

# Study the Ground Settlement of Soft Clay using Discrete Element Method

P. Kajoijilertsakul<sup>1</sup>, S. Soralump<sup>2</sup>, and S. Prempramote<sup>3</sup>

<sup>1,2,3</sup>Department of Civil Engineering, Kasetsart University, Bangkok, Thailand

E-mail: kppairoj@live.com

**ABSTRACT:** This research work studies the effect of ground settlement due to construction of electrical facilities using Discrete Element Method (DEM) via Particle Flow Code 3 Dimensional (PFC3D) simulation program. The model boundary is setup with length of 60m, width of 50m and 10m depth from the Bangkok Ground level consisting of Soft clay. In the analysis, Horizontal Directional Drilling (HDD) with size of 1 meter in diameter of High Density Polyethylene (HDPE) are presented. Five different level of HDD starting from 1 meter to 5 meter from ground level are conducted to observe behaviour of ground settlements on each assigned level. Additionally, the influence zone of Bangkok soft clay at final stage and affected area at the surface of ground level of the construction work has also been disclosed. The simulation data shows that, with constant diameter of HDD, the settlement increases with increase in depth of HDD work whereas expansion of influence zone at ground layer has a reverse relation with the depth of HDD.

**KEYWORDS:** Horizontal Directional Drilling (HDD), PFC3D, Settlement

## 1. INTRODUCTION

The population in Bangkok city is increasing due to the increase in facilities and good accommodation. Considering the fact that space in big city is limited, utilities such as gas pipe line, water pipe line, and electrical system are constructed based on underground technology in order to maximize the limited area. Trenchless technology might lead to a serious problem as these facilities are constructed under footpath or on road and therefore the ground loss phenomena must be taken into consideration. However, the construction technique by Horizontal Directional Drilling (HDD) has become realistic nowadays since there are several obstacles of using other facilities underground.

Horizontal Directional Drilling was started by the oil and gas industry for the purpose of installation of utilities pipeline cross-over the river or alongside the highway (Allouche et al.2000). The main advantage of this method is that the drill bit can go below the traffic road without any disruption of transportation system above ground where as the conventional method of open-cut disrupts the traffic system and is time consuming. Traditional work of open-cut experiences different issue such as cracking of working duct bank as well as severe settlement due to a block of working shaft self-weight which accelerated the ground loss. (Yanfeng W et al.2019).

In modern days high-density polyethylene (HDPE) is applied for increased flexibility of construction work since there are several utilities buried nearby. Before inception of HDD, borehole must be carried out at several locations to determine the soil properties of respective location. The borehole stability is widely revealed through conventional algorithm of finite element (Wang and Sterling 2007). The stability of borehole can also be pre-analyzed by visual check of ground level settlement. The collapse of the borehole underground requires the soil which gathers around the borehole diameter to balance inside and outside pressure of the borehole. This mechanism can lead to consequence damage since the influence zone of damage depends on the depth of borehole (Conroy et al. 2002). Likewise, other factors such as diameter and soil strength parameter also play a vital role for borehole stability. The parametric study based on FLAC3D simulation discloses that the majority expand of failure zone in borehole comes from diameter of ream head, depth of the borehole as well as strength parameter of soil profile (Biao S. and Baosong M 2015).

## 2. MODEL OF PARTICLE IN PARTICLE FLOW CODE 3D (PFC3D)

### 2.1 Coding of Particle Flow Code 3D

PFC3D program was developed for the analysis of twin tunnel problem (Cundall 1988). Later, the evolution of PFC3D program has been represented by Itasca as a powerful tool for analysing the discrete problem (Itasca 2005). Two major algorithm for analysing the soil behaviour in PFC3D program follows Newton’s second law and the force – displacement Law as shown in Figure 1. Since the particles is denoted as dynamic process with state of equilibrium developing of interaction, the particle movement will occur through the contact forces as well as displacements. Movement of particle due to propagation of interaction force from the nearby particles results in transmission of energy to surrounding particles whereas dynamic behaviour is represented numerically by time stepping along the period with each particle having identity of velocity and acceleration. The relationship between force and displacement is expressed as shown in Fig 2. Hence for modelling correctly, several following step needs to be followed.

$$m_i \frac{dv_i}{dt} = \sum (F_{ij}^n + F_{ij}^t) + m_i g \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum (R_i x F_{ij}^n - \tau_{ij}^t) \quad (2)$$

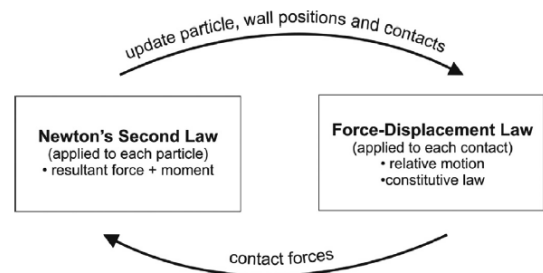


Figure 1 Algorithm to assign particles in PFC3D

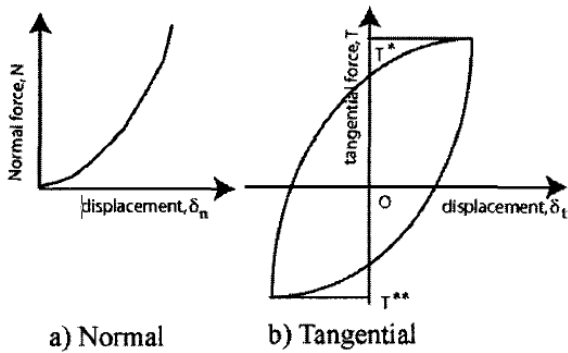


Figure 2 Relationship between force and displacement of particle

$$\Delta t_{cr} = \sqrt{m/k^{tran}} \quad (3)$$

$$\Delta t_{cr} = \sqrt{I/k^{rot}} \quad (4)$$

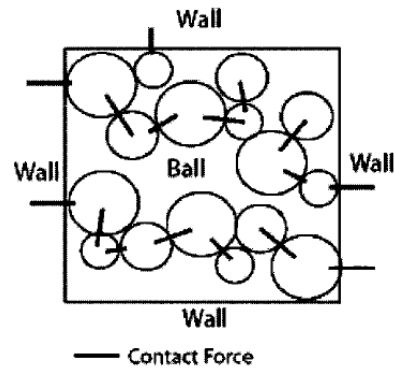


Figure 3 Algorithm to assign particles in PFC3D

### 2.1.1 Wall

The wall property of each portion can be specified independently. The general property of wall is the manifold material because the surface is defined as mesh. Furthermore, the rotational parameters of wall such as velocity and angle can also be assigned.

### 2.1.2 Boundary Condition

There are three possible ways to create the boundary conditions.

- The first one is using walls as boundaries and due to which the interaction force between particle and wall does not obey the Newton's Second law.
- Using particles as boundaries conditions together with the dynamic behaviour of particle such as velocity or external force.
- Using periodic boundaries

### 2.1.2 Ball particles

Ball in PFC3D is presented as soil particles since the surface of ball is defined by the sphere radius (R). The ball can be translated and rotated and its property such as density and radius can be defined. Regarding to loading conditions in term of force and moment, interaction with other ball as well as external force can be applied.

### 2.1.4 Contact Model

Contact model plays an important part for state equilibrium calculation. To understand behavior of particle at state equilibrium accurately an appropriate contact model must be assigned. PFC3D has 3 instant contact model build in namely, linear contact model, linear-parallel contact model and Hertz contact model. There is also an option to create personalized contact model through fish function as well. However, in this modelling the linear-parallel contact model has been applied because the linear contact model can transmit only force to the interaction particle while the linear-parallel contact model can transmit both force and moment which is more realistic.

### 2.1.5 Time Stepping

The force displacement equations are applied for evaluating the particle velocities and positions assuming fixed interaction force and moments of particle. For time step,  $\Delta t$  is denoted as a small scale which is less than critical value  $\Delta t_{cr}$ . This critical value can be determined by the mass and stiffness properties of particle because PFC3D algorithm determines translational and rotational stiffness of particle which is related to the mass and moment of inertia of particle as shown in Eq.3 and 4, respectively.

### 2.1.6 Particle Measurement

Two major parameters have been studied and recorded for particle measurement. The first parameter is the settlement of soil due to the ground loss at each assigned scenario. The tracing of unbalanced force along simulation by increasing the time step can be applied for tracking behavior of movement of particle since the definition of this unbalanced force is the net force acting on each ball particle on defined boundary conditions. When all particles reach an equilibrium state, the net force vector at each particle is indicated zero. In reverse, if the unbalanced force detected is not zero, it can be used to identify the continuous movement of the particle within the model. This technique can be applied to observe the change of force with interaction within surrounding particle. Likewise, it can also be implemented that the more unbalanced force occurs, the more energy transmits resulting in accelerated ground loss phenomena.

## 3. MODELLING OF SOIL LAYER IN PFC3D

The soft clay in Bangkok, Thailand is modelled in one geological layer with the boundary conditions size 50 m (Width) x 60 m (Length) x 10 m (Depth) as illustrated in Fig 4.

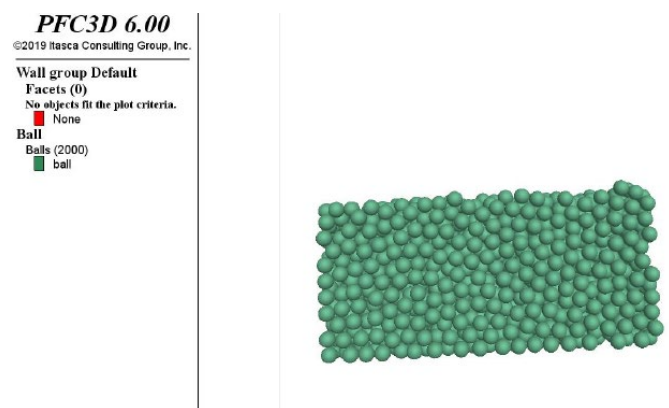


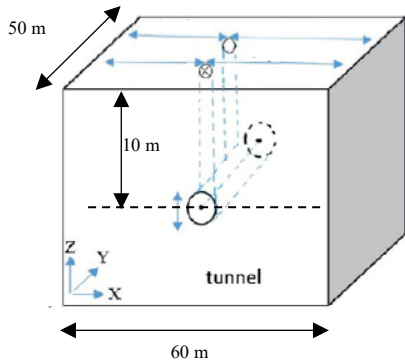
Figure 4 Bangkok soft clay model in PFC3D

The micro-parameter has been calibrated by the clay and is assigned in PFC3D. The 4 steps were involved in the calibration process to generate PFC3D material assembly to represent the mechanical properties (Cundall 1988) in consideration of undrained water condition as shown in Table 1.

**Table 1 Model parameters used in this simulation**

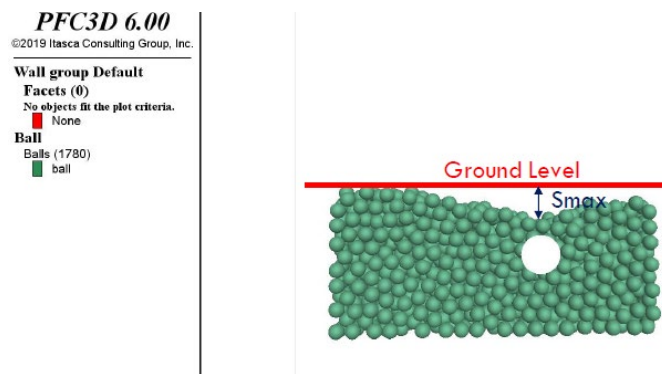
Parameter	Value
Particle density	2,600 kg/m <sup>3</sup>
Normal Stiffness Kn	10.0 N/m
Shear Stiffness Ks	10.0 N/m
Particle friction coefficient	0.1
Particle wall friction coefficient	0.1
Critical damping ratio	0.1

Later, Horizontal Direction Drilling (HDD) is performed through the soft clay layer at each assigned level. There are 5 levels of excavation work that are considered in this study starting from the depth of 1 to 5 m measured at ground level as a reference point. The HDD activity has been conducted along the Y-axis with the center line at X-axis and the depth of HDD level varies on Z-axis as shown in Fig 5.



**Figure 5 Position of Horizontal Directional Drilling**

In PFC3D simulation, the excavation is performed and the settlement of soft clay ( $S_{max}$ ) is recorded as well as the behaviour of unbalanced force at each individual conditions has been studied. The model of soft clay settlement phenomena is illustrated in Fig 6.

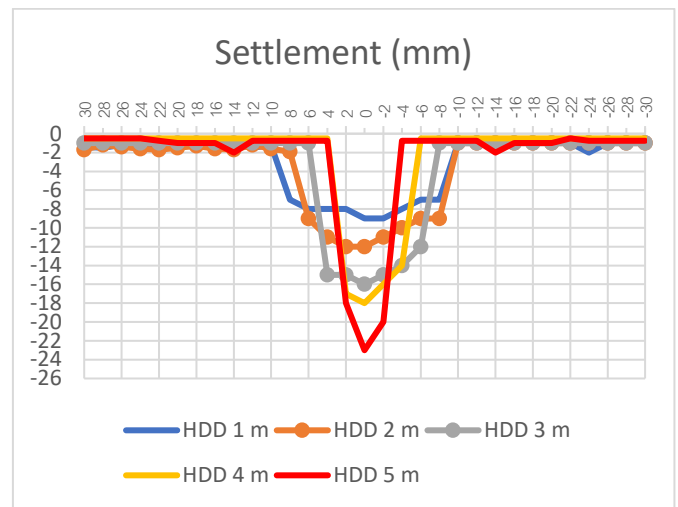


**Figure 6 Bangkok soft clay model in PFC3D**

### 3. RESULT

The settlement of soil profile is recorded at the depth of 1,2,3,4 and 5 m of HDD with reference from ground level. The diameter of horizontal direction drilling is taken as 1m based on the size of standard electrical cable circuit used nowadays. The result has been measured by the displacement of the soil particles at the ground surface of soil since each particle in PFC3D has been assigned based on their position in 3 co-ordinate system. The result reveals that the settlement increases with increase in excavation depth as illustrated in Fig 7. Additionally, the influence zone of soil affected by these

excavation work also shows significant association with the depth of horizontal directional drilling.



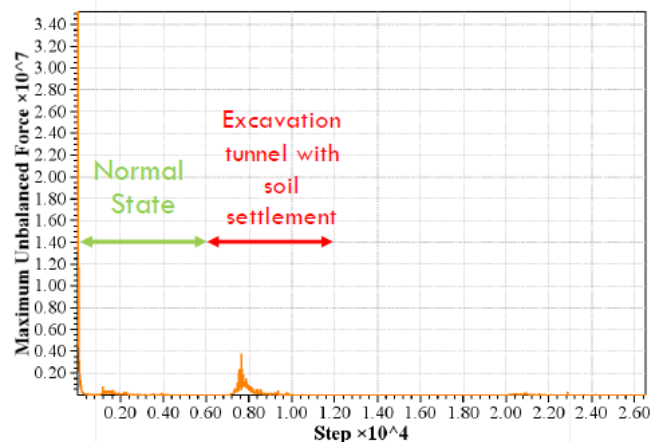
**Figure 7 Ground Displacement of soft clay model in PFC3D where the HDD position are located at the centre on Y-Axis**

Furthermore, from the settlement curve, the influence zone of ground loss behavior can be observed by assigned criteria that if the settlement of ground level exceed 2 mm, the influence zone are recorded as presented in Table 2. The shallow depth of HDD diameter results in expansion of influence zone on the ground level whereas increase in depth leads to limited area of influence zone.

**Table 2 Influence zone at each individual depth of Horizontal Direction Drilling**

Scenario	Influence zone (m) (Left)	Influence zone (m) (Right)
HDD at depth 1 m	8	8
HDD at depth 2 m	6	6
HDD at depth 3 m	4	4
HDD at depth 4 m	3	3
HDD at depth 5 m	2	2

Tracking of unbalanced force on how the force effects on the surrounding particle is shown in Fig 8.



**Figure 8 Unbalanced Force in Particle**

Further analysis of stress contour surrounding the HDD reveals that the stress is higher at location close to the diameter of Horizontal

Directional Drilling whereas the stress is reduced when the location of soil level is far from the HDD hole as shown in Fig 9.

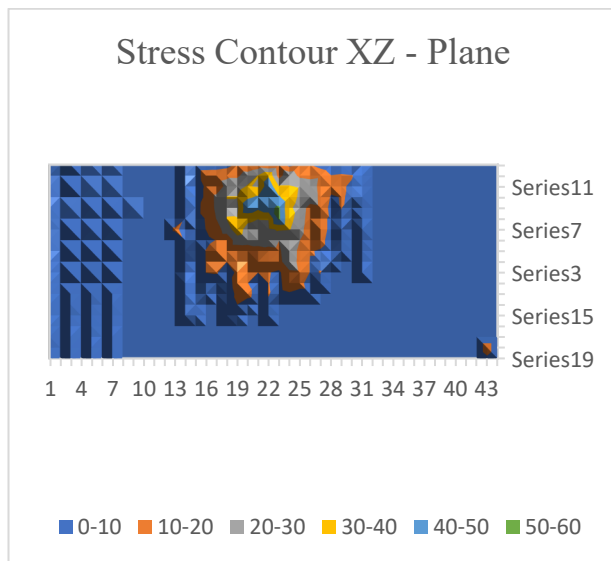


Figure 9 Stress Contour on XZ-Plane

#### 4. CONCLUSION

The influence of Horizontal Directional Drilling work for underground cable of electrical system on Bangkok soft clay soil has been investigated using PFC3D. The five level of excavation starting from 1 – 5 meters with drilling bit of diameter 1 meter has been set as initial condition. The ground settlement on ground level and the influence zone are recorded during starting of the excavation on each individual layer. In addition, the behaviour of unbalanced force are observed in association with stress contour distribution on the soil particle. The result shows that with increase in depth of the HDD on Bangkok soft clay, the more settlement occurs whereas the expansion of influence zone on the ground level shows behaviour in reverse direction. It has been noticed that higher depth of excavation shows limited area of influence zone but resulting in higher settlement. The stress contour on XZ plane also shows a related behaviour i.e., the stress reduces with increase in distance from the centre of the HDD diameter.

#### 5. REFERENCES

Allouche, E.N., Ariaratnam, S.T., and Lueke, J.S. (2000). Horizontal Directional Drilling: Profile of an Emerging Industry. *Journal of Construction Engineering and Management*, 126(1), 68–76.

Asif Ahmed and Md. Azijul Islam (2022). Parametric Study on Ground Settlements of Sand and Clay Layer due to Horizontal Directional Drilling. *ASCE Pipelines 2020*

Biao Shu and Baosong Ma (2015). Study of ground collapse induced by large diameter horizontal directional drilling in sand layer using numerical modeling. *Canadian Geotechnical Journal · February 2015*

Chehab, A. G., & Moore, I. D. (2010). Parametric study examining the short and long term response of HDPE pipes when installed by horizontal directional drilling. *Tunnelling and Underground Space Tech.*, 25(6), 782–794.

Cording, E. J., Hansmire, W. H. (1975). Displacement around soft ground tunnels, General Report: Session IV, Tunnels in soil", In: *Proceedings of the 5th Panamerican Conference on Soil Mechanics and Foundation Engineering*, Buenos Aires, Argentina, 87–95

Clough, G. W., Schmidt, B. (1977). Design and performance of excavations and tunnels in soft clay. State of the Art report", In: *International Symposium on Soft Clay*, Bangkok, Thailand, 980–1032.

Cundall, P. A. "Computer Simulations of Dense Sphere Assemblies", *Studies in Applied Mechanics*, 20, pp. 113-123, 1988.

ITASCA "PFC2D/3D (Particle Flow Code in 2/3 Dimensions) User's Guides", *Itasca Consulting Group Inc., Minneapolis, MN, USA, 2004/2005*.

Jiao, R.Y., Zeng, C., Ma, B.S., (2011). Study on influence factors to application of largescale HDD to oil and gas pipe installation. In: *Reston, VA: ASCE Copyright Proceedings of the International Conference on Pipelines and Trenchless Technology 2011 October 26. 29, 2011, Beijing, China* d 20110000. American Society of Civil Engineers

John P. de Bono and (2022). Discrete element modelling of normal compression of clay. *J. Mech Phys. Solids* 162 (2022)

Karam A. Jaradat and Sherif L. Abdelaziz (2019). On the use of discrete element method for multi-scale assessment of clau behavior. *Computers and Geotechnics* 112 (2019), 329-341

Loganathan, N., Poulos, H. G. (1998). Analytical Prediction for Tunneling-Induced Ground Movements in Clays", *Journal of Geotechnical and Geoenvironmental Engineering*, 124(9), 846–855

Sarfarazi, V., Haeri, H., Shemirani, A. B. (2017). Direct and indirect methods for determination of mode I fracture toughness using PFC2D", *Computers and Concrete*, 20(1), 39–47

Schmidt, B. "Settlements and Ground Movements associated with tunneling in soil", PhD Thesis, University of Illinois, 1969.

Terzaghi, K. "Applied Sedimentation", In: *Trask, P. D. (ed.) Geologic Aspects of Soft-Ground Tunnelling*, John Wiley and Sons, Inc., New York, NY, USA, 1950, 193–209.

Van, B.G., Hergarden and H.J.A.M., (1997). Installation of pipelines beneath levees using horizontal directional drilling. *Delft Geotechnics*, SO-59407-701/2, 1–16.

Vabah Sarfarazi, Hadi Haeri and Kaveh Asgari (2022). Three-dimensional Discrete Element Simulation of Interaction between Aqueduct and Tunnel. *Periodica Polytechnica Civil Engineering*, 66(1), 30–39

Yanfeng Wang, Jingen Guo, Yongfeng Tang, Tingjin Liu and Yubing Yang (2019). Settlement and damage analysis of working shaft for underground high-voltage electricity cables. 2019 International Conference on Civil and Hydraulic Engineering,

Yanfeng Wang, Jingen Guo, Yongfeng Tang, Tingjin Liu and Yubing Yang (2019). Settlement and damage analysis of working shaft for underground high-voltage electricity cables

Yanfeng Wang, Jingen Guo, Yongfeng Tang, Tingjin Liu and Yubing Yang. Settlement and damage analysis of working shaft for underground high-voltage electricity cables. 2019 International Conference on Civil and Hydraulic Engineering

Yuan Guo and Xiong Yu (2023). Insight on bulk shear strength parameters of clay using discrete element approach incorporating physics-based interparticle force model. *Soils and Foundations*, Volume 63, Issue 1