Numerical modeling the uplift bearing capacity of transmission line tower foundation on expansive soil

Xilin Lü i), Kunye Zhou ii), Maosong Huang ii)*, Zheng Su iii)

i) Professor, Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 20092, China.
ii) Graduate student, Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 20092, China.

ABSTRACT

To solve the energy shortage problem, transmission lines are widely built in the middle-west of China where the expansive soil is widely distributed. The transmission tower foundation may suffer wetting and shrinking load due to weathering. To solve this problem, consolidated undrained shear tests are conducted to obtain the mechanical behavior of expansive soil with different water content. The bearing behavior of pile foundation and plate foundation under uplift force are simulated by finite element method. The bearing capacity, axial force and lateral friction of pile foundation are analyzed. The bearing capacity of plate foundation is also investigated. These obtained numerical results can provide a good reference for the design of transmission line tower foundation when it is located in an expansive soil area.

Keywords: expansive soil, transmission line tower foundation, uplift bearing capacity, finite element simulation

1 Introduction

In order to solve energy shortage problem for people's production and living, numerous long-distance transmission lines are built around China these years. Expansive soil is widely distributed in China from middle-west to south-west, and it has the properties of swelling and reduction in strength when absorbing water, shrink and increase in strength when dehydration. The electric power pylon built on expansive soil may suffer the risk of collapse due to the peculiar characteristic of expansive soil. Hence, it’s necessary to study the bearing behavior of plate and pile foundation systematically based on the basic mechanical properties of expansive soil.

The shear strength of expansive soil has been widely studied in the past decades. Based on wetting-drying cycle tests of Nanyang unsaturated expansive soil, Miao et al. (2002) conducted a series of wetting-drying cycles tests to investigate the soil-water characteristic curve and shear strength. A hyperbolic equation of suction stress and suction strength was presented to describe the influence of suction. Sheng et al. (2011) summarized and compared three kinds of shear strength equations to experimental data, and the empirical and phenomenological equations were shown be applicable to all kinds of unsaturated soil. By using X-ray microtomography, Scheel et al. (2008) studied the influence of liquid content on the mechanical properties of glass beads; the findings provide a profound understanding on the wet granular material, including soil. Lu et al. (2007) studied this problem in silty sand (50-200μm), fine sand (80-400μm), and medium sand (200-900μm), and found that the results are sensitive to particle size. Results of silty sand showed that the tensile strength increases dramatically to a peak and then decreases gradually with the increase in the saturation. Based on the direct shear tests and 3D molecular dynamic simulation of wet sand and glass beads with diameter of 0.1-1mm, Richefeu et al. (2006) found that with the gradual increase in the water content, the cohesion of wet granular materials increases firstly and then tends to be unchanged, while the friction angle is irrespective of water content. Tang et al. (2015) investigated the influence of water content and dry density of compacted clay soil on its tensile strength, a peak value of the tensile strength characteristic curve (TSCC) was observed at the critical water content around 11.5%.

The bearing behaviors of foundations for transmission power line have been studied. Xiao et al. (2009) investigated the pile-soil interaction behaviors in expansive soil, results show that the upward pile movements are affected by pile length, and the tensile stresses along pile increases with an increasing pile length. Based on deformation compatibility, Yuan et al. (2016) studied the failure mode of transmission tower

https://doi.org/10.3208/jgssp.v07.097 636
pile foundation. Based on the in-door plate loading tests on unsaturated expansive soil, Xu (2004) analyzed the bearing capacity characteristic of unsaturated expansive soil. The prediction agrees well with the measured results of in-situ test of Ningxia and Handan expansive soils. Pacheco et al. (2008) discussed the distinctions between shallow and deep failure modes of transmission tower in tension load, and proper modification was applied to the Grenoble models to apply it to inhomogeneity soil caused by compacted backfill. However, the uplifting bearing behavior of foundations for transmission power line located at expansive soil area is seldom studied, and the influence of soil expansion and shrinkage on the bearing capacity is still not clear.

This paper studied the uplifting bearing of power transmission tower on expansive soil by numerical simulation. The Mohr-Coulomb criterion was adopted to illustrate the shear strength of unsaturated expansive soil. Based on the triaxial tests, the strength parameters were obtained to simulate the mechanics behavior of classical foundations. The pile foundation and plate foundation on expansive soil are analyzed by elasto-plastic finite element analysis, and the influence of water content is discussed.

2 Triaxial Tests On Expansive Soils

To investigate the property of expansive soils, a series of consolidated drained triaxial tests were conducted on remodeled soil sample by using the expansive soil from Nanyang city, Henan province. The confining pressure and water contents are presented in the Table1.

| Initial water content (%) | Saturation (%) | Confining pressure(kPa) |
|--------------------------|---------------|-------------------------|
| 7.65                     | 25            | 50/100/200              |
| 13.78                    | 45            |                         |
| 19.90                    | 65            |                         |
| 26.03                    | 85            |                         |
| 31.00                    | 100           |                         |

According to the stress-strain curve, the Mohr-Coulomb strength parameters under different water content were obtained as shown in Table2.

| Initial water content (%) | Saturation (%) | Cohesion (kPa) | φ (° ) |
|--------------------------|---------------|---------------|--------|
| 7.65                     | 25            | 143.27        | 32.46  |
| 13.78                    | 45            | 155.76        | 31.60  |
| 19.90                    | 65            | 139.44        | 17.04  |
| 26.03                    | 85            | 64.23         | 15.57  |
| 31.00                    | 100           | 14.91         | 16.60  |

Based on the experiment results, the cubic polynomial and Pearl curve were adopted to illustrate the characters between unsaturated expansive soil and water content as shown in Fig. 1.

\[ c = aw^3 + bw^2 + cw + d \]  \hspace{1cm} (1)

\[ \varphi = \frac{1}{m+n}e^{w-p} + q \]  \hspace{1cm} (2)

Fig. 1. Varying characteristic of the strength parameters with water content

3 Numerical Simulation of Pile Foundation and Plate Foundation

3.1 Numerical Simulation Procedure

The loading behavior of a transmission tower foundation was simulated by finite element simulation. The uplift bearing capacities of plate foundation and pile foundation was studied. As shown in Fig. 2 and Fig. 3, the finite element mesh is composed of 1 eight-node linear brick with reduced integration elements for two classical foundations. The soil-artificial structures interaction in normal direction is set as hard contact, and the frictional behavior in tangential behavior is set as penalty contact with the coefficient of tan (0.75 φ). Besides, the unit weight of expansive soil is 18.5kN/m³, elastic modulus E=60 MPa, Poisson’s ratio is 0.26, and the unit weight is 23.0kN/m³, elastic modulus E = 200GPa, Poisson ratio is 0.33 of the foundation. To investigate the influence of water content on uplift bearing behavior, three different water content conditions were considered. The water content in the depth of atmospheric layer is changed to 7.65%,13.78%,18%, 19.90%, and 26.03% from 18%. Besides, the depth of atmospheric layer is set as 5m, based on the practical experience and engineering.

Fig. 2. Finite element mesh and boundary condition (pile foundation)
Mechanical Behavior of Pile Foundation

The uplift bearing capacity of a tower foundation on expansive soil can be obtained by applying an uplift load on the top of foundation. The load-displacement curve of the tower foundation can be obtained according to the results. The obtained plastic strain and displacement distributions are shown in Figs. 4 and 5.

Compared to the result for w=18% and w=26.03%, the equivalent plastic strain zone of the pile foundation occurs at the top of pile due to the swelling behavior of expansive soil when absorbing water. The swelling behavior could increase the normal stress between soil and pile, leading to a larger lateral frictional resistance and the soil around pile top yield.

During uplifting procedure, the soil around pile shows an upward movement with the pile body. Compared the displacement distribution between w=18% and w=26.03%, the moving range increases with water content. A larger lateral frictional resistance induced by the swelling behavior induces "grasp effect", which causes vertical soil deformation in the depth of the atmospheric influence layer obviously.

The lateral frictional resistance with different soil-pile relative displacement under classical water content is obtained as shown in Fig. 6. The positive value of lateral frictional resistance indicates that the pile body suffers tensile force. Results show that the axial force of pile body with different soil-pile relative displacement under different water content is obtained as shown in Fig. 7. The positive value of axial force indicates that the pile body suffers tensile force. Results show that the axial force decrease with the increase in depth as an approximate exponential functional distribution. Compared the distribution of axial force with different soil-pile relative displacement, the axial force increases with relative displacement and become to stable when the soil-pile relative displacement reaches 30mm. This phenomenon indicates that the uplift bearing capacity reaches the ultimate situation.

The axial force of pile body with different soil-pile relative displacement under different water content is obtained as shown in Fig. 7. The positive value of axial force indicates that the pile body suffers tensile force. Results show that the axial force decrease with the increase in depth as an approximate exponential functional distribution. Compared the distribution of axial force with different soil-pile relative displacement, the axial force increases with relative displacement and become to stable when the soil-pile relative displacement reaches 30mm. This phenomenon indicates that the uplift bearing capacity reaches the ultimate situation.
With the increase in displacement, the force on the foundation increases linearly at first, and then increase slowly as shown in Fig. 8. There exists an obvious inflection point in the load-displacement curve of the pile foundation. The ultimate uplift capacities of foundation with different water content are shown in Table 3. The bearing capacity increases significantly with water content. As shown in Table 3 the limit capacity of foundation increases nearly 23.64% when the water content increases from 18% to 26.03%.

| Initial water content (%) | Ultimate uplift bearing capacity (MPa) |
|---------------------------|----------------------------------------|
| 7.65                      | 13.11                                  |
| 13.78                     | 12.92                                  |
| 18                        | 13.28                                  |
| 19.90                     | 16.42                                  |
| 26.03                     | 16.4                                  |

3.3 Mechanical Behavior of Plate Foundation

Similarly, the uplifting load was applied on the plate foundation to obtain the bearing capacity. The load-displacement curve of plate foundation can be obtained according to the results. The plastic strain and displacement distribution are shown in Fig. 9 and Fig. 10.

During uplifting procedure, soil around plate shows an upward movement with the plate body. Compared the obtained displacement distribution between w=18% and w=26.03%, an obvious moving area of soil concentrate to foundation center and the range of movement decreases with water content.

With the increase in displacement, the force on the foundation increases linearly at first, and then increase slowly as shown in Fig. 11. There exists an obvious inflection point in the load-displacement curve of the pile foundation. The ultimate uplift capacities of foundation with different water content are shown in
Table 4. The bearing capacity decreases significantly with water content. As shown in Table 4 the limit capacity of foundation decreases nearly 80% when the water content increases from 18% to 26.06%. This indicates that the plate foundation is not suitable for the uplifting foundation, especially in expansive soil area.

Table 4. Ultimate uplift bearing capacity under different water content for plate foundation

| Initial water content (%) | Ultimate uplift bearing capacity (MPa) |
|---------------------------|----------------------------------------|
| 7.65                      | 1.01                                   |
| 13.78                     | 1.00                                   |
| 18                        | 0.91                                   |
| 19.90                     | 0.85                                   |
| 26.03                     | 0.66                                   |

4 Conclusions

With the increase in water content, the cohesion of expansive soil firstly increases slightly, then decreases sharply, and generally presents a parabolic curve. While friction angle presents an inverse S-shaped curve; its value basically remains unchanged when water content is low or high enough, but sharply decreases when water content is in the middle region.

When the frictional force at the pile-soil interface reaches the maximum value under uplifting condition, the soil does not yield, so the failure mode of foundation is still frictional failure at the pile-soil interface. After the surface expansive soil absorbs water and swells, the "grasp effect" on pile foundation causes the lateral friction resistance of this part of pile to increase sharply, and the axial force of pile body to decrease sharply, which makes the ultimate uplift bearing capacity increases to a certain extent when the water content increases.

The results of plate foundation under uplifting load show that the influence of water content on the deformation of expansive soil foundation is greater than that on the equivalent plastic strain zone. With the increase in water content, the deformation range of foundation soil gradually shrinks and gathers near the foundation.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC through grant No. 41877252) and State Grid Corporation of China (through Grant No. 5217L0160001), these supports are gratefully acknowledged.

References

1) Lu, N., Wu, B., Tan, C. P. (2007): Tensile Strength Characteristics of Unsaturated Sands. Journal of Geotechnical and Geo-environmental Engineering, 133(2), 144-154.
2) Miao, L., Liu, S., Lai, Y. (2002): Research of soil–water characteristics and shear strength features of Nanyang expansive soil. Engineering Geology, 65, 261–267.
3) Pacheco, M.P., Danzigier, F.A.B., Pereira, P.C. (2008): Design of shallow foundations under tensile loading for transmission line towers: an overview. Engineering Geology, 101(3–4), 226–235
4) Richefeu, V., M.Samp, Juml. (2006): Shear strength properties of wet granular materials. Physical Review E, 73, 051304.
5) Scheel, M., Seemann, R., Brinkmann, M. et al. (2008): Morphological clues to wet granular pile stability. Nature Materials, 7(3):189-193.
6) Sheng, D., Zhou, A., Fredlund, D. G. (2011): Shear strength criteria for unsaturated soils. Geotechnical and Geological Engineering, 29(2), 145–159
7) Tan C.-S., Pei, X.-J., Wang D.-Y., et al. (2015): Tensile Strength of Compacted Clayey Soil. Journal of Geotechnical and Geoenvironmental Engineering, 141(4), 4014122.
8) Xu, Y. (2004): Bearing capacity of unsaturated expansive soils. Geotechnical & Geological Engineering, 22, 611–625
9) Yuan, H. P., Zhao, P., Wang, Y. X., Zhou, H. L., Luo, Y. H., & Guo, P. (2016): Mechanism of deformation compatibility and pile foundation optimum for long-span tower foundation in flood-plain deposit zone. International Journal of Civil Engineering, 15(6), 887-894.
10) Zhang, C. S., Wang, Y. H., Xiao, H. B., et al. (2009): Soils and rock instrumentation, behavior, and modeling- numerical simulation of soil-pile interaction in expansive soils foundation. GeoHunan International Conference 2009, 99-105.