Liquefaction Mitigation using Rapid Impact Compaction and a Comparison of SPT and CPT Confirmation Testing

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ABSTRACT
The East Quadrant Water Distribution System in Kemptville, Ontario was expanded in 2014 to include a new pump station and at-grade water silo. The geotechnical investigation for the expansion identified a 2.3 m to 3.4 m thick layer of potentially liquefiable sand. Rapid Impact Compaction (RIC) was specified to densify the sand layer, thereby increasing the factor of safety against liquefaction to be confirmed using Standard Penetration Testing (SPT). After completing the SPT confirmatory testing, the resulting SPT N60 values were found to have a wide range of results. Cone Penetration Testing (CPT) was carried out to supplement the SPT results. This paper discusses the use of RIC to densify the sand layer within a 5 m radius of the new structures and compares the results of both the SPT and CPT confirmatory testing.

RÉSUMÉ
Le système de distribution d'eau dans le Quadrant, situé à Kemptville, en Ontario, a été élargi en 2014 pour inclure une nouvelle station de pompage et un silo d'eau à niveau. L'étude géotechnique pour l'agrandissement a identifié une couche de sable potentiellement liquéfiable de 2,3 à 3,8 m d'épaisseur. Un compactage à impact rapide (RIC) a été requis pour densifier la couche de sable, ce qui augmente le facteur de sécurité contre la liquéfaction, qui sera confirmé en utilisant le test de pénétration standard (SPT). Après l'achèvement de l'essai de confirmation SPT, il a été trouvé que les valeurs SPT N60 ont un large éventail de résultats. Un essai au pénétromètre (CPT) a été réalisé pour compléter les résultats du SPT. Ce document traite de l'utilisation du RIC pour densifier la couche de sable dans un rayon de 5 m des agrandissements et compare les résultats des deux essais de confirmation du SPT et du CPT.

1 INTRODUCTION

With the increase in Peak Ground Accelerations (PGA) in the 2005 National Building Code of Canada (NBCC), the potential for liquefaction of soils has become greater and improved methods of liquefaction mitigation and soil investigation to assess the potential for liquefaction are needed.

Rapid Impact Compaction (RIC) provides liquefaction mitigation by densifying potentially liquefiable soils through the use of controlled dynamic compaction. The results of the densification, in Canada, are generally confirmed through the use of Standard Penetration Tests (SPTs), performed as per ASTM D1586. Given that the soils to be densified by RIC are generally sandy soils under the ground water table, there is potential for disturbance during borehole drilling resulting in erroneous SPT results, and consideration should be given to the use of alternative testing methods which are less prone to disturbance during testing such as Cone Penetration Testing (CPT).

1.1 Project Description

The East Quadrant Water Distribution System in Kemptville, Ontario was expanded in 2014 to include a 98 m^2 well building and a 14.5 m diameter storage reservoir with plans for an additional 14.5 m diameter storage reservoir to be constructed in the future.

The site is located in the Ottawa region, a moderate seismically active area. The overburden soil at the site consist of sands below the groundwater table that may be liquefiable during a significant seismic event.

1.2 Subsurface Conditions

A subsurface investigation was completed at the site. The results of the investigation revealed the subsurface conditions generally consist of compact to very loose sand that extends down to about elevations of 87.1 m to 87.7 m. The SPT ‘N’ values recorded in the sand layer were of Weight of Hammer to 16 blows for 300 mm of penetration, as shown in Figure 1. The sand is underlain by 1 m to 1.2 m thick layer of stiff to very stiff silty clay over compact to very dense sandy silt till. Limestone bedrock was encountered below the till deposit at about elevation 85.3 m to 85.6 m.

A standpipe piezometer was installed in one of the boreholes advanced at the location of the well building and storage reservoirs. Groundwater was measured to be between elevations 89.8 m and 89.6 m in the piezometer.

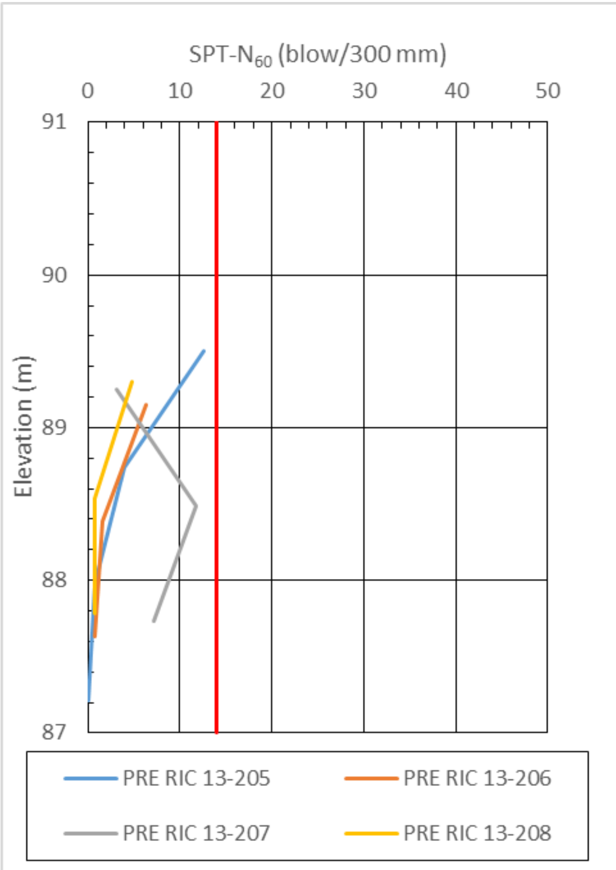

Figure 1. Pre-RIC SPT-N_{60} values by SPT Methods

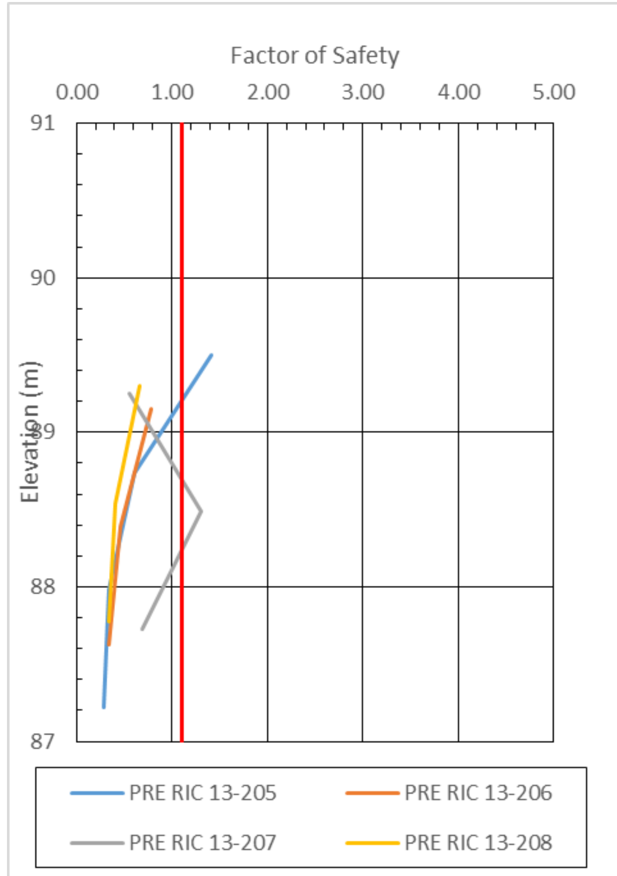

Figure 2. Pre-RIC factor of safety against Liquefaction based on SPT Methods

1.3 Seismic Considerations

The project site is underlain by very loose to compact saturated sand, and is located in a moderate seismically active area. Given this, the potential for liquefaction of the saturated sandy soils needed to be evaluated.

An assessment of the liquefaction potential was carried out using the Seed and Idriss (1971) simplified procedure, considering an area specified earthquake magnitude of 6.2 and a peak ground acceleration (PGA) of 0.38 g. The assessment resulted in Cyclical Stress Ratios (CSRs) of 0.25 to 0.36 and Cyclical Resistance Ratios (CRRs) of 0.10 to 0.35 corresponding to a factor of safety against liquefaction of 0.3 to 1.4 suggesting the saturated sandy soils are potentially liquefiable. A liquefaction settlement analysis was then carried out estimating total settlement in the order of 100 to 200 mm.

This amount of liquefaction settlement was considered unacceptable, and densification of the sandy soils was recommended to mitigate the potential for liquefaction settlement. In addition to the liquefaction settlement, the unimproved soil would result in a Seismic Site Class F as per the 2012 Ontario Building code. Upon densification to a minimum SPT 'N_{60}' value of 14 blows per 300 mm of penetration or greater, the Site Class could be increased to Seismic Site Class D.

1.4 Liquefaction mitigations

In order to eliminate the potential for liquefaction and increase the seismic site class, RIC was specified to provide densification of the saturated sandy soils. Analysis indicated an increased Standard Penetration Test blow count (SPT 'N_{60}' value) of 14 blows per 300 mm of penetration or greater was required to increase the factor of safety against liquefaction to 1.1.

The densification was to be confirmed by drilling three (3) confirmatory boreholes to a minimum elevation of 87.0 m and carrying out SPT testing at every 0.75 m. Time for aging of the sand was not permitted. Aging of sand following dynamic ground improvement methods has been widely studied and aging generally increases penetration resistance following ground improvement techniques (Schmertmann 1991).

2 RAPID IMPACT COMPACTION

The RIC System is an effective means of providing densification of various types of soil. Controlled impact compaction of the soil is achieved by using a 7.5 to 9 ton weight that is dropped 1.2 m (4 feet) on to a 1.5 m (5 foot) diameter tamper capable of imparting 40 to 60 blows per minute.

RIC increases the bearing capacity and stiffness of soils through controlled repeated impact loading. Controlled impact loading is important since it allows deflection to be monitored per blow to confirm when compaction of the soil is complete (i.e. determining when additional blows will not be effective). A 3 m by 3 m grid (10ft x 10 ft) followed by subsequent passes that tighten up the pattern, as needed (see Figure 3).

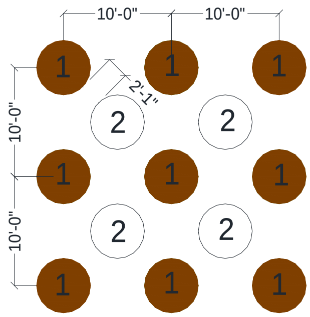

Figure 3. RIC hit pattern

RIC has been successfully used in gravel, sands, and miscellaneous fills consisting of sand, silt, and clays and industrial and mine waste fills. The depth of influence and soil improvement will vary based on soil type, but in general RIC improves soils to depths of up to 6 m (20 feet).

Figure 4. Picture of RIC rig

2.1 RIC for the East Quadrant Water Distribution Project

For this project the RIC densification was taken to a distance of 5 m outside the structures footprints and was planned to be completed in 2 passes; however, computer feedback had shown possible inadequate densification of several areas of the site following the second pass resulting in the need for a third pass for portions of the site. The use of the on board computer data allowed for targeted re-compaction where results appeared inadequate after a given RIC pass. RIC has a tendency to "even out" a site that may have natural variations (in the case of a loose native sand deposit) or unnatural variations (in the case of sandy fills).

2.2 RIC Quality Control

Quality control (QC) data was recorded by the RIC on board computer, which showed average blows of 28, an average final set of about 9 mm/blow, and an average total penetration of about 340 mm. To supplement the data recorded by the computer, pre and post-elevation survey was also completed at the site showing an average site drop of 425 mm due to the use of the RIC. Both the data recorded by the on-board computer and the results of the pre and post-elevation survey indicated that substantial densification of the sandy soils had occurred.

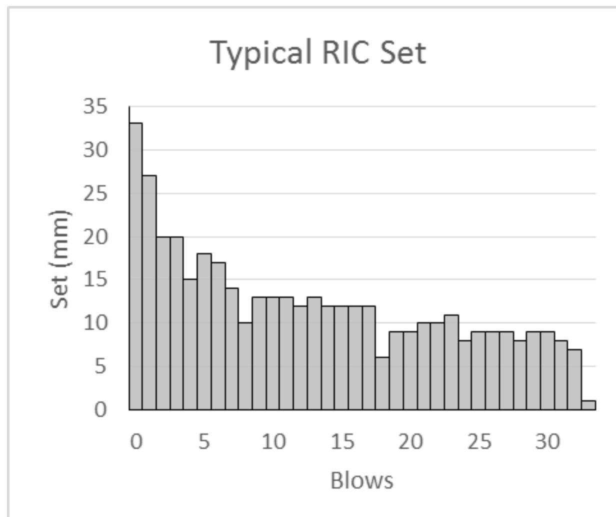

Figure 5. Typical RIC Set

3 CONFIRMATORY TESTING

As per the project specifications confirmatory testing was to be carried out by advancing three (3) boreholes through the saturated sandy soils performing SPT every 0.75 m. The results obtained via SPT were erratic and in areas did not meet the densification criteria of SPT-N60 greater than 14 blows per 300 mm of penetration (i.e. SPT-N values of greater than 18 blows per 300 mm of penetration uncorrected). Given the erratic SPT results, three (3) CPTs were carried out adjacent to the boreholes to supplement the SPT results.

3.1 Borehole and SPT Results

Three (3) post-RIC boreholes, numbered 14-1 to 14-3 were advanced to elevation 85.7 m to 86.7 m using washbore drilling techniques, and SPT was carried out at intervals of 0.75 m depth. The post-RIC SPT investigation was carried out on the same day that the completion of the final pass of RIC was completed and therefore no aging of the sand occurred.

The results of the post-RIC SPT showed increased 'N_{60}' values of 7 to 34 blows per 300 mm of penetration within the sand deposit.

The results, while showing that SPT'N_{60}' values increased by up to 15 blows per 300 mm with a large scatter of up to 3 to 22 blows per 300 mm, did not fully meet the required SPT 'N_{60}' value of 14 or greater.

Using the SPT confirmation method showed that the RIC improvement was unsuccessful at meeting the requirements of the specification for liquefaction mitigation.

Due to the large scatter and relatively low SPT'N_{60}' values, it was suspected that the sandy soil may have been disturbed from borehole drill operations resulting in the low SPT 'N_{60}' values. In order to confirm this data, CPT testing was carried out to supplement the boreholes.

3.2 CPT Results

Three (3) CPT's were carried out adjacent to the post-RIC boreholes and within a day of the completion of the final RIC pass, numbered CPT 14-1 to CPT 14-3, to supplement the SPT results. The results of the CPT showed tip stresses (Q_t) of 8.0 to 19.5 MPa.

In order to directly compare the borehole and SPT testing to the CPT, equivalent SPT 'N_{60}' values were determined from the measured CPT tip stress using the flowing empirical correlation of:

$$Q_t \,/\, \text{Empirical Ratio} = N_{60}\text{-value} \quad [1]$$

The empirical ratio of 600 for fine to medium grained sand (figure 4.2, Canadian Foundation Engineering Manual, 4th Edition). Equivalent SPT-N_{60} values of 19 to 69 blows per 300 mm of penetration were calculated, confirming the suspicion of disturbance during drilling of the boreholes.

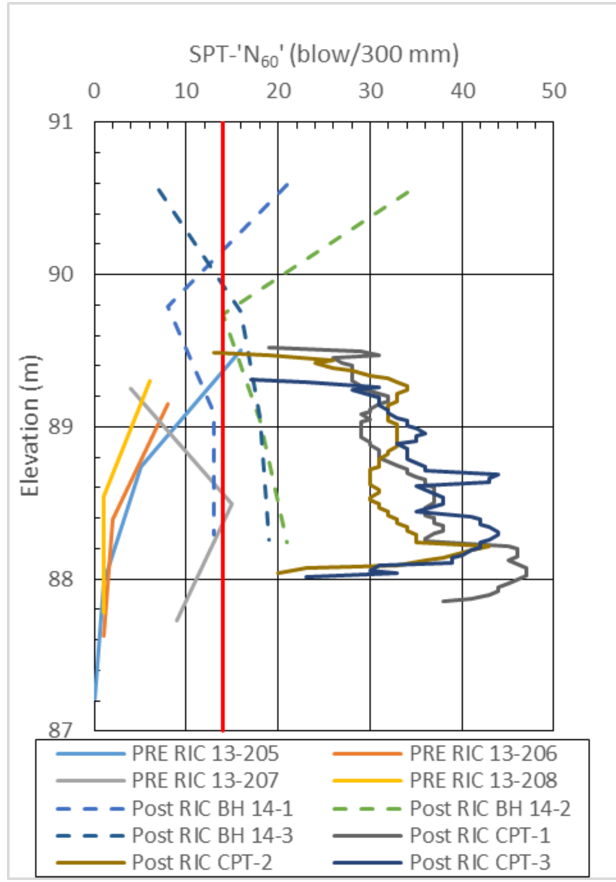

Figure 6. Pre and Post-RIC SPT-'N'60 values comparison

3.3 Post-RIC Liquefaction Assessment

The potential for liquefaction of the densified sand was assessed using both the results of the SPT and CPT testing. The SPT assessment was carried out using the Seed and Idriss (1971) simplified procedure and the CPT analysis was carried out using the method proposed by Youd et.al. (2001).

The SPT analysis considered the SPT-"N60" values obtained from the confirmatory testing and correcting for effective overburden stress and fines content. The assessment resulted in CRR values of 0.12 to 1.0, which corresponds to a factor of safety against liquefaction of 0.7 to 2. Based on this analysis, the sandy soils were still considered liquefiable.

The CRR was also determined from the CPT normalized tip stress data. The CRR computed using the CPT data was higher than the SPT data with CRRs of 0.26 to 0.36 and corresponding factors of safety against liquefaction of 2.8 to 3.9.

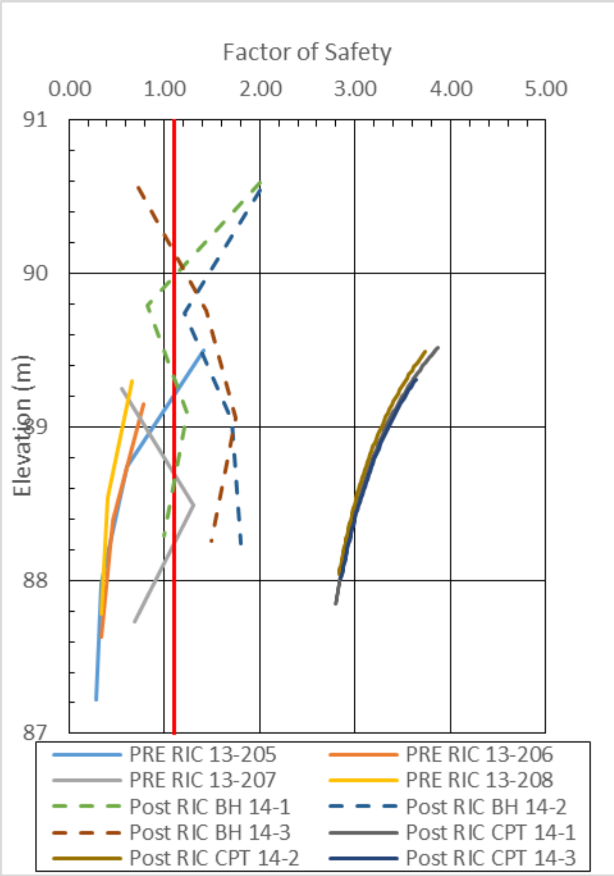

Figure 7. Post-RIC factor of safety against Liquefaction

The marked decrease in scatter of the CPT based results shown in Figure 6 and Figure 7 are more in keeping with typical post RIC results in terms of density, consistency and tip resistance across a RIC treated site, based on past experience.

4 CONCLUSION

RIC proved to be an effective method to densify the sandy soils and mitigate potential liquefaction for the East Quadrant Water Distribution project. RIC successfully densified the sandy soils, increasing the CRR and thereby increasing the factor of safety against liquefaction to well over the required 1.1 factor of safety, and by up to 7 times the original factor of safety.

As evident by the discrepancies between the CPT and SPT data it is critical to select the appropriate confirmatory testing procedure and method. Liquefaction generally occurs in loose sands below the groundwater table, which is also subject to disturbance during conventional borehole drilling and potentially creating artificially low SPT results.

CPT testing is a direct push method, therefore there is no soil disturbance from standard hollow stem augers used during conventional drilling. As a result of this, CPT test results are more representative of actual in-situ conditions.

Future studies could include the use of both CPT and SPT in sands prior to RIC treatment to determine the potential for liquefaction.

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