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EXPERIMENTAL AND NUMERICAL STUDY ON HOLDING POWER OF RECTANGULAR-SHAPED ANCHORS

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ABSTRACT

This paper discusses the experimental and numerical investigations for the holding power of rectangular-shaped anchors. As the offshore developments are promoted, the mooring systems are often used as the station keeping systems of the marine floating structures. From a viewpoint of the energy consumption, the mechanical mooring systems with anchors are better than the dynamic mooring systems with thrusters. Up to now, however, the research and development regarding the mooring systems with the high holding anchors in the deep sea area, especially more than 500 m in depth, have hardly been carried out in Japan.

In most cases, the conventional anchor shapes have experimentally and/or empirically been decided. In addition, only a few studies which relate the numerical analysis to the experimental test have been performed for the holding power. In order to obtain the optimal shape of anchors theoretically, therefore, the purpose of this study is to develop the estimation method for the holding power and to clarify the penetration mechanism of anchors in soil.

In this paper, a series of experiments utilizing the small-sized anchor model is conducted. Here, the fluke shape of specimen is modeled by the rectangular flat plate for simplicity. From several experiments varying the geometric characteristics of the anchor model, the experimental results, e.g., the history of the holding power, the penetration depth, and the fluke surface angle at the maximum holding power, are obtained. Furthermore, the numerical simulation to evaluate the holding power is also carried out using the dynamic explicit non-linear finite element analysis (NLFEA) code, LS-DYNA, as well as the in-house distinct element method (DEM) code. From the comparison between the numerical results and the experimental results, the calculation accuracy is verified.

INTRODUCTION

Japan has the world's 6th largest area of the exclusive economic zone (EEZ). The existence of many resources in EEZ is becoming clear under the seafloor. It is wished to collect these resources using the own technique in the future. In the marine resources development, the use of marine floating structures such as FPSO, which adapts to the various sea depths and the various sea states and are superior in mobility, recently spreads. One of the basic problems of the marine floating structures is the mooring. The mechanical mooring systems using anchors have substantial merits in terms of the energy consumption compared with the dynamic mooring systems with thrusters [1]. Up to now, nevertheless, the research and development of the mooring systems in the deep sea area (more than 500 m in depth), especially the high holding anchor, have been hardly done in Japan. It is necessary to accumulate the knowledge about the anchor in order to promote marine resources development in Japan in future.

In most cases, the conventional anchor shapes have been experimentally or empirically decided. In some studies, the acquisition of the holding power data by the model experiments on shore [2-4], the experiments in the sea area [5-8], and the mechanical considerations about the holding power [9-12] have been conducted. Masuda and Minami [4] preformed the model experiment utilizing the sand tank on shore. From a series of horizontal pulling experiments, they proposed a new type high performance anchor. Sato et al. [5] examined the holding ability of three types of anchors in relation to the resistance against various towing angles through experiments at sea.

As listed above, some experimental studies were carried out. However, there are only a few studies conducting the numerical analysis, because it was difficult to simulate the soil-structure interaction problems with large deformations by the previous computational capability. Therefore, in order to acquire the optimal shape of anchors theoretically, this study aims for establishing the estimation method for the holding power and clarifying the mechanism that anchors penetrate into the soil.

EXPERIMENTAL TEST

In order to acquire the experimental data of holding power with regard to drag anchors, a series of experiments utilizing the small-sized anchor model is conducted [13]. Figure 1 shows the general shape and the name of each part about the drag anchor. Here, the fluke shape of specimen is modeled by the rectangular flat plate for simplicity. From several experiments varying the geometric characteristics of the anchor model, the experimental results, e.g., the history of the holding power, the penetration depth, and the fluke surface angle at the maximum holding power, are obtained.

Test Specimen and Experimental Setup

A wooden sand tank of 3,600 mm in length, 900 mm in width, and 540 mm in depth is produced, and the sea sand is filled to 500 mm in depth as shown in Fig. 2 so as to model the seafloor. An anchor model is connected to a crane with a wire through a pulley in order to pull the anchor model horizontally, and the holding power is measured by the load cell installed between the pulley and the crane. In this experiment, two different traction speeds, i.e., 19 and 123 mm/s, are considered.

Figure 3 shows the schematic diagram of anchor model. Both the fluke part and the shank part of the anchor model are made from the mild steel, and so they are jointed with bolts that they are removable in order to change not only the shape of fluke part but also the shank angle. The basic size of fluke part modeled by the rectangular flat plate is 160 × 240 mm (see Figs. 3 and 14) in order to apply it to mechanical consideration and numerical simulation. The penetration depth is measured by inserting a stainless steel ruler into sand after the maximum holding power is observed. The angle of the fluke face for the horizontal direction is calculated by measuring the shank angle after the upper sand above the anchor model is calmly removed.

The sea sand is used for the soil. The soil type is mainly sandy soil composed of the rough sand. As the physical properties of the soil, the bulk density of the sand is 1.48 × 10^{-9} ton/mm^3, the friction angle between the sand and the fluke is 35 deg., and the repose angle of the sand is 35 deg.

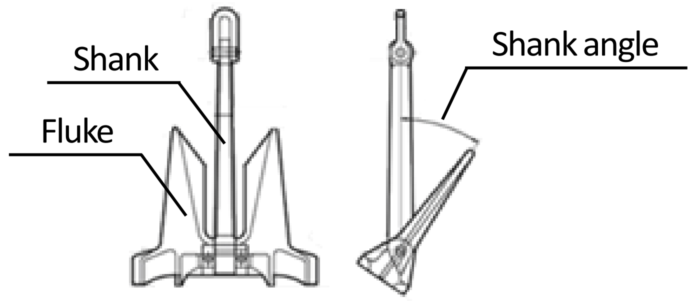


Figure 1. Schematic diagram of drag anchor.
(Source: Sotra Anchor & Chain AS HP, AC-14)

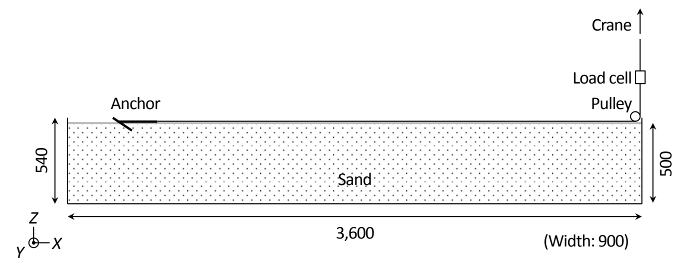


Figure 2. Experimental setup (unit: mm).

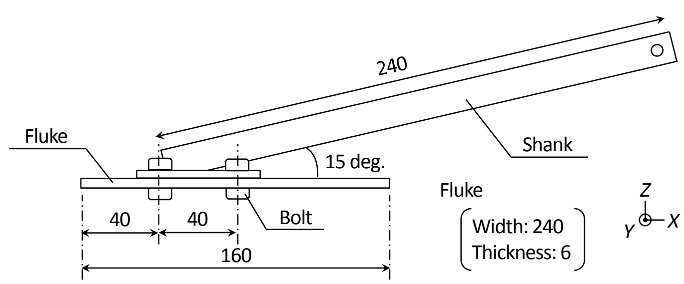


Figure 3. Basic anchor model (unit: mm).

Experimental Parameters

A series of experiments is carried out varying the following parameters.

(1) Shank angle
(2) Fluke area
(3) Fluke tip angle
(4) Shank length
(5) Shank position
(6) Fluke aspect ratio
(7) Fluke thickness
(8) Fluke weight
(9) Traction speed

Experimental Results

The experimental results for some parameters, which show the significant characteristic as regards the holding power, are as follows.

Shank angle

Since anchors become unstable and overturn when the shank angle is above 30 deg., this experiment is measured every 5 degrees from 0 deg. to 25 deg. Figure 4 shows the relationships between the holding power and the traction distance, and this is generally called the holding power curve. Figures 5-7 show the relationship between the maximum holding power and the shank angle, the relationship between the maximum penetration depth and the shank angle, and the relationship between the fluke face angle and the shank angle, respectively. For other parameters described above, same experiments are performed. In the following, the remarkable points are only featured. The holding power increases with increasing the traction distance regardless of the shank angle in Fig. 4. The phenomenon of increasing the penetration depth of the anchor, which is caused by the increase of traction distance and/or the larger shank angle (see Fig. 6), results in the increase of holding power. As indicated in Fig. 4, the holding power rapidly increase soon after the traction is started, and then the increasing rate of holding power gradually declines, and finally the holding power converges at a certain constant value (i.e., maximum holding power). From Figs. 5 and 6, it is found that the holding power as well as the penetration depth increases as the shank angle becomes larger, and it is considered that the penetration depth is the main factor for the holding power.

Fluke area

The fluke areas are changed with 38,400, 60,000, and 86,400 mm^2. In Fig. 8, the vertical axis is the holding power divided by each fluke area, and the horizontal axis is the traction distance. In this figure, the larger fluke area is, the higher holding power is, but other factors which increase the holding power are considered since the complete agreement between three cases varying fluke areas cannot be observed. One of these factors seems to be the penetration depth increasing with the increase of fluke area as shown in Fig. 9. In addition, the fluke face angle at the maximum holding power keeps almost 0 deg. regardless of the fluke area in Fig. 10. It has to be noted that the similar characteristic is also observed in the experiments varying other parameters.

Fluke tip angle

The fluke tip is cut at 30 deg. and defined it as +30 deg., 0 deg., and -30 deg. as indicated in Fig. 11. Although the almost same results are obtained between the fluke tip angles of 0 deg. and +30 deg., the holding power greatly decreases at the fluke tip angle of -30 deg. in Fig. 12. Since the cause of this phenomenon has not been yet elucidated, the more detailed consideration is still to be done.

Shank length

The shank lengths are changed with 160, 240, and 320 mm. The longer shank length gives the higher holding power as observed in Fig. 13.

Shank position

The experiments of two different types of shank position, i.e., the 50% position and the 75% position (see Fig. 14), are carried out. In the 50% and 75% positions, the shank root is attached to the center of fluke and the fluke more posterior side, respectively. The holding power is bigger when the shank is posterior side of the fluke (75% position) in Fig. 15.

Although similar experiments are conducted varying the following parameters as indicated below, the remarkable characteristic as for the holding power cannot be confirmed in the results obtained from the experiments.

Fluke aspect ratio

The fluke aspect ratios, i.e., (length):(width), are changed with 1:1, 2:3, and 1:2.

Fluke thickness

The fluke thicknesses are changed with 3.2, 6.0, and 9.0 mm.

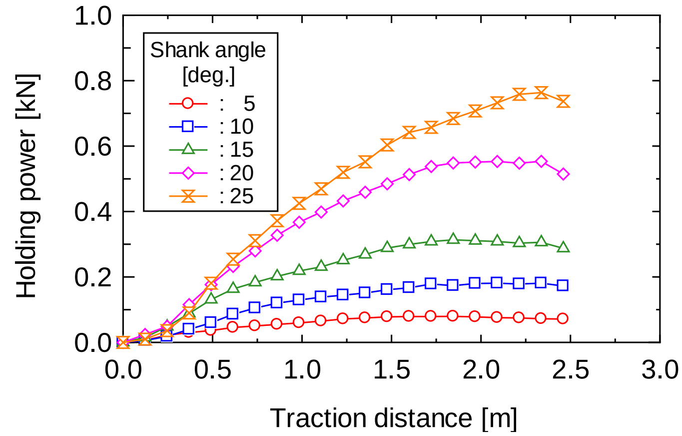


Figure 4. Relationships between holding power and traction distance (varying shank angles).

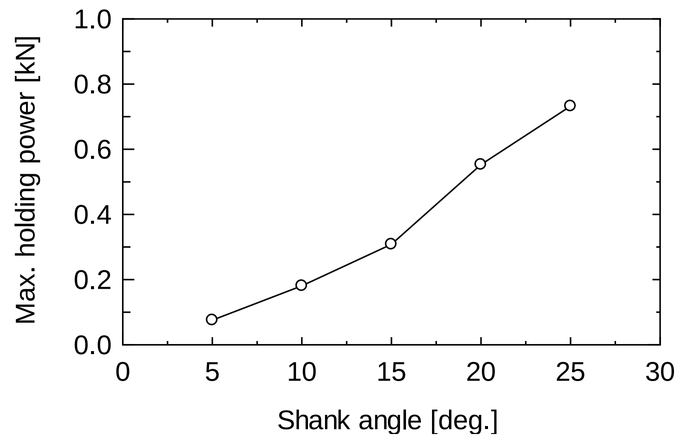


Figure 5. Relationship between maximum holding power and shank angle.

Fluke weight

The fluke weights are changed with 2.7×10^{-9} and 7.9×10^{-9} ton/mm^3.

Traction speed

The traction speeds are changed with 19 and 123 mm/s.

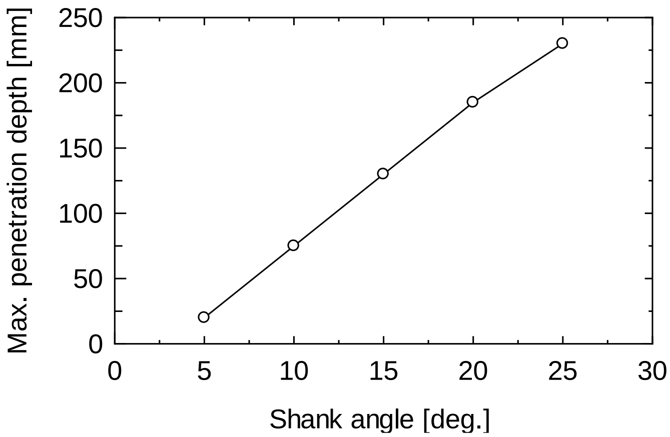


Figure 6. Relationship between maximum penetration depth and shank angle.

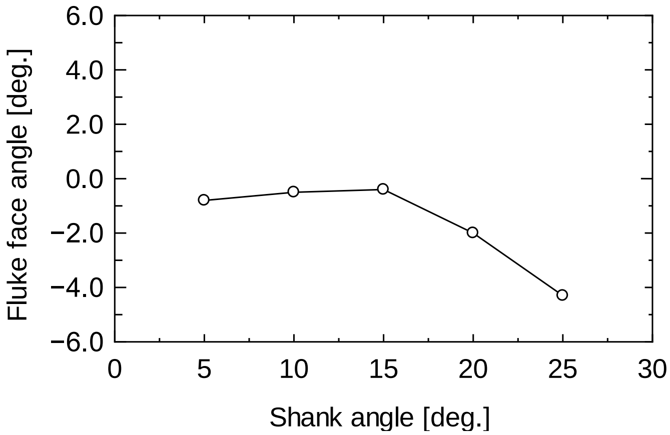


Figure 7. Relationship between fluke face angle and shank angle.

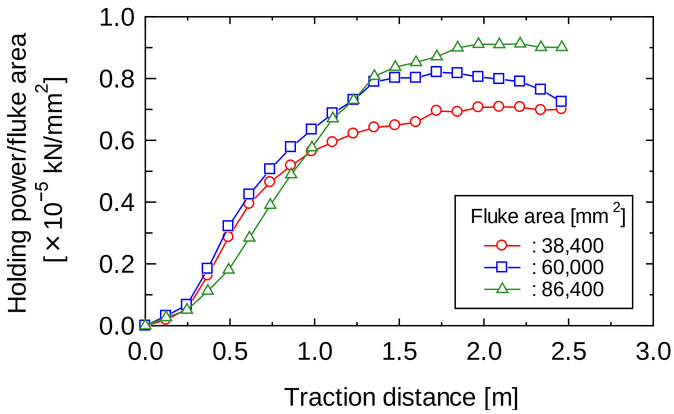


Figure 8. Relationships between holding power / fluke area and traction distance (varying fluke areas).

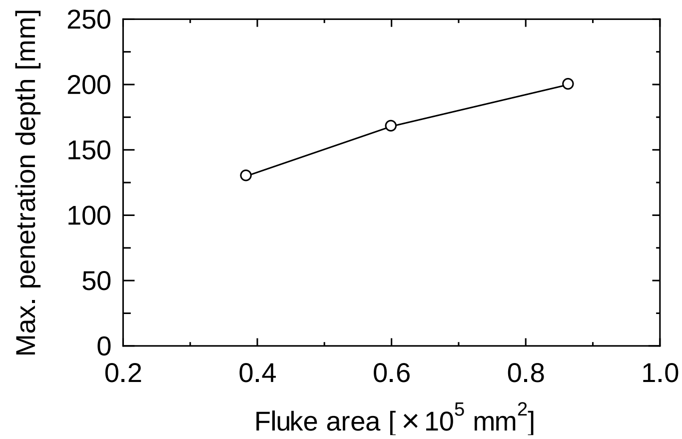


Figure 9. Relationship between maximum penetration depth and fluke area.

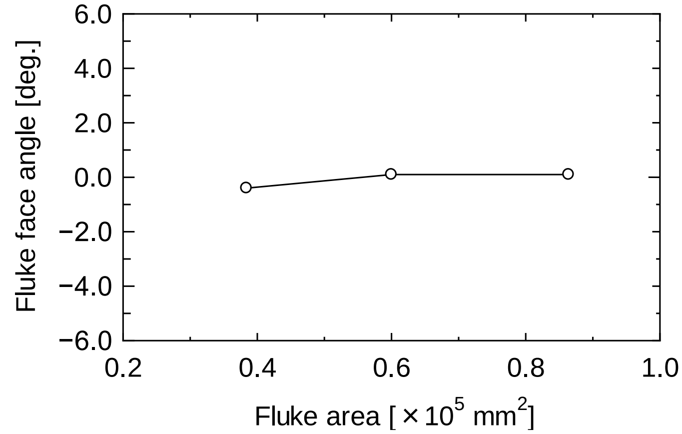


Figure 10. Relationship between fluke face angle and fluke area.

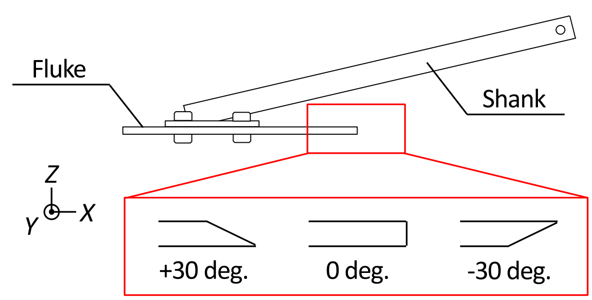


Figure 11. Definition of fluke tip angle.

Summary of Experiments

In this experiment, the larger holding power is obtained when the shank angle is larger, the shank length is longer, and the shank position is fluke posterior side. It is expected from the experimental results that the anchor behaves like Fig. 16 in the soil. It is considered that the penetration depth increases by a moment indicated in Fig. 16 and the holding power consequently increases.

The knowledge obtained from this experiment is as follows.

(1) As the traction distance becomes longer, the anchor penetrates into the soil deeply. As a result, the holding power increases.

(2) The holding power converges to a certain constant value (i.e., maximum holding power) for each experimental condition.

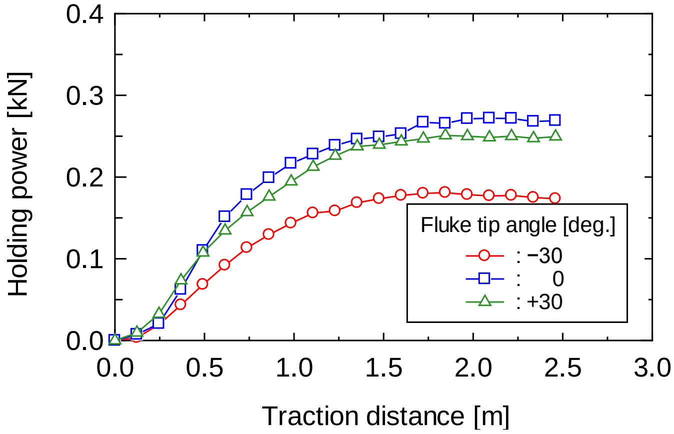


Figure 12. Relationships between holding power and traction distance (varying fluke tip angles).

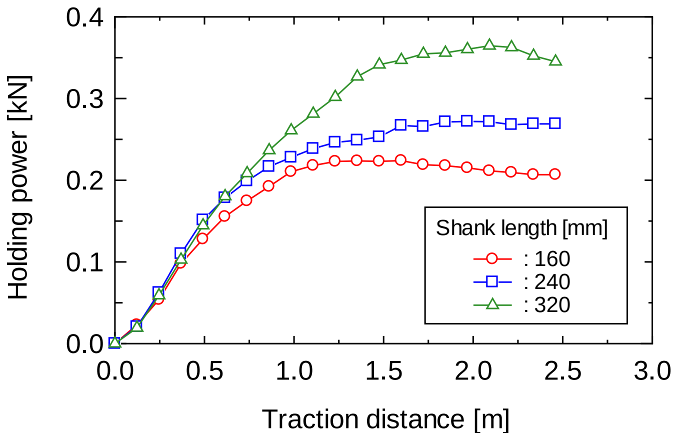


Figure 13. Relationships between holding power and traction distance (varying shank lengths).

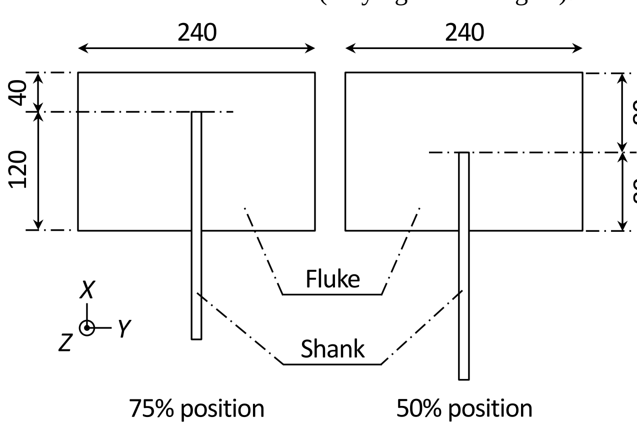


Figure 14. Definition of shank position.

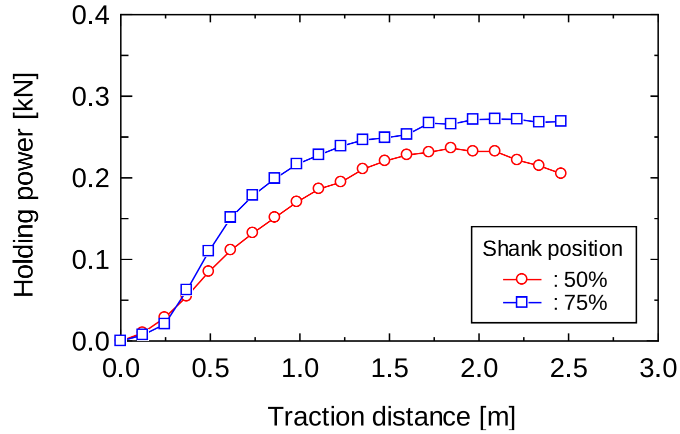


Figure 15. Relationships between holding power and traction distance (varying shank positions).

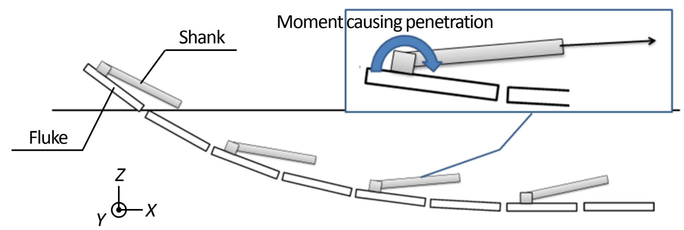


Figure 16. Forecast of penetration behavior of anchor.

(3) The final fluke face angle at the maximum holding power converges to a constant value (almost 0 deg.).

(4) Since the penetration depth increases by the effect of the moment applying at the joint point between shank and fluke, the holding power increases when the shank angle and the shank length are larger, and the shank position is posterior side of fluke.

NUMERICAL SIMULATION

The purposes of numerical simulation are both to establish the technique to estimate the holding power and to obtain clues of the formulation by visualizing the behavior of anchors with the numerical computation. The holding power is dynamically calculated by NLFEA applying the Arbitrary Lagrangian-Eulerian (ALE) method mounting in the non-linear dynamic explicit code, LS-DYNA, as well as DEM simulation utilizing the in-house code. These numerical simulations are preformed using the two-dimensional (2D) calculation model with consideration for the computing time.

Non-linear Finite Element Analysis (NLFEA)

ALE is one of the calculation methods to link the Lagrange elements to the Euler elements. The ALE method is robust and/or suitable for the large fluid problem, which is generally difficult to be solved even if the dynamic explicit simulation is performed. In this NLFEA by ALE method, the anchor and the soil are modeled utilizing the Lagrange elements and the Euler elements, respectively.

Model for NLFEA

The calculation model shown in Fig. 17 is used so as to calculate only the maximum holding power in the final posture after the penetration of anchor, viz., the simulation of penetration behavior is omitted. The soil and void parts are modeled by the solid elements, and the fluke of anchor, whose length and thickness are 100 and 10 mm, respectively, is modeled by rigid body utilizing shell elements. The properties of sea sand and calculation conditions are summarized in Table 1. The destruction behavior of the sand is based on the Mohr-Coulomb yield criterion indicated in Fig. 18. In Fig. 18, τ is the shear stress, σ is the normal stress, c is the apparent cohesion, and ϕ is the angle of internal friction. The mesh size of each solid element is 2.5 × 1 × 2.5 mm in *x*-, *y*-, and *z*-directions, respectively, and the quasi-2D model, i.e., one element in the *y*-direction, is used in this calculation in order to save the computing time. The fluke is so wider than the shank in actual anchors that the fluke has a predominant influence on the holding power of anchors. In this calculation, therefore, the only interaction between the soil and the fluke is taken into account, namely the shank and chain parts do not link to the soil. The value of holding power per the fluke width (1 mm) obtained from the numerical calculation is converted into the value for actual fluke width (240 mm) of the anchor using in the model experiment, and the NLFEA results are compared with the experimental values.

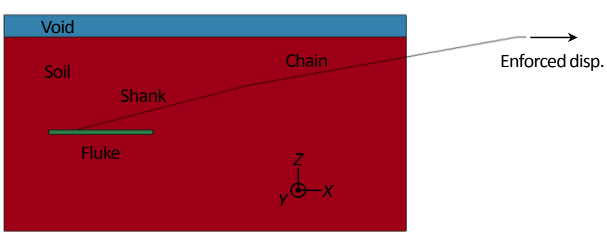


Figure 17. Model for NLFEA.

Table 1. Properties of sand
and calculation conditions of NLFEA.

Item	Value	Unit
Density	1.48×10^{-9}	ton/mm^3
Angle of internal friction, ϕ	35	deg.
Angle of friction to fluke	35	deg.
Apparent cohesion, c	0.002	N/mm^2
Loading rate (enforced disp.)	50	mm/s

Distinct Element Method (DEM)

DEM is used in the civil engineering for the granular dynamics. In this DEM simulation, sand particles are modeled by 2D circles, and the fluke of anchor is only modeled by a rectangular-shaped plate.

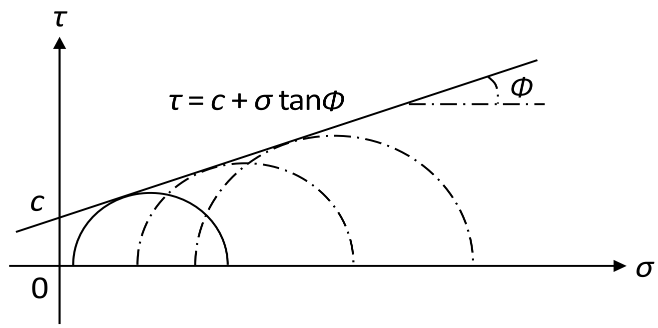


Figure 18. Mohr-Coulomb yield criterion.

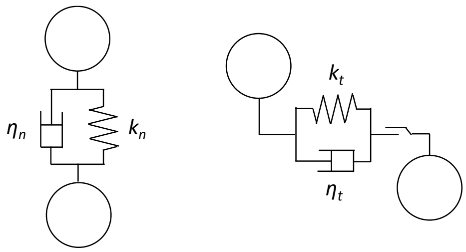
Model for DEM

In this DEM, not only the holding power but also the penetration behavior is simulated, and particles are assumed to be circular rigid elements, and contact forces due to the relative motion between elements are expressed by setting an elastic spring and a dashpot in normal and tangential directions, respectively, between contacting elements as shown in Fig. 19, which is generally called the Voigt model. Figure 20 indicates the model for DEM. In this calculation, the fluke of anchor is only modeled, and the element size of particles and the loading rate (traction speed) shall be decided by considering the balance of accuracy and computing time. After several trial calculations, the radius of particle size is from 1.2 to 1.8 mm, i.e., the average size is 1.5 mm, and the traction speed is 500 mm/s in this simulation. Here, it is noted that this conditions (the particle size and the traction speed) do not affect the holding power.

Since the particles of actual sand are not circles but angular, in DEM simulation using circular elements, the repose angle, which is one of the most important properties of sand, often results in the lower value compared with the real value even if the suitable interparticle friction coefficient is used. In this calculation, therefore, the critical rotational moment, M_c, given by Eq. 1 is considered, and the particles do not rotate if the moment acting on each particle is less than M_c. The value of coefficient of critical rotational moment, C_c, is set so that the value of repose angle agrees with the measured value (35 deg.). The properties of sea sand are decided according to the properties of quartz, which is the main component of sea sand in this model experiment. The properties of sea sand and calculation conditions are summarized in Table 2. The model dimension for this DEM simulation indicated in Fig. 20 is 1,600 × 400 mm in *x*- and *z*-directions, respectively. The value of holding power obtained from the DEM simulation utilizing the 2D model is converted into the value for actual fluke width (240 mm) of the anchor using in the model experiment, and the DEM results are compared with the experimental values.

$$M_c = C_c \times W \times g \times r \qquad (1)$$

Where, W is the weight of particles, g is the gravitational acceleration, and r is the radius of particles.



(a) Normal direction (b) Tangential direction

Figure 19. Voigt model representing interaction force between particles.

Table 2. Properties of sand and calculation conditions of DEM.

Item	Value	Unit
Density	1.80×10^{-9}	ton/mm^3
Young's modulus	70	MPa
Poisson's ratio	0.17	—
Interparticle friction coefficient	0.7	—
Coefficient of critical rotational moment, C_c	2.0	—

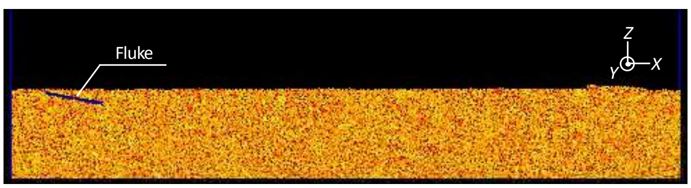


Figure 20. Model for DEM.

Comparison between Simulation Results and Theoretical Speculation

Before the simulation for holding power of anchor, some calculations for the simple problem are carried out applying NLFEA and DEM in order to confirm the validity of calculation conditions.

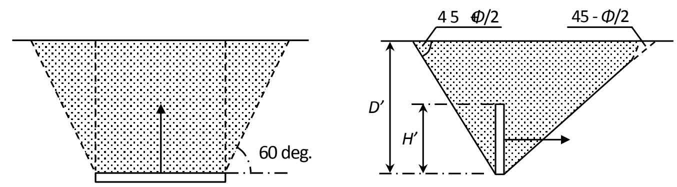
As for the horizontal anchor, Downs and Chieurzzi (1966), based on theoretical works, investigated an apex angle was always equal to 60 deg. in shallow conditions, irrespective of the friction angle of the soil as shown in Fig. 21a (left) [14]. As for the vertical anchor, on the other hand, Terzaghi (1943) indicated the failure surface in shallow conditions (D'/H' equals 1-2) as shown in Fig. 21a (right) [15].

The failure surfaces obtained from NLFEA and DEM, and the comparison between simulation results and theoretical values are shown in Figs. 21b, 21c, 21d, and 21e, respectively. As shown in Figs. 21a, 21b, and 21c, almost same failure modes are observed both in the theory and NLFEA/DEM. In addition, the relatively good agreement is observed between simulation results and theoretical values in regard to the resistance (see Figs. 21d and 21e).

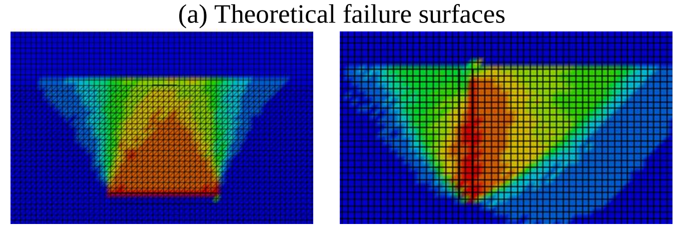
Conversion Method of Numerical Results from Two-dimensional (2D) Value to Three-dimensional (3D) Value

In the numerical simulations utilizing NLFEA and DEM, the 2D analyses are performed so as to save the computing time. In contrast, the holding power obtained from the experimental tests is the 3D value. In order to compare the numerical results and the experimental results, thus, the 2D results have to be converted into the 3D values.

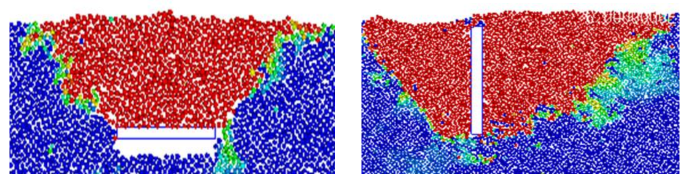
In this investigation, the value of holding power per the fluke width obtained from the numerical calculations is converted into the value for actual fluke width (240 mm) of the anchor using in the model experiment. In addition, the effect of shear force acting on the sliding plane of sand has to be also taken into account. The dashed lines in Fig. 22 show the sliding plane by the yielding of sand from the view in the traction direction (x-direction).



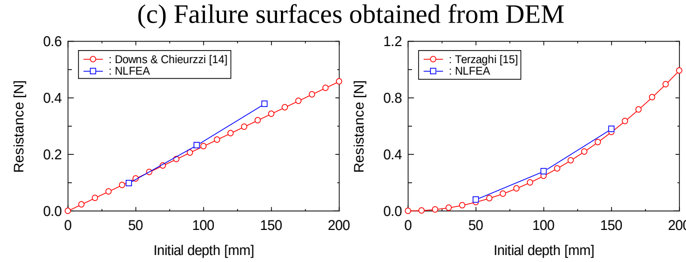
(a) Theoretical failure surfaces



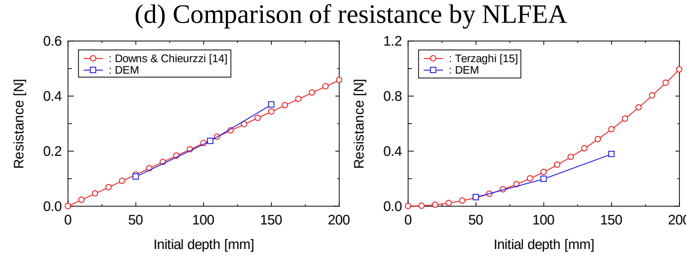
(b) Failure surfaces obtained from NLFEA



(c) Failure surfaces obtained from DEM



(d) Comparison of resistance by NLFEA



(e) Comparison of resistance by DEM

Figure 21. Comparison between simulation results and theoretical values (left: horizontal anchor, right: vertical anchor).

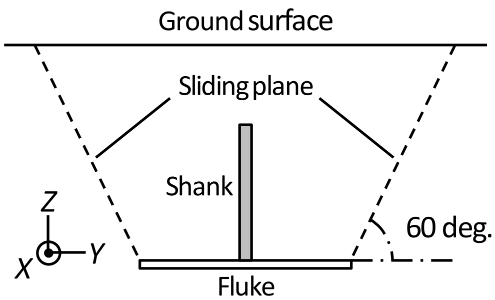


Figure 22. Sliding plane of sand.

In this paper, the 2D results are converted into the 3D values utilizing Eq. 2;

$$\mathrm{H.P.}_{3\mathrm{D}} = \mathrm{H.P.}_{2\mathrm{D}} \times (B + D/\tan\alpha)/B + 2\mu P_{sp} HD/\sin\alpha \quad (2)$$

Where, H.P. is the holding power, B is the fluke breadth, D is the penetration depth, H is the fluke length, μ is the interparticle friction coefficient of sand, α is the angle of sliding plane (here, α is assumed to be 60 deg. for simplicity based on the investigation by Downs and Chieurzzi), and P_{sp} is the pressure acting on the sliding plane given by Eq. 3;

$$P_{sp} = K_{sp} \rho g z \quad (3)$$

Where, ρ is the volume density of sand, g is the gravitational acceleration, z is the depth acting on pressure, and K_{sp} is the coefficient of pressure acting on the sliding plane given by Eq. 4;

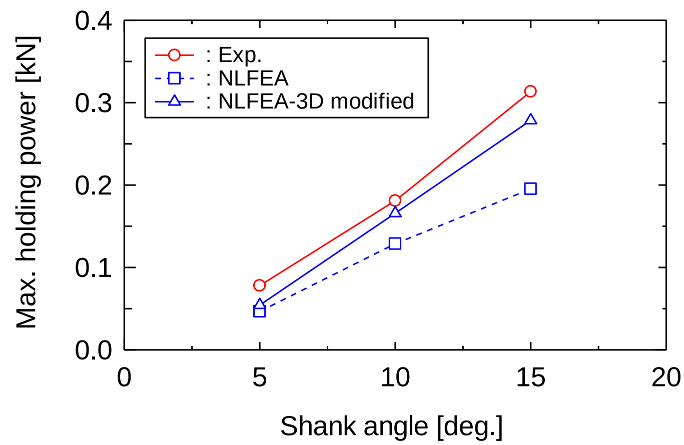
$$K_{sp} = \cos^2\alpha + (1 - \sin\varphi)\sin^2\alpha \quad (4)$$

Where, φ is the repose angle of sand.

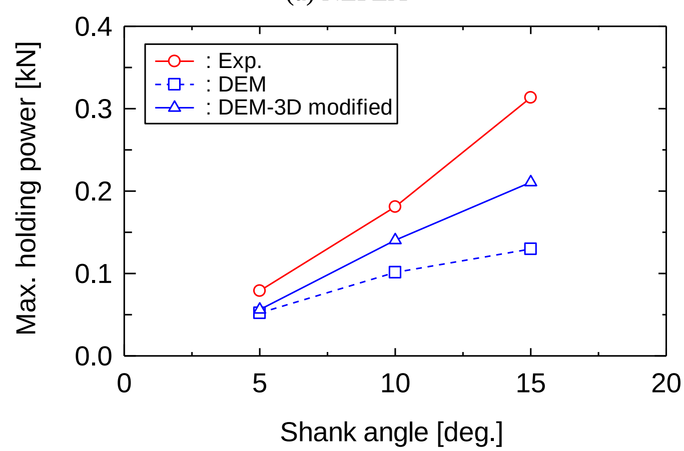
RESULTS AND DISCUSSION

The relationships between the maximum holding power and the shank angle obtained from the model experiment and numerical simulations by NLFEA/DEM are shown in Fig. 23. In Fig. 23, the blue dashed lines and the red solid lines show the calculation results and the experimental results, respectively, and the blue solid lines indicate the conversion values of the numerical results from 2D to 3D utilizing Eq. 2.

In Fig. 23a, the relatively good agreement between the 3D modified NLFEA result and the experimental result is observed. Although the holding power obtained from the numerical calculation is a bit small compared with the experimental result because the friction effect between the soil and the shank and/or the anchor chain is not considered in this calculation, the calculation result by NLFEA corresponds quantitatively and qualitatively well with the experimental result.



(a) NLFEA



(b) DEM

Figure 23. Comparison between maximum holding power obtained from numerical simulations and experimental test.

In Fig. 23b, the similar tendency is observed in both the DEM result and the model experiment, namely the holding power increases when the shank angle is larger. However, the holding power obtained by the DEM simulation is largely different from those by the model experiment. One of the possible causes might be the setting method of the repose angle as well as the critical rotational moment.

The differences of NLFEA and DEM results against the experimental result with regard to the holding power are within abt. 20% and abt. 30%, respectively. Since the cause of this difference is still not clarified, the more detailed numerical simulations and the improvement of the conversion method from 2D to 3D are still to be done.

CONCLUSIONS

In the present paper, a series of experiments utilizing the small-sized anchor model is conducted. Moreover, the numerical simulation to evaluate the holding power is also carried out using the dynamic explicit NLFEA code, LS-

DYNA, as well as the in-house DEM code, and these numerical results are compared with the experimental results. In this study, the following conclusions can be drawn.

(1) From the experimental results, it is found that the holding power of anchor increases when the shank angle and the shank length are larger, and the shank position is posterior side of fluke.

(2) Based on the experimental results, the holding power of anchor seems to have a cause-and-effect relationship with the penetration depth.

(3) The holding power might be calculated with relatively accuracy by NLFEA applying the ALE method mounting in LS-DYNA. The qualitative agreement is observed between the experimental tests and the calculation results utilizing the DEM method, while the holding power is different.

It is necessary to investigate more the following items.

(1) More detailed investigations by DEM for improving the calculation accuracy.

(2) The consideration for effects of the repose angle and the critical rotational moment on the holding power in the DEM simulation.

(3) The improvement of conversion method from 2D to 3D applying the numerical simulation.

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