The Frontiers of Society, Science and Technology
ISSN 2616-7433 Vol. 1, Issue 07: 145-160, DOI: 10.25236/FSST.2019.010718

A novel method of simulating under-excavation to save the leaning tower of Pisa

ShuoChen[1],Liangcheng Jiang[2],Chang Liu [3,*], Ronaldo I. Borja[4]

1 Universi ty of Illinois at Urbana 一Champaign, U.S.A
2 Shanghai Qibaodwight High School shanghai 200000 China
3 Ridley college Canada
4 Stanford University U.S.A
**E-mail: chang_liu@ridleycollege.com*
**Corresponding Author*

ABSTRACT. *This paper describes a novel simulation technique that captures the effect of under-excavation to save the leaning tower of Pisa. The method of under-excavation has been applied successfully to partially correct the excessive tilt of this world-famous monument. The method involves removing a small volume of soil underneath the foundation of the tower so that the differential settlement it generates pulls the tower to a more upright position. Instead of directly simulating the process of under-excavation, the numerical approach presented in this paper consists of applying self-equilibrating forces that compress the soil volume underneath the tower, thus generating an effect similar to under-excavation. The feasibility and effectiveness of the numerical technique is investigated using Plaxis 2D, a finite element analysis software. The simulation technique is tested in 2D with the goal of eventually extending it to 3D. Results of the simulations strongly suggest that the method of under-excavation indeed generates differential settlement that pulls the tower to a more upright position by a fraction of a degree. In the words of Professor John Burland, the reduced inclination gives the tower about a hundred more years of life.*

KEYWORDS: *Tilt buildings; underground excavation*

1. Introduction

If a building – especially a tall but slender building – is constructed on a foundation not solid enough, it will tend to lean toward a certain direction[2]. The tilting of a structure can take place during the construction process or even decades after it was built. Sometimes the tilt of a building is designed to make the structure look more aesthetic (such as the pair of leaning towers at the Puerta Europa in Madrid, Spain). However, there are real-life examples where the tilt of a building was not intentional. For example, the tilting of the Cathedral of Mexico City in Mexico, the Millenium Tower in San Francisco, USA, and the Tower of Pisa in Italy, was not made by design. These buildings tilted because of unexpected engineering problems, including the uneven soil consolidation of the foundation, inadequate design and construction of the structure, and anthropogenic factors[4].

Excessive tilting of a building can leads to detrimental effects and could even cause the structure to collapse. This generally occurs when the line of action of the weight of the structure, which is an imaginary vertical line through its center of gravity, does not pass through the centroid of its foundation. Take the leaning tower of Pisa for example. In this structure, the line of action of gravity falls well outside the centroid of its ring-shaped foundation. This eccentric force causes the tower to keep tilting to the southeast direction, making the condition worrisome and dangerous.

With respect to the leaning tower of Pisa, different approaches have been adopted to stabilize this world-famous monument. In 1993, counterweights have been placed on the north side of the tower that exerted a stabilizing force designed to keep the structure from overturning. Subsequently, soil was under-excavated underneath the foundation of the tower to reduce its excessive tilt. Several other stabilization approaches have been proposed for this structure but were never implemented. This includes the use of electro-kinetic consolidation, which entails the application of an electric potential to cause the groundwater to move in a certain direction and produce a differential settlement that reduces the tower's tilt.

The objective of this research is to investigate the mechanics and kinematics involved in the underground excavation scheme that has been applied successfully to stabilize the leaning tower of Pisa. The idea behind this method is to create a void in the soil region underneath the northern side of the foundation of the tower so that the ensuing compaction of the void produces a differential settlement that reduces the tower's tilt. In the context of finite element analysis, a logical approach for simulating the process of under-excavation would be to remove finite elements from the mesh, but this could lead to numerical difficulties owing to the overburden stress that the excavated elements would suddenly release. A novel approach is thus presented in this paper, which entails applying sets of self-equilibrating forces that compress a small region of soil underneath the tower. Results of the analysis show that the proposed numerical technique does generate differential ground settlements that pull the tower by a fraction of a degree to a more upright position.

Questions that need to be answered after the simulation:

- Without any adjustment, what will the graph of tilting angle with respect to time look like?
- How would the adjustment in soil body change the curve of tilting angle with

respect to time?

- What will the graph of tilting angle with respect to time look like after the adjustment?
- How long would the tower cost to recover back?
- Can the adjustment to restore the tower to an equilibrium position? And where would it be?
- Is the solution method effective according to the result of the simulation?

2. Background of leaning tower of pisa

Among various leaning buildings (structures) around the world, one of the most famous one is the leaning tower of Pisa, Italy. The tower was standing in the “Piazza Dei Miracoli”, which in English is the “Square of Miracles”, a square contains four famous buildings, being built in the middle ages to represent the religious, political and spiritual power at that time. The history and the art of those architectures has become the extraordinary character and the symbol of the city[5].

The reason of the tilt has always triggered the interest of the researchers. Now the reason of tilt is thought because of the uneven displacement of the foundation under the tower due to the insufficient rigidity of the ground beneath the foundations. The building process of the tower lasted for 198 years because of different reasons during the process of building. The tower was started to be built in August 1173, which experience two suspensions during 1173-1178 and 1272-1278. Finally, in 1370, the building had been completed. It took almost two hundred years to build the tower[5].

As mentioned, the rate of the consolidation under the foundation of the tower on two sides are not consistent. This begins during the building process of the tower. The engineers had already mentioned that during the process of building the tower and they tried to stop it. The possible way used by them is they compensate the inclination by placing next blocks off-centre on the side opposite the lean.

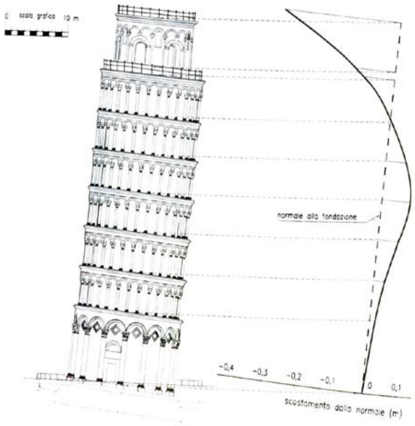


Fig. 1.5
Forma dell'asse della Torre
The shape of the axis of the Tower

Figure. 1 The shape of the axis of the tower[5]

However, this method did not stabilize the tower, the angle of tilt has increased. In 1990, because of the risk of sudden collapse, the tower was closed to the public. Then an international committee was formed to research the current situation of the tower and to stabilize it. It took them 10 years to stabilize it. At present, the tower is leaning back. During this process, different kinds of methods were proposed and have been applied successfully to decline the leaning of the tower[5].

Solution 1: lead counterweight [3].

In 1993, 600 tons of lead ingots were put around the foundation of the north side of the tower to counterweight the lean. Installation of the lead ingots began on July 1993 and lasted until January 1994. This action reduced the inclination of the Tower by about 50’’. The equivalent of a reduction of the out-of-plumb was about 12 mm. The application of the counterweights made the inclination of the Tower towards the south, which until then had proceeded at a rate of increase of the overhang of about 1 mm per year.

Solution 2: the ground anchors scheme [3]

In 1995, the team opted for 10 underground steel anchors, to invisibly yank the tower northwards. The anchors were to be installed, 40 meters deep, from tensioned cables connected to the tower’s base. In view of Pisa’s high-water table, the team froze the underlying ground with liquid nitrogen before any anchors were installed, to protect their excavations from flooding. However, they didn’t consider the consequence that water would expand after a freezing and caused the space among soil bigger. The tower tilted more due to more space in the soil. On the night of September 7, 1995, the tower lurched southwards by more than it had done in the entire previous year. The anchor plan was immediately abandoned, and another 300 tons of lead ingots were added in a desperate attempt to prevent the loss of the tower.

Solution 3: underground excavation

Finally, all experts in the team agreed that excavation of soil from the underground of the tower was the only feasible solution because it wouldn't directly touch the tower itself. Work began in 1999 and halted in 2001 after approximately 77 tons of soil had been removed and the tower had been straightened by 44 centimeters, returning to its 1838 inclination. The team estimated that it would take about 200 years for the tower to return to its pre-stabilization inclination[3].

Based on the success of final method raised by experts to excavate soil from the underground of the tower, this method by Plaxis 2D to simulate the excavation of some soils under the ground and see the possible conditions would happen after excavation. What's more, the time taken by the tower to fix itself to the original degree of tilting after the excavation of soil will be varied.

The Principle of drawing soil out horizontally deviation-rectifying method is to use drawing soil out horizontally deviation-rectifying method. That means using man-working or machines to excavate soil out from the less settlement side of the foundation of tilting building in designed order and amount. Its purpose is to reduce the area of stress at the bottom of the foundation to increase its additional stress. When the additional stress of the bottom of the foundation increases, the soil under the bottom of the foundation changes from compaction deformation to plastic deformation. At the same time, use push jack to increase the stress of foundation to make the soil be compressed again and cause the less settlement side of the tilting building settling more until the foundation of the building reaches horizontal[1].

For the soil in the process of drawing, because of normal stress and shear stress, when it reaches a critical state, some soil starts to be damaged by dilative shear failure. Because the soil has already consolidated before, we can consider the soil wouldn't have strain. We use to represent the soil damaged by dilative shear failure, the mechanical property can be expressed as:

$$S = (1-\omega)S_i + \omega S_d$$

In the equation, S is some mechanical index of soil. and S_i and S_d are mechanical indexes of initial soil and damaged soil respectively[1].

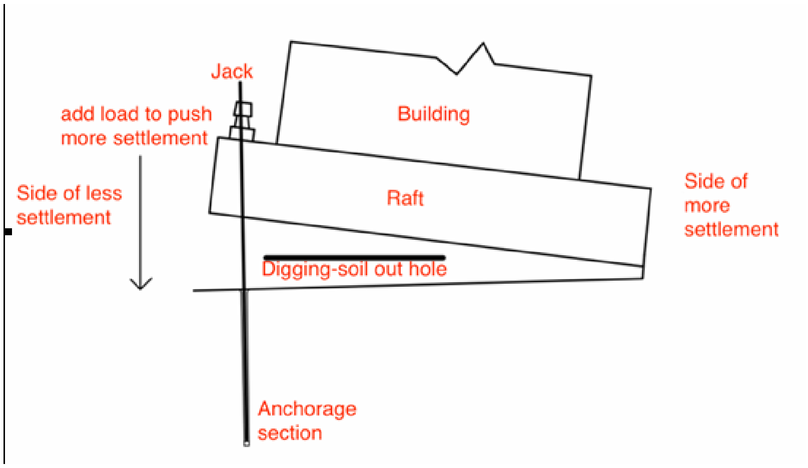


Figure.2 The schematic diagram of the underground excavation of Tower of Pisa

3. Proposed study

Among these stabilizing methods, the most efficient one is the underground excavation. The real process of the underground excavation is that the engineers drill into the ground and remove tons of soil under the Tower. Moreover, there are safeguard structures built. For instance, the scheme of the anchors was prestressed on the north side under the foundation of the tower. The anchors enable the tower freeze, which means that the tower will not able to move due to the vibration during the process of construction. Something important is that the main purpose of building the safeguard structures was not conceived to actually support the Tower but only to apply a stabilizing force to it[1]. With those safeguard structures, the engineers are able to pay more attention on the fixing method.

The initial condition of the building in this case is a tilt building. So, the methods of underground excavation could be applied. The Plaxis 2D, which is a finite element analysis software will be used to simulate the methods of underground excavation. However, because of the way of how software works, the remove of the soil body could not be applied. As a result, the way to simulate this method will add a compressing load to a specific area of surface in the soil body. The aim of adding this load is to simulate the same effect caused from the underground excavation.

3.1 Assumption:

- Without any adjustment, the consolidation on the lower side of the building will be greater than that of the higher side of the building.
- Based on the assumptions of the consolidation, the building will tilt to the lower side.
- After the underground excavation, the building will be recovered by a certain ratio with respect to the area of the “void space”.
- The deformation of the building is neglected.
- The stiffness of the material that made building is very high.
- The relative movement between the soil and the building at their interface.

3.2 Initial condition of the building:

A eight-story building is rectangular in shape, and its weight is distributed uniformly in the horizontal direction. The height of the building is 60 meters and 5 meters of the building is embedded under the ground surface as the foundation of the building.

The width of the building is 19 meters and that its length perpendicular to the plane of the model in Plaxis 2D. The building is tilted towards a direction with 5 degrees relative to the ground.

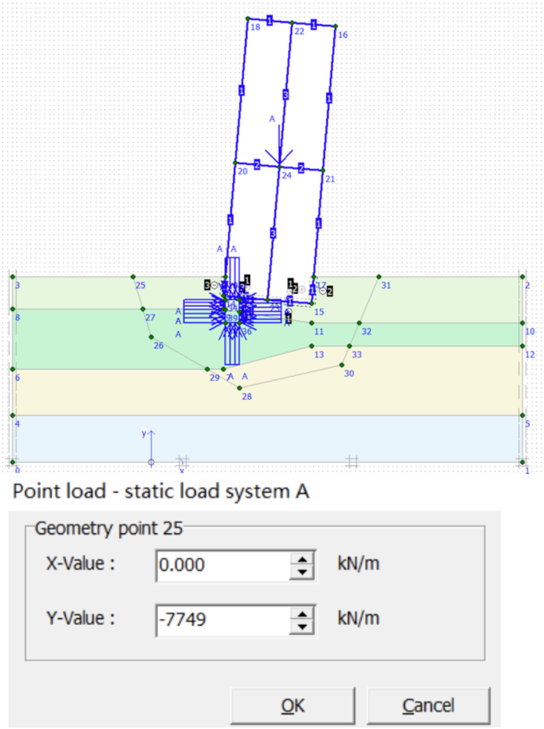
Please refer to the appendix for the details of the calculation for:

- The coordinates of each joint after the initial tilting
- The centroid of the cross-section of the tower
- The property of the soil body
- The location of the underground excavation

3.3 The finite element analysis

The 15-node-elements is chosen to provide a more accurate result. Moreover, due to the geometrical symmetry of the building, the Plane Strain model is applied. Following by the soil information table, the soil body is constructed. After then, the boundary restriction is added to avoid excess deformation of soil body. However, in the process of defining the soil properties, it comes out with a serious concern---which type of material model should be applied? Since each material model will construct completely different soil, it should be considered two separate models before starting any further calculation.

They are model based on the Linear Elastic Model and one with the Mohr-Coulomb Model. In Mohr-Coulomb Model, the stiffness of soil won’t stay still when the force is applied, while Linear Elastic does. With the accurate coordinates of the center of mass, the plate’s weight of the building can be set to zero. All the mass is added on the mass-center, which is the point 25 in the graph. The interfaces between building and the soil are used to keep the result precise. The force of the point load will be 774.9 MN according to the information given.



Point load - static load system A

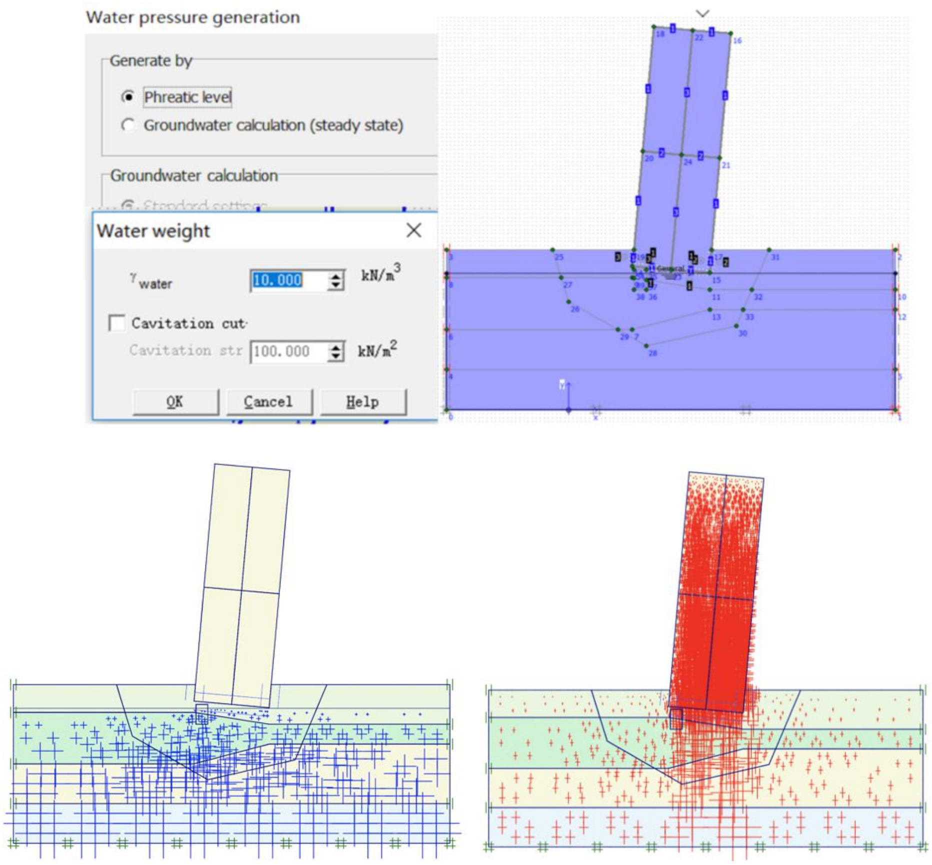
Geometry point 25

X-Value : 0.000 kN/m

Y-Value : -7749 kN/m

Figure. 3 The underground excavation

According to the background information about the method of underground excavation and the Plaxis 2D, the remove of the soil body can be simulated through a couple of compressing forces on a small portion of soil body under the higher part of the building. As shown in the graph, the rectangle section is being compressed by the load equally in all directions. As a result of its geometrical shape and the direction of the loads, there will be no moment for this section. The mesh analyzes the initial condition of the structure in more detail. The over global coarseness is chosen as coarse while the particular part including building and the soil near the foundation of it is regulated to very fine. This way to mesh the model can produce an accurate result while wasting no more time during the calculation.



Water pressure generation

Generate by

● Phreatic level

○ Groundwater calculation (steady state)

Groundwater calculation

Water weight

γ_{water} 10.000 kN/m^3

☐ Cavitation cut

Cavitation str 100.000 kN/m^2

Figure.4 Water pressure and soil stress

After the mesh result, the water pressure and the soil stress can be calculated. At this point, it will be ready to do the final calculation.

4. Result and analysis

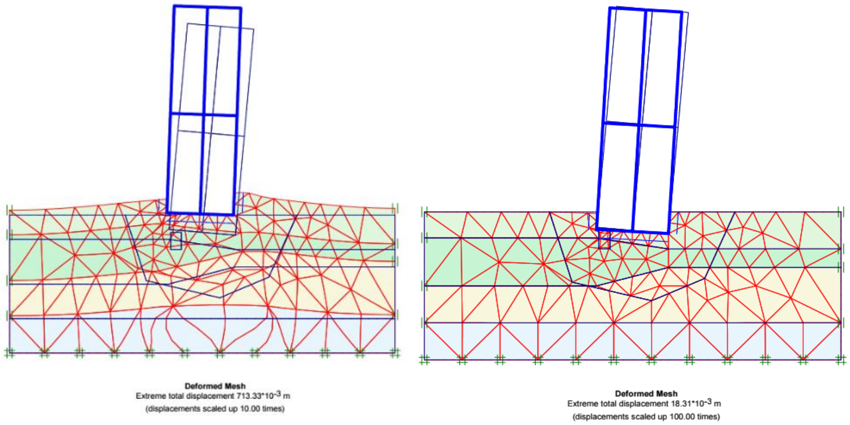


Figure.5 The results of the deformation simulation based on Mohr-Coulomb Model

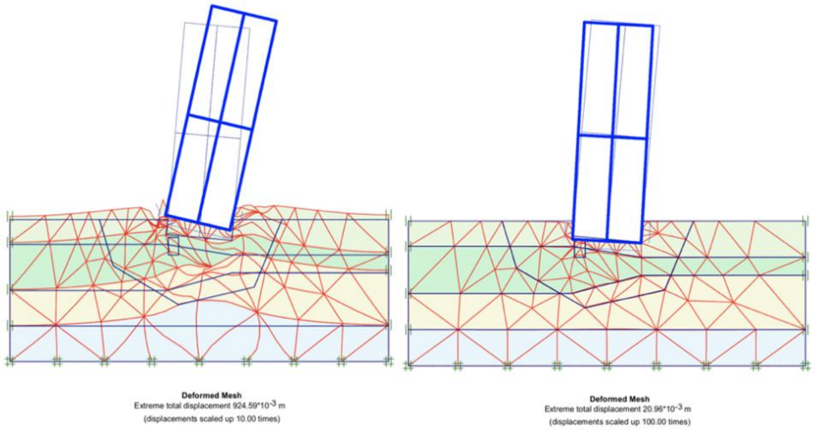


Figure.6 The results of the deformation simulation based on Linear Elastic Model

Two different results are shown since the model of the soil is Mohr-Coulomb and Linear Elastic. On the left-hand side is the first phrase calculation result which represents the case without any underground adjustment. It clearly shows that the building will tilts to the left, therefore the assumption of tilting direction got proved. However, the initial condition of the Linear Elastic is different from the Mohr Coulomb.

This is because of the different property of the soil body. As a result, the first graph of result of the Linear Elastic model has not reference value in this case. On the right-hand side is the second phrase calculation result, which shows the final result after compressing the soil beneath the building. This picture proves the truth that regulating the soil on the higher side can cause the building to recover in both types of models.

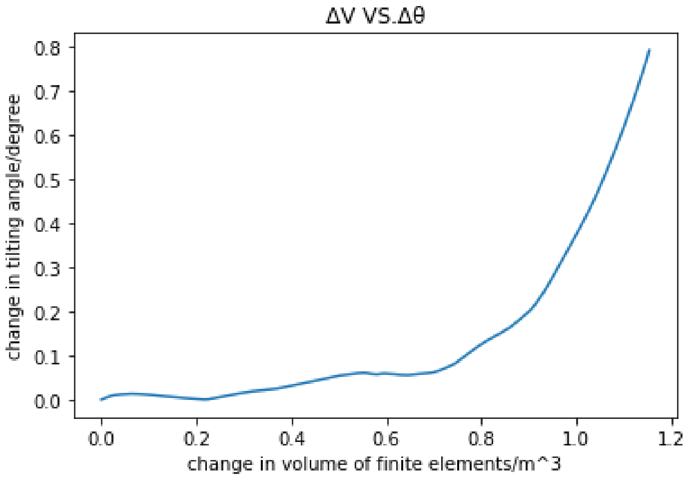


Figure.7 Curve of change in tilting angle(degree) with respect to change in volume of finite element (Based on Mohr Coulomb Model)

Above is the graph of change of tilting angle with respect to that of volume of finite element, which will be the volume of excavation in the real scenario. Assuming the solution is right, it shows the directly proportional relationship between the volume of excavated soil and the change of tilting angle of the building. It represents the way of underground excavation to correct tilting building is effective.

5. Conclusion and evaluation

Based on the previous analysis, applying underground excavation to reduce tilting angle of a tilting building is theoretically feasible and effective. However, on account of the non-uniform slope of the curve, there are several concerns about the possibility that may have a very rapid change of inclination. This uncontrollable fact will increase the danger of collapsing.

5.1 Advantage

Using Plaxis 2D to analyze the settlement of building has several benefits. Firstly, it decreases the time spending due to its simplicity of model constructing. Furthermore, Plaxis 2D can easily modify the parameter of material properties.

Limitation

5.2 Limits of 2D analysis

In the real-world situation, the properties of soil body under the ground surface can be varied at different dimensions. In Plaxis 2D, it can only consider the variables between 2 dimensions. However, the variables from the other dimension of the tower should also be considered.

5.2.1. Limits of the Modelling

The varied length of the guide tube for underground excavation is ignored.[6]

In fact, the length of the guide tube, which is connected to the excavated region, can be varied while the angle relative to the horizontal axis is constant. Therefore, the underground depth of the excavated section can be variable, which means the soil can be removed from different layer. As mentioned in the soil properties table, each layer has its own material property. As a result, the outcome can be dissimilar. In the finite element analysis process, the soil layer being excavated is Artificial fill and Fine sand, while in the real situation the range could be varied from this.

Effect of digging-out-soil hole on soil stress effect is ignored.[1]

In the simulation model, the existence of digging-out-soil holes is ignored. This neglection will affect the soil stress of the excavated part. The holes will reduce the area to get in touch with load of the building, which increases the normal stress on the soil. As the stress increases, the soil around the hole will transfer from elastic state to a plastic state. Thus, the area of plastic soil will increase with the amount of digging-out-soil increasing.

Because drawing soil out can make the stress of the soil smaller than the critical stress, the soil in the digging hole can be considered as elastic deformation by following General Hooke's Law:

$$\begin{cases} \varepsilon = \dfrac{\sigma_0(D+L)}{EL}, \dfrac{\sigma_0(D+L)}{L} \le \sigma_{er} \\ \varepsilon = \dfrac{\sigma_0(D+L)}{E[L-(2r-D)]}, \sigma_{er}\ \dfrac{\sigma_0(D+L)}{L} \le \sigma_{qr} \end{cases}$$

From the equation, it shows that when the stress caused by drawing soil is greater than critical stress, because the area to hold load is reduced due to increase in damaged area, the stress will be greater and the rate of settlement will be faster. This is the reason that digging-out-soil hole is an irreplaceable factor in this model.

Ignorance of possible deformation of the building

Since the material of the building is not perfectly rigid, tiny deformation of the structure in the building caused by the weight of itself should be considered when the building is settlement. Change in shape of the building may lead to a change of the center of mass of the building, which will change the moments of the building. Excess moments can change the settlement of the building differently.

5.2.2 Limits of the finite element analysis software (Plaxis)

Neglection of the impact by the construction process

The construction process, especially in the Mohr Coulomb model, in the real situation will change the properties of the soil to a certain extent. This includes the stress acting by the construction team and construction facility. In the modelling process, this factor has been ignored while it should be considered.

Limit on simulation of excavated part of soil

In the model, in order to avoid the situation that Plaxis displays an error of soil body collapse, the excavated part of the soil is simulated to be compressed by loads. However, this alternative plan can’t compress the soil to an absolute zero volume. Therefore, it cannot be treated the same as the real underground excavation method.

Possible improvement

Compared to the 2D model, Plaxis 3D can make a better model which will contain all three dimensions. Moreover, Plaxis 3D can produce a more complete and accurate simulation. Furthermore, a complete structure of the building can show the stability of the building in the process of settlement. Thus, more variables can be added, such as digging-out-soil holes, to improve the simulation.

References

[1] ZhengDing Deng, Zhang XiaoBing, Wang Long (2016). Mechanism Analysis and Calculation Methed of Horizontal Soil Landing Rectifying Method. Journal of Civil Engineering and Management,vol.33, no.5, pp. 39-43.

[2] Li KeJi, Sun Qi, Liang ShouYuan, Zhao HongLiang (2017). Causes of Tilt of a High-rise Building and the R ectification and R einforcement Approach. CONSTRUCTION TECHNOLOGY, no.47, pp.50-55.

[3] Magorzata Kijanka, Magdalena Kowalska (2017). Inclined Buildings-Some

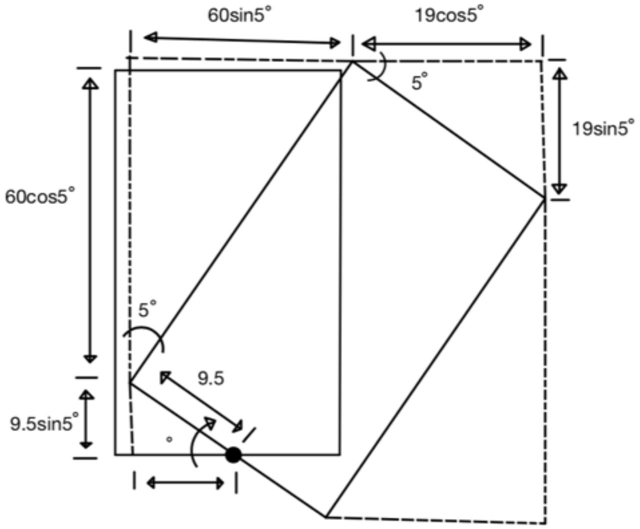
Reasons and Solutions. IOP Conference Series, pp.1-8.

[4] Raffaello Bartelletti, Paolo Heiniger, Carlo Viggiani. LA TORRE SALVATA UNA STORIA PER IMMAGINi. PACINIeditore, n.d.

[5] Zhang XiaoBing, Zhang WenQing (2018). Analysis of tilt Reasons or the Tall building and Research on Rectification and Reinforcement. Constrcution Technology, no.47, pp.53-56.

APPENDIX

Part 1 Calculations of initial coordinates



In this step, Trigonometry is utilized to calculate the coordinates of each point in the building.

Coordinates of building’s corners:

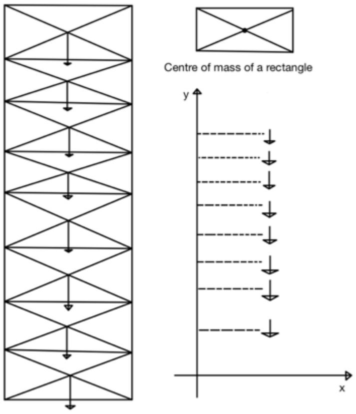
A $(25-9.5\times\cos 5^\circ, 35+9.5\times\sin 5^\circ)$

D $(25+9.5\times\cos 5^\circ, 35-9.5\times\sin 5^\circ)$

B $(25-9.5\times\cos 5^\circ+60\times\sin 5^\circ, 35-9.5\times\sin 5^\circ+60\times\cos 5^\circ)$

C $(25+9.5\times\cos 5^\circ+60\times\sin 5^\circ, 35-9.5\times\sin 5^\circ+60\times\cos 5^\circ)$

Part 2 Calculation of coordinate of centroid of the building



y= i= 1kmiyim=g(i= 1kmiyi)g(m)=i= 1kWiyiW

$$y = \frac{\sum_{i=1}^{8} W_i y_i}{\Sigma W} = 28.82m$$

Part 3 condition of building and soil

Table 1 The weight and height for each layer of the building

Number of Layers	Layer Height (m)	Total weight of the current floor (Mn)
1	11.8	165.23
2	6.94	99.27
3	6.94	92.92
4	6.59	84.23
5	6.24	77.04
6	6.24	75.19
7	6.94	82.52
8	8.32	98.5

Table 2 The Soil information on the side of the building with lower foundation stress

Soil profile	Depth (m)	Unit weight (kN/m^3)	Saturated unit weight (kN/m^3)	Permeability coefficient (m/d)	Elastic modulus (kN/m^2)
Artificial fill	0~-7	15	18	1	15000
Fine sand	-7~-20	17	20	1	20000
sand	-20~-30	16	18	1	18000
clay	-30~-40	14	17	0.001	4000

Table 2 continued

Soil profile	Poisson's ratio	Cohesion (kN/m^2)	Friction angle, degrees	Dilatancy angle, degrees
Artificial fill	0.2	3	35	0
Fine sand	0.2	4	30	0
sand	0.25	2	30	0
Clay	0.15	15	20	0

Table 3 The Soil information on the side of the building with higher foundation stress

Soil profile	Depth (m)	Unit weight (kN/m^3)	Saturated unit weight (kN/m3)	Permeability coefficient (m/d)	Elastic modulus (kN/m^2)
Artificial fill	0~-10	15	18	1	15000
Fine sand	-10~-15	17	20	1	20000
sand	-15~-30	16	18	1	18000
clay	-30~-40	14	17	0.001	4000

Table 3 continued

Soil profile	Poisson's ratio	Cohesion (kN/m^2)	Friction angle, degrees	Dilatancy angle, degrees
Artificial fill	0.2	3	35	0
Fine sand	0.2	4	30	0
sand	0.25	2	30	0
Clay	0.15	15	20	0