



Numerical Simulation Study on Ground Subsidence and Structural Stress Characteristics of Open Caisson Construction

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Abstract This paper studies the stress characteristics of caisson construction in complex strata and its influence on the surrounding environment, and focuses on the application effect of structural reinforcement technology of pipe jacking working well. Through the numerical simulation analysis of the Nanniwan power tunnel project in Wuhan, this paper analyzes the settlement deformation law of the surrounding environment during the sinking process of the caisson structure, and studies the stress characteristics of the caisson itself after the reinforcement measures. The results show that the construction of the reinforced structure can effectively reduce the settlement of the surrounding environment caused by the sinking of the caisson and improve the stability and safety of the structure. The contact pressure between the outer wall of the caisson and the soil increases sharply and then slowly during the sinking process, and the maximum value appears at the edge angle at the bottom of the caisson. The stress distribution on the section of the caisson is more uniform. As the depth increases, the stress decreases first and then increases. The research in this paper provides theoretical guidance and reference for disaster prevention and field construction of caisson construction in complex strata.

Keywords- Caisson reinforcement, Settling volume, Force characteristic.

1. Introduction

At present, the construction of power facilities in China is developing rapidly, but the underground space in the city is limited, the pipeline layout is complex, and the road construction is frequent, so the protection of cables is particularly important. In the past design and construction process, for the laying of power cables crossing rivers or roads, the combined technique of pipe jacking and sinking wells has become an ideal choice because of its clear pipe jacking trajectory, precise burial depth, and strong self-protection ability of reinforced concrete pipes^[1]. This technology does not require additional wind, water, electricity and other auxiliary facilities, and compared to power tunnels, its cost is lower, so it is widely used in urban power cable laying projects, which can effectively reduce the operational risks of power cables and reduce the cable relocation problems caused by external construction.

Sink is the pre-project of pipe jacking project, which is an important part of pipe jacking method construction, providing operation space for pipe jacking reception and later inspection and maintenance^[2]. In all kinds of underground space projects, immersed wells can not only be used as foundations, but also as enclosure structures, and their internal space can be fully utilized as starting wells for shield structures or pipe jacking^[3]. The immersed well working well in pipe jacking project as the main bearing structure of pipe jacking project may cause large deformation to the surrounding area, resulting in serious environmental impacts. The greater the jacking force the softer the soil, resulting in serious loss of soil layer on the forward side, and the surface uplift on the back side is aggravated, which is likely to cause engineering disasters and bring losses if there is no prior knowledge and early warning for the size of settlement in urban municipal engineering.

In recent years, many scholars at home and abroad have conducted some research on the force and settlement problems during the construction of sinkhole foundation. Chen Xiaoping (2005)^[4], Wang Jian (2013)^[5], Mu Baogang (2014)^[6], Shi Cong (2015)^[7] and others have analyzed the sinking resistance of sinking wells and concluded that: when the sinking depth of sinking wells is relatively small, the lateral resistance of the well wall and the depth of the entry into the earth is basically a linear relationship; with the increase in the sinking depth, the distribution of the sidewall friction presents a small up and



down, large in the middle of the parabolic distribution of approximate form. The research results of Xu Pengfei (2014)^[8], Luo Shihan (2016)^[9] and Wang Hailin (2010)^[10] show that the influence of sinkhole construction is in the range of 1.5~1.7 times of the sinking depth from the sinkhole sidewall, and in the range of 0.5~0.62 times of the sinking depth, the soil body is affected more, which is the main influence range. Ren Fengming^[11] used finite element program to study the force and deformation of rectangular working wells under different conditions, and concluded that increasing the thickness of the wall, the cross-section size of the wall, and the addition of bedding layer can reduce the displacement and stress of the well body. Mao Jiming^[12] used ABAQUS finite element simulation software to simulate the horizontal displacement along the depth direction of the pit under different excavation stages of sinkhole excavation and deepening, and concluded that in the stage of pit excavation and unsinking of the working well, the rotary piles were able to reduce the tendency of the soil to settle and influx into the pit, which was manifested in the soil bulge at the bottom of the pit and the displacement of rotary piles. When the well is sunk and stabilized, the rotary piles can also effectively reduce the horizontal displacement of the soil and the vertical uplift of the pit bottom, thus reducing the risk of soil collapse around the working well and suppressing the uplift of the pit bottom after the sinking of the well.

In summary, there are many studies on the deformation characteristics of open caisson foundation during construction, but the discussion on the reinforcement technology of pipe jacking working well structure is still limited. In addition, when the caisson structure is constructed in complex strata, the influence of reinforcement on the surrounding environment and the stress characteristics of the caisson structure after reinforcement are not clear.

Therefore, based on the Nanniwan power tunnel project in Wuhan, this paper uses the method of numerical modeling to carry out multi-angle research on the reinforcement technology of the working well of the open caisson project in the complex stratum of the urban area, analyzes the settlement and deformation law of the open caisson structure sinking to the surrounding environment under the condition of reinforcement or not, and analyzes the force characteristics of the open caisson itself after the reinforcement, which provides first-hand information for the prevention and control of engineering disasters and provides theoretical guidance for on-site construction.

2.Engineering Overview

2.1Project background

This project is Nanniwan Health Industrial Park and Infrastructure Construction Project - Nanniwan Avenue (Third Ring Road - Hanxi Third Road) Renovation Project Power Tunneling Project, the starting point for the intersection of Gongnong Road and Yuanbo Avenue A1 work shaft, along the Gongnong Road through the Hurong Railway, H&S railroad, the end point of the Nanniwan Avenue and the intersection of Hanxi Third Road A23 work shafts, the power channel is 6.289km long. A20, A10~A10.1, A20~A20.1 well section adopts $\phi 3\text{m}$ pipe jacking (length 5424m); A20~A23, A5~A5.1, A13~A13.1, A15~A15.1 well section adopts $\phi 2.7\text{m}$ pipe jacking (length 865m), and the total number of working wells is 27.

The main channel consists of work shaft A1 at the intersection of Gongnong Road and Yuanbo Avenue, with an inner diameter of $\phi 3\text{m}$ jacking tunnel aligned on the motorway on the south side of Gongnong Road to work shaft A3; turn east and adopt $\phi 3\text{m}$ jacking tunnel to align along the south side of Gongnong Road, crossing the Han-Dan Railway, Changfeng Avenue, Rudder Lok Kou Road, Luen Yih Road, Luen Yih Road, and connecting to work shaft A7; turn north and adopt $\phi 3\text{m}$ jacking tunnel to cross the Light Rail Transit (LRT) No. 1 line, and connect to work shaft A10; use $\phi 3\text{m}$ jacking tunnel to cross LRT No. 1 line, and connect to work shaft A10 Work shaft; $\phi 3\text{m}$ header tunnel along the north side of Nanniwan Avenue, crossing Lianyou Road, Fengfan Road, Gutian 1st Road, Chaiji 1st Road, Fengshuo Road, Fengsheng Road, Fengyi Road, Gutian 2nd Road, Gule Road, Gutian 3rd Road, Guxiao Road, Gutian 4th Road, and connecting to the A20 work shaft; $\phi 2.7\text{m}$ header tunnel along the north side of Nannawan Avenue and continue to cross Qingyun Road, Hanxi 3rd Road, and connecting to the A22 work shaft; turning south and adopting $\phi 2.7\text{m}$ header tunnel through LRT No.1 Line, connecting to A22 work shaft; turning south and adopting $\phi 2.7\text{m}$ header tunnel through LRT No.1 Line. Turning to the south, the $\phi 2.7\text{m}$ jacking tunnel will be aligned to cross Nanniwan Avenue and be connected to the A23 working well. The cross-section of the pipe jacking tunnel is shown in Figure 1.

In the numerical modeling process, considering the actual influence range of sinkhole construction, the length and width of the soil body are set to be 50m and the depth to be 30m, and the area is pre-demarcated. As shown in Figure 2.

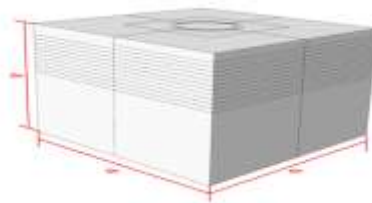


Figure 2 Soil component diagram

According to the geological investigation report and indoor test results, taking into account the mechanical parameters between multiple strata are more similar, so in the simulation of the similar strata to do the appropriate merger, and ultimately get the stratigraphic parameters of this paper for the A13 working well, according to the order from top to bottom of the soil body is divided into three parts, in turn, the clay, pulverized clay and silt sand sandy clay layers of the soil body as well as the mechanics of the sunken well parameters as shown in Table 1.

Table 1 Mechanical parameters

Stratigraphy/structure	Depth/m	Density/g·cm ³	Force of cohesion/kPa	Angle of internal friction/°	Elastic modulus/MPa	Poisson ratio
Clay	2	1.85	19	7	7	0.35
Silty clay	11	1.78	20	8	18	0.38
Silty sand mixed with clay	17	1.80	10	15	23.3	0.32
Concrete	—	2.20	—	—	30000	0.2

The concrete grade is C30, and other parameters are set with reference to the corresponding specifications and literature [13]. The “life and death cell method” is adopted to realize soil excavation and structural sinking, and the “built-in region” function in the interaction is used to realize the coupling effect between reinforcement and concrete. The grid cell type of both soil and concrete materials is C3D8R (eight-node linear hexahedral cell). As shown in Figure 4. The sink sinking simulation is carried out using the “life and death cell method” to analyze the working condition of the sinkhole as a reinforcement, in order to further investigate the impact of sink construction.

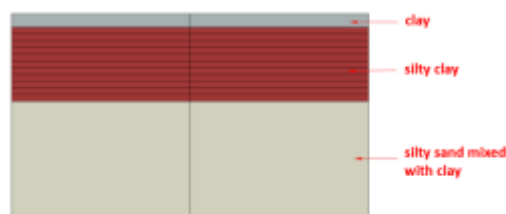


Figure 4 Map of stratigraphic attribute settings

3.2 Analysis of results

(1) Analysis of the impact of the sink structure on the surrounding environment

With the fabrication and excavation of the sink, the weight of the well body and the depth of the soil are increasing, the strata in contact with it provide upward friction force and at the same time, they are also subjected to the downward reaction

force from the sink and appear to be sinking, and the accumulation of the settlement of multiple strata eventually acts on the surface, resulting in the settlement of the surface. In order to study the actual impact of reinforcement construction measures on the surface settlement around the sink, firstly, the simulation results were used to obtain the settlement at different distances around the sinkhole, so as to visually reflect the difference between the two under ideal conditions. After the simulation was completed, “displacement” was selected as the field output variable and focused on the U2 direction (i.e., vertical direction), which resulted in the vertical deformation diagram in Figure 5, which accurately depicted the distribution of settlement.

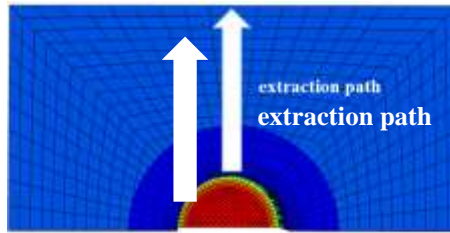
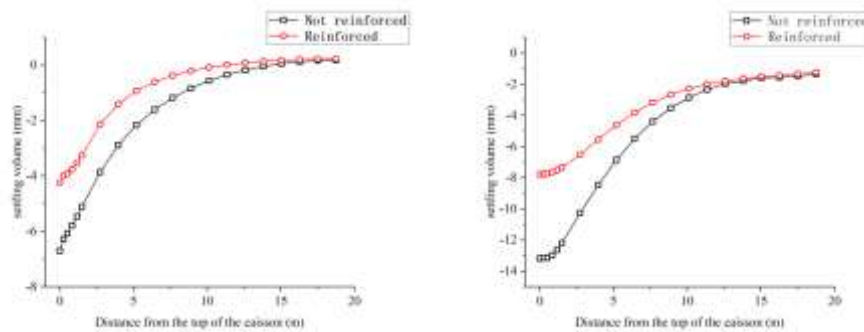


Figure 5 Vertical deformation profile of the soil body

By creating a nodal path on the soil surface pointing vertically along the outside of the sink towards the edge of the soil body and extracting the data, the settlement of the ground surface under different simulated construction phases can be obtained. The surface settlement at the end of the first section of sink sinking and at the end of the overall sinking is presented in the form of vertical displacement, as shown in Fig. 6.



(a) Completion of the sinking of the first section (b) Completion of overall sinking

Fig. 6 Comparison of surface settlement in different simulation stages

Under the same simulation conditions, the surface settlement of the first section of the sinkhole and the whole sinkhole have a similar trend, with the surface settlement gradually decreasing away from the sinkhole, and the variation of the settlement decreases with the increase of the distance. At the completion of the first section of sinking, the soil body away from the sinkhole will be slightly elevated, which may be due to the deformation of the soil body furthest away from the sinkhole at the initial stage of sinking is very small due to the settlement of the neighboring soil body extrusion of the edge of the soil body, resulting in the slight elevation of the soil body.

The maximum settlement value of the unreinforced surface after the completion of the first section sinking is 6.7mm; the maximum settlement value of the reinforced surface is 4.2mm. the maximum settlement value is reduced by 37.3% after the reinforcement, and the magnitude of the surface settlement and the amount of the surface settlement after the reinforcement is smaller than that without reinforcement, which initially shows that the reinforcement can reduce the surface settlement due to the sinking of sinks.

After sinkhole sinking, the minimum settlement value of the surface without reinforcement is 1.36mm, and the maximum settlement value is 13.18mm; the minimum settlement value of the surface after reinforcement is 1.23mm, and the

maximum settlement value is 7.78mm; the maximum settlement value is reduced by 41% after reinforcement; in order to visualize and compare the settlement of the sinkhole sinking as a whole and the effect of reinforcement, the increase of the settlement at the end of the conditions and the increase of the settlement value of the stages are listed in Table 2. The increase of settlement value at the end of each condition and each stage are listed in Table 2.

Table 2 Table of changes in sedimentation

Stage	Working condition	Maximum settlement	Reduced reinforcement	after	Increase in stages	in different
The first section sinks	Not reinforced	6.7mm			/	
	Reinforced	4.2mm	37.3%		/	
Overall sinking	Not reinforced	13.18mm			96.7%	
	Reinforced	7.78mm	41%		85.2%	

From the data shown in the above table, it can be seen that in the process of sinking the caisson, the effect of reinforcement construction on controlling the surrounding settlement is gradually highlighted. After all the sinking work is completed, the increase of the settlement value after reinforcement is less than that of the non-reinforcement condition, and the decrease of the settlement value is also improved compared with that of the first section after sinking. Compared with the unreinforced stratum, the maximum surface settlement value of the reinforced stratum is reduced by 37.3 % after the first section is sunk, and it is reduced by 41 % after all sinking, indicating that the reinforcement construction can effectively control the soil deformation generated during the caisson construction. In order to understand the stress of the soil after the reinforcement construction, the contact pressure and stress after the reinforcement construction will be analyzed below.

(2) Analysis of contact pressure of caisson structure after reinforcement construction

Due to the contact friction relationship between the open caisson and the surrounding strata during the sinking process, the contact pressure on the outer wall of the open caisson can be studied to reflect the earth pressure. The contact pressure of the caisson under different analysis steps is intercepted, and the contact pressure of the outer wall of the caisson under different analysis steps is analyzed, as shown in Figure 7. The earth pressure on the outer wall of the open caisson increases roughly with the increase of the depth of the soil, and the influence range also increases.

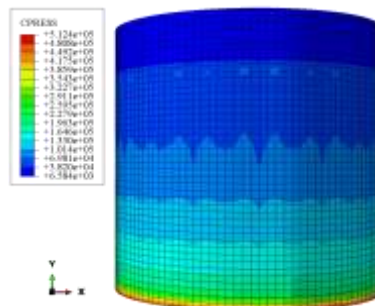


Fig.7 Contact pressure cloud diagram of caisson structure

Considering that in the simulated environment, the mechanical properties of the nodes at the same depth are less different, so a node path is created along the vertical direction of the outer wall. As shown in Figure 8, the contact pressure of the nodes on the path at the end of different sinking analysis steps is extracted to study the change of the earth pressure during the sinking process of the open caisson, and the curve is drawn as shown in Figure 9.

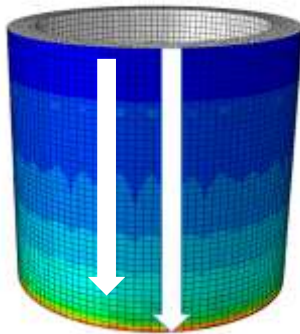


Fig.8 Contact pressure extraction path

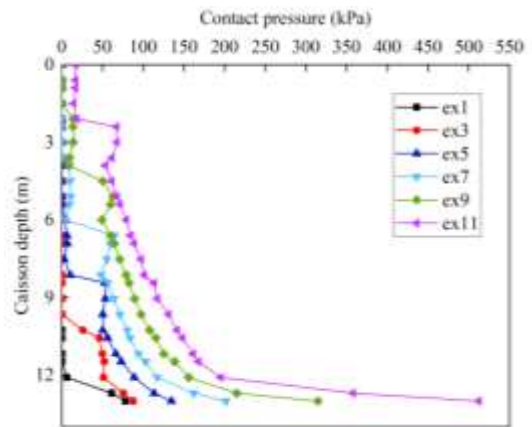


Fig.9 Contact pressure of caisson at different depths

In the initial stage of ex1 excavation, the caisson structure began to sink, and most of the outer wall did not enter the soil without contact pressure. With the continuous excavation, the outer wall of the caisson continued to contact with the soil, resulting in contact pressure. In the excavation stage from ex1 to ex11, the change of contact pressure with depth is roughly the same. The change trend of contact pressure with depth is as follows: the contact pressure increases sharply at the contact with the soil, and then the contact pressure increases slowly with the increase of depth. At this stage, the increase of contact pressure is relatively stable. When it is close to the bottom of the structure, the contact pressure increases sharply, and the maximum contact pressure appears at the bottom edge of the caisson. The maximum values of contact pressure in each excavation stage are 77.9kPa, 87.6kPa, 134.9kPa, 201.7kPa, 304.6kPa and 512.3kPa, respectively. The increase of contact pressure at the blade angle is 12.5%, 54%, 49.5%, 51% and 68.2%, respectively. From this, it can be concluded that the increasing trend of the contact pressure at the blade corner of the caisson structure during the excavation process is to surge after a period of time in the initial excavation stage, then enter the steady increase stage, and then surge again when approaching the bottom of the structure, and obtain the contact pressure at the final blade corner.

(3) Pressure analysis of caisson structure after reinforcement construction

In order to understand the change of stress in the construction process of the receiving caisson structure after the reinforcement construction, the simulation results are analyzed. The overall stress cloud diagram after the sinking of the caisson is shown in Figure 10. It can be seen from figure 10 that the caisson foundation is after the sinking. The buried part of the caisson foundation is tensioned; the stress value of the caisson wall increases gradually from top to bottom, and reaches the maximum value of 1.74MPa at the bottom section near the blade foot.

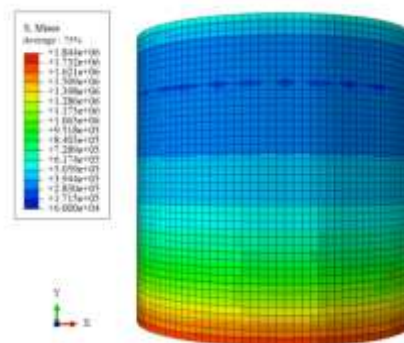


Fig.10 Stress cloud diagram of caisson structure

The stress under ex11 condition is analyzed in detail. Seven points on the edge of half of the caisson foundation in Figure 11 are taken as the path, and the path stress at the top, 3m, 5m, 8m, 11m and different heights at the bottom is analyzed. Draw the radar diagram as shown in Figure 12.

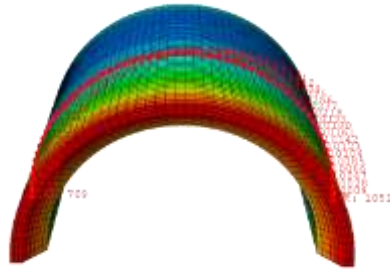


Figure 11 Stress extraction path under ex11 condition

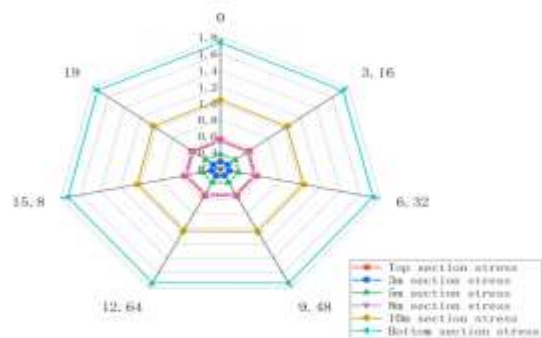


Fig.12 Stress distribution under ex11 condition

It can be seen from Fig.12 that the stress distribution of each point on the section is relatively uniform under ex11 condition, indicating that the force is uniform on the section. The structural stress of the caisson decreases first and then increases with the increase of depth. The average stresses at different cross-section heights are 0.55MPa, 0.29MPa, 0.38MPa, 0.54MPa, 1.04MPa, and 1.74MPa, respectively. The stress growth rates of each cross-section height are 47.3%, 31%, 42.1%, 92.6%, and 67.3%, respectively. The analysis of the increase of stress shows that with the increase of depth, the increase of stress increases first and then decreases. The simulation results show that the caisson structure is in a low stress state as a whole, which may mean that the structure is sensitive to external load and the stress increases greatly in the early stage of caisson sinking. With the increase of depth, the structure gradually adapts to the external environment, and the increase of stress decreases.

In order to further study the stress distribution of the outer side of the caisson foundation under different working conditions. Therefore, as shown in Figure 13, the stress of the nodes on the path at the end of different sinking analysis steps is extracted to study the change of stress under different working conditions during the sinking of the caisson, and the curve is drawn as shown in Figure 14.

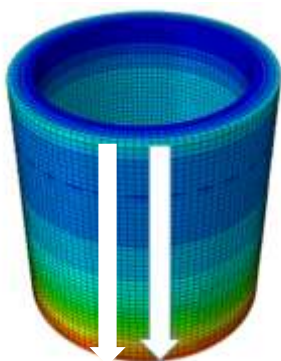


Fig.13 Stress extraction path

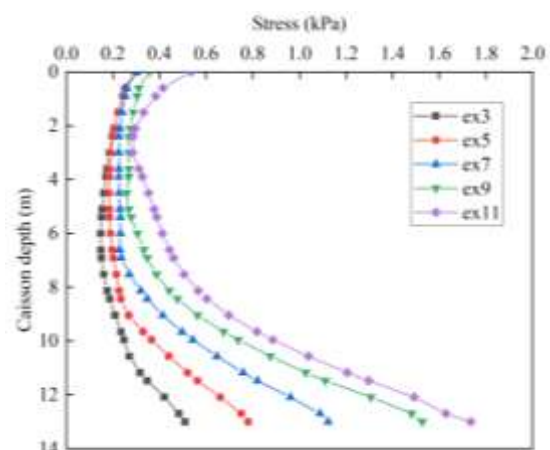


Fig.14 The stress of caisson at different depths

In the excavation stage of different working conditions from ex1 to ex11, the stress change of the caisson stress on its own part is small, and the stress change is stable. The variation range of stress in the lower part of the caisson is obviously different from that in the upper part. The variation range of stress in the lower part of the caisson gradually increases, and finally reaches the maximum at the edge angle. As the sinking depth of the caisson increases, the stress at the same height

on the caisson increases. The maximum values at the edge angle of the caisson under different working conditions are 0.51MPa, 0.78MPa, 1.12MPa, 1.53MPa and 1.74MPa, respectively. The results show that the change of contact pressure with depth is roughly the same under different working conditions. The change of contact pressure with depth is parabolic, and the stress decreases first and then increases.

4. Conclusion

- (1) The reinforcement structure construction can reduce the settlement of the surrounding environment caused by the construction during the sinking process of the pipe jacking work well structure, effectively restrain the deformation of the surrounding soil, and effectively improve the stability and safety of the structure sinking.
- (2) The contact pressure in the reinforced structure increases sharply when the outer wall of the caisson contacts with the soil for the first time, and then increases slowly with the increase of depth. When approaching the bottom of the caisson structure, the contact pressure increases sharply again, and the maximum value appears at the corner of the bottom of the caisson. The increase of contact pressure at the corner of the open caisson increases sharply at the initial stage of excavation, then increases steadily, and increases again when it is close to the bottom.
- (3) The stress distribution of each point on the section of the caisson is relatively uniform, indicating that the force is uniform on the section. In the excavation stage from ex1 to ex11, the contact pressure of the open caisson shows a parabolic shape with the change of depth, that is, it decreases first and then increases. The stress change of the upper part of the caisson itself is small and the stress change is relatively stable. The stress increase of the lower part is obviously increased, and the maximum value is reached at the blade corner.

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