Nazarbayev University
Department of Civil and Environmental Engineering

Masters Thesis

“Role of unsaturated soil mechanics in foundation design”

Presented by: Allah Bahman Ibrahimi
Supervisor : Professor Alfrendo Satyanaga
Co-Supervisor: Professor Sung Woo Moon

TABLE OF CONTENT

Introduction:

Background

- Earth surface
- Difference between saturated and unsaturated soil
- Layers of unsaturated zone
- Importance of unsaturated soil
- The effect of climate changes on soil
- Unsaturated soil in foundation design

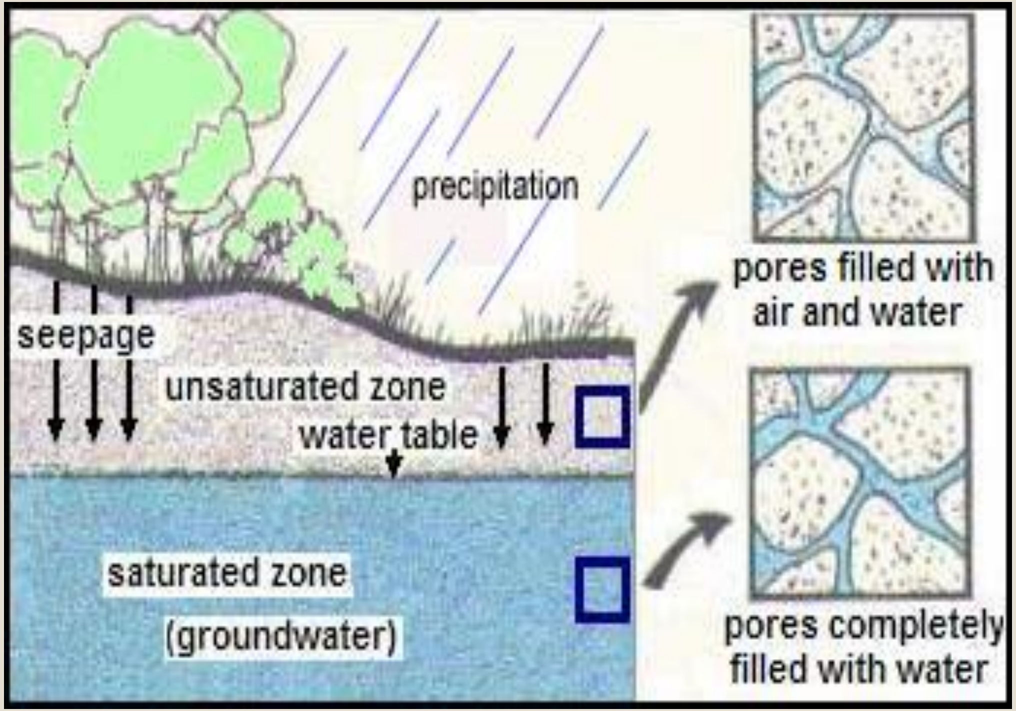

Figure1. Effect of flux boundary conditions on unsaturated soil layers

Introduction:

Objectives:

- To investigate the importance of unsaturated soil mechanics principles in foundation design with respect to dimension of foundations and the behavior of soils surrounding foundation under the effect of climatic conditions, such as: rainfall.

Hypothesis:

- The effect of climatic condition on the unsaturated soil properties. Rainfall infiltrate to unsaturated soil and reduce the matric suction within the soil and results in reduction of the shaft Capacity of pile foundation.

Thesis statements:

- Effect of rainfall on characteristics of soils surrounding the foundation
- Shaft capacity of pile foundation due to the changes of moisture content in unsaturated soil properties

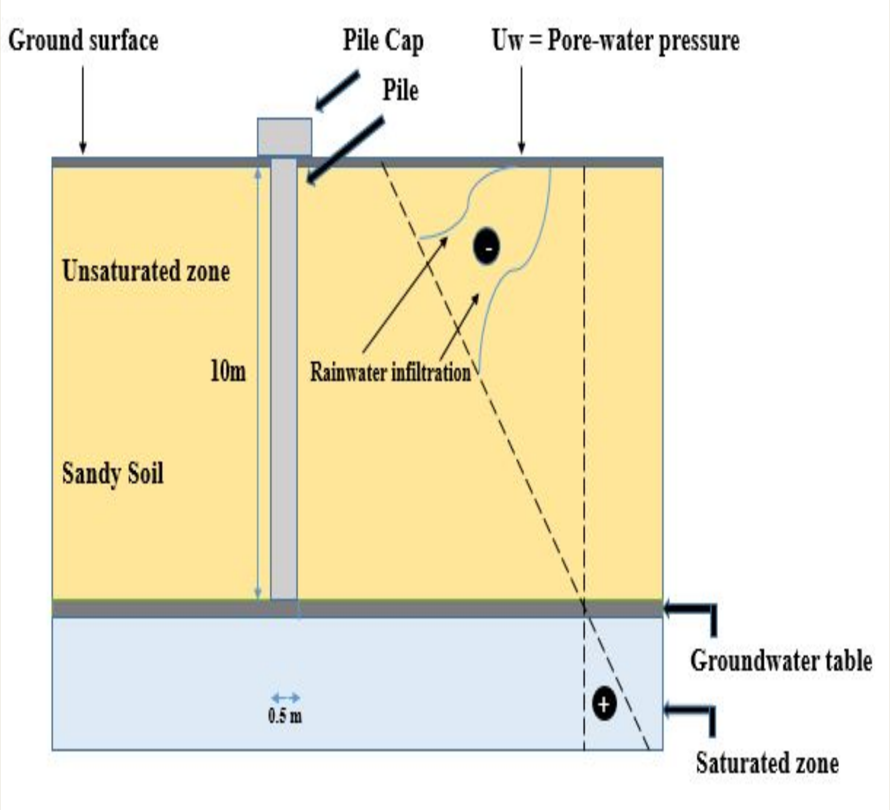

Figure 2. Pile foundation in unsaturated soil

2. Literature review

Reviewed more than **50 journal, conference and review papers** on unsaturated soil mechanics, foundation design, soil water characteristic curve and Foundation modelling and unsaturated soil analyses using plaxis.

Unsaturated soil mechanics:

(Fredlund et al., 1993), (Rahardjo et al., 2012), (Zhai et al., 2021)

Foundation design:

(Douthitt et al. 1998), (Vanapalli et al., 2007), (Vanapalli et.al., 2021)

Soil water characteristic curve:

(Jakariac et.al., 2013), (Shaldykova et. Al. 2020), (Satyanaga et. al. 2020)

Foundation modelling and unsaturated soil analyses using plaxis:

(Ayeman et al., 2006), (Mohammad Alkhaali et al., 2020), (Mohammad Rehan et al., 2022)

Methodology

Soil-water characteristic curve (SWCC)

HYPROP and WP4C testing equipment are used to generate SWCC. The mechanism of using Hyprop is related to the natural evaporation process and WP4C is related to measurement of dew point within soil surface which is equivalent to suction measurement (Satyanaga et al. 2019)

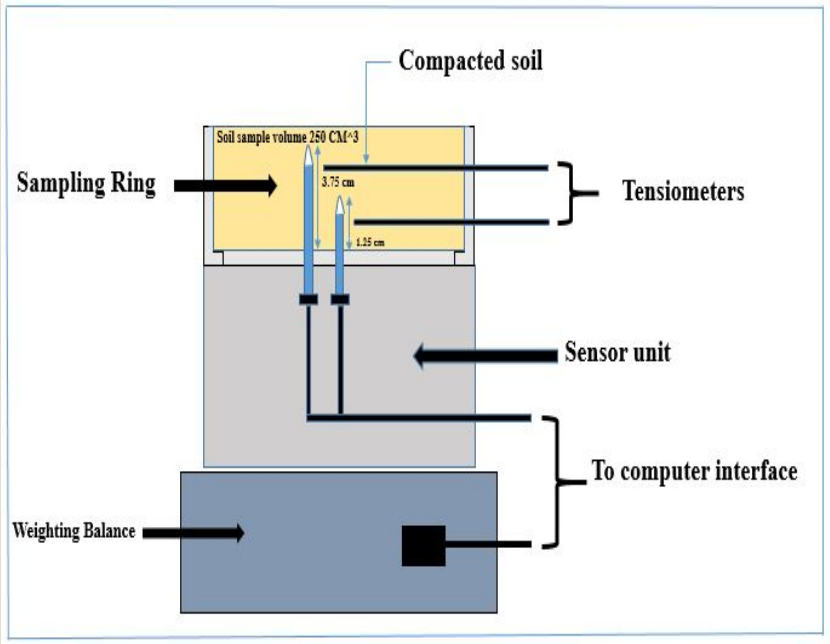

Figure 3. Cross section of Hyprop

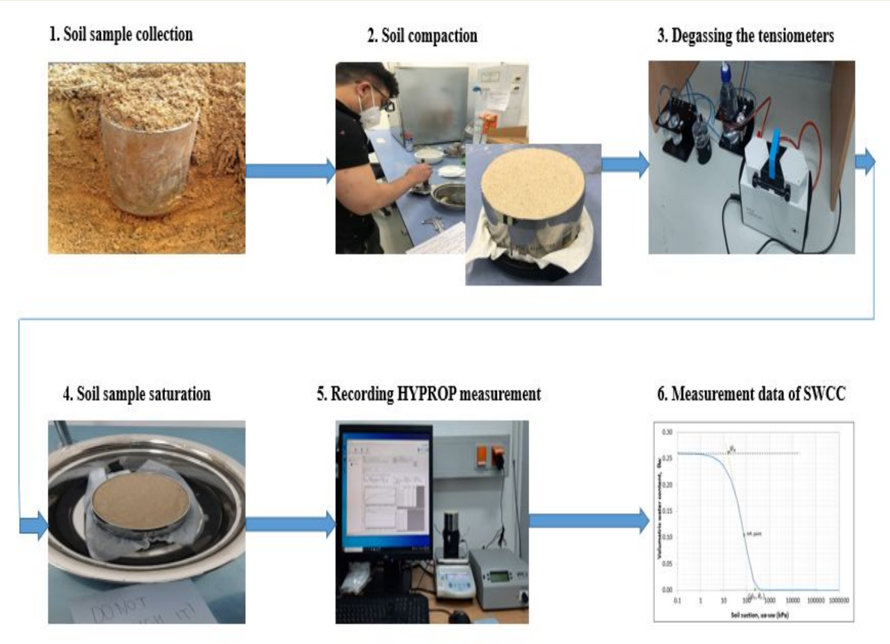

Figure 4. Measurement of soil water characteristic curve using Hyprop

Grain size distribution and specific gravity test:

Grain size distribution analysis and Hydrometer tests were conducted for soil classification.

Figure 5. Grain-Size Analysis: ASTM D422-63

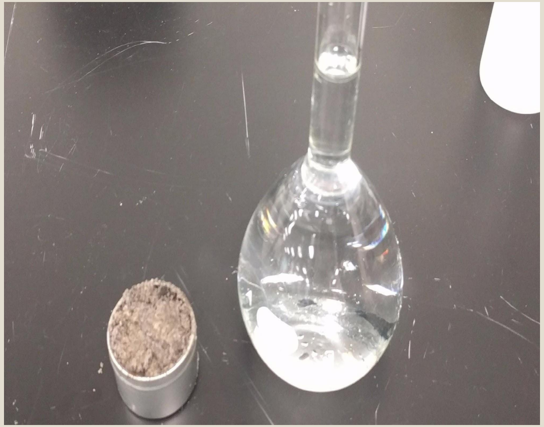

Figure 6. Specific gravity Test: ASTM D854-06

Figure . 7 Hydrometer analysis ASTM D7928-21e1

Index properties by Atterberg limit:

Atterberg's Tests were used for classification for fine grained and coarse grained soil based on -ASTM, D4318-10

Using Atterberg limit we can find:

- Liquid limit (LL)
- Plastic limit (PL)
- Plasticity Index (PI)

Figure 8. Atterberg test equipment

Permeability test:

Saturated Permeability (k_s) using constant head for course grained soil and falling head for fine grained soil.

Calculation of unsaturated permeability of soil using statistical method:

$$k_w(\theta_w)_i = \frac{k_s}{k_{sc}} A_d \sum_{j=i}^{m} \left\{ (2j+1-2i)(u_a-u_w)_j^{-2} \right\}$$

$$i = 1, 2, \ldots, m$$

where;

$k_w(\theta_w)i$ predicted water coefficient of permeability for a volumetric water content, $(\theta_w)_i$, corresponding to the i[th] interval (m/s)

i interval number which increases as the volumetric water content decreases

j a counter from "i" to "m"

m total number of intervals between the saturated volumetric water content and the lowest volumetric water content on the experimental SWCC

k_s measured saturated coefficient of permeability

k_{sc} saturated coefficient of permeability

A_d adjusting constant

$(u_a-u_w)_j$ matric suction corresponding to the j[th] interval (kPa)

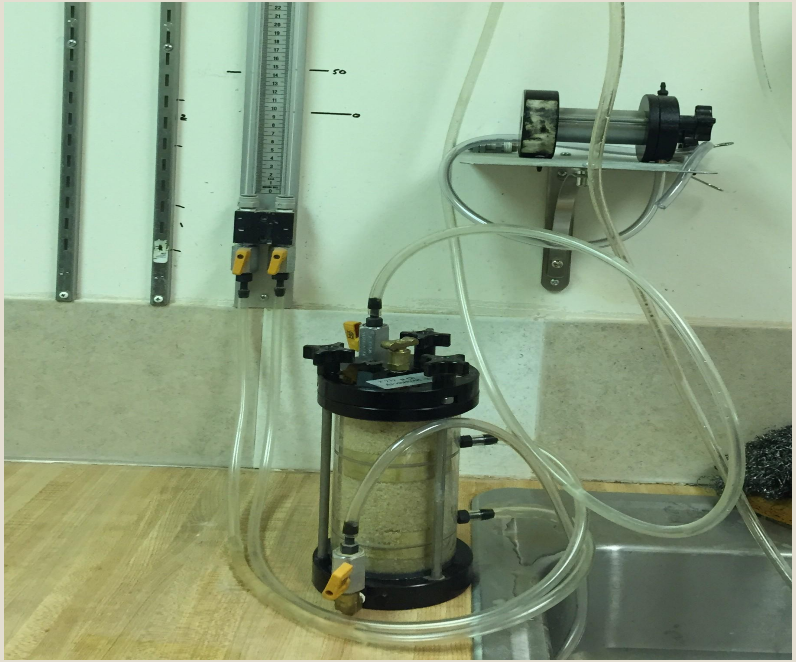

Figure 9. Constant head permeability test

Shear strength (τ) using Triaxial

- Saturation
- Consolidation
- Shearing

Consolidated drained triaxial test (CD)was performed for shear strength of sand and consolidated undrained triaxial test (CU)was used for shear Strength of the Kaolin.

The shear strength test was based on ASTM D4767-11(2020)

Figure 10. Triaxial test

Calculation of Shaft capacity of pile foundation

Table 1. Shaft capacity calculation using conventional and modified methods

Method	Conventional formulas	Modified formulas (Vanapalli et al, 2012)
Beta method	[illegible] = [illegible] = [illegible]	[illegible] = [[illegible] + [illegible] + ([illegible] − [illegible])([illegible])([illegible])] [illegible]
Alpha method	[illegible] = [illegible] x [illegible] = [illegible]	[illegible] = [illegible][1 + $\frac{([illegible] - [illegible])}{(\frac{[illegible]}{101.3})}$ [illegible]/ [illegible]] [illegible]
Lambda method	[illegible] = [illegible]([illegible] + 2c_u) [illegible]	[illegible] = [illegible][[illegible] + 2[illegible](1 + $\frac{([illegible] - [illegible])}{(\frac{[illegible]}{101.3})}$ [illegible])]

Numerical analyses using Plaxis 3D:

To simulate the effect of rainfall on bearing capacity of foundation due to changes of suction in the unsaturated soil surrounding the foundation.

Table 2. Laboratory data used for foundation modeled in sandy and Kaolin soil using plaxis 3D

Soil type	**Sand**	**Kaolin**
Soil Model	Mohr-Coulomb	Mohr-Coulomb
Drainage Type	Drained	Drained
Unsaturated unit weight	15 kN/ m^3	14 kN/ m^3
Saturated unit weight	20 kN/ m^3	20.83 kN/ m^3
Void ratio	0.71	0.33
Modulas of elasticity	430 kN/ m^3	15.76 kN/ m^3
Cohesion	0	18 kPa
Friction angle	45	23

Foundation modeling using plaxis procedure:

- Choosing the project properties such as the unit and dimension of the project
- Creating the borehole, where the depth of soil and depth of groundwater table can be constructed
- Entering the values for the soil properties
- Generating the mesh of the structure
- Adding the precipitation
- The outcome of the modeled pile foundation

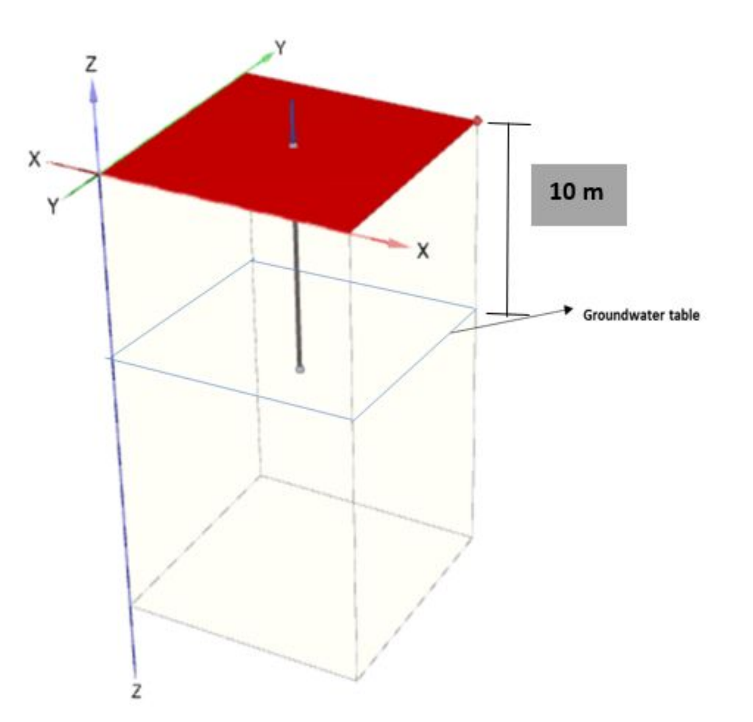

Figure 11. *Foundation modelling using Plaxis 3D*

Research method:

- well graded sand and kaolin is assumed in surrounding of a square driven pile with **0.5m** diameter and **2 to 10** meters length.
- Analytical calculation of shaft capacity of square driven pile foundation using the six methods **($\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\lambda}$ *and modified* $\boldsymbol{\alpha}$ *, modified* $\boldsymbol{\beta}$*, modified* $\boldsymbol{\lambda}$)**
- The ground water table is considered 10m according to Astana geological distribution which the typical ground water table is between 2-10 meters depth (Zhussupbekov et al., 2021)
- The study focus on Astana city Kazakhstan because of the current construction progress and also to study the rainfall effect on the unsaturated soil properties in this city as it has a high rainfall intensity during summer.
- The maximum rainfall intensity in Kazakhstan is **20 mm per day** for 12 days (Chepelianskaia et al., 2022)
- In the preliminary study fifteen sets of analytical calculation were done to measure the shaft capacity of pile foundation in state of saturated for **10m, 8m, 6m, 4m, and 2m depth** of foundation and fifteen sets of analytical calculation is performed to calculate the shaft capacity of pile foundation in state of unsaturated for **10m, 8m, 6m, 4m, and 2m** depth of foundation. And also fourteen sets of analytical calculations were done for estimating the bearing capacity of pile foundation after rainfall intensity and changes in suctions.
- By the comparison of conventional and modified methods calculation and also the calculation bearing capacity before and after rainfall intensity the result is obtained

Particle size distribution curve from sieve and hydrometer analyses:

,

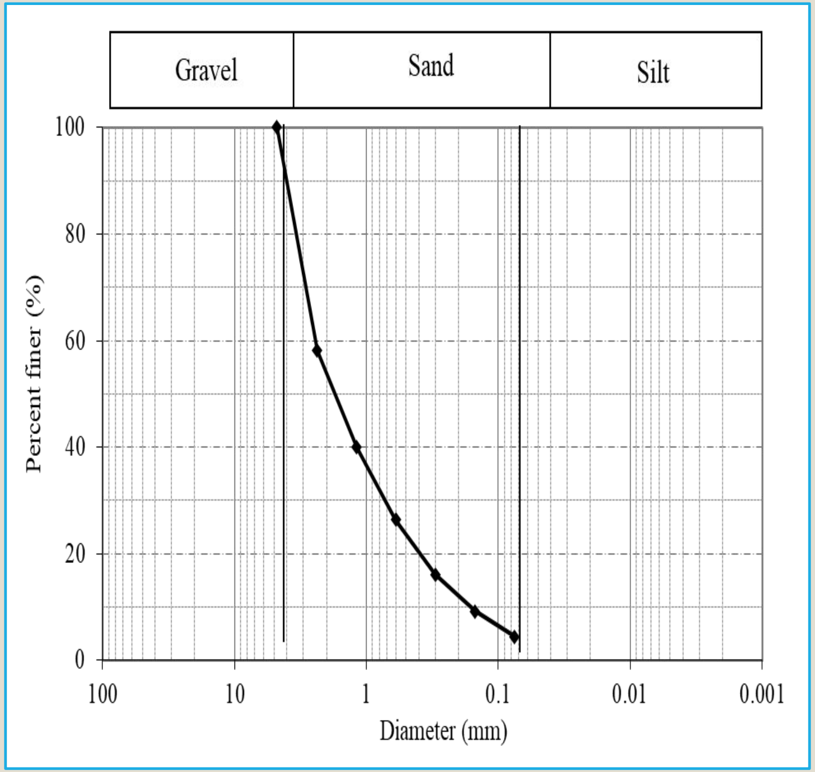

Figure 12. Particle size distribution of Sand

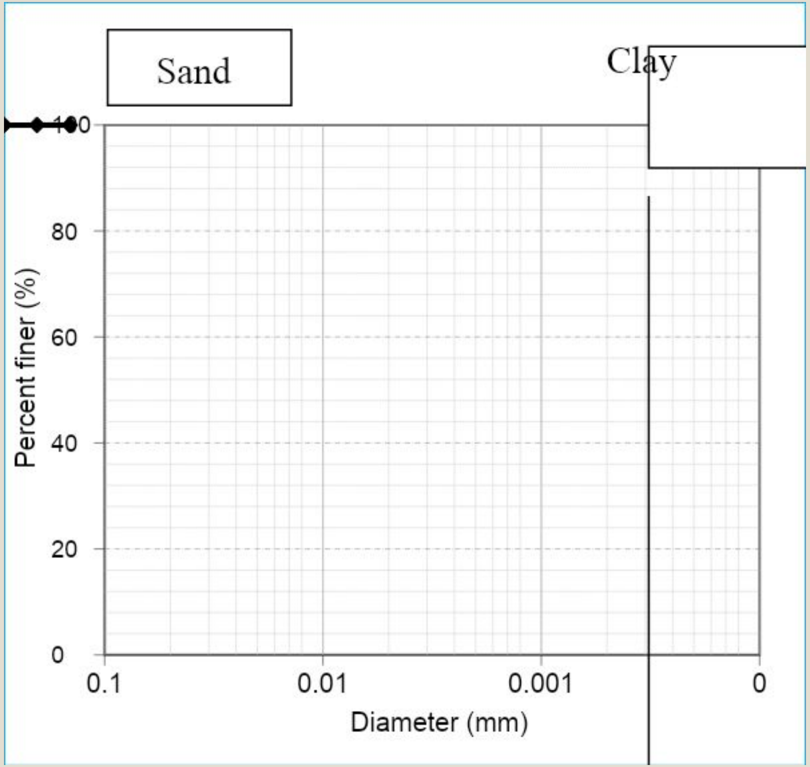

Figure 13. Particle size distribution of Kaolin

Result from laboratory testing:

Table 3. Index properties of Sand and Kaolin

Soil Type	Sand	Kaolin
Specific gravity, Gs	2.69	2.64
Liquid Limit, LL (%)		66.3
Plastic Limit, PL (%)		41.7
Plasticity Index, PI (%)		24.6
Void Ratio, e	0.71	0.33
Dry density, ρd (Mg/m^3)	1.5	1.45
Water content, w (%)	25.9	28.5
Soil classification according USCS	SW	MH

SWCC Result from laboratory testing:

Figure 14 shows the soil water characteristic curve (SWCC) of sandy soil and figure 15 illustrates the SWCC of Kaolin which are generated using Hyprop testing tool. The (Fredlund and Xing, 1994) best fitting equation was used for this curve.

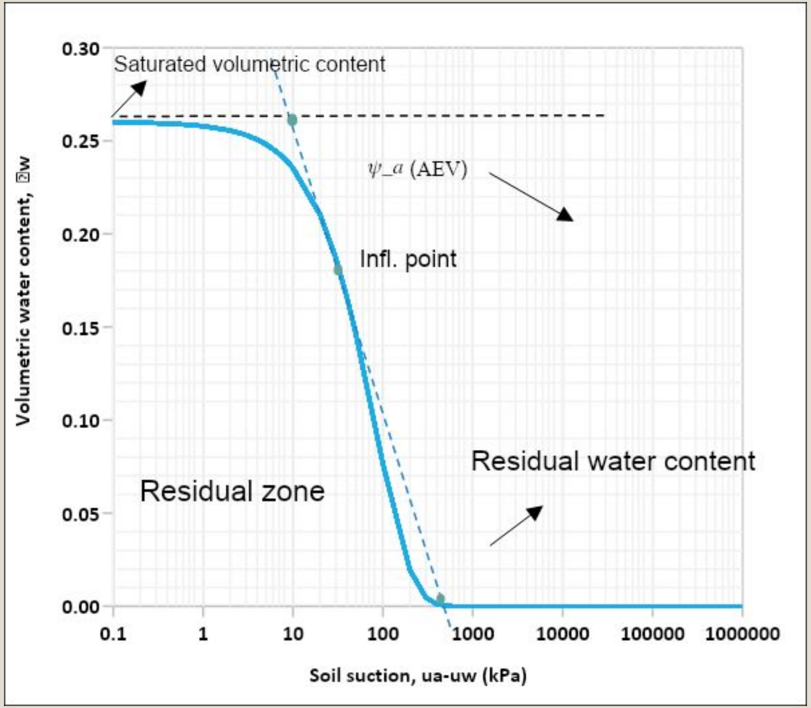

Figure 14. SWCC of sand

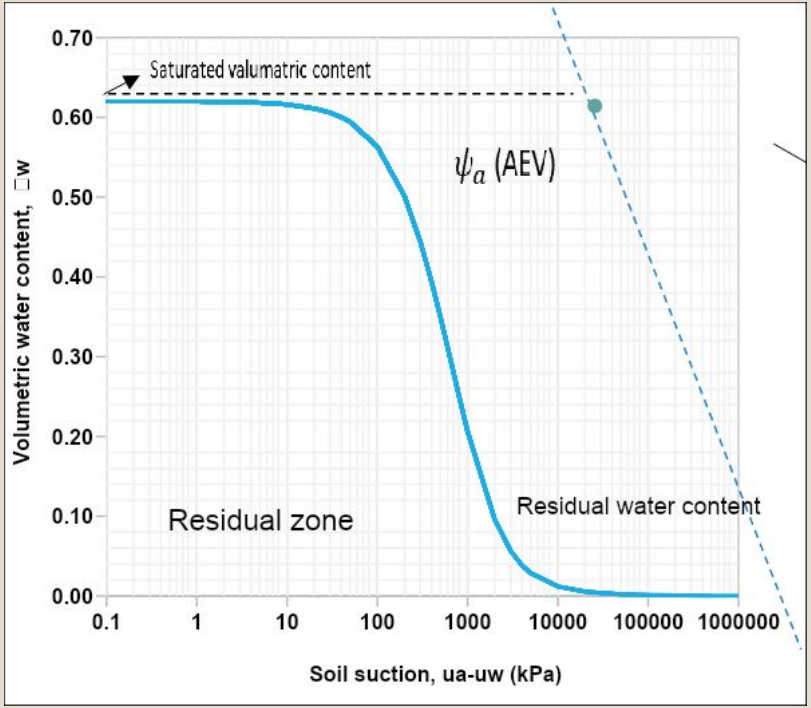

Figure 15. SWCC of Kaolin

5. Results from laboratory testing:

Figure 16 shows the variations of degree of saturation with depth.

This plot was drawn with the assumption of 10 m groundwater table

Below ground surface.

The negative pore-water pressure or soil suction was assumed hydrostatic.

It can be seen that maximum suction of 100 kPa was observed at the

ground surface.

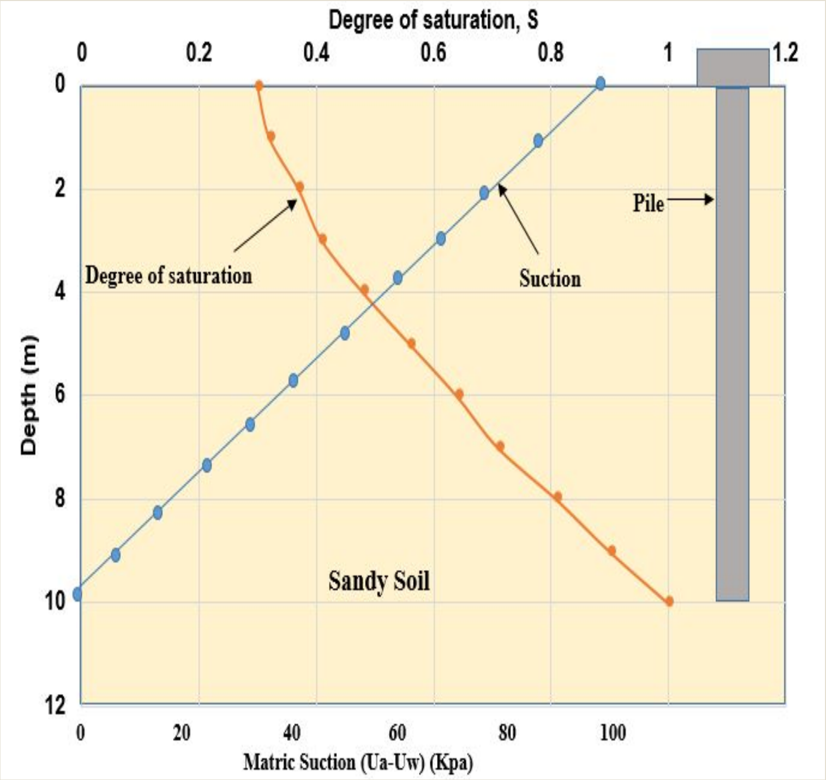

Figure 16. Degree of saturation and matric suction with 10 meters GWT

Permeability test result:

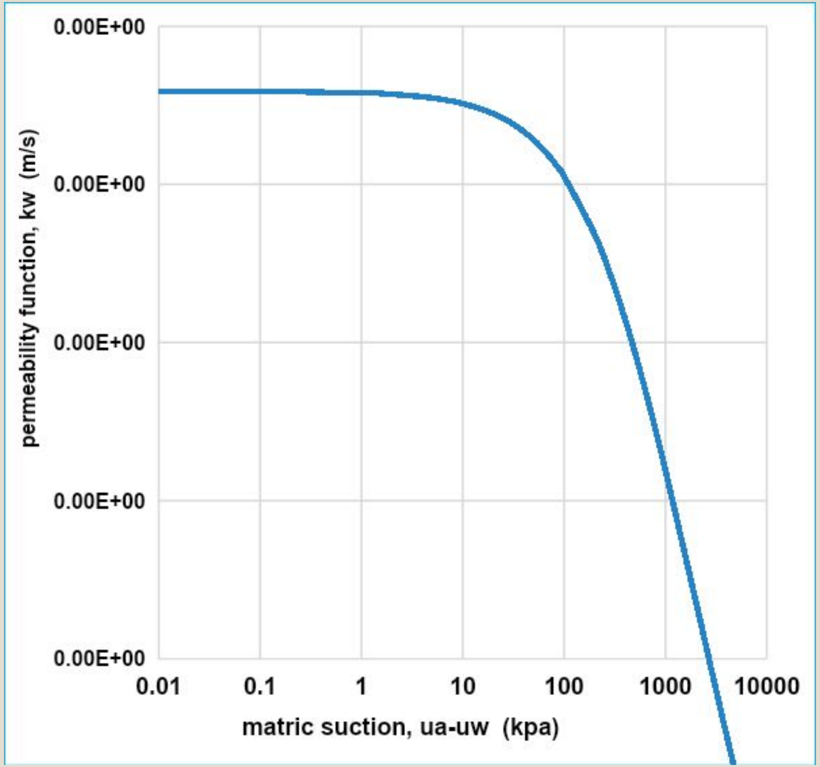

Figure 17. Permeability of kaolin

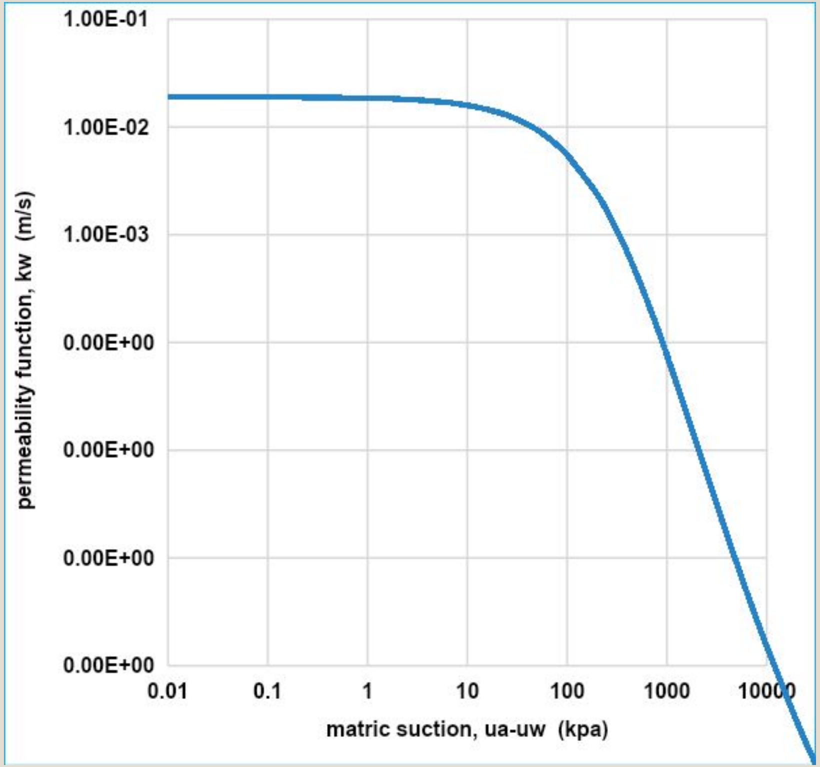

Figure 18. Permeability of sand

Shear strength properties of sand and kaolin

Table 4. Fine grained soil kaolin shear strength data from triaxial test.

Description	Symbol	Sand	Kaolin	Unit
Cohesion	c'	0	18	kPa
Friction angle	φ'	45	23	Degree
Unit weight	γ	15	14	kN/m3
Phb	φ^b	22.5	11.5	Degree

Comparisons of sand shaft capacity between the β method and modified β method

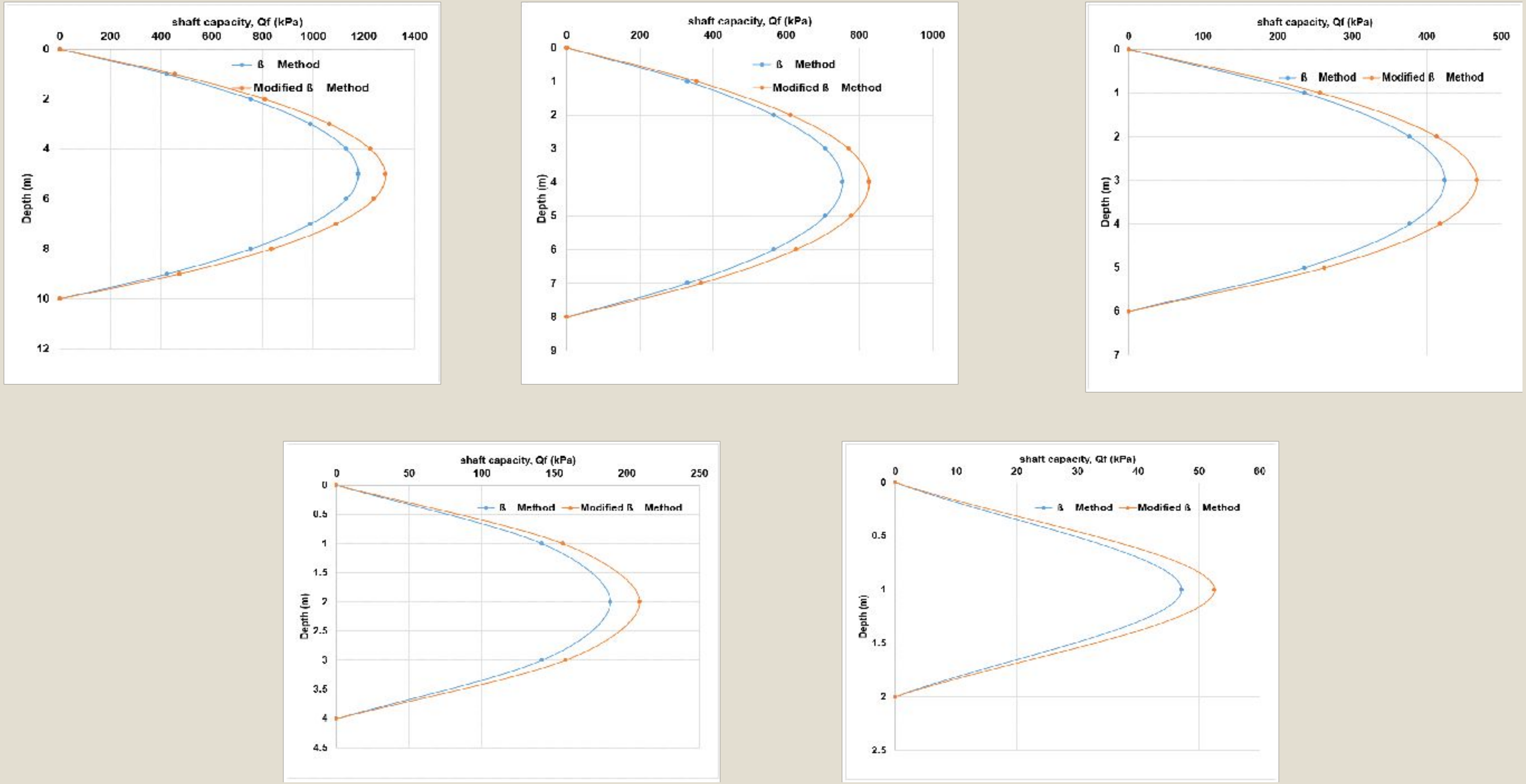

Figure 19. Shaft capacity of pile based on β and modified β method in sand

Comparisons of kaolin shaft capacity between the β method and modified β method

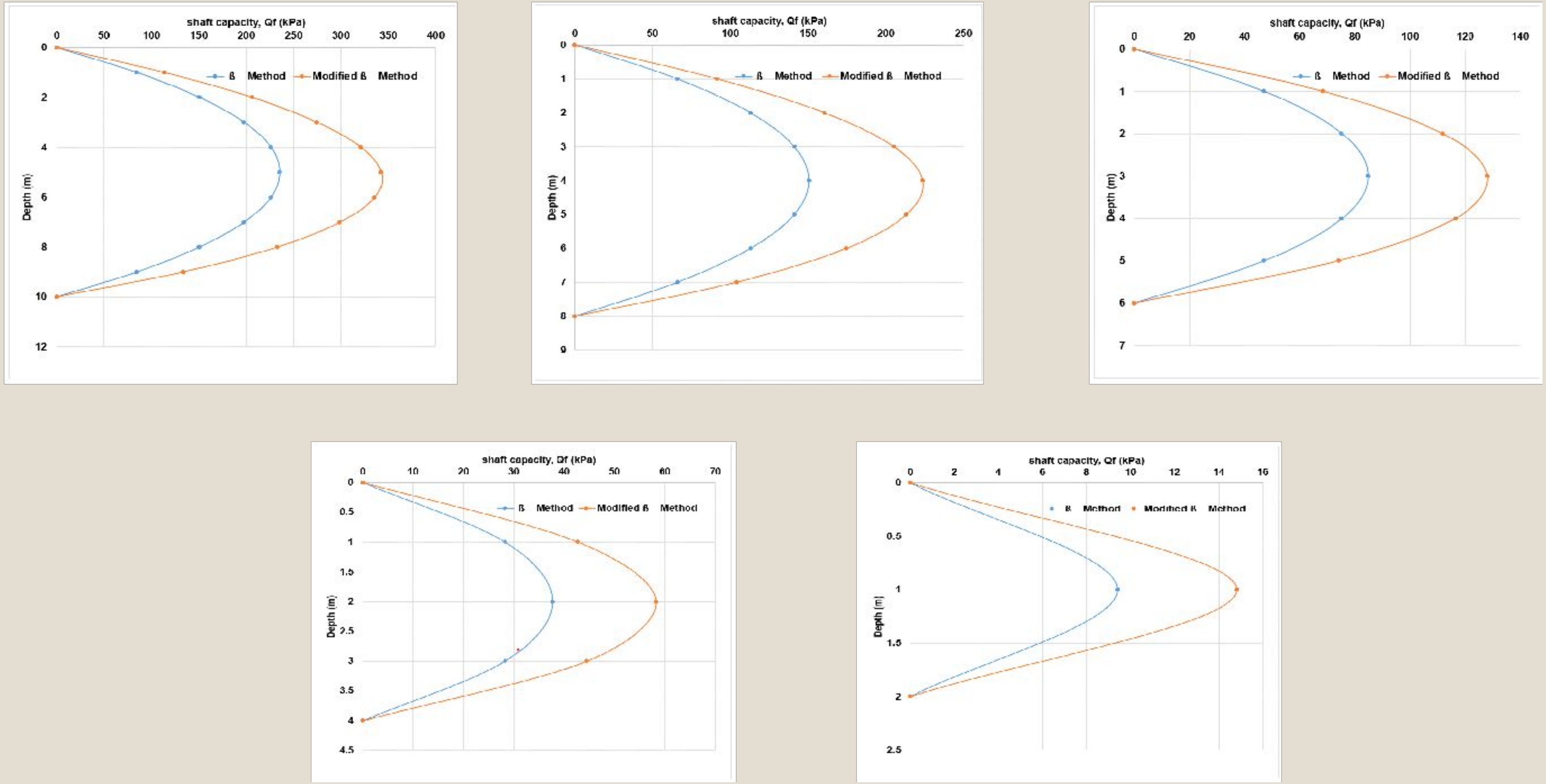

Figure 20. Shaft capacity of pile based on β and modified β method in kaolin

Comparisons of sand shaft capacity between the α method and modified α method:

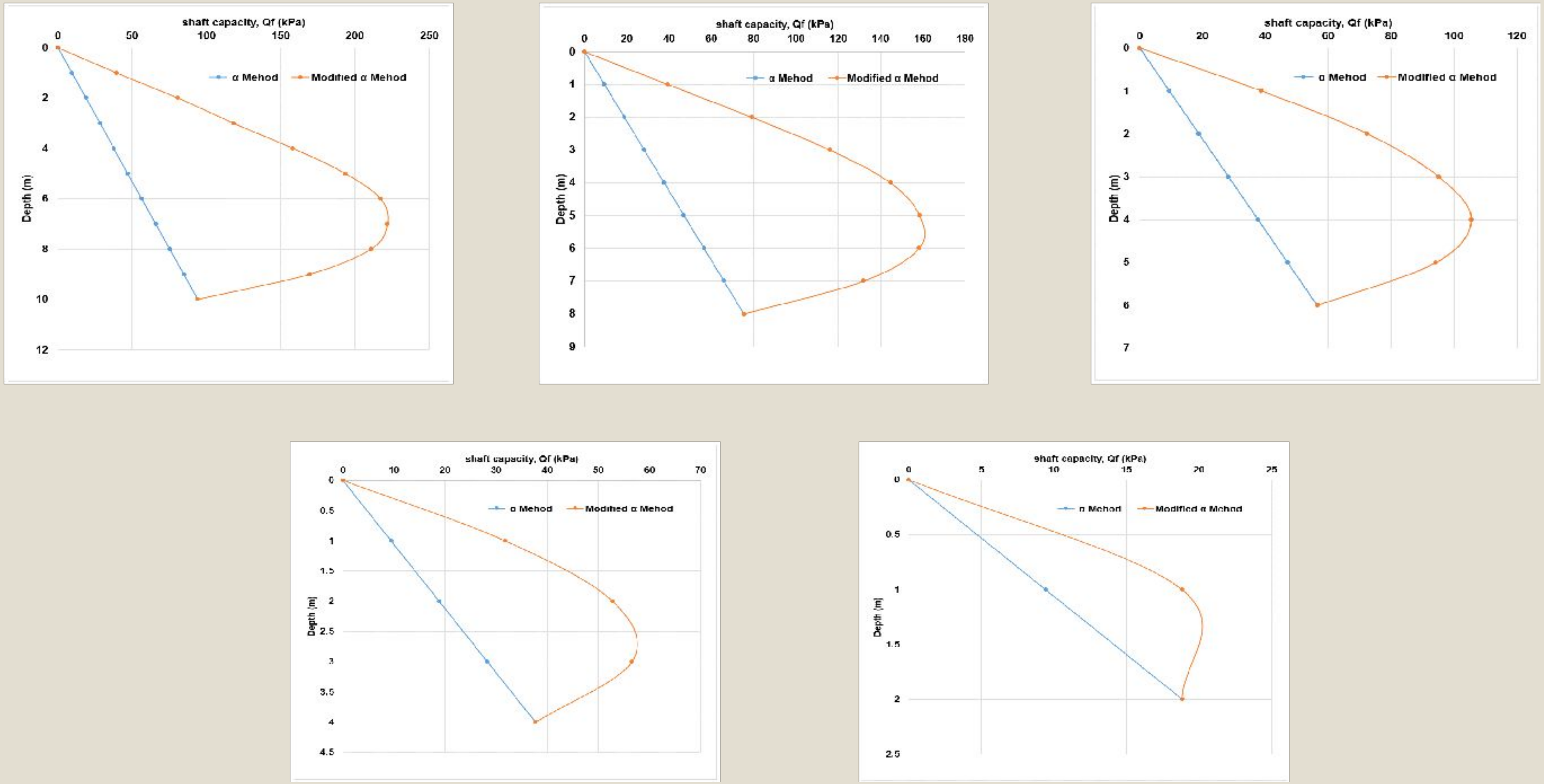

Figure 21. Shaft capacity of pile based on α and modified α method in sand

Comparisons of kaolin shaft capacity between the *α* method and modified *α* method:

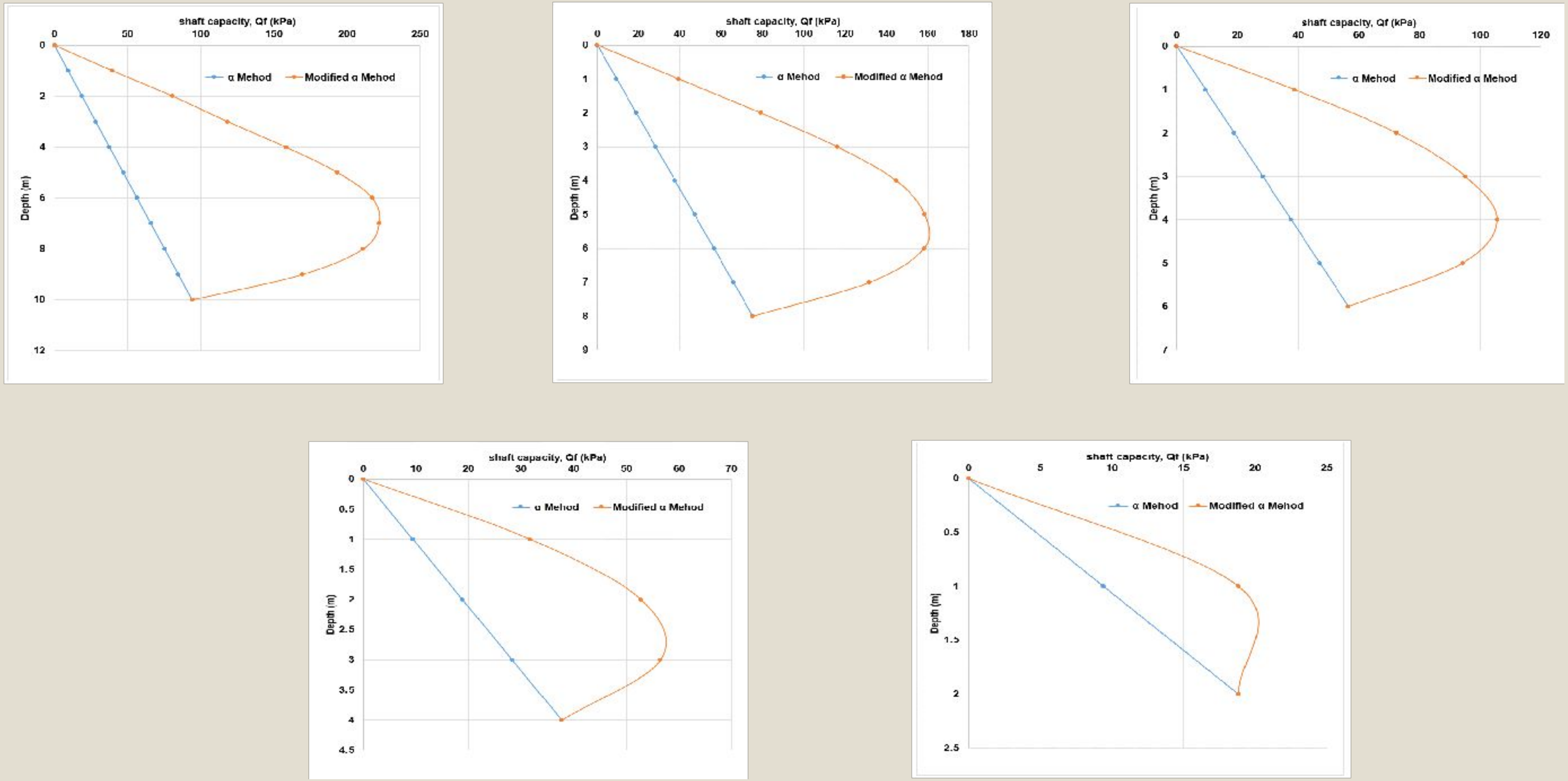

Figure 22. Shaft capacity of pile based on *α* and modified *α* method in kaolin

comparisons of sand shaft capacity between the λ method and modified λ method:

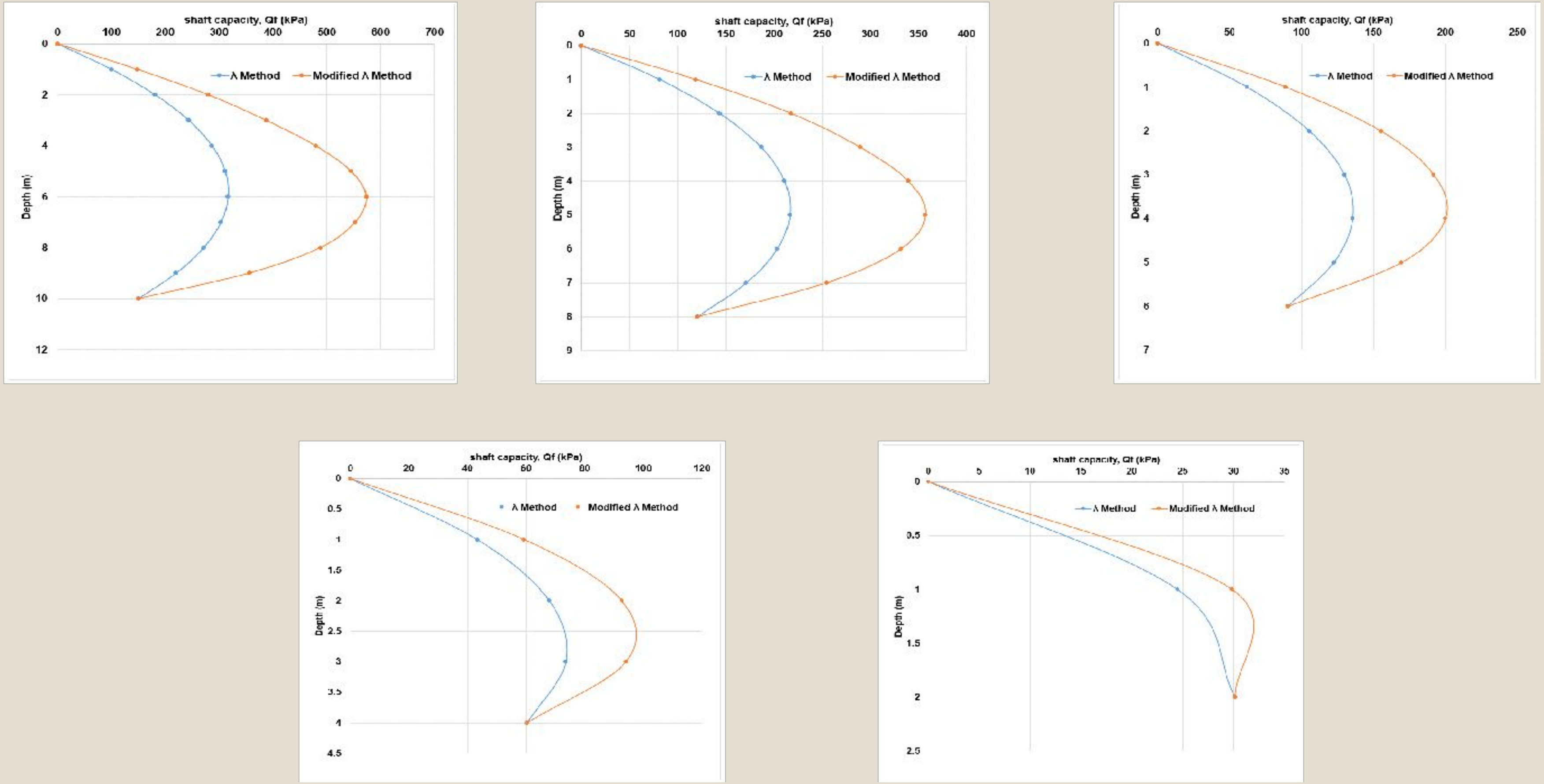

Figure 23. Shaft capacity of pile based on λ and modified λ method in sand

comparisons of kaolin shaft capacity between the λ method and modified λ method:

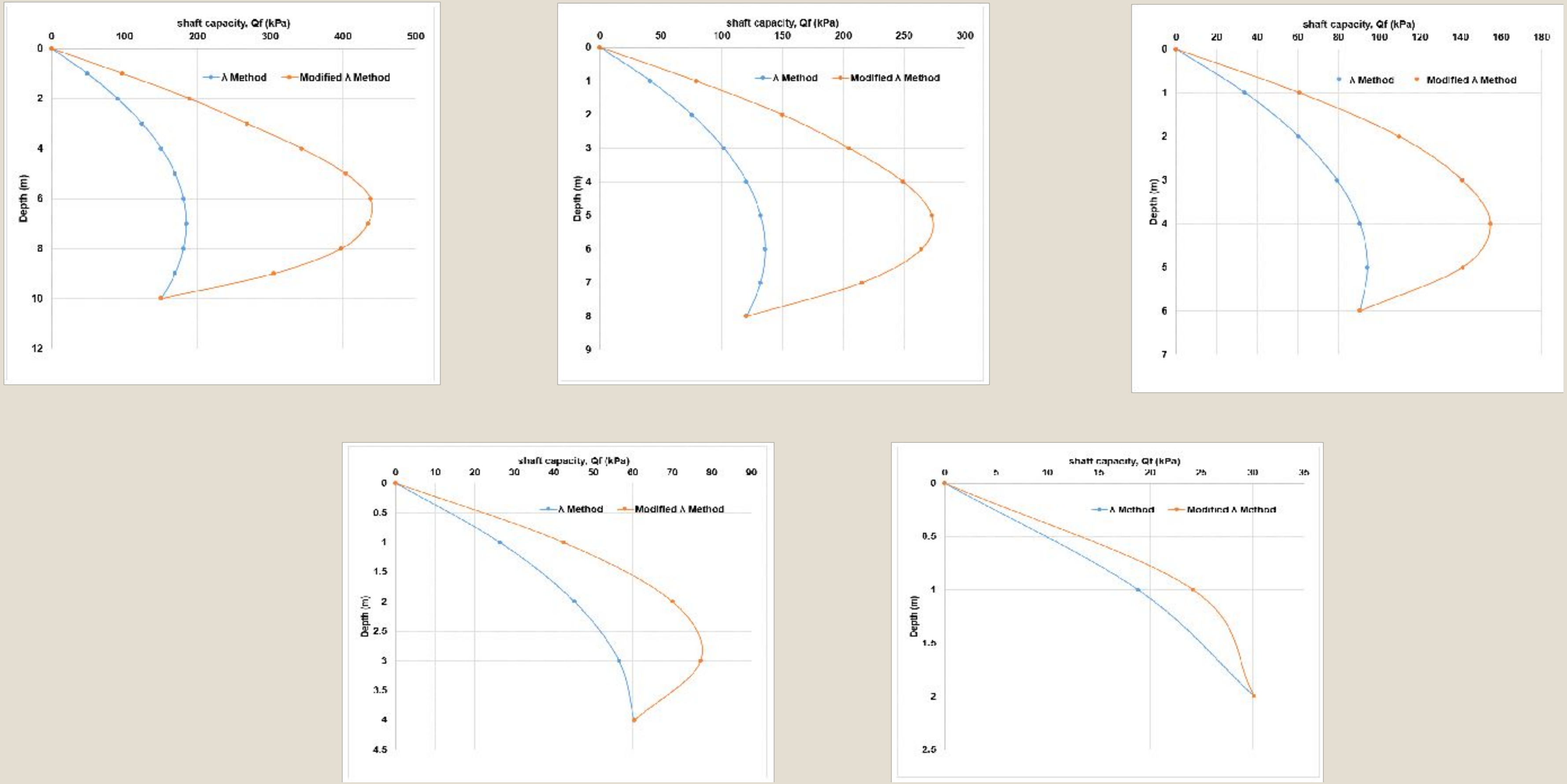

Figure 24. Shaft capacity of pile based on λ and modified λ method in kaolin

Suction of sand before the rainfall:

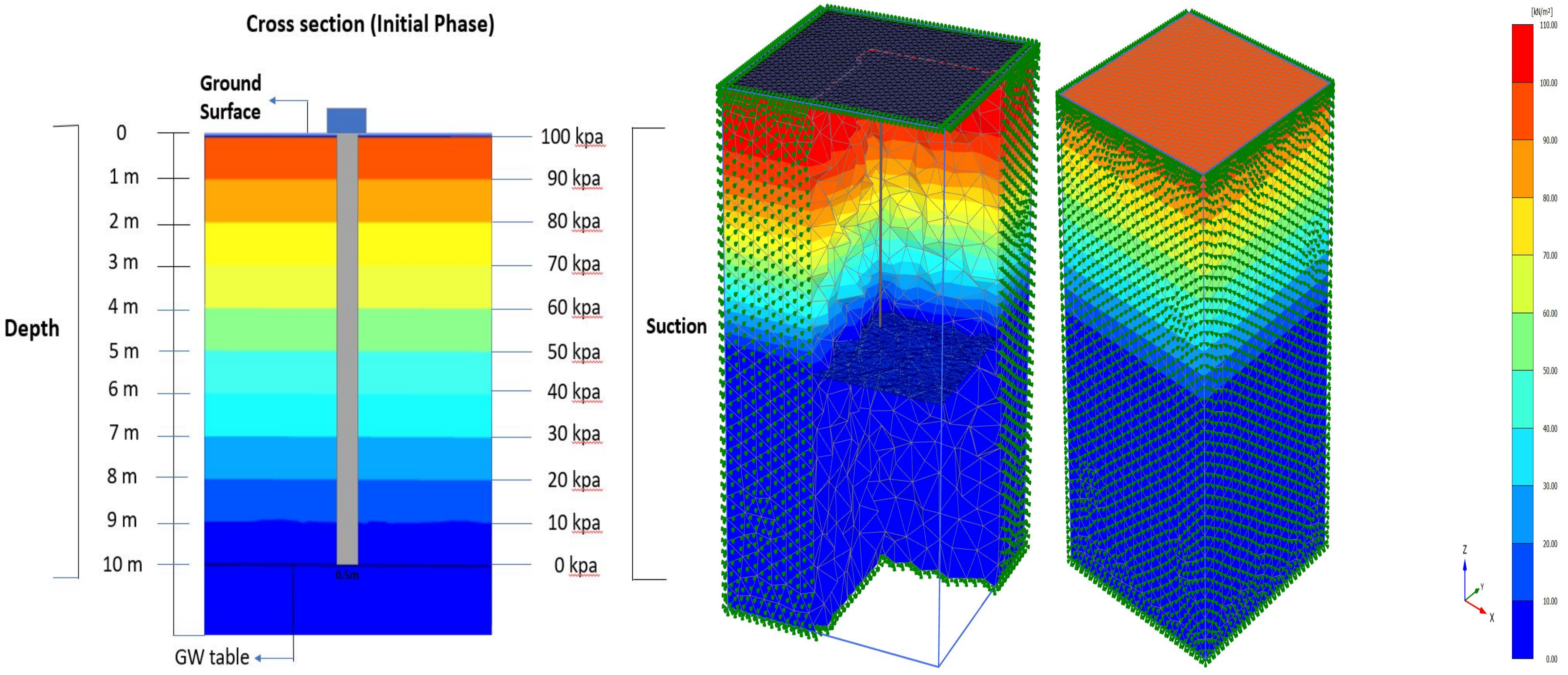

Figure 25. Initial phase in plaxis 3D analyses

Suction of sand after 12 days of rainfall:

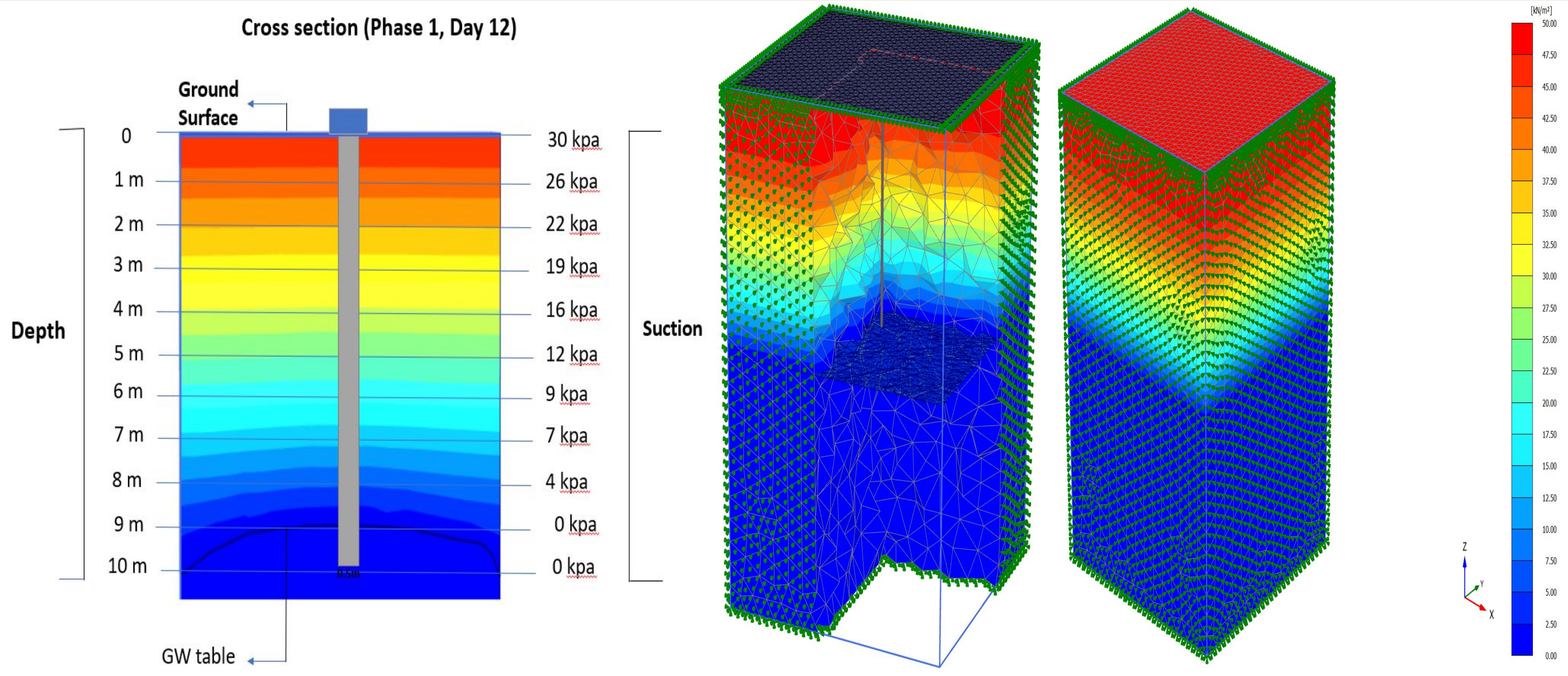

Figure 26. Suction variation of sand due to rainfall in plaxis 3D analyses

Suction variation due to rainfall in sand:

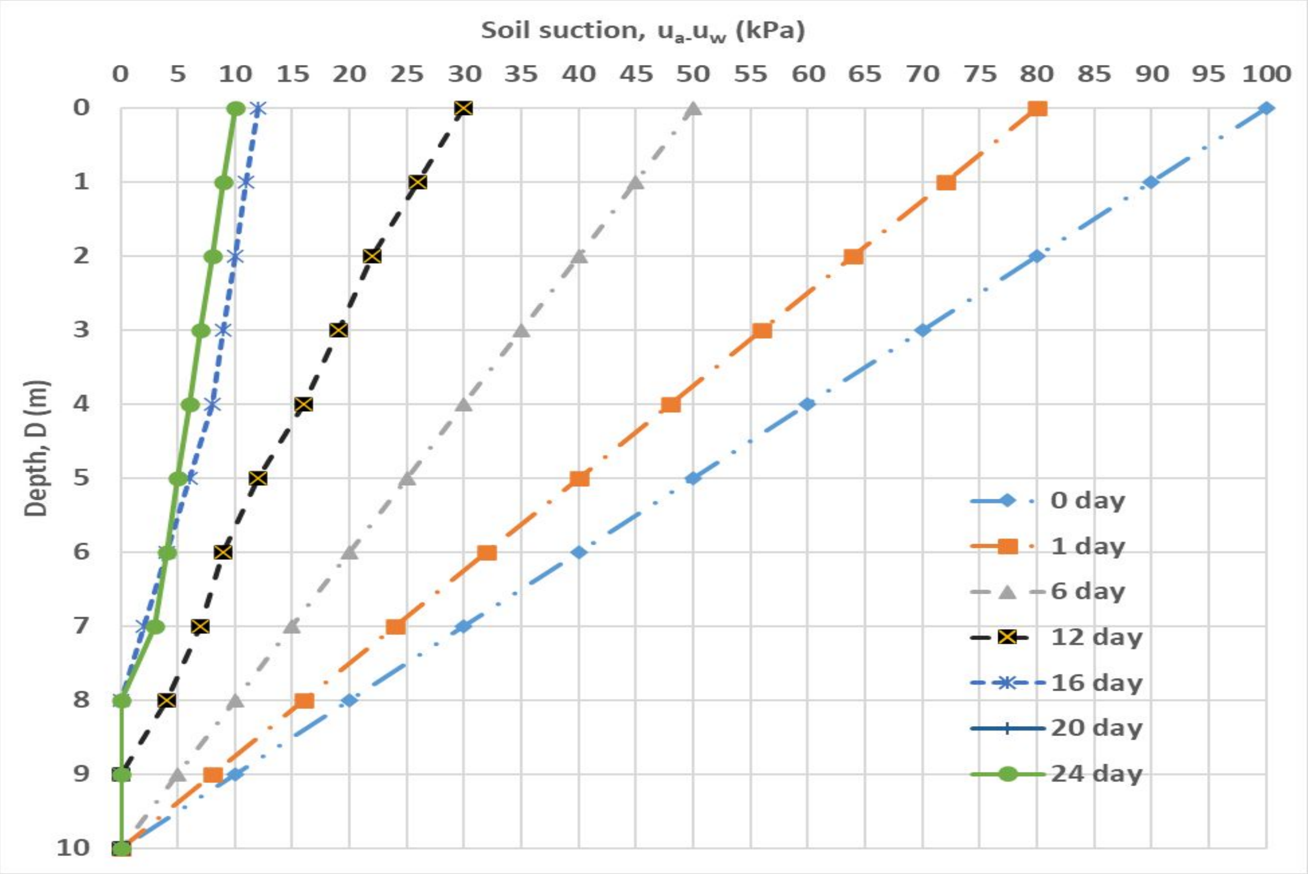

Figure 27. Graph of suction variation of sand due to 24 days rainfall by plaxis 3D analyses

Variation of shaft capacity of pile due to suction changes in sand:

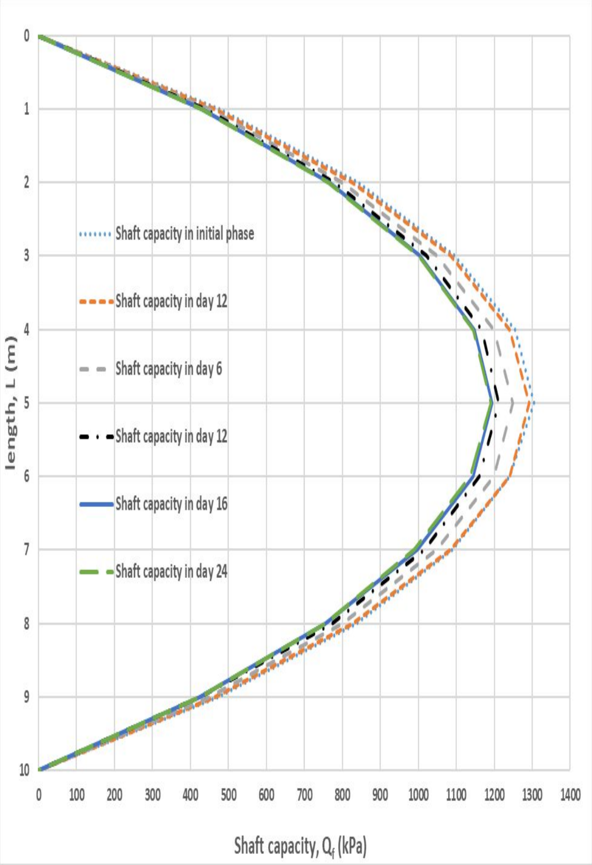

Figure 28. Shaft capacity after rainfall using modified beta in sand

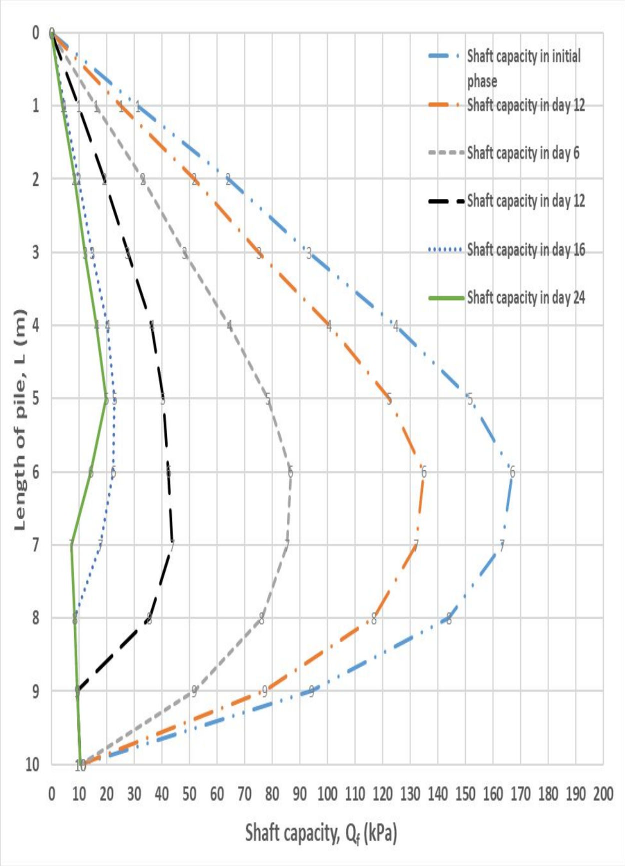

Figure 29. Shaft capacity after rainfall using modified alpha in sand

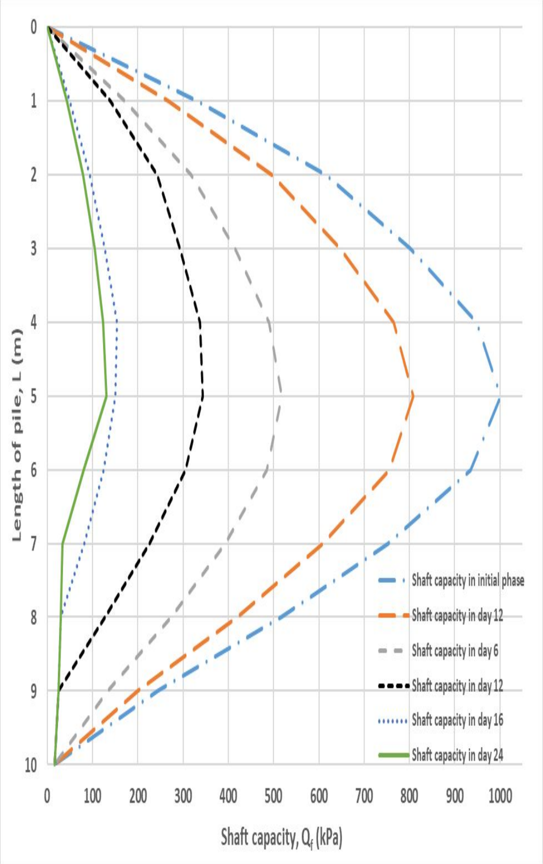

Figure 30 result of sand using modified lambda

Suction of kaolin before the rainfall:

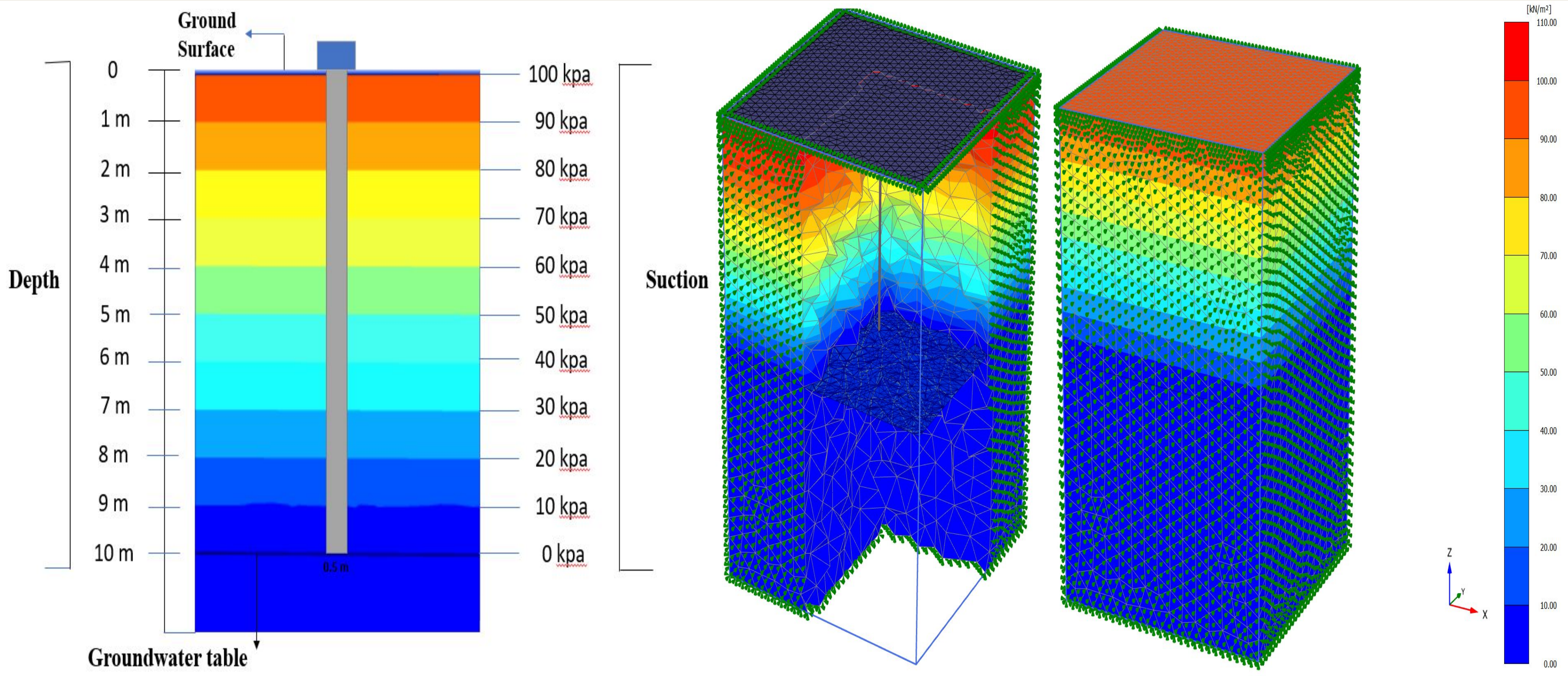

Figure 31. Initial phase in plaxis 3D analyses

Suction of kaolin after 12 days of rainfall:

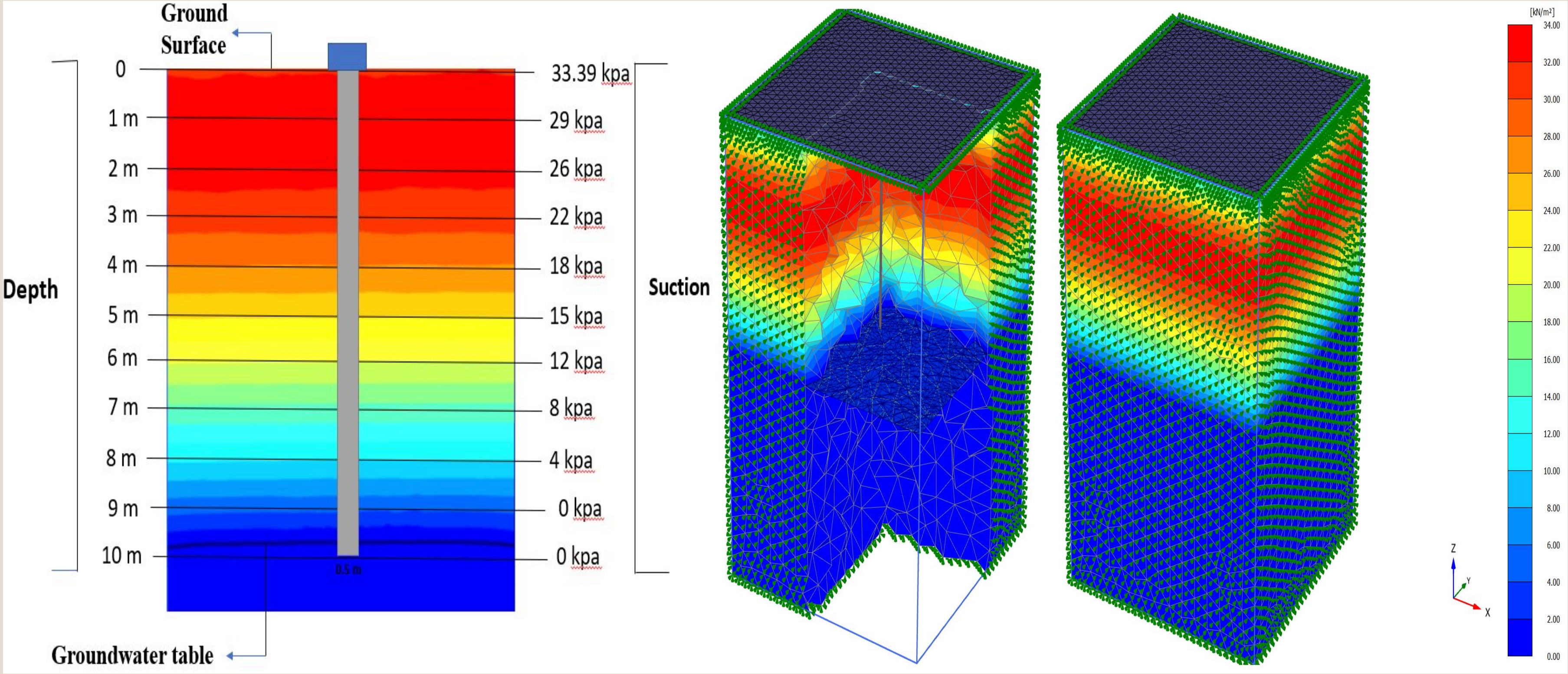

Figure 32. Suction variation of kaolin due to rainfall in plaxis 3D analyses

Suction variation due to rainfall in kaolin:

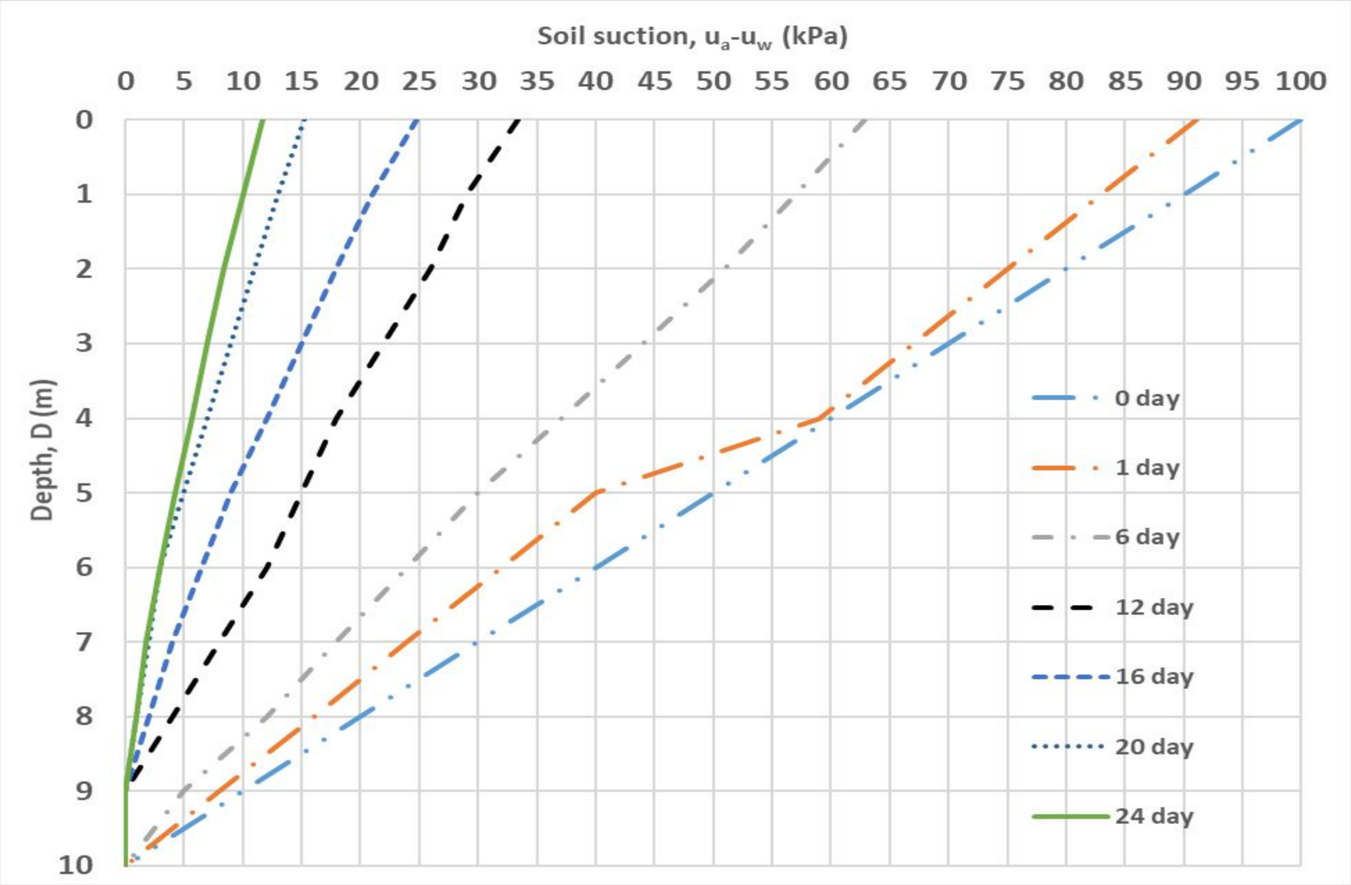

Figure 33. Graph of suction variation of Kaolin due to rainfall in plaxis 3D analyses

Variation of shaft capacity of pile due to suction changes in kaolin:

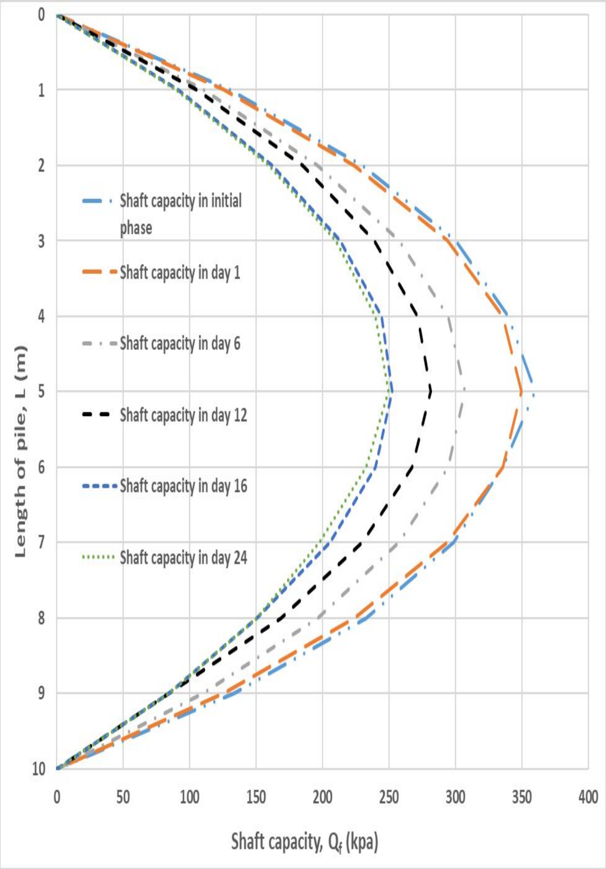

Figure 34. Shaft capacity after rainfall modified beta in kaolin

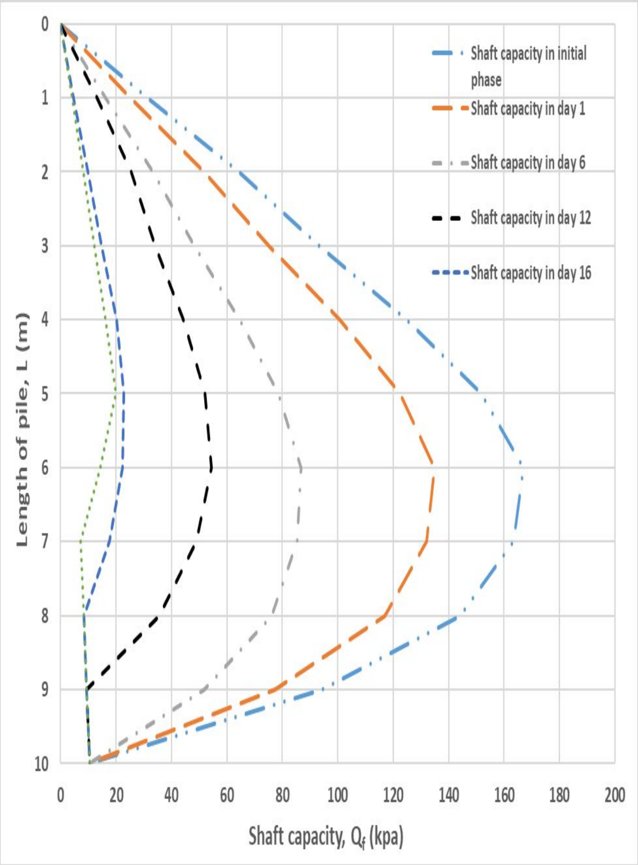

Figure 35. Shaft capacity after rainfall modified alpha in kaolin

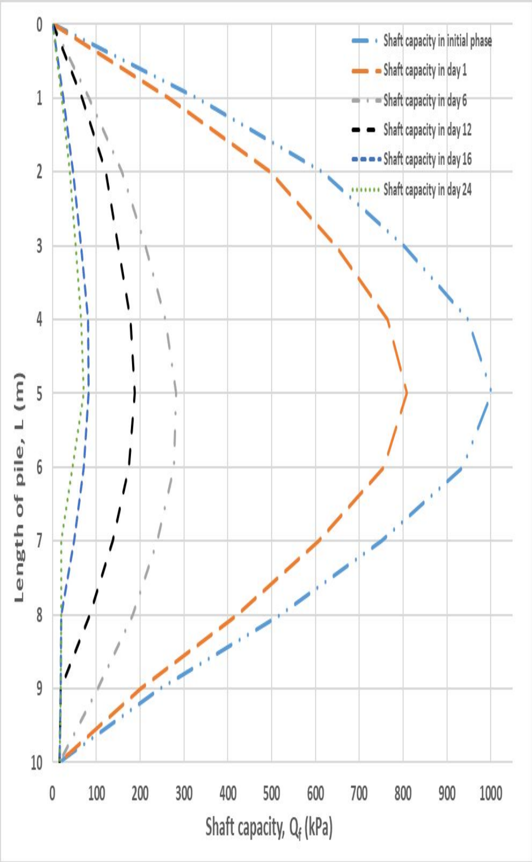

Figure 36. result of kaolin using modified lambda

Conclusion

1. The laboratory data from hyprop test shows that the sands air entry value **(AEV1)** happens in **20 KPa** suction where kaolin's happens in the less than **100 KPa** suction.

2. Fine grained soil (Kaolin) shows lower permeability compare to the coarse-grained soil (sand). According to the results the permeability of the sand is around **0.02 m/s** however the permeability of the kaolin is **0.000006 m/s**.

3. For 10-meter depth of groundwater table in sand with 10 m length of pile, shows a **100 KPa, 165 KPa and 160 KPa differences between two conventional and modified** beta, alpha and lambda methods respectively. Similarly for kaolin shows a **100, 165 and 160 KPa between two methods**. The differences between three methods are the same for both type of soil. Based on the above outcomes, unsaturated soil utilization is **recommended in foundation design for higher shaft capacity and pile optimization**.

4. The suction within the course-grained soil (sand) decreases **70%** in 12 days of rainfall similarly continues to decreases by **20%** in 12 days of dry period. Overall, it falls down by **90%** in 24 days period. The same trend with the fine-grained soil, the suction decreases **66%** in 12 days of rainfall similarly continues to decreases by **13%** in 12 days of dry period. Overall, it falls down by **88%** in 24 days period.

5. The result of incorporating result of numerical analyses in analytical calculation demonstrates that the shaft capacity of 10-meter pile in sand reduces from **1280 KPa to 1120 (beta method) 168 to 44 (Alpha method) and 1000 to 350 (Lambda method)** during 12 days of rainfall. Similarly, the shaft capacity of 10-meter pile in kaolin reduces from **320 KPa to 275 (beta method) 170 to 50 (Alpha method) and 1000 to 180 (Lambda method)** during 12 days of rainfall.

Publications

- **Conference paper**

"Direct and Indirect methods in determination of water retention curve of residual soils" is accepted to be present in the 17th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering 2023 (17ARC) to be held on 14-18 August 2023 in Nur-Sultan city, Kazakhstan.

- **Technical paper**

"Water characteristic curve for soils in Kazakhstan" is accepted in south east Asian Geotechnical Engineering Journal of the SEAGS & AGSSEA.

- **Technical paper**

"Effect of groundwater table on pile capacity" is in preparation to submit to Canadian geotechnical journal and hopefully will be done by end of February.

References

Baymahan, A.R., Baymahan, R.B., Kalimoldayev, M.N. (2015). Development of plasticity conditions for a subfundament soil base of the anisotropic structure. Stroitel'nyye konstruktsii i materialy, 3 (57), (in Russian). Retrieved from http://rmebrk.kz/journals/1548/36472.pdf

Borgekova, K. Analysis of complex tests on the precast concrete joint pile. 6th International Young Geotechnical Engineers Conference (IYGEC). Retrieved from https://www.issmge.org/uploads/publications/48/49/ground-improvement-7.pdf

Buranbayeva, A. M., Zhussupbekov, A. & Omarov, A.R. (2021). Numerical analysis and geomonitoring of the behavior of foundation of Abu-Dhabi Plaza in Nur-Sultan. Journal of Physics: Conference Series.

Fredlund, D.G. and H. Rahardjo (1993) "Soil Mechanics for Unsaturated Soils". John Wiley & Sons, Inc., New York, 517 pages (ISBN 0-471-85008-X).

Fredlund, D.G. & Xing, A. (1994). Equations for the Soil-Water Characteristic Curve. Canadian Geotechnical Journal, (31), pp. 521 – 532.

Fredlund, D.G., H. Rahardjo and M.D. Fredlund (2012). "Unsaturated Soil Mechanics in Engineering Practice". John Wiley & Sons, Inc., New York, 926 pages (ISBN 978-1-118-13359-0).

Fredlund, D.G., Sheng, D. and Zhao, J. (2011). Estimation of soil suction from the soil-water characteristic curve. Canadian geotechnical journal, 48(2), pp.186-198.

Kezdi, A. (1974). Handbook of Soil Mechanics. Elsevier, Amsterdam.

Khomyakov, V. A., Iskakov, E. E., & Serdaliev, E. T. (2013). Investigation of Gravelly Soil During Underground Construction in Almaty. Soil Mechanics and Foundation Engineering, 50(4), pp. 171–177. doi:10.1007/s11204-013-9230-z

Kim, Y., Satyanaga, A., Rahardjo, H., Park, H. and Sham, A.W.L. (2021) “Estimation of effective cohesion using artificial neural networks based on index soil properties: a Singapore case” Engineering Geology, August, vol. 289, No 106163.

Kristo, C., Rahardjo, H. and Satyanaga, A. (2019) “Effect of Hysteresis on The Stability of Residual Soil Slope”. International Soil and Water Conservation Research. September 2019. Vol. 7, pp. 226-238. https://doi.org/10.1016/j.iswcr.2019.05.003

Mercer, K., Rahardjo, H., Satyanaga, A. (2019). Soil–Water Characteristic Curves for Materials Classified According to the Unified Soil Classification System. ISBN 978-0-9876389-0-8.

Morris, P. H., Graham, J., & Williams, D. J. (1992). Cracking in drying soils. Canadian Geotechnical Journal, 29(2), pp.263-277.

Pachikin, K., Erokhina, O., & Funakawa, S. (2013). Soils of Kazakhstan, Their Distribution and Mapping. Environmental Science and Engineering, pp.519–533.

Rahardjo, H., A. Satyanaga and E.C. Leong (2012) “Unsaturated Soil Mechanics for Slope Stabilization.". Southeast Asian Geotechnical Journal, March, Vol. 43, No.1, pp. 48-58.

Thank you!!!