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Assessing liquefaction resistance in granular soils: a new method integrating bulk and particle-level properties

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ABSTRACT: In-situ stress, bulk properties, such as relative density and particle characteristics, including shape and size, influence the soil's shear strength and liquefaction resistance. Considerable attention has been directed toward studying the individual effects of these factors on the shear strength and liquefaction resistance of granular soils, particularly sand. However, it is essential to recognize that the three critical soil parameters (bulk density, particle shape and size) interact combinedly while deriving the resistance against external loading. To address this, a coupled parameter, termed the 'packing index,' has been proposed, which integrates both bulk and particle characteristics of sand. A power law equation was developed through rigorous statistical analysis to establish a relationship between the cyclic resistance ratio (CRR) and internal friction angle (ϕ) with the packing index, providing a simplified approach for assessing the liquefaction resistance. The proposed method was compared with existing liquefaction resistance assessment techniques to evaluate its applicability under both field and laboratory conditions. Analysis revealed that existing methods tend to overestimate CRR values for very loose to medium-dense sands while underestimating them for higher SPT-N values ($N \geq 24$). In contrast, the relationship between the internal friction angle (ϕ) and SPT-N, as proposed by Mujtaba et al. (2018), along with the current method, yields CRR that closely aligns with those from established methods. However, its applicability is restricted to clean sands with a uniformity coefficient of ≤ 2.5, relative densities ranging from 20% to 90%, and a confining stress of 100 kPa. Notably, this study does not account for factors such as stress history, soil fabric, aging effects, silt content, or the initial stress state.

KEYWORDS: Cyclic resistance ratio, Particle shape, Particle size, Packing index.

1 INTRODUCTION

Liquefaction is a complex process that mostly occurs in loose, saturated granular soils. It's triggered by dynamic loading like earthquakes and blasting which builds up excess pore water pressure and drastically reduces the soil strength, often leading to failure. Tang et al. (2016) categorized the key factors influencing liquefaction into three broad groups: earthquake characteristics, soil properties, and site conditions. Among the soil characteristics, they revealed that relative density, fines content, particle size has a higher weightage (influence) on the liquefaction resistance. However, they found that the particle shape was given relatively low weightage, likely because its role in liquefaction hasn't been studied as thoroughly. However, Vaid et al. (1990) and Kokusho et al. (2004) shows that particle shape can significantly affect the liquefaction resistance in granular soils.

Particle shape is a critical factor influencing the liquefaction resistance of granular soils. In general, for a given gradation and relative density, an increase in particle roundness tends to reduce liquefaction resistance. Previous studies have shown that angular particles exhibit greater resistance to liquefaction particularly under low confining pressures, due to their enhanced dilative behavior during cyclic loading (Vaid et al. 1990; Kandasami & Murthy 2017; Keramatikerman & Chegenizadeh 2017; Latha & Lakkimsetti 2022). Soil gradation also plays a significant role. At low relative densities (< 45%), well-graded sands exhibit higher liquefaction resistance than poorly graded sands. However, this trend reverses at higher relative densities (> 60%), where poorly graded sands become more resistant (Vaid et al. 1990). A similar reversal was observed in numerical simulations by Banerjee et al. (2023), they reported that increasing the coefficient of uniformity initially enhances cyclic resistance at low densities but leads to a reduction beyond a certain threshold. This trend gets reversed at higher densities (> 50%).

In clean sands devoid of fines, and when effects such as stress history, aging, fabric, and initial stress anisotropy are neglected, the static and cyclic behavior of granular soils is primarily governed by three intrinsic factors such as particle shape, gradation, and packing. While the influence of each of these parameters, particularly particle morphology, grain size distribution, and relative density has been extensively examined individually, their combined effect on key mechanical responses such as static shear strength and liquefaction resistance remains insufficiently addressed in the literature.

To bridge this gap, the present study introduces a coupled parameter, referred to as the packing index (α), which integrates particle shape, gradation characteristics, and relative density into a single descriptor. This index is intended to holistically represent the structural state of granular assemblies and better capture their coupled influence on mechanical behavior. Using a comprehensive dataset compiled from previous studies on clean sands, empirical correlations were established between the packing index and both the cyclic resistance ratio (CRR) and the internal friction angle (ϕ). The dataset primarily includes results from cyclic triaxial tests conducted under a standardized confining pressure of 100 kPa. Building upon these correlations, a simplified predictive approach is proposed to directly estimate the CRR from the packing index. This offers a practical and efficient method for assessing liquefaction resistance based on easily measurable or inferable grain-scale properties. To evaluate the reliability of the proposed formulations, a detailed error analysis was performed, highlighting the predictive capability and limitations of the approach in comparison to existing empirical models.

2 FORMULATION OF A SIMPLIFIED METHOD

This study presents a simplified, data-driven approach to evaluate the liquefaction resistance of clean sands by integrating both bulk properties and particle-scale characteristics. The experimental data (such as the coefficient of uniformity, maximum and minimum void ratios, relative density, and cyclic resistance ratio) obtained for this study corresponds to cyclic triaxial tests conducted under a confining pressure of 100 kPa. Particle shape descriptors such as roundness, sphericity, and regularity were derived from

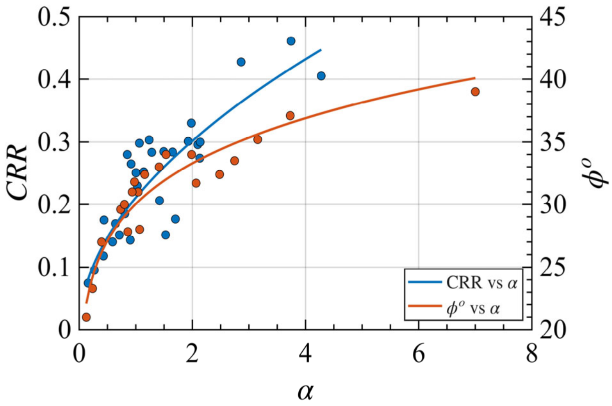

Figure 1. Variation of CRR and ϕ with α.

empirical relationships based on the extreme void ratios (Cho et al. 2006). Regularity was defined as the average of roundness and sphericity. Recognizing that liquefaction resistance increases with relative density and gradation but decreases with increasing regularity, a new combined parameter, termed the packing index, was introduced.

$$\alpha = 0.01\frac{C_u \times RD}{\rho} \tag{1}$$

This index captures the coupled effect of density, gradation, and particle shape factors that have typically been studied in isolation till now. A power-law relationship was established linking the packing index with both the cyclic resistance ratio and the angle of internal friction. Figure 1 shows the variation of CRR and ϕ with α.

$$CRR = x.\alpha^{y} \tag{2}$$

Where, “x” and “y” are fitting coefficients and are equal to 0.217 and 0.48 respectively. It can be observed that for α values less than 1, most of the CRR data points align closely with the regression line, indicating that the proposed equation predicts CRR accurately. For values between 1 and 2.5, the predicted CRR shows slight scatter from the actual data. However, for α values greater than 2.5, the limited number of data points prevents a thorough evaluation of the prediction accuracy. Similarly, from regression analysis ϕ vs α relationship was obtained as shown in Figure 1.

$$\phi = p.\alpha^{q} \tag{3}$$

Where, “p” and “q” are fitting coefficients and are equal to 30.12 and 0.14 respectively. The resulting equation between ϕ vs α, with a coefficient of determination (r^2) of 0.90, effectively captures the influence of both bulk properties such as relative density and particle-scale characteristics, including gradation and shape. However, the applicability of this relationship, as well as the one developed for cyclic resistance ratio, is limited to granular soils with C_u less than 2.5.

Based on the established equations (Equation (1), Equation (2) and Equation (3)), this study formulates a simplified and unified approach for evaluating the cyclic resistance ratio of clean sands. The proposed framework systematically incorporates both bulk properties (such as relative density) and particle-scale characteristics (such as shape and gradation), offering a more holistic assessment of liquefaction resistance than traditional methods. To demonstrate the applicability of this approach, SPT-N values corresponding to very loose to medium dense sands were initially selected. For each of these N-values, CRR was first estimated using well-established empirical methods, specifically the correlations developed by Youd et al. (2001) and Idriss & Boulanger (2014). These CRR values served as benchmark references for comparison. Also, for the same N-values, ϕ was determined from the various pre-existing relationships proposed by Peck et al. (1974), Terzaghi et al. (1996), Kumar et al. (2016), Puri et al. (2018) and Mujtaba et al. (2018). These relationships relate the penetration resistance (SPT-N) to ϕ, capturing the effect of relative density and granular packing influence on the shear strength of soil. Using the derived ϕ values, the packing index (α) was then computed via the ϕ–α relationship established in this study. With α known, the final CRR prediction was obtained using the CRR–α equation, which accounts for the coupled effects of relative density, gradation, and particle shape. Figure 2 illustrates the approach adopted for the development of simplified approach.

To validate the accuracy of the proposed method, an error analysis was carried out by comparing the predicted CRR values (via the packing index method) with the benchmark CRR values obtained from the empirical formulations of Youd et al. (2001) and Idriss & Boulanger (2014). This comparative analysis helped quantify the degree of agreement between the simplified model and existing standards. The detailed methodology is thoroughly discussed in Rehman et al. (2025), which provides the foundational basis for the current approach.

3 RESULTS AND DISCUSSION

3.1 *Comparison of simplified approach with existing studies*

This section presents a comparative evaluation of the proposed simplified method against well-established empirical models for assessing liquefaction resistance in clean sands. To maintain consistency and relevance, the comparison was restricted to SPT-N values less than 30, representing very loose to medium-dense sands, which are generally considered most susceptible to liquefaction. SPT-N values exceeding 30 were excluded, as they typically correspond to dense sands or heavily over consolidated conditions, which are widely recognized as non-liquefiable under seismic loading (Youd et al. 2001).

To carry out the comparison, SPT-N values were first used to estimate the φ using various empirical correlations available in the literature, specifically those compiled and outlined by Rehman et al. (2025). Once φ was determined, the CRR was then calculated using the α, following the methodology proposed in the current study. Further, CRR values were also obtained directly using established empirical models, particularly the widely recognized equations provided by Youd et al. (2001) and Idriss & Boulanger (2014). This allowed for a meaningful evaluation of the predictive capability

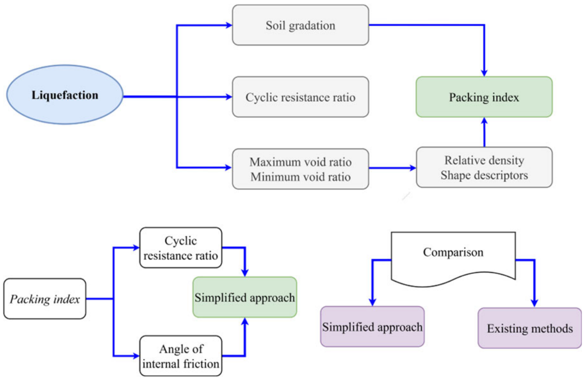

Figure 2. Block diagram illustrating the development of simplified approach.

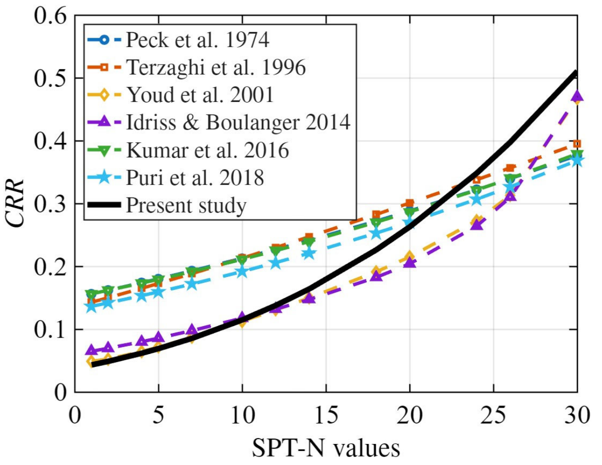

Figure 3. Comparison of the simplified method with existing methods.

and consistency of the proposed method relative to existing approaches in the field. Figure 3 presents a comparative evaluation of the proposed simplified approach against several established methods used for assessing liquefaction resistance. The comparison is based on clean sands, using SPT-N values as the input parameter. The results indicate that conventional methods generally over predict the CRR when compared to the benchmark studies of Youd et al. (2001) and Idriss & Boulanger (2014). However, this trend shifts at higher SPT-N values (N ≥ 24), where these methods tend to underestimate CRR. In contrast, the proposed approach demonstrates close agreement with the reference methods across the full range of N-values considered. Notably, for N-values greater than 16, a slight overestimation of CRR is observed in the proposed method when compared with Youd et al. (2001) and Idriss & Boulanger (2014). This comparison highlights the improved predictive performance of the proposed method, particularly when used in conjunction with the N–φ correlations developed by Mujtaba et al. (2018). The results suggest that this combined approach provides a more accurate estimation of CRR for clean sands across a range of densities. The key strength of the proposed method lies in its unified framework, which integrates friction angle, particle shape, gradation, and relative density into a single index, the packing index. This allows for the development of two robust relationships, one correlating the α with CRR, and the other with the ϕ. Unlike traditional models that rely on separate empirical equations for each parameter, this approach offers a more holistic representation of soil behavior by directly linking particle-scale properties with macroscopic liquefaction resistance. It is important to note, however, that the applicability of this method is currently limited to clean sands with a coefficient of uniformity less than or equal to 2.5, relative densities ranging from 20% to 90%, and a confining stress of 100 kPa. Despite these limitations, the proposed method offers a practical and physically meaningful tool for characterizing the liquefaction potential of granular soils, with significant promise for use in geotechnical engineering applications.

3.2 Error Analysis

To evaluate the accuracy of the proposed method, the mean absolute percentage error (MAPE) and mean absolute error (MAE) was calculated using Equation (4) and Equation (5) respectively, which compares the MAPE and MAE values for the present study, existing studies with the studies of Youd et al. (Youd et al. 2001) and Idriss & Boulanger (Idriss & Boulanger 2014).

$$\mathrm{MAPE}(\%) = \frac{1}{t}\sum_{i=1}^{t}\left|\frac{\mathrm{CRR}_{\mathrm{pred,i}} - \mathrm{CRR}_{\mathrm{ref,i}}}{\mathrm{CRR}_{\mathrm{ref,i}}}\right| \tag{4}$$

$$\mathrm{MAE} = \frac{1}{t}\sum_{i=1}^{t}\left|\mathrm{CRR}_{\mathrm{ref,i}} - \mathrm{CRR}_{\mathrm{pred,i}}\right| \tag{5}$$

Where, “t” is the total number of data points, $\mathrm{CRR}_{\mathrm{ref},i}$ is the reference CRR value (from the studies of studies of Youd et al. (2001) and Idriss & Boulanger (2014)) for the i$^{\mathrm{th}}$ data point, and $\mathrm{CRR}_{\mathrm{pred},i}$ is the predicted CRR value (from the present study and existing studies). Equation (4) computes the MAPE, which is the average of the absolute percentage differences between the predicted and actual CRR values across all data points and Equation (5) computes MAE which is the average of the absolute differences between prediction and actual values. A lower value of MAPE and MAE indicates better agreement between predicted and reference CRR values, reflecting higher model accuracy.

Figure 4 illustrates the Mean Absolute Percentage Error (MAPE) of various CRR estimation methods Peck et al. (1974), Terzaghi et al. (1996), Kumar et al. (2016), Puri et al. (2018), and the present study compared against two benchmark references Youd et al. (2001) and Idriss & Boulanger (2014). Among all methods, the present study consistently exhibits the lowest MAPE values against both benchmarks, indicating a strong agreement with the established liquefaction evaluation frameworks. In contrast, older methods such as Peck et al. (1974) and Terzaghi et al. (1996) show comparatively higher MAPE values, suggesting significant deviation from reference studies. The minimal gap between the MAPE values of the present study for both references also highlights its robustness and general applicability across different evaluation criteria. This comparison reinforces the reliability and improved predictive capability of the proposed approach in estimating CRR from field SPT-N values.

The Mean Absolute Error (Figure 5) presents a comparison of absolute errors between different CRR estimation methods Peck et al. (1974), Terzaghi et al. (1996), Kumar et al. (2016), Puri et al. (2018), and the present study relative to two reference datasets Youd et al. (2001) and Idriss & Boulanger (2014). The y-axis shows the MAE values, which indicates the average absolute deviation of predicted CRR values from the reference values, measured in the same units. Lower MAE values suggest closer agreement with the benchmark. Among the methods, the present study consistently shows the lowest MAE for both references, highlighting its superior predictive accuracy. In contrast, existing methods like Peck et al. (1974) and Terzaghi et al. (1996) exhibit larger errors, indicating a poorer fit to the reference trends. Overall, the plot demonstrates that the proposed approach provides more reliable CRR predictions than traditional empirical methods. Together, the MAPE and MAE analyses confirm that the present study offers both relatively and absolutely more accurate CRR predictions than traditional methods, demonstrating its consistency, robustness, and suitability for modern liquefaction assessment.

4 CONCLUSION

This study investigated the combined influence of intrinsic soil parameters including relative density, coefficient of uniformity, and particle morphology on the liquefaction resistance of clean sands. A comprehensive analysis of an extensive literature-based dataset led to the development of two key empirical relationships one linking the packing index to the cyclic resistance ratio, and another relating the packing index to the angle of internal friction. These formulations incorporate both

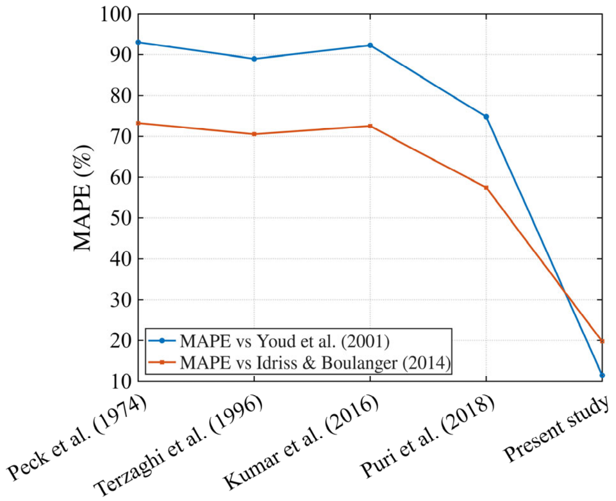

Figure 4. Comparison of the MAPE of present study and existing studies.

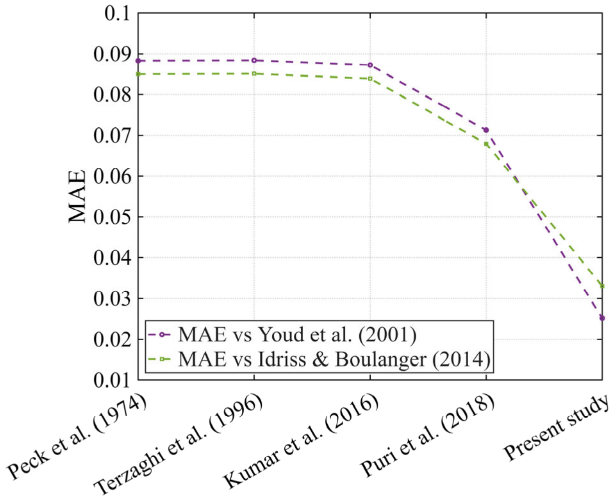

Figure 5. Comparison of the MAE of present study and existing studies.

bulk characteristics and particle-level descriptors, providing a unified framework for predicting CRR under defined initial conditions. The findings confirm that particle shape, in addition to density and gradation, plays a critical role in determining CRR. The proposed packing index captures this combined effect and exhibits a clear power-law correlation with both CRR and ϕ. Leveraging these relationships, a practical method was introduced for estimating liquefaction resistance from either field SPT-N data or laboratory parameters. This approach allows the angle of internal friction to be inferred from N-values using the equation proposed by Mujtaba et al (2018), followed by CRR prediction through the packing index. Error analysis using MAPE and MAE metrics revealed that the proposed method yields significantly lower errors compared to conventional empirical methods. Specifically, it avoids the common trend of over predicting CRR for loose-to-medium sands and under predicting for dense sands ($N \geq 24$). It closely matches the benchmark estimates of Youd et al. (2001) and Idriss & Boulanger (2014), validating its predictive accuracy and consistency.

While the method shows strong potential for both field and lab applications, its applicability is currently limited to clean sands with a coefficient of uniformity ≤ 2.5, relative density between 20% and 90%, and a confining stress of 100 kPa. It does not account for additional factors such as stress history, aging, fabric effects, silt content, or initial stress anisotropy, which may influence liquefaction behavior in more complex soil conditions. Nonetheless, the integration of shape descriptors and performance-based validation positions the proposed method as a reliable and versatile tool for practical liquefaction assessment.

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