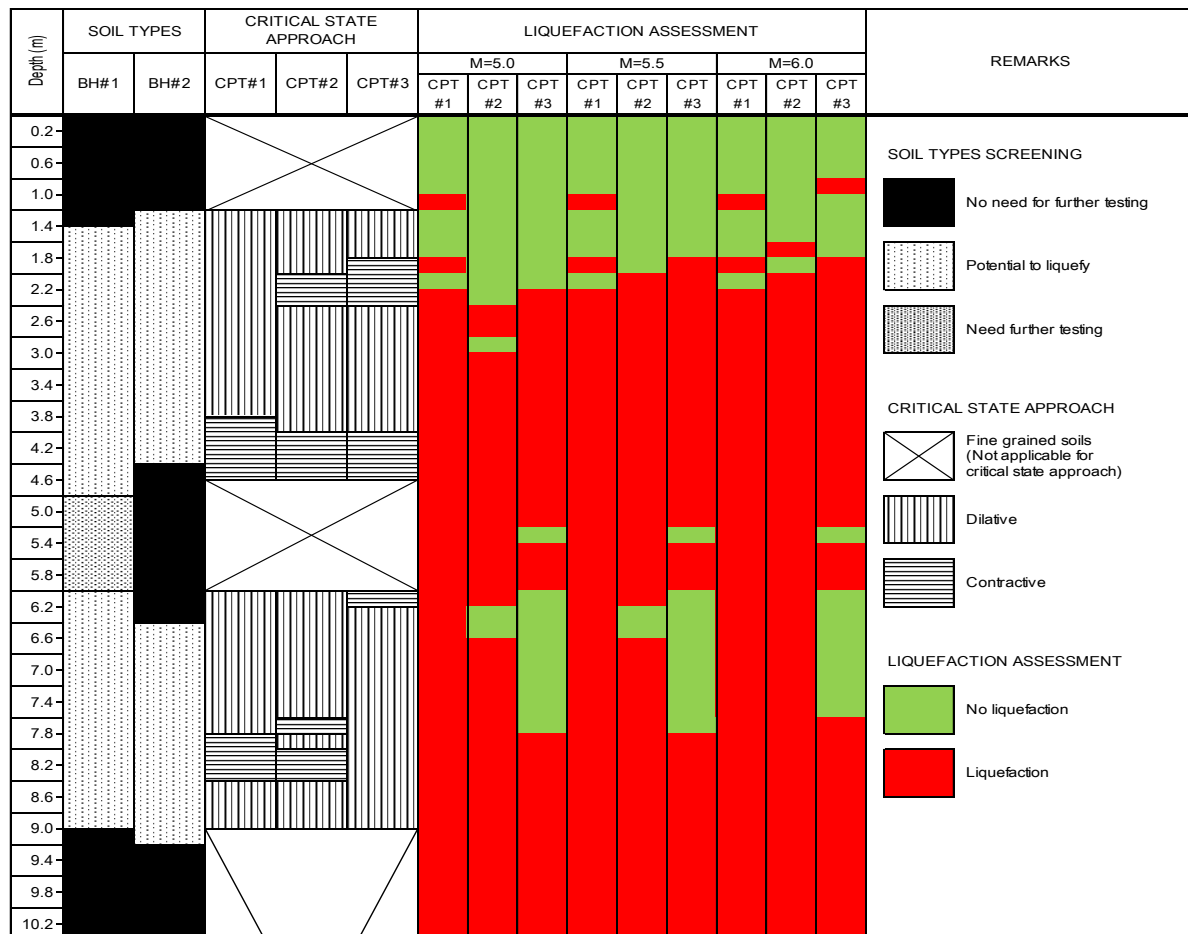


Figure 3. Comparison between the critical state approach and CPT liquefaction assessments without accounting for aging at Gillman, SA

CPT-based liquefaction assessments with and without the inclusion of aging soil show very different results, as indicated by Figures 3 and 4. The liquefaction assessments, which were based on the CPT method without the application of correction for soil aging, suggest that most soils of the St. Kilda Formation tend to liquefy in an earthquake of magnitude as low as 5.0. In contrast, the liquefaction assessment using the CPT method accounting for aging shows that the chances of liquefaction are insignificant for the soils at the study site when the earthquake magnitude is 5.5 or below. Liquefaction at the study site is only triggered by an earthquake of approximately magnitude 6.0 or beyond. The probability of the magnitude 6.0 or beyond is presented in Setiawan (2017).

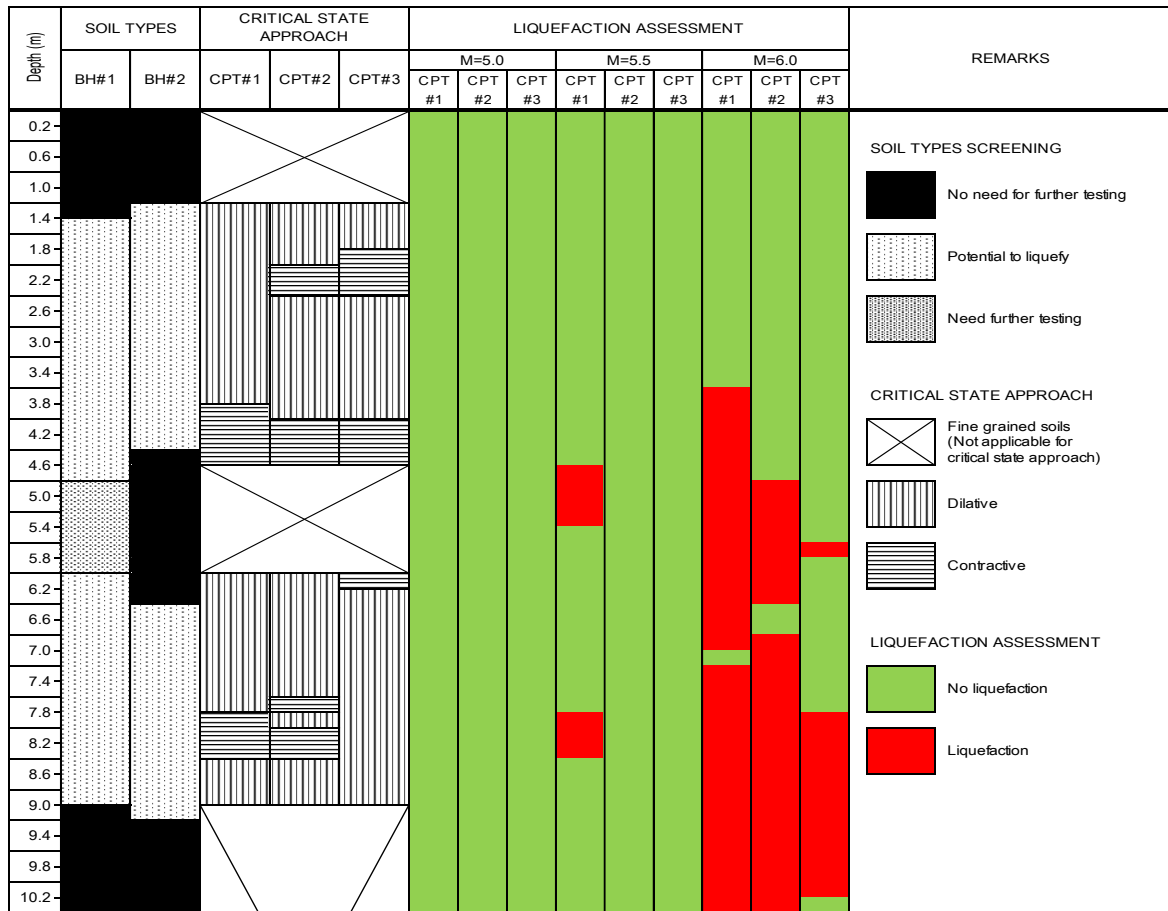


Figure 4. Comparison between the critical state approach and CPT liquefaction assessments accounting for aging at Gillman, SA

Furthermore, a recent study by Setiawan et al. (2018) suggests an amplification of up to 3.4 at Adelaide's regolith. These results indicate that the CPT-based liquefaction assessment accounting for soil aging has better agreement with the critical state liquefaction assessment approach than the CPT-based liquefaction assessment ignoring soil aging. In addition, the seismic hazard history of the study site also suggests that liquefaction accounting for aging is more appropriate. The nearest and strongest recorded earthquake in Adelaide occurred in 1954. The magnitude of the earthquake is estimated to be 5.5, and there is no liquefaction observed during the earthquake (Love, 1996). Thus, the liquefaction assessment demonstrates good agreement between the CPT liquefaction assessments accounting for the aging effects with the state parameter of the soil determined from laboratory testing and the seismic hazard history of the study site.

Conclusion

CPT data obtained at Gillman, South Australia study site was used to examine the liquefaction potential of the soils by employing the method recommended by the 1996 NCEER & 1998 NCEER/NSF Workshops. In addition, incorporating the aging correction factor proposed by Hayati et al. (2008) into the CPT-CRR recommended method was carried out. The results of both assessments, with and without accounting for aging were verified using the critical state parameter approach and the seismic hazard history of the study site. The results showed that the CPT-based liquefaction assessment method including aging yielded better predictions appropriate to the study site than the CPT-based method ignoring aging. In this study, an earthquake magnitude of up to 7.5 is used in the analysis..

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