An inverse analysis of weak structural plane parameters for a limestone foundation pit based on critical stability

LIU Jun yan¹, ²,a, SONG Xiang hua ¹, ²,b, LIU Yan ¹, ²,c

¹ School of Civil Engineering and Architecture, University of Jinan, Jinan 250022, China;
² The engineering technology research center for urban underground engineering supporting and risk monitoring of Shandong Province.
  a liujunyan@vip.sina.com, b 970311967@qq.com, c liuyan322@163.com

Abstract. The article uses the Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) to make an analysis of the deformation characteristics of the structural plane, which is based on a real rock foundation pit in Jinan city. It makes an inverse analysis of the strength of the surface structure and the occurrence of the parameters by Mohr-Coulomb strength criterion value criterion in the way of numerical simulation, which explores the change of stress field of x-z oblique section of pit wall and the relation between the exposed height of structural plane and the critical cohesion, the exposed height and critical inclination angle of the surface structure. We can find that when the foundation pit is in the critical stable state and the inclination angle of the structural plane is constant, the critical cohesive force of the structural plane increases with the increase of the exposed surface height. And when the foundation pit in the critical stability of the situation and the cohesive force is constant, the structural surface exposed height increases and the structural angle of inclination is declining. The conclusion can provide theoretical basis for the design and construction of the rock foundation pit with structural plane.

1. Introduction

The deformation and failure mechanism of rock mass are determined by the structural planes of rock mass and the rock structure. It plays an important role in the rock mass structure characteristics. Luo Qiang makes an analysis of the critical height of rock foundation pit self-stability in Chongqing area. He finds that the critical height of foundation pit self-stability will change in U-type rule with the dip angle of rock slope for the hard structure plane. Tang Liang qin finds that the strength of weak interlayer increases with the decrease of water content and trait, and increases with the increase of dry density by many experiments. Lu Dun hua establishes a three-dimensional model of stratified rock slope by numerical simulation, and finds that the overall safety factor of the slope increases with the increase of the cohesion of the structure, and both of them are in line with the linear relationship under the condition of different structural planes.

Jinan lies in the transition zone of The Mountain of Luzhong and The Plain Of Lubei. The present geomorphic form is the result of long-term evolution of internal and external forces, especially during the Cretaceous Yanshan movement. The limestone rock is located in the southern and eastern regions of Ji'nan city. Its rock formations are exposed and contain many structural planes. The excavation process of foundation pit may cause some impact due to the geological structure surface coverage. This paper makes an inverse analysis of the strength of the surface structure and the occurrence of the parameters by Mohr-Coulomb strength criterion value criterion in the way of numerical simulation,
which explores the change of stress field of x-z oblique section of pit wall and the relation between the exposed height of structural plane and the critical cohesion, the exposed height and critical inclination angle of the structure surface. It can provide the criterion for the design of the foundation pit support.

2. The value basis of the Mohr-Coulomb strength criterion of limestone geological rock with structural plane.

The force units of the rock mass with structural planes is shown in Fig.1, the external load are \( \sigma_1 \) and \( \sigma_3 \), the angle between the structural plane and the \( \sigma_3 \) is \( \beta \). The Mohr circle and the strength line of the force unit are shown in Fig.2. The line of CD is the intensity line of rock mass, the line of AB is the intensity line of structure plane and the point of M means stress state point of structural plane.

![Fig.1 A rock sample with stresses applied on it](image)

![Fig.2 The stress state of joint](image)

It is assumed that the intersection points of the strength surface and Mohr's circle are A and B respectively. If the point of M is located below the arc AB, the structure surface will not break, and if the M is between AB, the structural plane will be destroyed. Thus, the angle \( \beta_1 \) and \( \beta_2 \) play a key role in determining whether the rock mass is destroyed along the structural plane.

Assume: \( \sigma_m = \frac{\sigma_1+\sigma_3}{2}, \tau_m = \frac{\sigma_1-\sigma_3}{2} \),

\[
\beta_1 = \frac{1}{2} \left[ \varphi_j + \arcsin \left( \frac{\sigma_m \sin \varphi_j + c_i \cos \varphi_j}{\tau_m} \right) \right]
\]

\[
\beta_2 = \frac{1}{2} \left[ \pi + \varphi_j - \arcsin \left( \frac{\sigma_m \sin \varphi_j + c_i \cos \varphi_j}{\tau_m} \right) \right]
\]

As the strength value criterion shows that if the Mohr circle of the rock mass is determined by the calculation to intersect the strength line of the structural plane, which are \( \beta_1 \) and \( \beta_2 \), between the Mohr circle and the strength line of the structural surface by calculation, the rock mass may be damaged along the structural plane \( \beta \) between the \( \beta_1 \) and \( \beta_2 \).

| Cohesion of structural plane | Friction angle | \( \sigma_1=22.9 \), \( \sigma_3=0 \) (MPa) | \( \sigma_1=76.4 \), \( \sigma_3=0 \) (MPa) |
|-----------------------------|---------------|--------------------------------|--------------------------------|
| \( C_1=0.01MPa \)         | 20°           | [20.0125°,89.98°]            | [20°,90°]                      |
|                            | 30°           | [30.0125°,89.98°]            | [30°,90°]                      |
|                            | 40°           | [40.0125°,89.98°]            | [40°,90°]                      |
| \( C_2=0.03MPa \)         | 20°           | [20.0375°,89.98°]            | [20°,90°]                      |
|                            | 30°           | [30.0375°,89.98°]            | [30°,90°]                      |
|                            | 40°           | [40.0375°,89.98°]            | [40°,90°]                      |
| \( C_3=0.05MPa \)         | 20°           | [20.063°,89.93°]             | [20°,90°]                      |
|                            | 30°           | [30.063°,89.93°]             | [30°,90°]                      |
|                            | 40°           | [40.063°,89.93°]             | [40°,90°]                      |

If the \( \beta \) within the \( \beta_1 \) and \( \beta_2 \), that is belong to \( [0, \beta_1) \cup (\beta_2,\pi/2] \), the rock mass will not be broken. If the dip angle of structure plane \( \beta \) exactly equals the \( \beta_1 \) or \( \beta_2 \), the rock mass is in a critical state of rock failure. If the \( \beta_1 \) and \( \beta_2 \) are not exist, the rock mass or the structure plane will not be broken by fixed value calculation.
On the one hand, the limestone formation in this region of Jinan city is 4.5m–22m in thickness, the unconfined compressive strength is from 22.9MPa to 76.4MPa and the range of cohesion of the structural surface is from 0.01MPa to 0.05MPa by 83 sets of experimental data. Meanwhile, it can be calculated that the value of $\beta$ is from $20^\circ$ to $90^\circ$ as the table 1 shows. On the other hand, the dip angle of structure plane is from $20^\circ$ to $40^\circ$ of this area by means of examining engineering on the spot. Therefore, the destruction pattern of the region may only be destroyed along the structural plane.

3. Model building

3.1. Engineering geology
The HanYuJinGu project engineering is located in the New and High-tech Zones of Jinan city. This project engineering is divided into from A1 to A8 plots and this paper is based on the A4 plot. Geomorphic units are piedmont slope alluvial fan, terrain ups and downs. The geological condition of the site is mainly composed of rock weathering limestone, and the upper part of the local area is not filled with thick soil layer. The foundation pit is deep and there are not many surrounding roads or buildings. The phreatic line is low and the rock mass structure surface is mainly composed of primary structural planes, mostly closed and larger in number. The rock mass type is from the third to the fourth grade. The south side wall of the foundation pit is inclined to the pit and the inclination angle is smaller than the slope angle, so that the pit is prone to collapse.

3.2. Finite element simulation

![Calculation Model](image)

![Mesh of Foundation Ditch](image)
Table 2 Calculation parameter

|        | Bulk modulus K/Gpa | shear modulus G/Gpa | Density Kg/m³ | Cohesion c/MPa | internal friction angle φ | tensile strength σ/MPa |
|--------|--------------------|---------------------|---------------|----------------|--------------------------|------------------------|
| limestone | 75                 | 24                  | 2300          | 0.1            | 35                       | 1.58                   |
| structural | 1.11               | 0.37                | 1938          | (0.01~0.05)    | 20-40                    |                       |

The calculation model of this paper is 45m long, height is 35m, width is 15m, and foundation pit depth is 15m through research and analysis, just as Fig.3 shows. At the top of the foundation pit, 5 monitoring points are arranged along the Y direction to measure the horizontal displacement and vertical displacement. The constitutive model uses the Mohr-Coulomb criterion, and the initial stress field is taken into account according to the self-weight stress. Keep the top surface a free surface, and constrain the velocity and displacement of the other 5 surfaces in order to ensure the real force balance of the model. The water is not considered in the calculation because the groundwater of the foundation pit is deep. On the one hand, the final parameter values and their ranges in this paper are determined by the geological survey reports. On the other hand, field samples are carried out through indoor tests. Above all, the comprehensive engineering parameters are obtained as shown in Table 2 below. In the end, the model structure basically maintains the consistency with the geological prototype.

4. The analysis of simulation results

During the simulation experiment, studying the stress changes of the structural plane deformation in the x-z oblique section and exploring the stability of the foundation pit. Then, making a sensitivity comparative analysis of structural surfaces with different dip angles and different parameters. In the process of simulation, taking the change of the displacement at the top of the foundation pit as the standard to diminish the range of structural surface parameters by the method of bisection and to determine the relationship between the parameters of the structural surface and the exposed height finally.

4.1. Analysis of stress field during excavation

![Stress nephogram of x-z direction in excavation of 3m, 7m](image)

Fig.5 Stress nephogram of x-z direction in excavation of 3m, 7m
Putting the gravity stress field through calculation as the initial stress field before the simulated excavation and making a numerical calculation without support in the process of excavation. The parameters in the calculation are selected according to Table 1. We can see it from the Fig.5 to Fig.6 that the stress change in the weak surface area is the most significant in the whole process of excavation of the foundation pit. With the deep excavation, the resulting temporary surface increases in the excavation from 3m to 7m. This will lead to increase stress at the bottom of the foundation pit, and the phenomenon will be bulging. When excavating to 11m, the weak structure will be in a bare state. The plastic area has been extended to the entire structural surface, the rock mass is most likely to slip along the weak structural plane at this time. At the same time, there is a large tensile stress area at the top of the structural surface and shows the trend of tensile fracture at the upper part, which has a bad influence on the surrounding buildings. With the continuous progress of excavation, the plastic zone along the structural surface is further extended, and the upper part of the structural surface presents greater tensile stress. The displacement of soil at the top of foundation pit is more and more big, whose maximum displacement is increasing greatly from 1.52mm to 3.18mm by the monitoring point data. The slope of the whole foundation pit shows a tendency about diagonal shear failure. It may cause surface cracking and the phenomenon of tension breaking in the middle of the foundation pit, and this threatens the safety of the surrounding buildings at present.

It can be seen clearly from the above analysis that the shear stress changes along the x-z direction of the rock foundation pit in the absence of support. The deeper the excavation of the foundation pit, the greater the possibility of damage. Therefore, we should be based on the actual situation to take different support measures to ensure the stability of the foundation pit for different depth of the rock foundation pit and reduce the impact on the surrounding buildings.

4.2. *The influence of exposure height on the cohesion of structures*

Taking the bare height of the structural surface as independent variable, this curve shows the corresponding relation between the exposed height of the structural surface and the critical cohesion when the slope of the foundation pit reaches the critical stable state, as shown in Fig.7.

The upper side of each curve shows convergence, that is, the foundation pit is in a stable state; the lower side of the curve represents divergence; that is, the foundation pit is in a state of instability. Firstly, it can be seen from the figure that when the foundation pit is in the critical stable state and the inclination angle of the structural plane is constant, the critical cohesive force of the structural plane increases with the increase of the exposed surface height. This indicates that the greater the exposed height of the rock mass structural plane, the more prone to damage, and its cohesion reflects the role of the more obvious. In the process of foundation pit excavation, if the cohesion of the structural surface is greater than the critical value, the foundation pit is in a safe state; if it is less than the critical value, the foundation pit may be in a state of instability.
When the structural planes with different inclination angles are at the same height, the corresponding cohesion of 40° structural plane is always significantly greater than the structural plane of 30°. Moreover, it can be seen from the figure that the curve of the 40° structure plane has been rising all the time. But the curve of the 30° structure plane tends to be stable in the later stage, and the slope of the former is greater than the latter. This shows that the sensitivity of the foundation pit slope to the structural surface cohesion is more and more obvious with the increase of the inclination angle.

On the one hand, the inclination angle of the structural plane is varied from 20° to 40°, and the dip angle inclination of the structural plane is as same as the slope inclination of the foundation pit through field survey of the field works. But I find that the critical cohesive force corresponding to the angle of 20° of inclination is reduced to 100Pa, and the normal range of this value is generally from 2KPa to 50KPa. Therefore, we can make a conclusion that the foundation pit slope in Ji'nan area will not be destroyed when the dip angle of rock mass structural plane less than 20°. It can be see that the different cohesion of the structure plane has a great influence on the critical depth of the slope of the foundation pit. Therefore, the structural surface of the cohesion should be considered as an important factor in the mechanism analysis and stability evaluation.

4.3. The influence of exposure height on structural invasion angle

The change of dip angle of the structure plane has an important influence on the stability. As shown in Fig.8, the curve stands the relation between the exposed height of the structural plane and the structure face the dip angle, and the bare height of the structural surface is independent variable. The top right section of each curve shows that the foundation pit is in a state of instability, and the lower left of the curve indicates that the foundation pit is in a stable state. It can be seen from the figure, when the foundation pit in the critical stability of the situation and the structural surface of the cohesive force is certain, the structural surface exposed height increases and the structural angle of inclination is
declining. When the foundation pit is excavated to a certain depth and the angle of the structural plane is less than the critical angle, the foundation pit is in the state of safe; if the inclination angle of the structural face is greater than the critical inclination angle, the foundation pit may be in a state of instability. When the exposed height of the structure plane is 6m, the critical inclination angle of the structural plane needs to reach 31.5° to make the foundation pit in a critical stable state. When the exposed height of the structure surface is 10m, the corresponding dip angle of structure plane is 26°. At the same time, the structural surface of the cohesion of 15KPa, 20KPa curve decline trend is more steep, which can be seen from the figure. But the trend of 10KPa cohesion curve is more gentle. We can make a conclusion of this area that the value of cohesion is sensitive to the stability of foundation pit when it is between [15KPa, 20KPa]. Moreover, for the range [6, 10] meters of the structural surface of the exposed height, its corresponding critical inclination dip angle is [26°, 46°]. That also confirms that the rock foundation pit slope will not be broken when the inclination dip angle of structure plane t is smaller than 20°.

Therefore, we should pay special attention to the influence from the dip angle of structure plane to the critical instability depth of foundation pit slope in the analysis of the mechanism and stability evaluation.

5. Summary
Through the above research, we can draw the following conclusions:

(1) When the foundation pit is in the critical stable state and the inclination angle of the structural plane is constant, the critical adhesion force will increase with the higher of the exposed height, which is a linear relationship. Moreover, the stability of the foundation pit in the limestone area of Ji'nan city is more sensitive when the cohesion of the structural surface is between 15KPa and 20KPa.

(2) When the foundation pit is in the critical stability state and the cohesion of the structural plane is constant, the higher the exposed height of structural plane, the smaller the critical inclination dip angle is, which is a linear relationship. The structural plane with a dip angle of 40° will be more sensitive than the dip angle of 30° when retaining the stability of the foundation pit. Moreover, when the rock surface plane angle is less than 20, the foundation pit can maintain the self-stabilized state in the limestone area of Ji'nan city.

(3) During the process of excavation, the place where the weak structural plane exposed will occur tension fracture failure and the phenomenon of compressive stress concentration will be found in the weak structural plane at the bottom of the foundation pit. We should set up the supporting structure (with bolt, hanging net, shotcrete, etc.) in time effectively to control the deformation of the foundation pit slope.

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