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# Response of Skirted Suction Caissons to Monotonic Lateral Loading in Saturated Medium Sand*

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## ABSTRACT

Monotonic lateral load model tests were carried out on steel skirted suction caissons embedded in the saturated medium sand to study the bearing capacity. A three-dimensional continuum finite element model was developed with Z_SOIL software. The numerical model was calibrated against experimental results. Soil deformation and earth pressures on skirted caissons were investigated by using the finite element model to extend the model tests. It shows that the "skirted" structure can significantly increase the lateral capacity and limit the deflection, especially suitable for offshore wind turbines, compared with regular suction caissons without the "skirted" at the same load level. In addition, appropriate determination of rotation centers plays a crucial role in calculating the lateral capacity by using the analytical method. It was also found that the rotation center is related to dimensions of skirted suction caissons and loading process, i.e. the rotation center moves upwards with the increase of the "skirted" width and length; moreover, the rotation center moves downwards with the increase of loading and keeps constant when all the sand along the caisson's wall yields. It is so complex that we cannot simply determine its position like the regular suction caisson commonly with a specified position to the length ratio of the caisson.

**Key words:** *skirted suction caissons*; *bearing capacity*; *model tests*; *monotonic lateral loading*; *numerical modeling*

## 1. Introduction

A regular suction caisson is a hollow circular tube closed by a lid at the top, like a bucket upside down. The lid can be a flat plate, or a dome. The maximum ratio of the wall length to diameter is smaller than the diameter of a pile, normally 1−6. The ratio of the wall thickness to diameter is also smaller, generally in the range of 0.3%−0.6%. The thickness of the wall is about 15−50 mm. Suction caissons are first lowered into the seabed partially under their self-weight. Water is then pumped out of the caisson interior, which creates a net pressure difference across the lid that helps the caisson penetrate into soil to the desired depth. Compared with driven-piles, a significant advantage of suction caissons is the cost effectiveness and reusability. Suction caissons have been widely used for mooring offshore floating facilities and as foundations for various offshore platforms (Kwang *et al*., 2010). So far, they have been extended to offshore wind turbines (Byrne *et al*., 2002).

Horizontal loads play a major role in design, especially for offshore wind turbines. Lateral loads,

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which result from wind, waves and tides, govern the design of suction caissons. The design of suction caissons under lateral loading is commonly based on two criteria. The first one considers the bearing capacity of foundations, and the other is based on an allowable lateral displacement under working conditions.

To increase the lateral bearing capacity and to limit the deflection, a modified suction caisson called the skirted suction caisson was proposed (Li *et al*., 2010, 2011a, 2011b). Regular suction caissons can easily penetrate sand, silt and clay with the aid of expelling water entrapped inside the caissons (Iskander *et al*., 2002; Guo *et al*., 2012). It has been proved that the skirted caissons can readily penetrate medium-sized sand under reasonable dimensions of "skirted structure" (Li *et al*., 2012).

Pullout and lateral capacity of regular suction caissons have received considerable research attention for decades (Jones and Bang, 2007; Zhu *et al*., 2011). Research methods focused primarily on model tests using 1*g* and centrifuge tests (El-Sherbiny, 2005; Wang and Yang, 2008), the finite element modeling (Bransby and Randolph, 1998), and theoretical analyses (Gourvenec and Barnett, 2011). Obviously, there is not much literature giving insight into the rotation center of the suction caisson. Although the skirted suction caisson is a novel type, studies on the lateral capacity can borrow some ideas from the previous literature.

This paper aims to study the behavior of skirted suction caissons under the monotonic lateral loading through a series of model tests carried out in saturated medium sand. Loading-deflection curves were established to determine the bearing capacity under working conditions and ultimate states including a variety of dimensions of the skirted suction caissons. And rotation centers of the skirted suction caissons were investigated considering dimensions of caissons and the loading process. Finally, the earth pressure distributions along the caisson wall and the deformation behavior around the skirted suction caisson were explored with the finite element package ZSOIL (Zace Services Ltd., 2011). Some results by the numerical method are in a very good agreement with the model tests.

## 2. Monotonic Lateral Loading Tests

### 2.1 Sand for Test

The sand used in the test was obtained from the estuary of the Fenghe River in Qingdao, China. Physical parameters of the relative density of 70% are listed in Table 1 by performing a series of laboratory tests, and some are used in the finite element modeling. Its particle size distribution curve is drawn in Fig. 1. Thus, the sand falls into a homogeneous medium state. To make sand in the steel tank (2.5 m long × 2.5 m wide × 1.3 m high) saturated, some water was first poured into, and dry sand was scattered into the water.

**Table 1** Physical parameters of sand

| $C_u$ | $C_c$ | $G_s$ | $\rho_{sat}$ (g/cm$^3$) | $\rho_d$ (g/cm$^3$) | $e$ | $k$ (cm/s) |
|---|---|---|---|---|---|---|
| 4.25 | 1.09 | 2.69 | 1.92 | 1.51 | 0.7 | 0.002 |

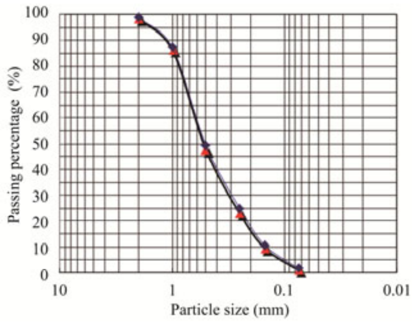


**Fig. 1.** Particle size distribution curves.

## 2.2 Suction Caisson Miniatures

Compared with regular suction caissons without "skirted", the skirted suction caissons (Fig. 2) made of steel have been added a "skirted structure" to enhance the lateral bearing capacity and to reduce the lateral deflection. Dimensions of the skirted suction caissons are shown in Table 2.

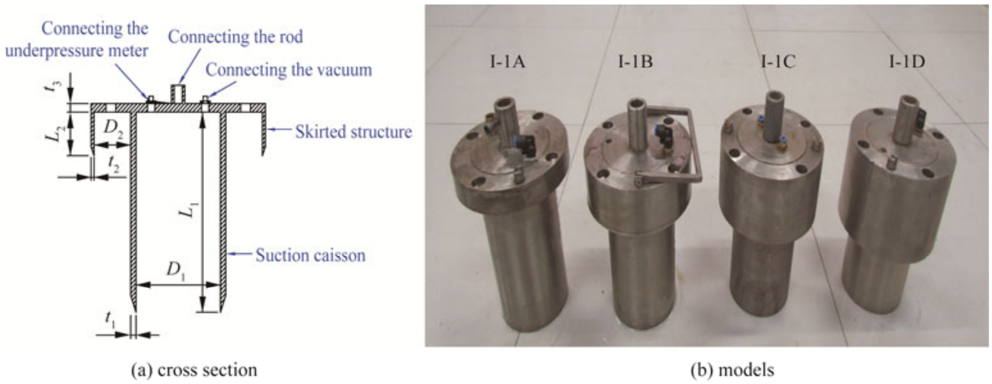


**Fig. 2.** Skirted suction caisson models.

**Table 2** Dimensions of skirted suction caissons (units: mm)

| No. of model caisson | $t_1$, $t_2$ | $t_3$ | $D_1$ | $L_1$ | $D_2$ | $H_2$ |
|---|---|---|---|---|---|---|
| I-1A | 2 | 10 | 120 | 240 | 30 | 30 |
| I-1B | | | | | | 60 |
| I-1C | | | | | | 90 |
| I-1D | | | | | | 120 |
| I-2A | | | | | 50 | 30 |
| I-2B | | | | | | 60 |
| I-2C | | | | | | 90 |
| I-2D | | | | | | 120 |

## 2.3 Test Procedures

It is vital to keep each test condition, especially sand property (the relative density of sand) at the same state in order to make the test results obey the principle of repetition. Hence, it is necessary to loosen the sand before installing the skirted caisson. The loosened region is about 300 mm (diameter) ×300 mm (depth) in a cylindrical shape. These dimensions are proved to be reasonable based on observations and results calculated by the finite element method. The skirted suction caisson has been then jacked into the sand and stayed there for 24 hours for every experiment. In consideration of efficiency of tests, the skirted caissons were installed by the jacked force instead of suction.

The horizontal monotonic loading was exerted by increasing standard weights gradually, with a load increment of 3 N, and the load position was set to be 250 mm above the lid of the suction caisson, as shown in Fig. 3. Two LVDTs were placed in the horizontal to touch the vertical rod to measure the horizontal displacements of the two separate points on the rod (Fig. 3). One LVDT was lined with the horizontal loading wire connected to the standard weights to set up the loading-deflection curves. The lower and the upper LVDTs are placed 10 cm and 25 cm respectively from the top of the lid. Readings of the two LVDTs can find the rotation centers of the skirted suction caisson.

In order to record the deflection corresponding to every incremental loading, the difference between two sequential deflections should be smaller than 0.01 mm that means the deflection is at a stable state. Simply speaking, the incremental loading was applied every 10 minutes.

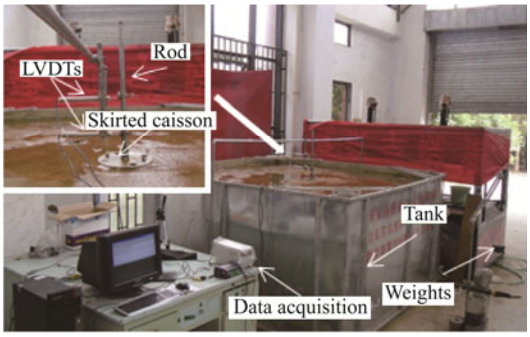


**Fig. 3.** Setup of testing model.

## 3. Test Results and Discussions

### 3.1 Loading-Deflection Curves

The process of loading can be divided into three phases: elastic (Zone I), plastic (Zone II), and failure phases (Zone III) based on the loading-deflection curves (Fig. 4). During the elastic phase, the maximum deflection of the load point on the rod is approximately 3 mm for all skirted suction caissons. It means that the effect of the skirt on limiting the deflection is not remarkable. It was also found that the heave or subsidence of sand around the caisson is so small that cannot be observed apparently. In the plastic phase, the loading-deflection curve bears a strong nonlinear relationship depending mainly on the dimensions of skirted structures, the same as the failure phases. The skirt can effectively control the deflection for the same load level. Heave and subsidence become more obvious than those during the elastic phase. And the magnitude and region of heave are much larger than those of the subsidence.

To study the effect of dimensions of the skirted structures, a series of experiments are carried out and the corresponding results are presented in Fig. 4. The ultimate lateral bearing capacities of skirted suction caissons for cases I-1A, I-1B, I-1C and I-1D (dimensions are referred to Table 2 and Fig. 2a ) are increased by approximately 8.02%, 16.7%, 22.8% and 30.5%, respectively, compared with a suction caisson without the skirted structure. Furthermore, the ultimate lateral bearing capacities of four cases

I-2A, I-2B, I-2C and I-2D are increased by 12.0%, 24.9%, 33.4% and 42.9%. For a specified depth of the skirted structure, the effect of width on bearing capacity is shown in Table 3. Results indicate that skirted suction caissons have higher lateral bearing capacity, and can significantly limit the lateral deflection under the same load level. However, more resistance will be encountered with a larger depth of the "skirted structure" during installation. Thus, the desired penetration depth may be blocked. Optimized dimensions of "skirted structure" should be taken into account by model tests and numerical modeling in future study.

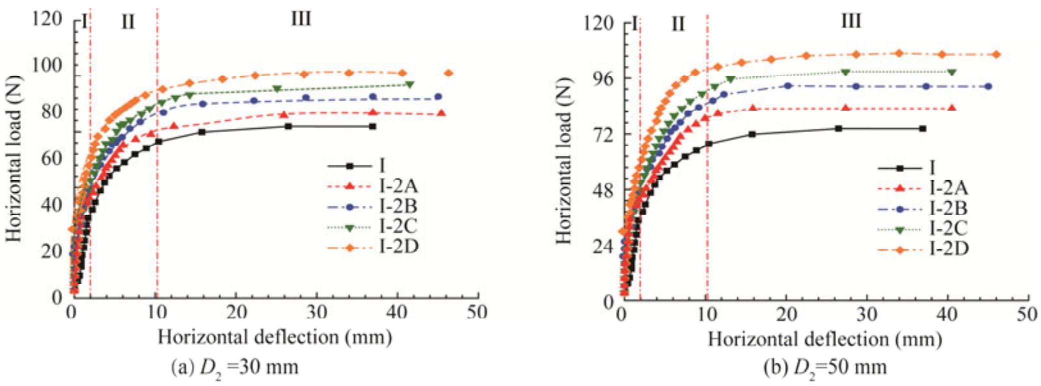


**Fig. 4.** Horizontal load-deflection curves of skirted suction caissons.

**Table 3** Horizontal ultimate bearing capacity

| No. of model caisson | Ultimate bearing capacity (N) | No. of model caisson | Ultimate bearing capacity (N) | Increment ratio (%) |
|---|---|---|---|---|
| I | 74.26 | | | |
| I-1A | 79.71 | I-2A | 82.90 | 3.55 |
| I-1B | 86.79 | I-2B | 92.39 | 7.07 |
| I-1C | 91.06 | I-2C | 98.83 | 8.64 |
| I-1D | 96.89 | I-2D | 106.21 | 9.48 |

### 3.2 Rotation Centers of Skirted Suction Caissons

It was found that the skirted suction caissons cannot slide during loading; consequently, they only rotate about a specified point. The positions of the rotation centers of skirted suction caissons can be obtained by two LVDTs (as shown in Figs. 3 and 5) depicted as below.

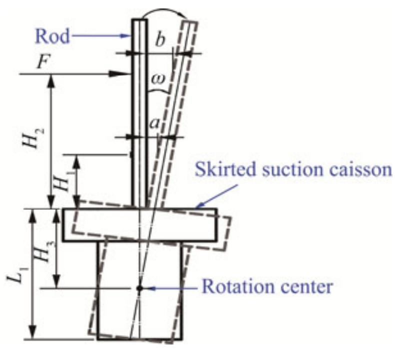


**Fig. 5.** Determination of rotation center.

The rotation center of the skirted suction caisson can be determined by

$$H_3 = \frac{aH_2 - bH_1}{b-a},$$

where $a$ and $b$ are the measured deflections by the lower and upper LVDTs, respectively; $H_1$, $H_2$ and $H_3$ are positions of two LVDTs and rotation center with respect to the mud line (Fig. 5).

Fig. 6 shows that rotation centers are not constants, varying with many factors such as soil properties, loading condition, and dimensions of suction caissons. Here the latter two influencing factors are mainly investigated. It is confirmed that rotation centers move upwards with the increase of the depth of the skirted structure. During the early phase of all tests, the rotation center moves downwards with the increase of the dead weight. Normally, when the deflection corresponding to the position of loading reaches about 10.0 mm (that means all of sand along the caisson wall yields), rotation centers tend to a stable position. It was also concluded that for the limit equilibrium state, the rotation center keeps constant so that it is helpful to set up the theoretical formula of lateral bearing capacity. In addition, it is suggested that the larger width of the skirted structure makes the rotation center move up with 2 cm in a relatively uniform manner (Fig. 7).

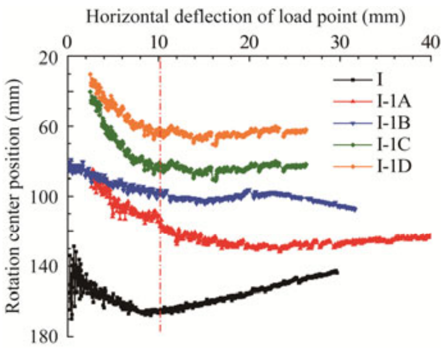

**Fig. 6.** Calculated results of the rotation center.

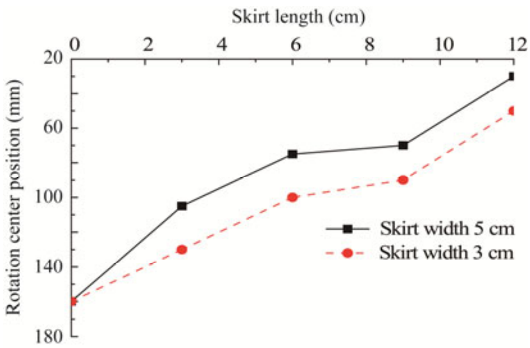

**Fig. 7.** Rotation center differential for the skirt width.

## 4. Numerical Modeling

The numerical modeling procedures to simulate the skirted suction caissons-soil interaction were developed by using the finite element software package Z_SOIL. A three-dimensional continuum model was developed for the model test. Dimensions of the modeled sand domain were selected to minimize the boundary effects on the predicted soil load, displacement, and failure mechanisms. The caisson-sand interface was simulated by using the contact surface element implemented in Z_SOIL, which allows for the separation with the finite amplitude and arbitrary rotation of the contact surfaces. The Coulomb friction model (the frictional angle is 17º; Iskander *et al*., 2002) was used for the frictional interface between caisson's walls and sand.

The skirted suction caisson is made of a linear elastic material with a Young's modulus ($E$), 210 GPa, and a Poisson's ratio ($v$), 0.31. The density of the skirted suction caisson is 78 kN/m$^3$.

A novel constitutive relation, hardening with small strain (*HSS*) (Clayton, 2011), for the saturated sand is used, and the corresponding parameters are given in Table 4. For these parameters, some are directly obtained from laboratory experiments, and some are back calculated by trial and error with the finite element method.

**Table 4** Mechanical parameters of sand for calculation

| Item | Symbol | Unit | Value |
|---|---|---|---|
| Unloading-reloading stiffness | $E_{ur}$ | kN/m$^2$ | 9000 |
| Unloading -reloading Poisson's ratio | $\nu_{ur}$ | – | 0.2 |
| Maximal soil stiffness | $E_0^{ref}$ | kN/m$^2$ | 18000 |
| Value of small strain | $\gamma_{0.7}$ | – | 0.0002 |
| Dry unit weight | $\gamma_D$ | kN/m$^3$ | 19.2 |
| Initial void ratio | $e_0$ | – | 0.7 |
| Friction angle | $\phi$ | ° | 34 |
| Dilatation angle | $\psi$ | ° | 10 |
| Cohesion | $c$ | kPa | 0 |
| Secant modulus | $E_{50}^{ref}$ | kN/m$^2$ | 3000 |
| tangent oedometric modulus | $E_{oed}$ | kN/m$^2$ | 3000 |
| Earth pressure coefficient | $K_0$ | – | 0.43 |

### 4.1 Validation on Test Results

Fig. 8 presents the comparison between the numerical and experimental load-deflection curves during lateral caisson-sand interaction. Table 5 shows the error analysis of the ultimate bearing capacity of skirted suction caissons from experiments and the finite element model.

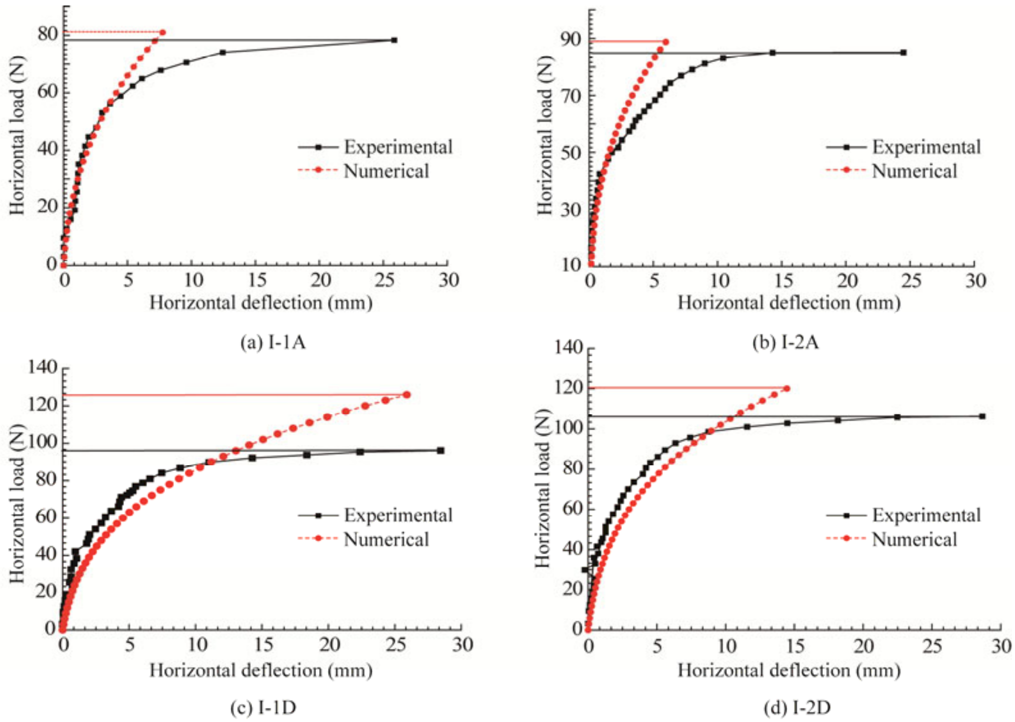


**Fig. 8.** Comparison between the numerical and experimental load-deflection curves.

**Table 5** Error analysis of the ultimate bearing capacity between experiments and simulations

| No. of model caisson | Tested results (N) | Calculated results (N) | Relative error (%) | No. of model caisson | Tested results (N) | Calculated results (N) | Relative error (%) |
|---|---|---|---|---|---|---|---|
| I-1A | 74.03 | 81.05 | 9.48 | I-2A | 83.33 | 86.81 | 4.17 |
| I-1B | 86.86 | 95.33 | 9.75 | I-2B | 91.29 | 100.93 | 10.55 |
| I-1C | 92.51 | 109.02 | 17.48 | I-2C | 100.93 | 110.02 | 9.00 |
| I-1D | 98.81 | 124.80 | 26.30 | I-2D | 108.79 | 118.38 | 8.81 |

### 4.2 Deformation of Sand Around the Caisson

Deformation of sand around all the caissons obtained from test and numerical modeling exhibits a consistent profile. Moreover, the region and magnitude of sand heave are much larger than those of sand subsidence (Fig. 9). The influencing region has dimensions of two times caisson diameter in the loading direction and about one time caisson lengths in depth. Especially, the calculated areas of the deformed sand surface agreed well with the observations of tests. The simulation and test results can help construct the theoretical formula of the ultimate bearing capacity based on the wedge limit equilibrium method (Ashour *et al*., 1998).

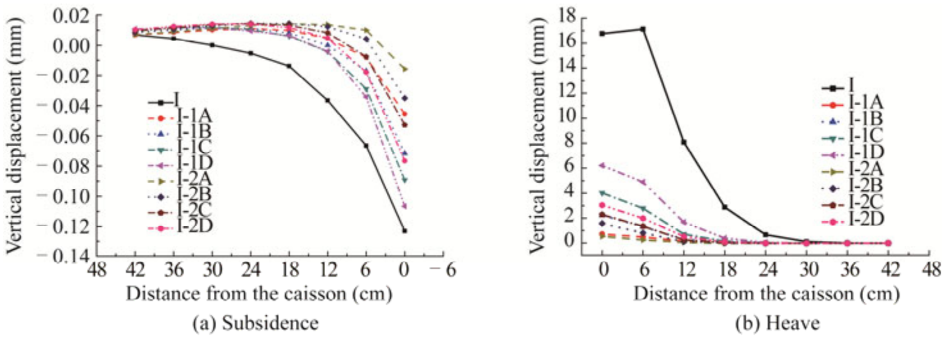


**Fig. 9.** Sand subsidence and heave around caissons.

### 4.3 Earth Pressures on Caissons' Wall

All of numerical models show that there exist stress concentrated areas resulted from the earth pressures on the skirted suction caissons' wall during monotonic lateral loading (for example, the case of I-1B in Fig. 10). A variety of modeling results prove that the skirted suction caissons indeed rotate about some points whose positions vary with dimensions of the "skirted structure" and the magnitude of deflection. When soil tends to yield, the concentrated stress zones may be regarded as the passive earth pressure. Upper and lower passive earth pressure zones are divided by the rotation center. These scopes of earth pressures also vary with the process of loading. Therefore, the working condition and limit state have a major effect on the design.

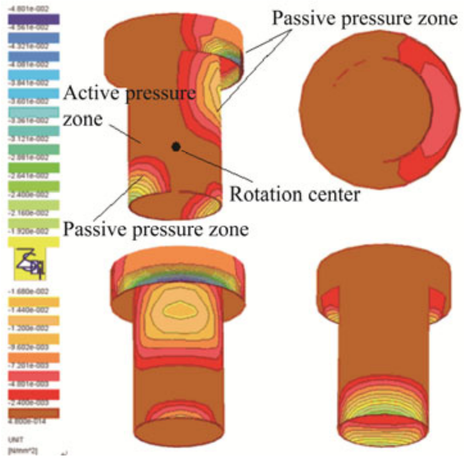


**Fig. 10.** Earth pressures on caisson.

## 5. Conclusions

Based on the experimental and numerical studies carried out on model skirted suction caissons, the following conclusions can be drawn:

(1) A series of load-deflection curves were obtained by monotonic lateral loading in model tests to determine the lateral capacity under the working and ultimate conditions. Hence, it can be also concluded that the skirted suction caisson can be capable of increasing the lateral capacity and reducing deflection.

(2) Rotation centers play a crucial role in the determination of the lateral capacity by using the analytical method. It was also found that the rotation center is related to dimensions of the skirted suction caissons and loading process, i.e. the rotation center moves upwards with the increase of the "skirt" width and length; moreover, the rotation center moves downwards with the increase of loading and keeps constant when all the sand along the caisson's wall yields. It is so complex that we cannot simply determine its position like the regular suction caisson commonly with a specified ratio to the length of the caisson.

(3) Mechanical parameters used in the finite element software were verified by model tests. The lateral bearing capacity of the skirted suction caisson can be extended to the prototype by using the finite element method.

The present research helps to obtain the analytical solution to the lateral capacity matching better with the model test results and satisfying the needs in the practical design. However, advanced model experiments may be needed to consider other parameters such as the earth pressures on the skirted suction caisson's wall and ground deformation.

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