Scientific Review – Engineering and Environmental Sciences (2021), 30 (2), 304–314
Sci. Rev. Eng. Env. Sci. (2021), 30 (2)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2021), 30 (2), 304–314
Prz. Nauk. Inż. Kszt. Środ. (2021), 30 (2)
http://iks.pn.sggw.pl
DOI 10.22630/PNIKS.2021.30.2.26

Hiba D. SALEEM, Asad H. ALDEFAE, Wissam H. HUMAISH
University of Wasit, College of Engineering

Verification of strength resistance of sandy soil using small scale penetrometer tests

Key words: cone penetration, tip resistance, sleeve resistance, relative density, angle of internal friction

Introduction

To study a problem concerning with geotechnical aspect, one of the main factor that should be considered by the geotechnical engineer during model preparation experimentally is obtaining soil strata properties in the prepared model close to that property of natural soil in-situ. Cohesionless soil can be defined clearly by its relative densities whereas the cohesive soil is defined by compressibility. Many verified methods to prepare sandy soil specimens model in the laboratory are widely used at different geotechnical laboratories and research center around the world (Presti, Pedroni & Crippa, 1992; Dave & Dasaka, 2012; Gade & Dasaka, 2016; Aldefae, Shamkhi & Khalaf, 2019; Aldefae & Saleem, 2020). One of the main characteristic and advantage of sandy soil specimen is "can be prepared experimentally in the laboratory at dry state". Different techniques are performed and followed to verify the soil strata characteristics of the prepared model and even in-situ (Juang, Huang, Holtz & Chen, 1996; Lunne, Powell & Robertson, 2002; Sivrikaya & Tođrol, 2006; Schneider, Randolph, Mayne & Ramsey, 2008; Al-Aayedi, Aldefae & Shamkhi, 2020).

Cone penetration resistance is very well known parameters that reveal the actual soil strength. It can be determined using the cone penetration test in which very important soil properties intended to help the engineers in the design earthworks and foundation for any structure. Direct results can be obtained in-situ as no borehole is required to perform this test. Based on the description detailed in the ASTM D3441-98 standard (American Society for Testing and Materials [ASTM], 2012), the diameter of the exterior wall of the cone tube is about 3.6 cm with projected (base) area 10 cm^2 and it has an inclined side slope cone of 60°. Cone tip resistance (q_c)

represents the developed soil resistance by the cone to the penetration (the governed force divided by the projected area) whereas the frictional (sleeve) resistance (f_c) represents the frictional force developed along the sleeve (above the cone) due to local surrounding soil divided by the surface area of the sleeve. Both forces and stresses are the main two forces and stresses components that represent the total cone resistance.

Experimentally, the different cone models were designed and many tests are performed to investigate the sandy soil resistance under 1 g (Zhuang & Yu, 2018) and even in a centrifuge using controlled installation system (Kim et al., 2014; Darby, Bronner, Para Bastidas, Boulanger & De Jong, 2016; Zhou et al., 2019). Six millimeter small scale penetrometer model was designed, manufactured and tested new 6 mm cone penetrometer (Kutter et al, 2017; Carey et al., 2018).

There are many correlations have been developed to investigate the cone resistance from main soil properties. For cohesionless soil, and because the mean particle size and the relative density plays a significant role in the soil resistance. The frictional resistance ratio (i.e. the sleeve resistance divided by the tip resistance $-f_c/q_c$), for both electrical and mechanical cone from the mean particle size of the soil particles (i.e. D_{50}) is computed by Anagnostopoulos, Koukis, Sabatakakis and Tsiambaos (2003) as follows:

$$F_r = 1 \cdot 45 - 1 \cdot 36 \log D_{50}$$
(for electrical cone) (1)

$$F_r = 0 \cdot 7{,}811 - 1 \cdot 611 \log D_{50}$$
(for mechanical cone) (2)

From Eqs. (1) and (2), it was observed that the sandy soil has large tip resistance with small frictional ratio (Zervogiannis, Bouckovalas & Christoulas, 1987). Similar behavior has been concluded by Carey, Gavras and Kutter (2020).

New empirical equation to determine the relative density from the cone resistance has been proposed after many experimental tests (Campanella, Robertson & Gillespie, 1983) as follows:

$$D_r\,[\%] = A + B \log_{10}\left(\frac{q_c}{\sqrt{\sigma_o'}}\right) \tag{3}$$

where:

A, B – imperial correlations coefficient as proposed by Jamiolkowski, Lo Presti and Manassero (2003),
σ'_o – vertical effective stress.

Other correlation equation between the relative density of sandy soil and the cone resistance has been proposed by Kulhawy and Mayne (1990) as follows:

$$D_r\,[\%] = 68\left[\log\left(\frac{q_c}{\sqrt{P_a * \sigma_o'}}\right) - 1\right] \tag{4}$$

where:

P_α – atmospheric pressure (≅ 100 kPa).

The drained angle of internal friction of sandy soil has been determined also using Eq. (5) as described by Campanella et al. (1983).

$$\varphi' = \tan^{-1}\left[0.1 + 0.38 \log\left(\frac{q_c}{\sigma_o'}\right)\right] \tag{5}$$

Other two empirical correlations equations between the drained friction angle for poorly graded sandy soil with silt (SP-SM) and the cone resistance have been presented by Ricceri, Simonimi and Cola (2002) and Lee, Salgado and Carraro (2004) respectively, as follows:

$$\varphi' = \tan^{-1}\left[0.38 + 0.27 \log\left(\frac{q_c}{\sigma_o'}\right)\right] \quad (6)$$

$$\varphi' = 15.575\left(\frac{q_c}{\sigma_h'}\right)^{0.1714} \quad (7)$$

In this paper, mini cone penetration test is performed on different relative densities models to investigate how the cone penetration resistance of sandy soil are significantly influenced by the some physical and drained shear strength. The experimental tests were performed at the University of Wasit, geotechnical laboratories of the Engineering Faculty. New equations are proposed based on the obtained results and were compared with well-presented previous studies which were explained in the introduction above.

Small scale cone penetrometer model

Small scale penetrometer is designed and manufactured at the geotechnical laboratory of engineering faculty to achieve 50 cm embedded length within the soil layers model. It has 10 mm diameter and 0.5 kN mini load cell is connected at the end (tip) of the cone to investigate the tip or bearing cone resistance. The cone is manufactured from similar steel properties that were used in designing of the in-situ penetrometer. Another load cell (5 kN in diameter) is connected at the top of the penetrometer which connected within the installation and loading machine to inspect the behavior of the total cone resistance (including the frictional resistance and the tip resistance). Figure 1 shows the small scale penetrometer model with load cells and slip ring (used in screw piles test which is not mentioned in this paper).

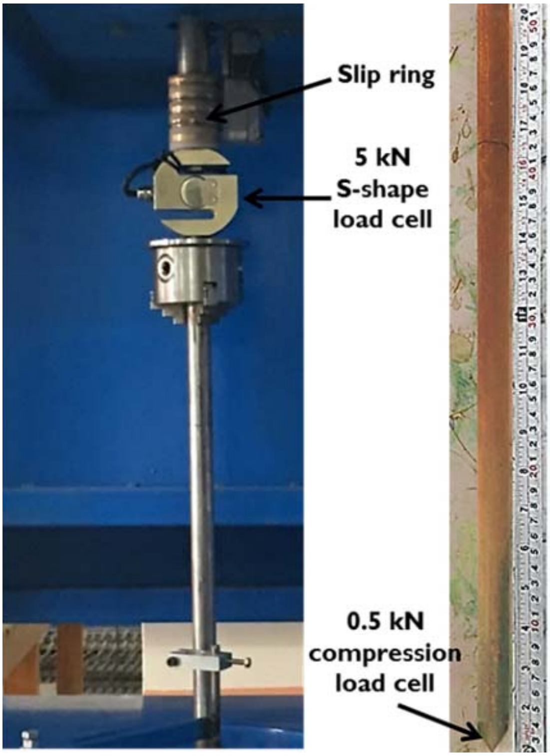

FIGURE 1. Small scale penetrometer

Model preparation and loading machine

Fine silica sand has 0.17 mm mean diameter size (i.e. D_{50}) is used in the model preparation utilizing 0.8 × 0.8 × 0.7 m steel container that was designed and fabricated by Aldefae et al. (2019) previously (Fig. 2). To achieve the desired relative density for each test in cohesionless soil, mechanical pluviator that was designed and manufactured in the geotechnical laboratory at the University of Wasit by Aldefae and Saleem (2020) is used. Similar procedure during the model preparation that was commonly used in the pluviation technique is followed here (Al-Aayedi et al., 2020). The prepared and tested models under many relative densities are inspected during the cone penetration tests to investigate how the soil strength is strongly influenced by the relative density. The tested models relative density ranges between loose to dense states. A universal loading machine (ULM) is used to perform the CPT tests under a displacement rate of 4 mm·min^{-1} (Fig. 2). In the prototype scale, the standard displacement rate for CPT tests is around 1,000 mm·min^{-1}, as described in the ASTM D3441-98 standard, which is totally different from the displacement rate in the model scale here. In spite of that, the cone penetration resistance in cohesionless soils is not strongly influenced by the displacement of the penetration machine as investigated carefully by Dayal and Allen (1975).

Soil strength in term of the penetrometer resistance (q_u) and the relationships between both the ultimate cone resistance with the relative density (D_r %) and the drained angle of internal friction (φ') have been determined and simple empirical equations are introduced between these parameters. Then, comparisons with dis-

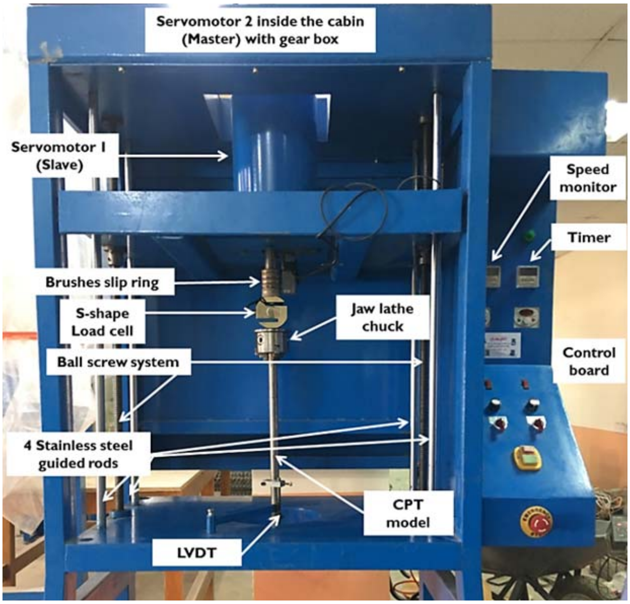

FIGURE 2. Loading rig machine and cone penetrometer

covered parameters from previous studies have been conducted with the parameters that were obtained from this paper.

Results and discussion

Penetrometer resistance results

Seven cone penetration tests are conducted in on cohesionless soil (sandy soil). Wide ranges of relative density are considered in the test procedure by preparation the models using the pluviator technique that was mentioned earlier in this paper. These relative densities have been represented the full density status for sandy soil (loose, medium, dense and very dense state). One cone penetration test is conducted for each test and the cone penetrates the soil at the center of the container and far from the container's side walls to prevent any boundary effect may develop due to the soil deformation. The penetration resistance results for identifying the variation of the soil strength within different soil relative density is illustrated in Figure 3. It should be noticed from the figure that the cone element penetrates the soil layer in the container up to 45 cm. Maximum penetrometer stroke is limited to be 47 cm and the machine is controlled to be stopped suddenly using digital draw wire to prevent any damages that may occur for the ball screw system.

The relative density effect is shown clearly as the cone resistance increases with depth once the relative density increases. High relative density has maximum cone resistance and it was three times the cone resistance in case of loose state (low density). This behavior can be attributed to the large void ratio in case of loose state and the downward and lateral movement of the soil particles occurs in low resistance while this resistance is going to increase sharply because of the soil particle interlocks when the cone penetrates the soil layers.

This behavior is compared with what was observed by Gade and Dasaka (2017) at dense state (i.e. 40 and 80% D_r) though the depth of penetration was 35 cm at previous study. Very close variation with depth of cone resistance between the measured and the art-of-literature values and this support what was discovered here in this paper. It can be seen that there is the slightly different trend in the measured value at low density (i.e. 40% D_r) at moderate stress level (i.e. 25 cm depth as shown in Fig. 3) whereas very close for the measured ultimate value at the final depth (i.e. 38 cm).

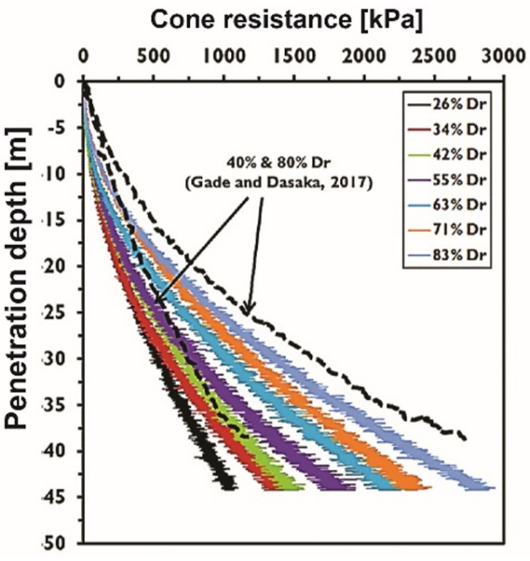

FIGURE 3. Cone penetration results of full range of relative density

Sleeve (frictional) resistance results

To determine the sleeve or frictional resistance (f_c) for different relative densities in this study, Eq. (2) is used as the cone model represents a mechanical cone. Frictional resistance ratio is calculated first which is constant because it is a function of the mean particle size (D_{50}). The measured ultimate cone resistances from the tested models at the maximum penetration are used then to calculate the sleeve or frictional resistance for each case (i.e. the wide range from low to dense state). Figure 4 shows the effect of the relative density on the calculated sleeve resistance. It can be seen also that the calculate sleeve resistance, tacitly, is small comparing with the measured cone resistance for all the range of the tested densities. This finding is consistent with what was discovered by Anagnostopoulos et al. (2003) when they noticed that the sandy soil has small frictional resistance. Accordingly, as shown in Figure 4, the frictional resistance ratio is (14%) approximately; thus, the calculated sleeve resistance is around 14% of the ultimate cone resistance at maximum penetration.

Angle of internal friction effect on the cone resistance

The angles of internal friction are determined using the basic direct shear test for dry sandy soil according to the wide range of the selected relative density (to cover the sandy soil status as mentioned before). It can be seen from Figure 5 that the cone penetration resistance increases from 1,000 to approximately 2,800 kPa as the angle of internal friction increase from 31.6 to 41.8°. It could be seen also that the variation of the cone resistance was about 180% and this is not surprising us as the sandy soil changed from the critical state (i.e. low strain level) to the peak state (i.e. at large strain level) and we have to say here that the dilation for the sandy soil effect has a significant effect on the measured cone resistance.

It is not true to say that both the internal friction angle and the dilation effect

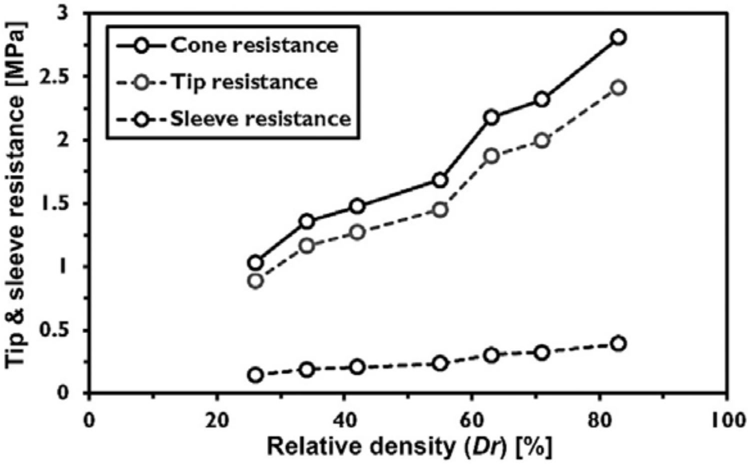

FIGURE 4. Effect of relative density variation on tip and sleeve cone resistance

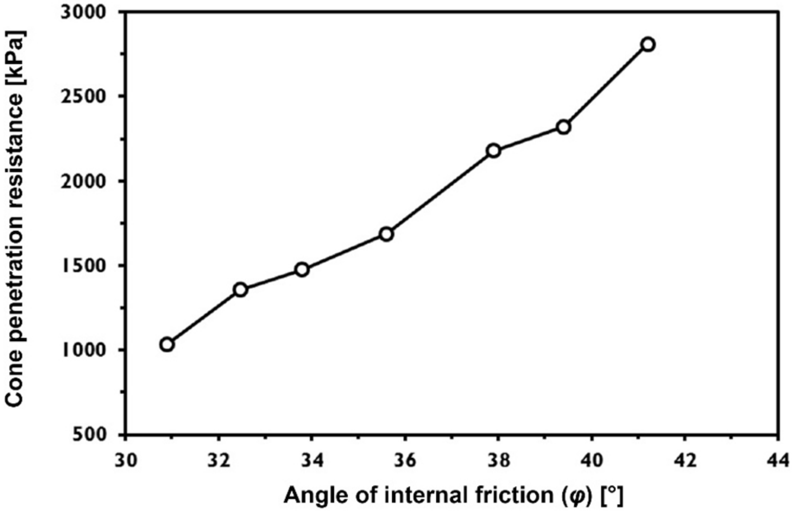

FIGURE 5. Effect of angle of internal friction on cone resistance

on the cone resistance are detached as discovered by Puebla, Byrne and Philips (1997). The overlapping between two parameters are significant and the most increasing in the cone penetration resistance as a results of the developing of the dilation which is very important parameter in sandy soils.

Calculated and measured cone penetration resistance

To predict the obtained results of the cone resistance, Eq. (5) is used in this paper. Excellent agreement can be seen in Figure 6 between the measured and calculated cone resistance. It should be seen noticed that this agreement between the calculated cone resistance and measured values cannot say it is under predicted or over predicted and it can only say that its slightly over predicted at low cone resistance (low to medium dense state) and under predicted at high cone resistance (dense state). This can be attributed to the confinement stresses increasing at large cone resistance (2,000 kPa and above). This behavior is consisted with

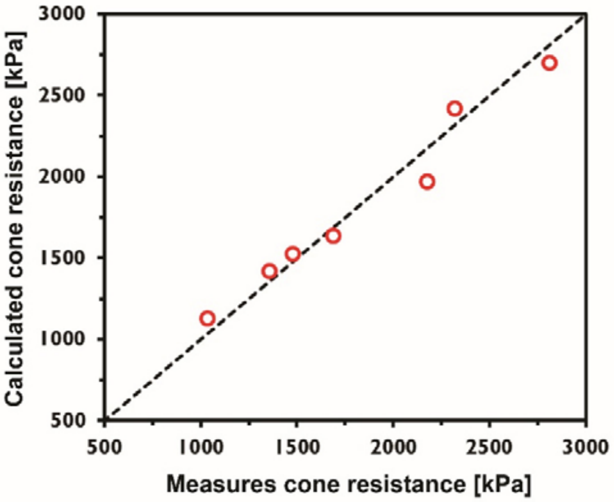

FIGURE 6. Measured and calculated cone resistance

the main finding discovered by Ahmadi, Byrne and Campanella (2005).

On the other hand, the over prediction of the measured cone resistance (i.e. below 1,500 kPa) can be attributed to the difficulties of achieving the boundary condition as the radial displacement cannot be controlled to be zero at the container boundary during the test and this behavior is exactly with what Salgado, Jamiolkowski and Mitchell (1998) came up with.

Comparison of the measured cone resistance

The obtained experimental results from the cone model penetration tests are compared with three different fields, numerical and experimental results selected carefully from many previous studies as shown in Figure 7.

It can be seen from Figure 7 that the cone resistance increases as the angle of internal friction increase. Actually this is not surprising as the relative density increases with the angle of internal friction. The "very well" finding here is the trend of the results in this paper comparing with results of field test (Campanella et al., 1983) and experimental (Ricceri et al., 2002) as well as numerical study (Lee et al., 2004). The convergence of these results with slightly under or over predicting can be attributed to the boundary condition of the problem that have been considered very well during the test particularly the cone penetration rate, the sandy soil layers model preparation as well as the boundary effects from the walls of container to the cone model.

Conclusions

The cone penetration test is one of the quick geotechnical tests that are widely used to investigate the soil layers strength characteristics for non-cohesive soil. The main conclusions can be listed as follows:

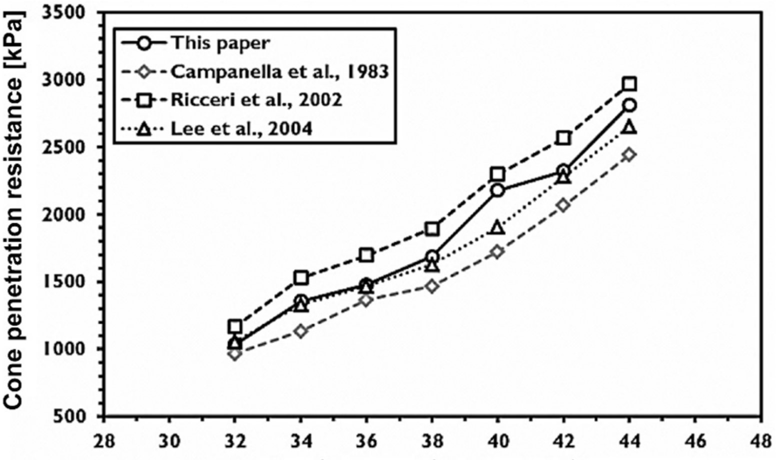

FIGURE 7. Comparison of measured cone resistance with previous obtained values

1. The small scale penetrometer model tests results replicated the actual strength behavior of sandy soil by comparing the experimental results with art-of-literature or previous field and numerical results.
2. The cone resistance results are increased up to 160% when the soil density changed from loose to medium dense state (1 MPa at loose state to 1.6 MPa at dense state). Whereas it increased to 280% when the density characteristics changed to dense state (2.8 MPa at dense state).
3. The cone resistance is strongly influenced by the angle of internal friction as the values increased sharply when the soil changed from the low density (i.e. $\varphi \cong 31 \cdot 5^\circ$) to dense state (i.e. $\varphi \cong 42^\circ$).
4. The sleeve resistance is small comparing with the tip cone resistance (around 15%) and this is consistence with fact of cohesion-less soil.

References

Ahmadi, M.M., Byrne, P.M. & Campanella, R.G. (2005). Cone tip resistance in sand: modeling, verification, and applications. *Canadian Geotechnical Journal*, *42*(4), 977-993.

Al-Aayedi, H.K., Aldefae, A.H. & Shamkhi, M.S. (2020). Seismic performance of bridge piers. *IOP Conference Series: Materials Science and Engineering*, *870*(1), 012069. https://doi.org/10.1088/1757-899X/870/1/012069

Aldefae, A.H. & Saleem, H.D. (2020). Design, manufacturing and testing of biaxial mechanical travelling pluviator. *IOP Conference Series: Materials Science and Engineering*, *870*(1), 012071. https://doi.org/10.1088/1757-899X/870/1/012071

Aldefae, A.H., Shamkhi, M.S. & Khalaf, T. (2019). Design and manufacturing of geotechnical laboratory tools used in physical modeling. *Cogent Engineering*, *6*(1), 1637622. https://doi.org/10.1080/23311916.2019.1637622

American Society for Testing and Materials [ASTM] (2012). *Standard test method for electronic friction cone and piezocone penetration testing of soils (ASTM D3441-98).* West Conshohocken (PA): American Society for Testing and Materials.

Anagnostopoulos, A., Koukis, G., Sabatakakis, N. & Tsiambaos, G. (2003). Empirical correlations of soil parameters based on cone penetration tests (CPT) for Greek soils. *Geotechnical & Geological Engineering*, *21*(4), 377-387.

Campanella, R.G., Robertson, P.K. & Gillespie, D. (1983). Cone penetration testing in deltaic soils. *Canadian Geotechnical Journal*, *20*(1), 23-35.

Carey, T., Gavras, A., Kutter, B., Haigh, S.K., Madabhushi, G.S.P., Okamura, M., Kim, D.S., Ueda, K., Hung, W-Y., Zhou Y-G., Liu, K., Chen, Y.M., Zeghal, M., Abdoun, T., Escoffier, S. & Manzari, M. (2018). A new shared miniature cone penetrometer for centrifuge testing. In *Physical Modelling in* Geotechnics. Vol. 1 (pp. 293-298). London: CRC Press.

Carey, T., Gavras, A. & Kutter, B. (2020). Comparison of LEAP-UCD-2017 CPT Results. In *Model Tests and Numerical Simulations of Liquefaction and Lateral Spreading* (pp. 117-129). Cham: Springer.

Darby, K.M., Bronner, J.D., Parra Bastidas, A.M., Boulanger, R.W. & DeJong, J.T. (2016). Effect of shaking history on the cone penetration resistance and cyclic strength of saturated sand. In *Geotechnical and Structural Engineering Congress 2016* (pp. 1460-1471). Reston (VA): American Society of Civil Engineers.

Dave, T.N. & Dasaka, S.M. (2012). Assessment of portable traveling pluviator to prepare reconstituted sand specimens. *Geomechanics and Engineering*, *4*(2), 79-90.

Dayal, U. & Allen, J.H. (1975). The effect of penetration rate on the strength of remolded clay and sand samples. *Canadian Geotechnical Journal*, *12*(3), 336-348.

Gade, V.K. & Dasaka, S.M. (2016). Development of a mechanized traveling pluviator to prepare reconstituted uniform sand specimens. *Journal of Materials in Civil Engineering*, *28*(2), 04015117. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001396

Gade, V.K. & Dasaka, S.M. (2017). Assessment of air pluviation using stationary and movable pluviators. *Journal of Materials in Civil Engineering*, *29*(5), 06016023. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001798

Jamiolkowski, M., Lo Presti, D.C.F. & Manassero, M. (2003). Evaluation of relative density and shear strength of sands from CPT and DMT. In *Soil behavior and soft ground construction* (pp. 201-238). Reston (VA): American Society of Civil Engineers.

Juang, C.H., Huang, X.H., Holtz, R.D. & Chen, J.W. (1996). Determining relative density of sands from CPT using fuzzy sets. *Journal of Geotechnical Engineering*, *122*(1), 1-6.

Kim, J.H., Kim, S.R., Lee, H.Y., Choo, Y.W., Kim, D.S. & Kim, D.J. (2014). Miniature cone tip resistance on silty sand in centrifuge model tests. In Ch. Gaudin, D. White (eds.), *Proceedings of the 8th International Conference on Physical Modelling in Geotechnics 2014* (pp. 1301-1306). London: CRC Press.

Kulhawy, F.H. & Mayne, P.W. (1990). *Manual on estimating soil properties for foundation design*. Palo Alto (CA): Electric Power Research Institute.

Kutter, B., Carey, T., Stone, N., Zheng, B.L., Gavras, A., Manzari, M.T., Zeghal, M., Abdoun, T., Korre, E.,Escoffier, S., Haigh, S.K., Madabhushi, G.S.P., Madabhushi, S.S.C., Hung, W-Y., Liao, T-W., Kim, D-S, Kim, S-N., Ha, J-G., Kim, N.R., Okamura, M., Sjafruddin, A.N., Tobita, T., Ueda, K., Vargas, R., Zhou, Y-G. & Liu, K. (2020). LEAP-UCD-2017 comparison of centrifuge test results. In B. Kutter, M. Manzari, M. Zeghal (eds.), *Model Tests and Numerical Simulations of Liquefaction and Lateral Spreading* (pp. 69-103). Cham: Springer.

Lee, J., Salgado, R. & Carraro, J.A.H. (2004). Stiffness degradation and shear strength of silty sands. *Canadian Geotechnical Journal*, *41*(5), 831-843.

Lunne, T., Powell, J.J. & Robertson, P.K. (2002). *Cone penetration testing in geotechnical practice*. Boca Raton (FL): CRC Press.

Presti, D.L., Pedroni, S. & Crippa, V. (1992). Maximum dry density of cohesionless soils by pluviation and by ASTM D 4253-83: a comparative study. *Geotechnical Testing Journal*, *15*(2), 180-189.

Puebla, H., Byrne, P.M. & Phillips, R. (1997). Analysis of CANLEX liquefaction embankments: prototype and centrifuge models. *Canadian Geotechnical Journal*, *34*(5), 641-657.

Ricceri, G., Simonini, P. & Cola, S. (2002). Applicability of piezocone and dilatometer to characterize the soils of the Venice Lagoon. *Geotechnical & Geological Engineering*, *20*(2), 89-121.

Salgado, R., Jamiolkowski, M. & Mitchell, J.K. (1998). Penetration resistance in sand: analysis and applications to liquefaction potential assessment and estimation of pile base resistance. *Rivista Italiana di Geotecnica*, *32*(4), 5-17.

Schneider, J.A., Randolph, M.F., Mayne, P.W. & Ramsey, N.R. (2008). Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. *Journal of Geotechnical and Geoenvironmental Engineering*, *134*(11), 1569-1586.

Sivrikaya, O.S.M.A.N. & Tođrol, E. (2006). Determination of undrained strength of fine-grained soils by means of SPT and its application in Turkey. *Engineering Geology*, *86*(1), 52-69.

Zervogiannis, H., Bouckovalas, G. & Christoulas, S. (1987). Correlation of mechanical characteristics and classification of soil deposits. *Bulletin of Central Public Works Laboratory*, *4*, 255-265.

Zhou, Y.G., Liang, T., Chen, Y.M., Ling, D.S., Kong, L.G., Shamoto, Y. & Ishikawa, A. (2019). A two-dimensional miniature cone penetration test system for centrifuge modelling. In Ch. Gaudin, D. White (eds.), *Physical Modelling in Geotechnics* (pp. 301--307). London: Taylor & Francis Group.

Zhuang, P.Z. & Yu, H.S. (2018). Size effects in cone penetration tests in sand. In W. Wu, H.S. Yu (eds.), *Proceedings of China-Europe Conference on Geotechnical Engineering* (pp. 283-287). Cham: Springer. https://doi.org/10.1007/978-3-319-97112-4_64

Summary

Verification of strength resistance of sandy soil using small scale penetrometer tests. This study focuses on utilizing cone penetrometer models to determine strength (resistance) of sandy soil and also assessment how the relative density and the angle of friction effects on the measured cone penetration resistance in sandy soil. Simple empirical equations are used also to determine the cone penetration resistance components such as the sleeve resistance and the tip resistance. Simple comparison is performed between the measured and calculated soil strength and well agreement is noticed between them.

Authors' address:
Asad H. Aldefae – corresponding author
(https://orcid.org/0000-0002-8725-4470)
University of Wasit
College of Engineering
Hay Al-Rabe', Wasit, Kut
Iraq
e-mail: asadaldefae@uowasit.edu.iq