# Liquefaction assessments of tailings facilities in low-seismic areas

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## Abstract

It is widely recognised that piezocone (CPTu) testing is a valuable technique for identifying the in situ engineering properties of tailings for use in stability and liquefaction assessments. Numerous empirical procedures have been developed to relate the results of piezocone testing to liquefaction potential. Appropriate assessments are particularly important for upstream raised tailings facilities which have an inherently higher risk of failure due to liquefaction following seismic events. This paper evaluates two commonly used procedures developed by Robertson (2010), and Idriss & Boulanger (2008) for determining liquefaction potential. These procedures calculate the factor of safety against liquefaction by comparing the cyclic resistance ratio (CRR) to the seismically induced cyclic stress ratio (CSR). During the design of an upstream raise to a tailings facility in Western Australia, it was found that Robertson's approach leads to improved estimates of the CRR by considering the influence of fines content. Idriss & Boulanger's recommendation of a cut-off value for earthquake magnitude scaling factors and magnitude-dependent stress-reduction coefficients offers a more conservative estimate of the CSR, particularly where the design earthquake magnitude is less than 7. The case study identified a gap between the methodologies for assessing the liquefaction potential for tailings facilities in areas with low seismicity that requires further research.

## 1. Introduction

Piezocone ($CPT_u$) testing is recognized as a valuable technique for identifying the in situ engineering properties of tailings. Continuous measurements enable profiling of the entire depth of tailings and foundation while identifying subtle changes in stratigraphy. The $CPT_u$ is particularly useful for evaluating the potential for soil liquefaction which requires a strong understanding of the soil stratigraphy and in-situ properties of the tailings.

Numerous empirical methods have been developed to relate the results of field $CPT_u$ testing to liquefaction potential. Most methodologies assess liquefaction potential by comparing an estimation of a seismically-induced cyclic stress ratio (CSR) to the cyclic resistance ratio (CRR) of the material. For the purposes of this paper, two commonly used procedures developed by Robertson (2010), and Idriss & Boulanger (2008) will be compared through the assessment the liquefaction potential for the design of an upstream raise to an existing tailings storage facility (TSF) in Western Australia.

## 2. METHODOLOGIES FOR ASSESSING LIQUEFACTION POTENTIAL

### 2.1 Overall approach

Both the Robertson and Idriss & Boulanger methods evaluate liquefaction potential using a deterministic relationship expressed as a Factor of Safety (FoS). The FoS is defined as the ratio of CSR to CRR calculated for a magnitude 7.5 earthquake, and scaled to the design earthquake by a magnitude scaling (MSF) factor, as summarised in Equation 1 below:

$$FoS = \frac{CRR}{CSR} \times MSF \qquad (1)$$

No liquefaction is expected when FoS is greater than 1, and a material is deemed potentially liquefiable when FoS is less than 1.

### 2.2 CSR and stress reduction coefficient, $r_d$ calculation

Both methods calculate CSR based on the simplified approach, originally proposed by Seed and Idriss (1971), as shown in Equation 2 below:

$$(CSR)_{7.5} = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65\left(\frac{\sigma_{v0}a_{max}}{\sigma'_{vo}}\right)r_d \qquad (2)$$

where $\tau_{av}$ is the average cyclic shear stress, $\sigma_{v0}$ is the total vertical overburden stress, $\sigma'_{v0}$ is the effective vertical overburden stress, $a_{max}$ is the maximum horizontal acceleration of the ground surface, and $r_d$ is a stress reduction factor. The constant 0.65 factor is used to convert the peak cyclic shear stress ratio to a cyclic stress ratio that is representative of the most significant cycles over the full duration of loading. The calculation of $r_d$ differs between the Robertson and Idriss & Boulanger methods. The former estimates $r_d$ using depth-dependent relationships (Equation 3), whereas the latter expresses $r_d$ as a function of both depth and earthquake magnitude (Equation 4).

$$r_d = 1.0 - 0.00765z \qquad \text{(if z < 9.15 m)} \qquad (3a)$$

$$= 1.174 - 0.0267z \qquad \text{(if 9.15 m < z < 23 m)} \qquad (3b)$$

$$= 0.744 - 0.008z \qquad \text{(if 23 m < z < 30 m)} \qquad (3c)$$

$$= 0.5 \qquad \text{(if z > 30 m)} \qquad (3d)$$

$$\ln(r_d) = \alpha(z) + \beta(z)M \qquad \text{(if z} \leq \text{34 m)} \qquad (4a)$$

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right) \qquad (4b)$$

$$\beta(z) = 0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right) \qquad (4c)$$

$$r_d = 0.12\exp(0.22M) \qquad \text{(if z > 34 m)} \qquad (4d)$$

where z represents the depth below surface. The implication on the overall factor of safety against liquefaction is described later in the paper.

### 2.3 CRR calculation

Both methods express CRR as a function of the $CPT_u$ cone resistance, $q_t$, where the CRR-$q_t$ relationship is derived from historical cases of liquefaction occurrences. The Idriss & Boulanger method has been developed for clean, cohensionless soils with fines content (FC) below 5%. For a known FC, the method provides a fines correction. This correction becomes constant for FC values greater than 35%. The Robertson method adjusts the measured $CPT_u$ cone resistance by a correction factor, $K_c$ that accounts for the effect of both fines content and plasticity of the material. Both methods employ an iterative approach to determine CRR. A summary of the calculation procedure is shown in Figures 1 and 2 that follow.

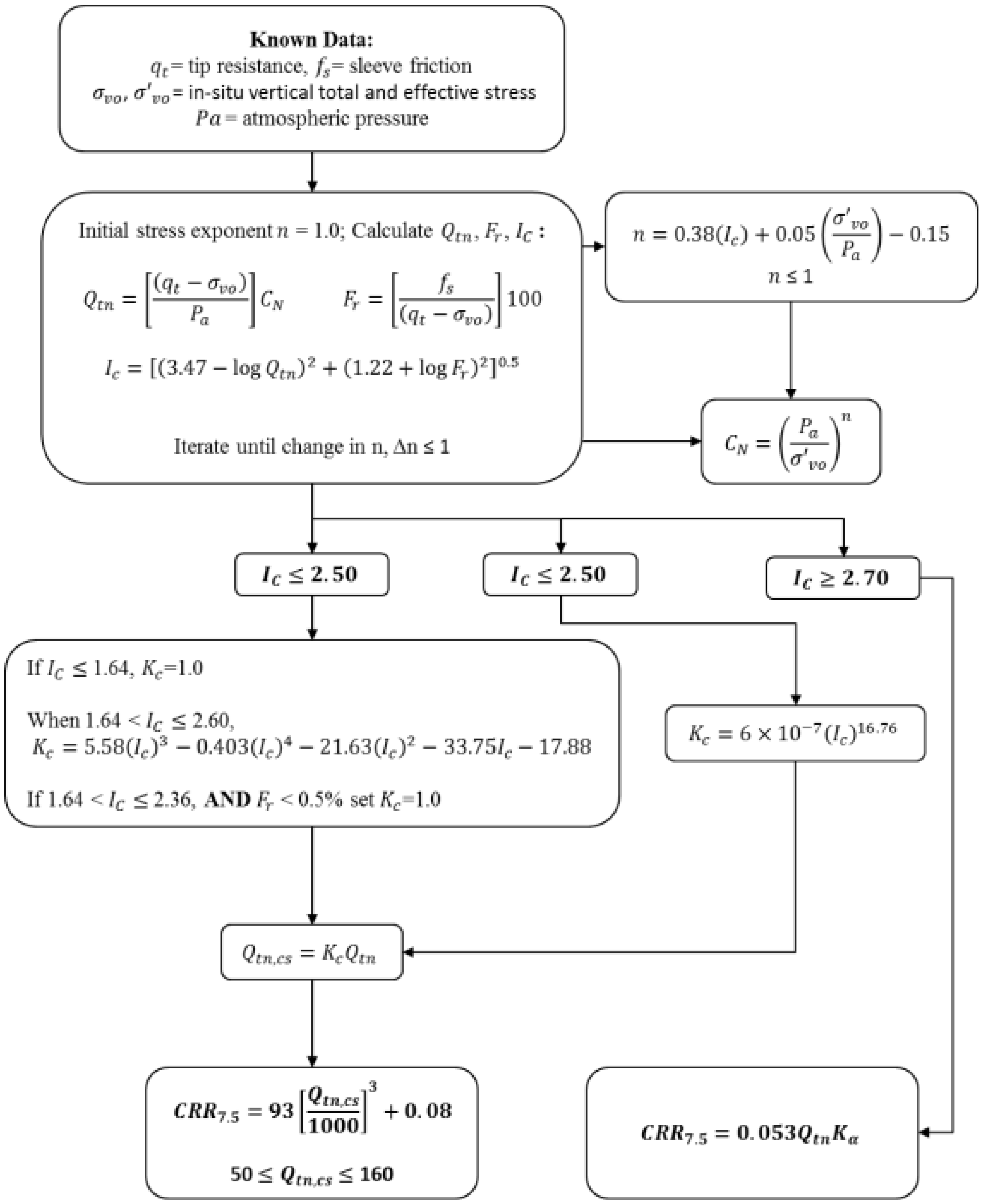


Figure 1. Flow chart to determine $CRR_{7.5}$ after Robertson 2009

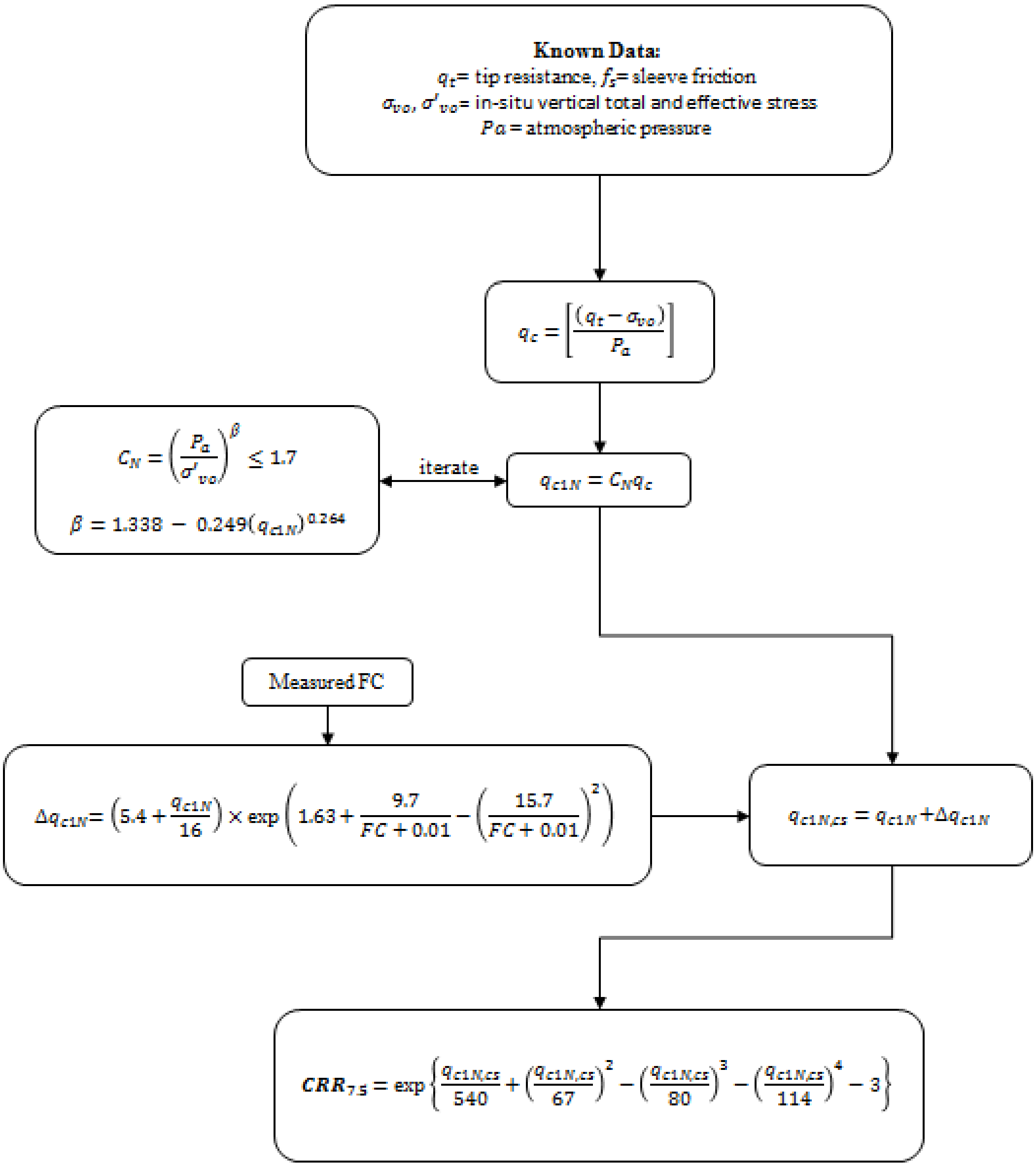


Figure 2. Flow chart to determine $CRR_{7.5}$ after Idriss & Boulanger 2008

### 2.4 Magnitude scaling factor, MSF

The MSF is used to scale the CSR estimated for a magnitude 7.5 earthquake to the design earthquake magnitude. The Idriss & Boulanger method used to calculate MSF is shown in Equation 5, and the Robertson method is shown in Equation 6. Idriss & Boulanger limit MSF to a maximum value of 1.8 for earthquake magnitudes less than 5.25.

$$MSF = 6.9\exp\left(\frac{-M}{4} - 0.058\right) \leq 1.8 \quad (5)$$

$$MSF = \frac{174}{M^{2.56}} \quad (6)$$

MSF and $r_d$ must be determined using consistent methodology. Idriss & Boulanger's magnitude-dependent $r_d$ will decrease with reduced design earthquakes and the associated MSF will increase. Robertson's $r_d$ is not related to earthquake magnitude and the total earthquake effect is represented in the MSF.

# 3. CASE STUDY

## 3.1 General

The TSF presented in this case study is a ring-dyke facility with tailings deposited through perimeter spigots. The TSF is located in the Yilgarn region of Western Australia and stores tailings from a nickel-sulphide operation. An upstream raise utilising *in-situ* tailings as the primary construction material was designed to accommodate the tailings production for the remaining life of mine. The potential for liquefaction of the embankment raise foundation was a key consideration for the design and a liquefaction assessment was carried out to confirm the suitability of an upstream raise.

## 3.2 Seismic Setting

There is limited information on seismic activity for the TSF site on which to base the $a_{max}$. The Earthquake Hazard Map of Western Australia (2003) presented in AS1170.4 (2007) recommends acceleration coefficients of between 0.08 and 0.09 g which corresponds to an event with a 1 in 500 annual exceedence probability.

A review of regional seismic events using data from the Geoscience Australia online Earthquake Centre (http://www.ga.gov.au/earthquakes/home.do) was undertaken to determine the magnitude and frequency of previous earthquake events in the region. The database was analysed for seismic events within the time period 1900 to 2012, and within a 300 $km^2$ radius of the project site. The results are presented in Figure 3.

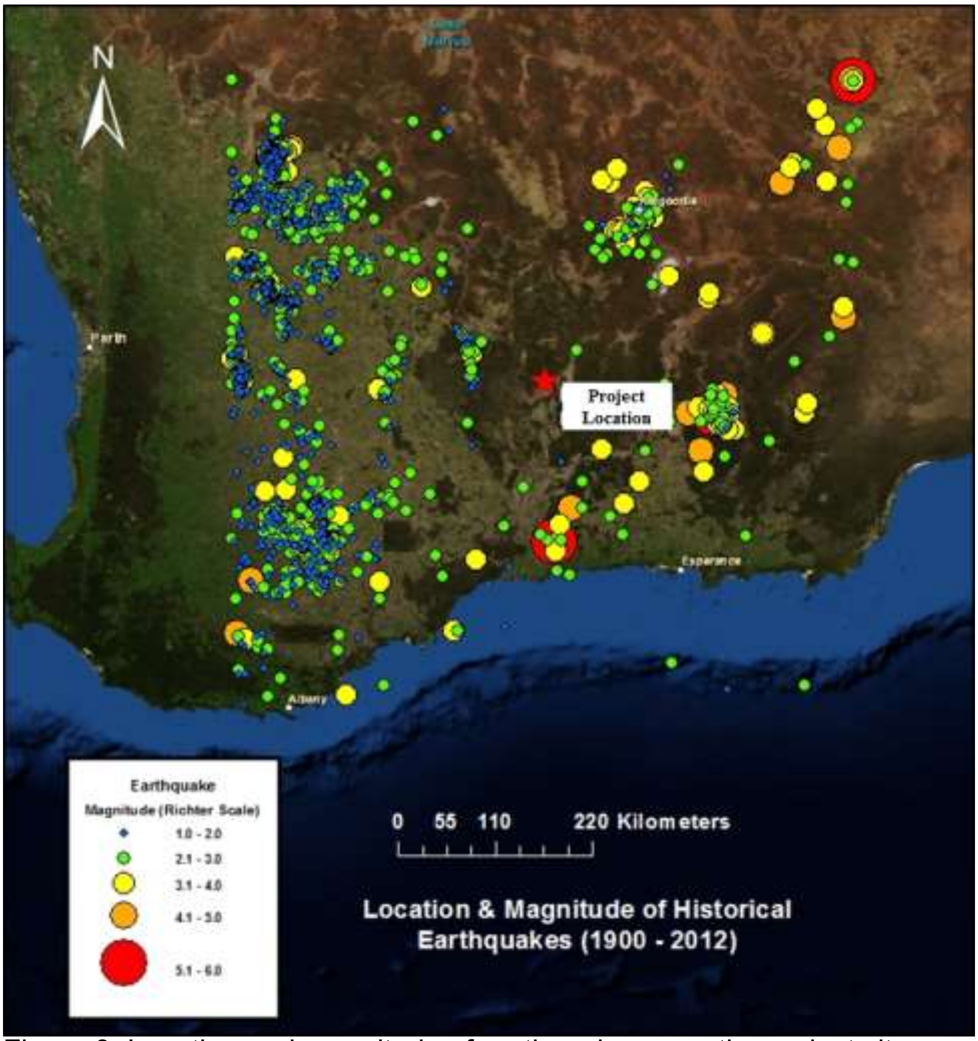


Figure 3. Location and magnitude of earthquakes near the project site.

The Richter magnitudes vary between 1.0 M and 5.6 M. Historical earthquake occurrences are clustered in two areas, around 200 km NE and approximately 175 km E of the project site. There are numerous earthquake occurrences to the west of the project site, though most of these earthquakes are of magnitude 3.0 M or less. The closest recorded seismic event, with a magnitude of 2.6 M, occurred at a distance of 43 km from the project site in April 2009.
In the absence of a site-specific seismic study the design earthquake magnitude was conservatively adopted as 5.0 M.

### 3.3 Results of the liquefaction assessment

Two $CPT_u$ tests were undertaken in 2012, with CPT-1 tested on the tailings beach approximately 8 m from the existing embankment crest and CPT-2 tested 20 m further down the beach. The results of the liquefaction assessment for the two test sites are shown in Figure 5 below.

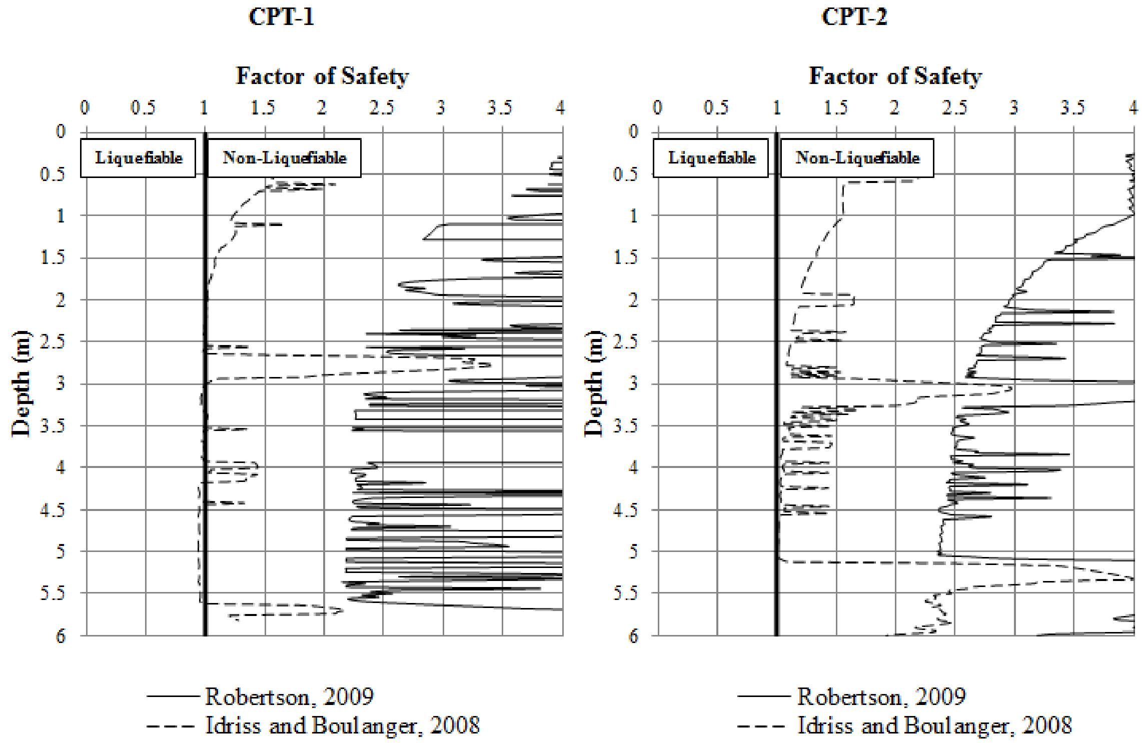


Figure 5. Results of the liquefaction assessment expressed as factors of safety

It can be observed that the Robertson method results in a significantly higher estimate of the FoS, generally 2 to 2.5 times the FoS determined using the Idriss & Boulanger method. Therefore the outcome of the liquefaction assessment is sensitive to the method selected for the analysis. Despite using different relationships to determine $r_d$, the relatively shallow depth of the TSF and low seismic parameters result in similar $r_d$ values which in turn yield comparable CSR estimates for both methods. The difference in FoS is therefore attributed to the variations in the CRR and MSF relationships. In low-seismic areas the difference is dominated by MSF and the CRR has a small contribution.

### 3.4 CRR calculation comparison

The range of CRR values calculated using both the Robertson and Idriss & Boulanger methods are shown in Table 1. The Robertson method consistently results in higher estimates of CRR.

Table 1. Range of CRR values calculated by Robertson and Idriss & Boulanger methods

| Method | Highest CRR | Lowest CRR | Median CRR |
|---|---|---|---|
| Robertson | 0.19 | 0.06 | 0.08 |
| Idriss & Boulanger | 0.08 | 0.05 | 0.06 |

The CRR determination is largely dependent on the measured cone tip resistance, corrected for atmospheric pressure and *in-situ* vertical total and effective stresses. The Robertson method includes a correction for the combined influence of particle size and plasticity which accounts for the higher calculated values of CRR. Numerous studies have identified these two parameters as key criteria for evaluating liquefaction potential.

A limited sampling program was carried out at the same time as the $CPT_u$ probing, with samples taken approximately 0.5 m below the surface. Six samples were tested for particle size distribution (PSD), three samples were taken next to CPT-1 and three samples next to CPT-2. The results of the PSD testing showed no evidence of segregation between the two test areas, and the average fines content from all four tests provides a good correlation to the apparent fines content determined through the Robertson method (Table 2).

Table 2. Comparison of apparent fines content to laboratory-tested fines content

| Test Location | Apparent Fines Content | PSD Fines Content |
|---|---|---|
| CPT-1 | 62 % | 63% |
| CPT-2 | 65% | |

The full PSD curves of the samples were compared to Ishihara et al.'s 1980 envelope of tailings susceptible to liquefaction (Fig 6).

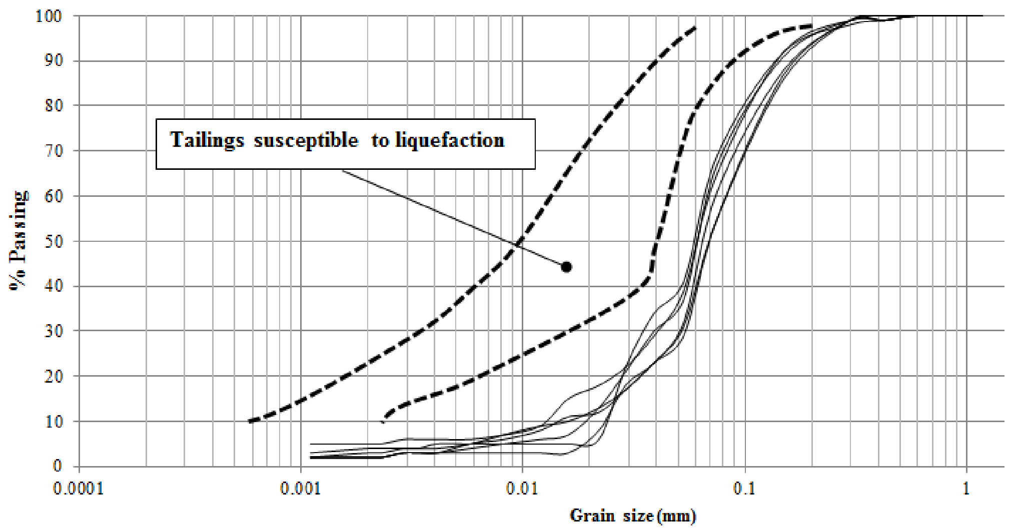


Figure 6 Tailings samples plotted against tailings liquefaction envelope after Ishihara, 1980.

On the basis of PSD alone, the tailings are expected to be non-liquefying suggesting that CRR values calculated using the Idriss & Boulanger method may be conservative. There are no plastic or liquid limit tests available to confirm this hypothesis on the basis of plasticity; however the tailings are classified as being non-plastic.

Direct comparisons cannot be made between the Idriss & Boulanger and Robertson methods as the overall CRR calculated is largely dependent on how the normalization of $q_c$ for total and effective stresses and influence of fines is carried out (see Figs. 1 and 2).

Idriss & Boulanger's method has been largely developed from SPT data, which may further contribute to the difference in CRR values. A 2010 study by Seed performed a comparison with Idriss & Boulanger's 2008 SPT and CPT-based methods. Although these methods were developed to be compatible, Seed states that the CPT correlation is approximately 35% more conservative than the SPT-based correlation for $q_c$ values less than 50kPa (Seed, 2010). Another study (Liao, 2010) discovered further discrepancies between the CPT and SPT-based methods for tip resistances in the range of 50 kPa $\leq q_c \leq$ 150 kPa, but in this case the SPT-based method was found to be more conservative. Idriss & Boulanger's fines correction requires known fines content from adjacent samples or, when samples are not available, relies on determinations from other methods. It is understood that rigorous sampling helps calibrate and improve the accuracy of CPT methods; however the need for sampling reduces some of the main advantages of the CPT (principally continuous data and speed) over other methods such as the SPT.

### 3.5 MSF calculation comparison

The MSF was found to be the dominant parameter for influencing FoS. The MSF relationship to earthquake magnitude is shown in Figure 7 for both the Robertson and Idriss & Boulanger methods using Equations 5 and 6. The Idriss & Boulanger MSF is limited to 1.8 for earthquake magnitudes less than 5.25 M.

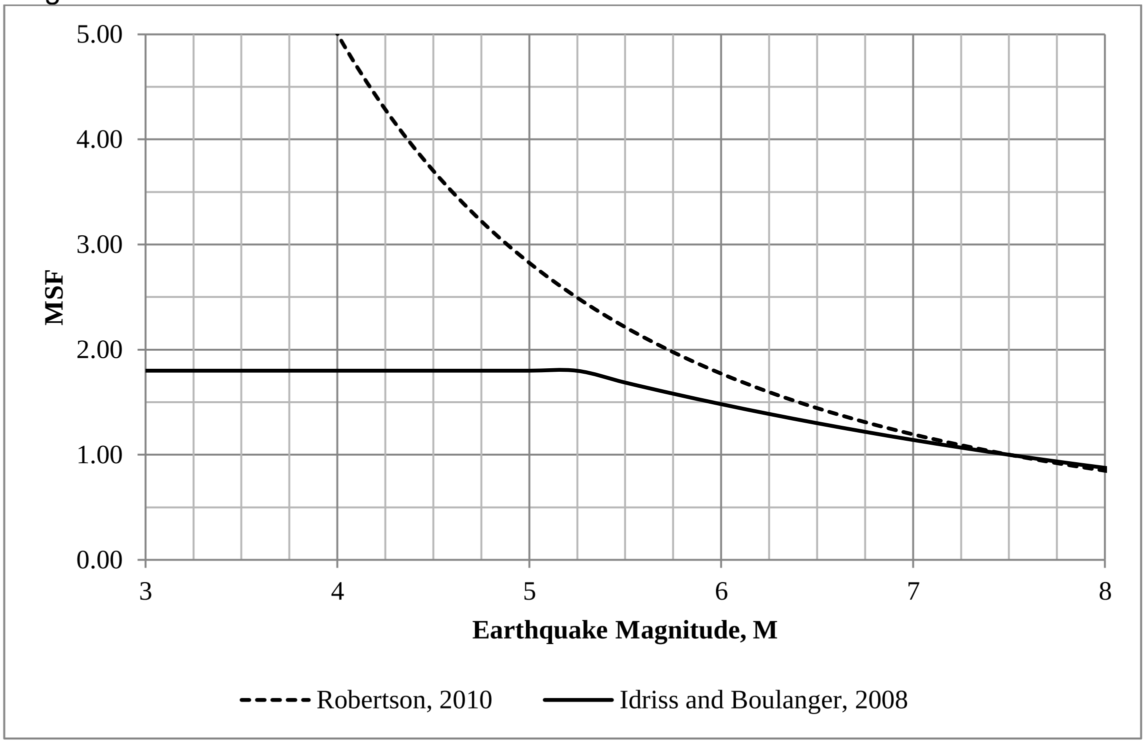


Figure 7 MSF comparison

For earthquake magnitudes 7.0 M or greater, both methods produce similar MSF values. As the earthquake magnitude decreases below 7.0 M, the difference between methods increases, with Robertson's method yielding larger MSF values. Applying the Robertson method in low-seismic areas will result in proportionally large MSF fluctuations for small changes in earthquake magnitude. As the MSF has a substantial influence on the overall FoS against liquefaction, Robertson's MSF relationship appears overly optimistic relative to the Idriss & Boulanger method, especially for areas where no site-specific seismic study has been undertaken to confirm the design earthquake.

## 4. SUMMARYOF RESULTS

A simple sensitivity analysis found MSF to have the greatest influence on FoS in the case study. The MSF is also the parameter with the least amount of confidence because it is exclusively dependent on the design earthquake magnitude. Using the Robertson method, increasing the design earthquake to 6 M decreases the FoS by 37% and decreasing the design earthquake to 4 M increases the FoS by 77%. For this case study, the Robertson method of calculating CRR is thought to provide an adequate representation of the fines influence, however his MSF relationship gives large variations for small changes to the earthquake magnitude. As a result, the Robertson method appears more suited to sites within medium-to-highly seismic areas. The fines correction by Idriss & Boulanger only considers fines content determined through laboratory testing or empirically using relationships derived by others, instead of the overall material behavior and is therefore only suitable for evaluating clean sands.

# 5. CONCLUSIONS

In the case study, the Robertson method resulted in significantly higher estimates of FoS than the Idriss & Boulanger method consistently across the entire profile; however this may not necessarily be the case for different projects. In general, the Robertson method is thought to provide a better representation of the effect of fines on soil behavior than the Idriss & Boulanger method. The Robertson method is preferable as it is not dependent on adjacent sampling and considers both $f_s$ and $q_c$ measurements to account for both particle grading and plasticity influences. The disadvantage of the Robertson method is the large fluctuations of MSF with small changes to the design earthquake affecting the overall FoS. Therefore the Robertson method appears more suitable for evaluating sites with silty and clayey material subject to medium to strong earthquake ground motions and the Idriss & Boulanger method is more suited to sites with clean sands subject to any earthquake magnitudes.

Each method has been developed with interdependencies within parameters and with the intention that all parameters be calculated using consistent methodology. Therefore the applicability of each method should be carefully assessed before use in a liquefaction assessment.

The case study identified an information gap between the methods that resulted in large variations of FoS. More research and site-specific test data is needed to adequately assess liquefaction potential, especially for tailings in low-seismic areas. When there is a discrepancy between reputable methods and site-specific data is scarce, general practice is to adopt the more conservative approach. Great benefits to cost and time savings could be achieved through a reduction to over-conservative designs by refining the methods to suit tailings facilities in low-seismic areas.

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