

ORIGINAL ARTICLE

A comparison between performances of the behavioral models in evaluating load-bearing capacity of piles in fine-grained unsaturated soil

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Virtually all structural piles are installed on the top of groundwater level, and these piles are located on unsaturated soils. In this case, the negative orifice water pressure caused by capillarity significantly influences the mechanical behavior of unsaturated soils. Consequently, structural suction is highly important to load-bearing capacity of loads. In this paper, an evaluation was drawn between the Mohr-Coulomb, modified Cam-Clay, and Barcelona behavioral models using the finite-difference method, and results of studies conducted to estimate load-bearing capacity in the static state were provided. The behavioral model guidelines matched the laboratory models. To estimate soil vividness on the suction level of concern, the water-soil curve (showing suction patterns in relation to moisture) utilized. The general tendencies of settlement gotten by the numerical examination are reliable with pile insert test results. Results suggest that the Barcelona personality model (BBM) yields more realistic estimates of load capacity as it looks at the effect of unsaturated soil suction.

Key words: single pile; Unsaturated soil; Ultimate bearing capacity; Mohr–Coulomb; modified Cam-Clay; BBM; matric suction

Ground is found in the nature in the dried, wet, and saturated varieties. Most soil mechanics hypotheses have been formulated for dry or saturated soil and little attention has been paid to unsaturated soils. However, significant breakthroughs in modeling unsaturated soil behavior have been discovered in the past two decades. Unsaturated soils are soils that are to some extent saturated with water. Several soils display characteristic changes after absorbing or giving out water. {When it comes to such soil, any change of level of saturation {can result can cause changes of volume, shearing durability, and hydraulic properties of soil. These results cause the soil nonlinear tendencies. A soil behavioral model should be capable of showing soil behavior under changes of pore water and air pressure as well as stress variants (Alonso et al., 1990; Vaca, 2015). Any type of soil can be saturated or unsaturated, and unsaturation is soil state rather than a soil type as exhausted by Gens et et al. almost all of the traditional soil mechanics principles are suitable for saturated soils, the following points should be taken into account in formulating principles for unsaturated soils (Gens et al., 2006; Solowski & Sloan, 2015; Xu & Cao, 2015).

Volume changes in relation to suction or changes of saturation degree:

Soil shearing strength in relation to suction or variations of saturation degree

In 1990, Alonso et al. proposed the first model of elasto-plastic behavior of unsaturated soil using the theory of plasticity, which was an oval-shaped model similar to the modified Cam-Clay Model (MCC). The structure of this oval differs depending on the suction level. This model is suitable for slightly to mildly expansive unsaturated soils such as soils containing sand, silt, clay, and

clay with low-plasticity. Most structural piles are installed on top of the groundwater level, and these piles are placed on unsaturated soils. In this case, the negative pore water pressure caused by capillarity significantly influences the mechanical behavior of unsaturated soils (Rutqvist et al., 2011; Thakur et al., 2005).

Structural suction equals the difference between the pore air pressure (u_a) and pore water pressure (u_w), and many studies have revealed that the engineering behavior of unsaturated soils (including load-bearing capacity) is mainly affected by structural suction.

The design of pile foundations for engineering practice applications using the mechanics of unsaturated soils has been getting research consideration during the last 15 years (Chung & Yang, 2014; Georgiadis et al., 2003; Zhang et al., 2017). The key information required in outline of pile establishments incorporates the bearing capacity and settlement behavior (Ravichandran et al., 2013; Sheng et al., 2004). The load-settlement (i.e. p - δ) conduct of pile establishment is fundamentally affected by the stiffness and shear strength parameters of the surrounding soil and soil-pile interface (Han et al., 2016; Oh & Vanapalli, 2012). A few studies highlighted the huge commitment of soil suction towards the soil mechanical properties, for example, the shear quality (Vanapalli et al., 1996; S. K. Vanapalli, Fredlund, & Pufahl, 1996), modulus of elasticity (Lu & Kaya, 2014; Oh et al., 2009), and additionally the soil interface properties (Hamid & Miller, 2009; Yavari et al., 2016).

Seldom do studies considered the impact of matric suction or capillary stresses on the load carrying capacity of pile foundations (Gui & Bolton, 1998; Vaca, 2015). Vanapalli and Taylan conducted a model test and suggested using a modified α , β and λ method to contemplate the impact of matric suction on heap shaft limit. Their results also show that the shaft capacity of a single pile is fundamentally affected by the commitment of matric suction. The objective of this study is to investigate the pole limit of a little scale single, tube shaped jacked pile installed in a compacted unsaturated clayey soil (Ghorbani et al., 2016; Mohamed, 2014). Numerical investigations of the little scale single pile in unsaturated clayey soil were conducted by FDM.

The FDM considered frictional strengths between the unsaturated soil and pile and was used to analyse load carrying capacity. To validate the FDM, analysis results were compared with results from small scale single pile load tests in the laboratory.

Testing program

A series of model pile load tests were performed in saturated and unsaturated compacted fine-grained soil under drained and undrained stacking conditions. The soil chosen for this study is a glacial till obtained from Indian Head, Saskatchewan, Canada. The key objective of the test program is to determine the influence of matric suction on the ultimate shaft capacity of model piles.

Soil properties

The properties of the tested soil are summarized in Table 1. The shaft bearing capacity of model piles were proposed to be determined at a water content; 13% (dry of optimum). This water contents was chosen from the compaction curve data. The dry densities of the compacted soil at this water content was respectively equal to 14.5 kN/m^3 . The experiments were not conducted for the water contents on the wet of optimum side since the degree of saturation values were greater than 90%, which resulted in significantly low matric suction values (Sheikhtaheri, 2014).

Table 1. Properties of the tested soil

Soil Properties	Indian Head till
Optimum water content, w_{opt} (%)	18.6
Maximum dry unit weight, γ_{dmax} (kN/m^3)	16.7
Saturated unit weight, γ_{sat} (kN/m^3)	18.5
Sand (%)	28
Silt (%)	42
Clay (%)	30
Liquid limit, LL (%)	32.5
Plastic limit, PL (%)	17
Plasticity index, I_p (%)	15.5
Effective cohesion, c' (kPa) (Sat)	15
Effective friction angle, ϕ' (deg.) (Sat)	23
Undrained shear strength, c_u (kPa)	11.5

The soil-water mixture (hereafter referred to as soil) was placed in a tank (300 mm in diameter and 300 mm in height). The soil was compacted statically with 350 kPa push into the test tank using a specially designed compaction base plate. The compaction and model pile load tests were conducted using a conventional triaxial test loading frame (Fig. 1).



Fig. 1. Test setup for model pile loading test: ① Adjustable height loading frame ② Test tank ③ LVDT ④ Load cell ⑤ Model pile, ⑥ Compaction base plate.

The soil samples prepared with an initial water content of 13% were tested under both unsaturated and saturated conditions considering both the drained and undrained loadings (i.e., SAT-Drained, SAT-Undrained, UNSAT-Drained, UNSAT- Undrained). Testing methodology and equipment of this study are discussed in greater detail by Vanapalli and Taylan respectively (Vanapalli & Taylan, 2012).

Degree of Soil saturation(s) was estimated using the related relation on a suction level of 205 KPa. Coefficients in this relation are estimated based on W.PI (soil plasticity or fines content) (Dolinar, 2015; Pedroso & Farias, 2011) - Fig 2.

$$S = \left[\frac{1}{1 + \left(\frac{u}{a}\right)^b} \right]^c \quad (1)$$

$$a = 0/0015(W.PI)^3 + 0/1028(W.PI)^2 + 0/5871(W.PI) + 11/813 \quad (2)$$

$$b = 0/00011(W.PI)^2 - 0/01358(W.PI) + 1/76987 \quad (3)$$

$$c = -5 \times 10^{-6}(W.PI)^2 - 0/00014(W.PI) + 0/14745 \quad (4)$$

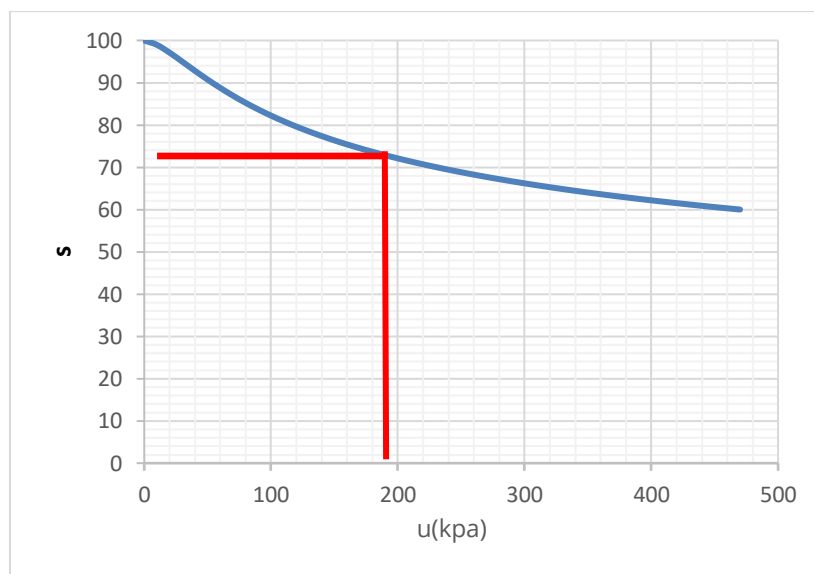


Fig. 2. The soil-water characteristic curve

Numerical modeling

In this part of the paper the numerical modeling method is described. The Mohr–Coulomb, modified Cam-Clay, and Barcelona behavioral models were also used in this research. Tables (1) and (2) present the parameters of these behavioral models. The modeling conditions are designed to resemble laboratory conditions to the possible extent. Concerning the model dimensions, it has a height and width of 30 cm and the pile height is 20cm (Vanapalli & Taylan, 2011).

Table 2. Mechanical properties for soil

Parameter	Value	Description
N	0.3	Poisson's ratio
K	0.01	Slope of the unloading-reloading line
λ_0	0.02	Slope of the saturated consolidation line
ks	1.14	Parameter to control the increase in apparent cohesion with suction
M	0.9	Slope of the critical state line
e0	0.22	Initial void ratio
Po* [kPa]	350	Saturated preconsolidation pressure
Pr [kPa]	100.0	Reference pressure
R	0.95	Parameter to control the maximum soil stiffness with suction
β [kPa ⁻¹]	12.5e-6	Parameter to control the rate of increase of stiffness with suction

To measure the load-bearing capacity of the wall in each state, 2mm of empty space is provided at the end of the pile. Numerical simulation of the process can be summarized as follows: (Al-Khazaali & Vanapalli, 2015; Fujiang et al., 2016; Ha & Hassanlourad, 2015; Han et al., 2016)

1. Construction of model geometry and pile.
2. Boundary conditions and in-situ stresses.
3. Run the program to primary balance.
4. Zero the amount of displacements in the direction of x and y.
5. Loading the pile with the corresponding rate.
6. Assessment of displacements and forces pile and model.

A displacement of 1.5mm was applied on the top of the pile to simulate the loading process. Interface elements were placed around the pile to imulate the interaction between the pile and soil. Standard fixities were used to define the boundary conditions to provide stability conditions. A distributed load on the top of the small scale single pile was used to simulate a static load. Before applying the load to the head of the small scale single pile, the analysis model was assumed to be in an initial state of equilibrium.

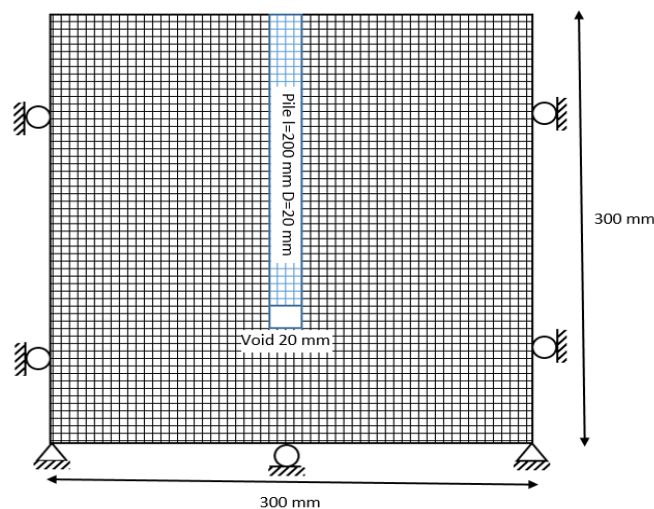


Fig. 3. Details of FDM model

Results and discussion

Numerical Modeling Using Mohr–Coulomb Behavioral Model

In this section, the load-bearing capacity of the pile is estimated experimentally using the Mohr–Coulomb behavioral model in the saturated and unsaturated drained states. Modeling was carried out using the finite difference method. Tables 1 and 2 present a list of parameters used in this model. The modeling conditions were designed to resemble laboratory conditions the most. Fig. 4 depicts the pile load-bearing capacity diagram resulted from the finite difference numerical modeling carried out using the Mohr–Coulomb behavioral model. As seen, the maximum pile load-bearing capacity in the unsaturated and saturated states is approximately 480 N and 150 N, respectively.

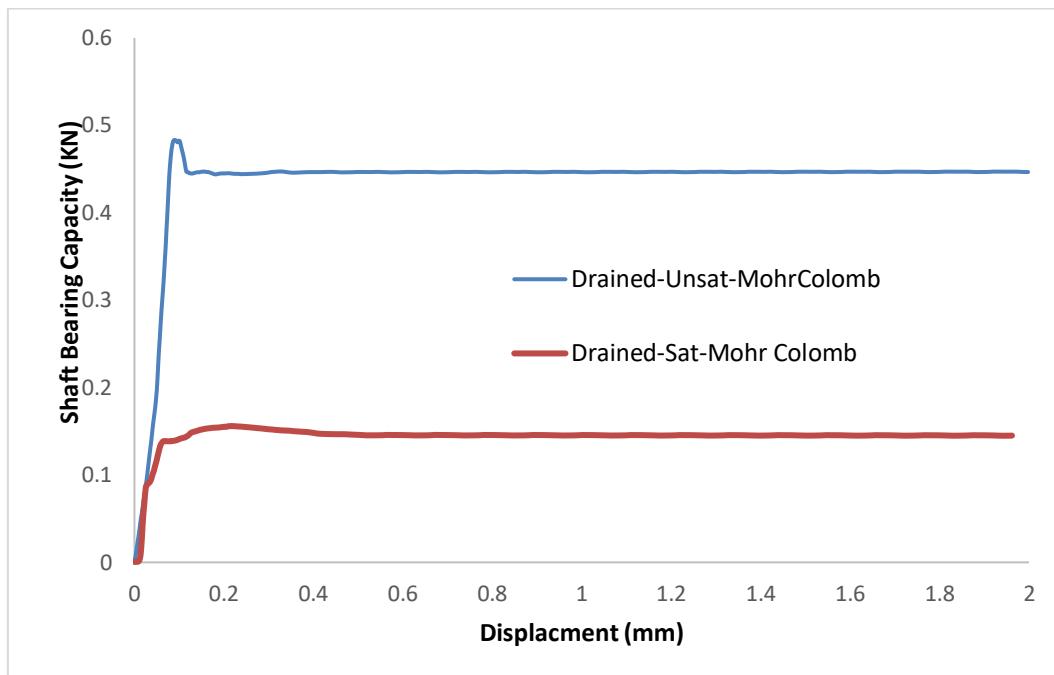


Fig. 4. Pile bearing capacity of saturated and unsaturated mohr_coulomb

Numerical Modeling Using Cam_Clay Behavioral Model

the load-bearing capacity of the pile is estimated experimentally using the Cam_Clay behavioral model in the saturated and unsaturated drained states. Fig. 5 depicts the pile load-bearing capacity diagram resulted from the finite difference numerical modeling carried out using the Mohr–Coulomb behavioral model. As seen, the maximum pile load-bearing capacity in the unsaturated states is approximately 700 N respectively.

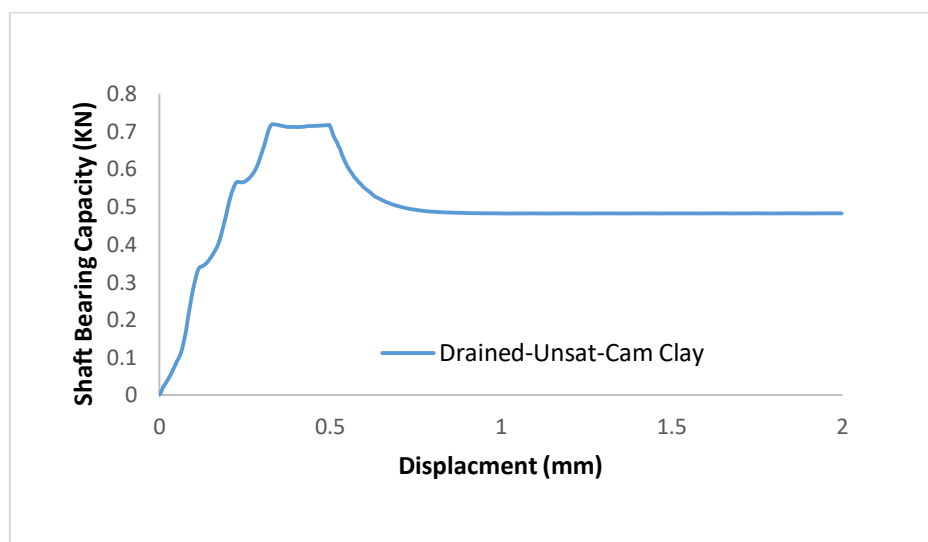


Fig. 5. Pile bearing capacity of unsaturated Cam_Clay

Numerical Modeling Using BBM Model

The Barcelona model is capable of modeling soil collapsing behavior during the wetting process but it is unable to predict irreversible concentrations during the drying process. Unlike previous models, two independent variables (net stress and suction) are used in this model to predict soil behavior Afterwards, the pile wall load-bearing capacity was estimated using the Barcelona behavioral model in the drained and non-drained unsaturated states. Modeling and coding were carried out using

the finite-difference method. Table 2 presents the parameters used in this model. As explained, in this state suction is 205 KPa and modeling conditions are the most similar to laboratory conditions. Fig. 6 depicts the pile load-bearing capacity diagram resulted from the finite difference numerical modeling using the Barcelona model. According to this diagram, the maximum pile load-bearing capacity in the drained and non-drained saturated states is approximately 820 N and 630 N, respectively.

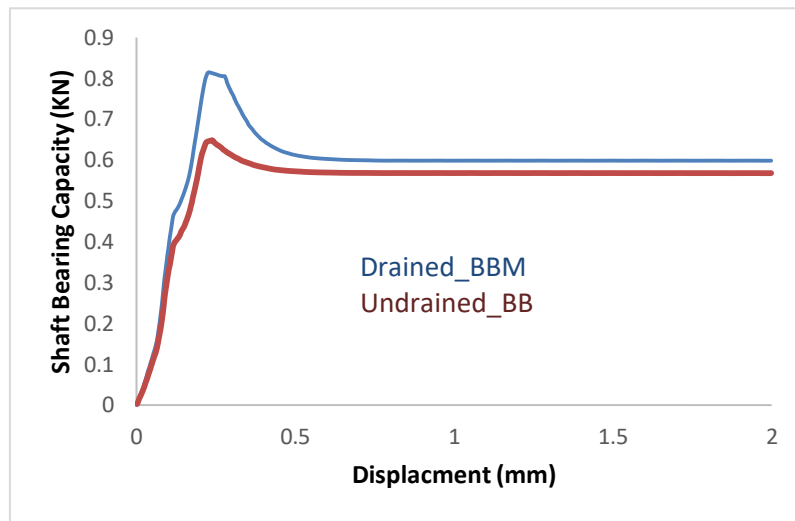


Fig. 6. Pile bearing capacity of unsaturated BBM

Summary and conclusion

In this paper, a comparison was drawn between the Mohr–Coulomb, modified Cam-Clay, and Barcelona behavioral models using the finite-difference method, and results of experiments conducted to estimate pile load-bearing capacity in the static state were presented. The behavioral model parameters matched the laboratory model's. To estimate soil saturation on the suction level of concern, the water-soil curve (showing suction behavior in relation to moisture) was used. Results of the finite-difference modeling using different behavioral models are presented in Table 3.

Table 3. Comparison of measured values and values resulted from numerical modeling in different states

winitial	($u_a - u_w$)	Drainage	Constitutive Model	Est. Qf(us)	Meas. Qf(s),(us)
%	KPa			KN	KN
13	0	Yes	Mohr	0.15	0.16
13	205	Yes	Mohr	0.48	0.82
13	205	Yes	Cam Clay	0.71	0.82
13	205	Yes	BBM	0.81	0.82
13	205	No	BBM	0.63	0.63

The results show that the estimate of Barcelona behavioral model to estimate the capacity of the pile, to consider the impact of unsaturated soil suction is closer to reality. It is necessary to consider unsaturated soil behavior in engineering projects such as earth dams, road and railway body, water supply canals, solid waste landfills, etc. The 1990 BBM model is capable to predict soil hardening due to suction changes and plastic and irreversible response of soil against stress and suction, which lead to failure and collapse of soil, i.e. change in hardness. It can be used for unsaturated soils with low to moderate plasticity such as sandy-clay, clayey sand, silt, and cohesionless soil. Adding the BBM model to FDM application allows engineers to model soil projects more realistically.

References

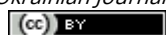
- Al-Khazaali, M., & Vanapalli, S.K. (2015). Numerical modelling technique to predict the load versus settlement behavior of single piles in unsaturated coarsegrained soils. Proc. of GeoQuébec.
- Alonso, E.E., Gens, A., & Josa, A. (1990). A constitutive model for partially saturated soils. *Geotechnique*, 40(3), 405-430.
- Chung, S., & Yang, S. (2014). Loading behaviour of small scale single pile in unsaturated clayey soil. *Materials Research Innovations*, 18(sup. 2), S2-177-S172-181.
- Dolinar, B. (2015). Prediction of the soil-water characteristic curve based on the specific surface area of fine-grained soils. *Bulletin of Engineering Geology and the Environment*, 74(3), 697-703.
- Fujiang, C., Jianlin, M., Lin, Z., & Dawei, L. (2016). Long-Term Settlement Process Prediction for Soft-Clay Pile Foundation Considering Creep Effect. *Electronic Journal of Geotechnical Engineering*, 21, 7033-7043.
- Gens, A., Sanchez, M., & Sheng, D. (2006). On constitutive modeling of unsaturated soils. *Acta Geotechnica*, 1, 137-147.

- Georgiadis, K., Potts, D.M., & Zdravković, L. (2003). The influence of partial soil saturation pile behaviour. *Geotechnique*, 53(1), 11-25.
- Ghorbani, J., Nazem, M., & Carter, J. (2016). Numerical modelling of multiphase flow in unsaturated deforming porous media. *Computers and Geotechnics*, 71, 195-206.
- Gui, M.W., & Bolton, M.D. (1998). Geometry and scale effects in CPT and pile design. *Geotechnical Site Characterization*, 1063-1068.
- Ha, M.M.H., & Hassanlourad, M. (2015). Numerical Modeling of the Negative Skin Friction on Single Vertical and Batter Pile. *Acta Geotechnica Slovenica*, 12(2), 46-55.
- Hamid, T.B., & Miller, G.A. (2009). Shear strength of unsaturated soil interfaces. *Can. Geotech. J.*, 46(5), 595-606.
- Han, Z., Vanapalli, S.K., & Kutlu, Z.N. (2016). Modeling behavior of friction pile in compacted glacial till. *International Journal of Geomechanics*, 16(6), D4016009.
- Lu, N., & Kaya, M. (2014). Power law for elastic moduli of unsaturated soil. *J. Geotech. Geoenviron. Eng.*, 140(1), 46-56.
- Mohamed, F.M.O. (2014). Bearing Capacity and Settlement Behaviour of Footings Subjected to Static and Seismic Loading Conditions in Unsaturated Sandy Soils. Université d'Ottawa/University of Ottawa,
- Oh, W.T., & Vanapalli, S.K. (2012). Interpretation of the bearing capacity of unsaturated fine-grained soil using the modified effective and the modified total stress approaches. *International Journal of Geomechanics*, 13(6), 769-778.
- Oh, W.T., Vanapalli, S.K., & Puppala, A.J. (2009). Semi-empirical model for the prediction of modulus of elasticity for unsaturated soils. *Canadian Geotechnical Journal*, 46(8), 903-914.
- Pedroso, D.M., & Farias, M.M. (2011). Extended Barcelona basic model for unsaturated soils under cyclic loadings. *Computers and Geotechnics*, 38(5), 731-740.
- Ravichandran, N., Krishnapillai, S.H., & Machmer, B. (2013). A novel procedure for physical modeling of unsaturated soil-pile system using geotechnical centrifuge. *J. Earth Sci. Geotech. Eng.*, 3(1), 119-134.
- Rutqvist, J., Ijiri, Y., & Yamamoto, H. (2011). Implementation of the Barcelona Basic Model into TOUGH-FLAC for simulations of the geomechanical behavior of unsaturated soils. *Computers & Geosciences*, 37(6), 751-762.
- Sheikhtaheri, M. (2014). Experimental and numerical modeling studies for interpreting and estimating the p - δ behavior of single model piles in unsaturated sands. Université d'Ottawa/University of Ottawa,
- Sheng, D., Sloan, S., & Gens, A. (2004). A constitutive model for unsaturated soils: thermomechanical and computational aspects. *Computational Mechanics*, 33(6), 453-465.
- Solowski, W., & Sloan, S. (2012). Equivalent Stress Approach in Creation of Elastoplastic Constitutive Models for Unsaturated Soils. *International Journal of Geomechanics*, 36(14), 1667-1681.
- Thakur, V.K., Sreedeeep, S., & Singh, D.N. (2005). Parameters affecting soil-water characteristic curves of fine-grained soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(4), 521-524.
- Vaca, I.Jc. (2015). The dry fraction of unsaturated soils. *Acta Geotechnica Slovenica*, 12(2), 67-75.
- Vanapalli, S., Fredlund, D., Pufahl, D., & Clifton, A. (1996). Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal*, 33(3), 379-392.
- Vanapalli, S., & Taylan, Z. (2011). Estimation of the shaft capacity of model piles in a compacted fine-grained unsaturated soil. Paper presented at the 14th Pan-Am Conf. on Soil Mechanics and Geotechnical Engineering & 64th Canadian Geotechnical Conf., Toronto, Canada.
- Vanapalli, S., & Taylan, Z. (2012). Design of single piles using the mechanics of unsaturated soils. *International Journal of Geomate*, 2(1), 197-204.
- Vanapalli, S.K., Fredlund, D.G., & Pufahl, D.E. (1996). The relationship between the soil-water characteristic curve and the unsaturated shear strength of a compacted glacial till. *Geotechnical Testing Journal*, 19(3), 259-268.
- Xu, Y., & Cao, L. (2015). Soil Mechanics of Unsaturated Soils with Fractal-Texture (pp. 519-523). In *Engineering Geology for Society and Territory*, 6. Springer.
- Yavari, N., Tang, A.M., Pereira, J.-M., & Hassen, G. (2016). Effect of temperature on the shear strength of soils and the soil-structure interface. *Canadian Geotechnical Journal*, 53(7), 1186-1194.
- Zhang, M., Shang, W., Wang, X., & Chen, Y.F. (2017). Lateral dynamic analysis of single pile in partially saturated soil. *European Journal of Environmental and Civil Engineering*, 1-22.

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