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MODEL TESTS OF DRAGGING HALL ANCHORS IN SAND

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Key words: analytical method, Hall anchor, holding capacity, limit equilibrium, model test.

ABSTRACT

Hall anchors are often used as the main anchors in great medium ships. However, the methods for determining the holding capacity of Hall anchors when being pulled in soil are rarely proposed. In this study, a series of model tests was carried out using four scaled Hall anchor models to determine the kinematic behavior, trajectory, and development rules of the holding capacity of the anchors relative to dragging distances. Moreover, the holding force coefficients of the Hall anchors in sand were identified after the tests.

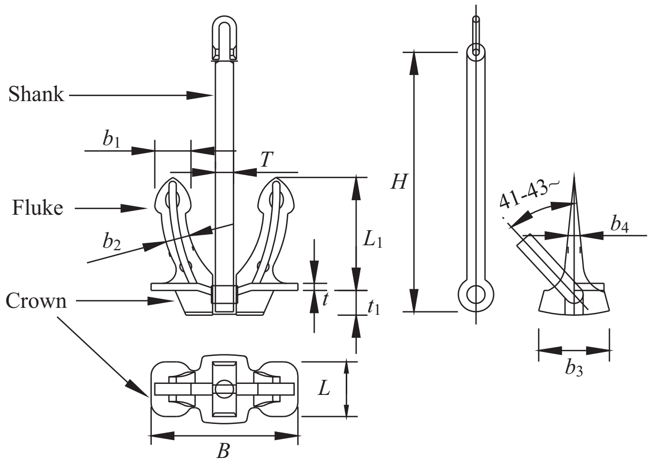

Fig. 1. Geometry and components of a Hall anchor.

I. INTRODUCTION

Hall anchors are widely used as the main anchors in great medium ships because of their considerable holding power, stability, and easy recoverability. A Hall anchor consists of an anchor crown, two flukes, a shank, shackles, and some pins. The structure and components of a Hall anchor are shown in Fig. 1. The crown and flukes are integrally and perpendicularly cast to each other. The shank is inserted to the crown, and the end of the shank is riveted by pins. This endpoint is also the center point of the crown. The shank and fluke can rotate around the center point of the crown. The maximum angle between the shank and fluke is 41° to 43°.

In Fig. 1, b_1 is the forepart width of the fluke, b_2 is the bending width of the fluke, b_3 is the terminal thickness of the fluke, b_4 is the middle thickness of the fluke, T is the diameter of the shank, t is the thickness of the front plate of the crown, t_1 is the total thickness of the crown minus t, L_1 is the length of the fluke, L is the length of the crown, B is the width of the crown, H is the length of the shank.

For the study about the anchor, the holding capacity is a primary issue. Empirical method and theoretical method have been taken for the research of anchors.

The Naval Civil Engineering Laboratory provided a classical and empirical method to predict load capacity on the basis of multiple flume experiments and ship trials; however, these methods were only applied to 20 specific tested anchors that did not include a Hall anchor (e.g., Rocker, 1985; US Navy Direction of Commander, 2000).

Shin et al. (2011) measured the holding power relative to the dragged distance of three scaled Hall anchor models, but the record of embedment motion and anchor rotation was limited, and only the final depths of the fluke tip were obtained after each test. Moreover, the authors presented the particle size distribution of the sand used in their tests, although other factors that significantly affect the development of holding force need to be introduced; these factors include the physical and mechanical parameters of sand, embedment motion, and rotation of anchors during the pulling process.

Several theoretical solutions of holding power have been proposed. (Stewart, 1992; Neubecker and Randolph, 1996; Dahlberg, 1998; Liu et al., 2012; Tian et al., 2013; Jiang et al., 2015).

The complicated structures of Hall anchors make their force analysis significantly difficult. An empirical range of the holding power coefficient (3.0-5.0) is usually adopted for Hall

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Table 1. Geomety of anchor models.

Weight (N)	Crown and fluke (mm)									Shank (mm)	
	B	L	b_1	b_2	b_3	b_4	L_1	t_1	t	H	T
57	210	85	49	31	93	20	145	34	10	350	25
239	323	135	81	49	150	27	234	54	16	580	40
385	405	185	100	67	195	35	320	70	20	735	50
705	500	200	120	75	210	45	350	80	25	920	60

Table 2. Physical and mechanical parameters of sand.

Dry unit weight (γ_d)	Water content ($\boldsymbol{w}$)	Relative compaction (D_r)	Internal friction angle (φ)
15.74 kN/m^3	3.08%	0.597	33.13°

Fig. 2. Model Hall anchors.

Table 3. Content of different particle sizes of sand.

Particle size (d/mm)	Content (%)
$d > 5$	0.7
$2 < d < 5$	0.9
$1 < d < 2$	2.0
$0.5 < d < 1$	23.0
$0.25 < d < 0.5$	59.1
$0.075 < d < 0.25$	13.3
$d < 0.075$	1.0

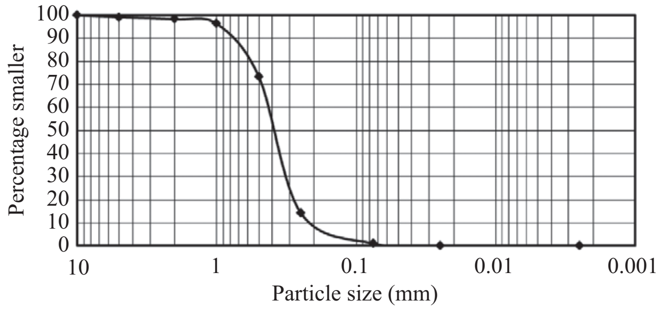


Fig. 3. Particle size distribution of sand.

anchors (Liu, 2009). However, this range is too large to be applied in practice. Until now, very few studies have investigated Hall anchors dragged in sand.

In the present study, different Hall anchor models are manufactured on the basis of a prototype anchor. A series of model tests is carried out in sand. Morphologic change, movement trajectory, and holding force during the pulling process are obtained, and the rules for the posture adjustment of anchors and the development law of holding power are determined.

II. MODEL TEST

To analyze the kinematic rules and mechanical characteristics of Hall anchors, four anchor models with weights of 57, 239, 385, and 705 N were manufactured. The motion rule, trajectory, and holding power of the anchors were measured in the model tests.

The four anchor models are shown in Fig. 2, and the weights and geometrical dimensions of the anchor models are presented in Table 1.

The physical and mechanical parameters of the sand used in the model tests were all measured with laboratory tests, and the values of these parameters are all shown in Table 2.

The particle size distribution curve of the sand used in the model test is plotted in Fig. 3 on the basis of a sieving analysis.The curve indicated that the mean particle size of the sand was 0.39 mm.

The content of the different particle sizes is presented in Table 3.

The model test was carried out in a tank (4,000 mm × 1,500 mm × 750 mm) filled with sand, as shown in Fig. 4. Dragging force was produced by a windlass through a wire rope and pulley block system. During the pulling process, the drag force acting on the anchors could be measured with a force transducer (Fig. 5(a)) and recorded with a data acquisition instrument (Fig. 5(b)) and a laptop. The location and rotation of the anchors in the pulling process were measured in the experiment.

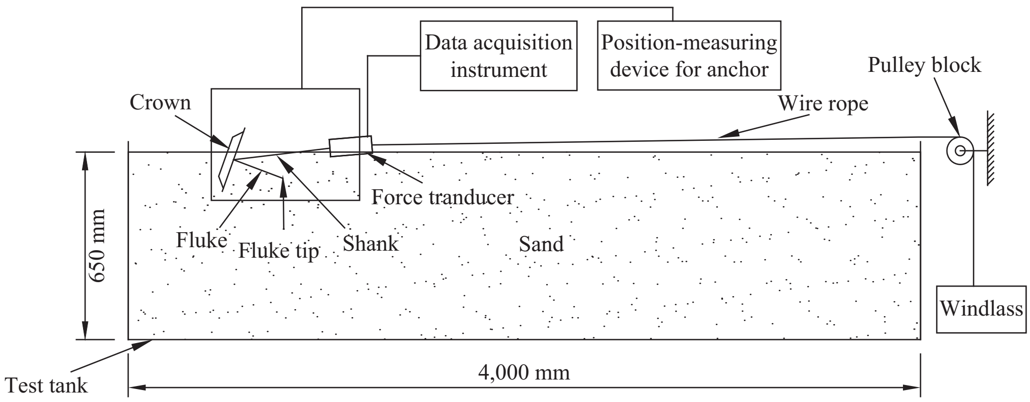


Fig. 4. Schematic diagram of the entire testing apparatus.

(a) Force transducer

(b) Data acquisition instrument

Fig. 5. Test equipment.

(a) Placed on soil surface (385N)

(b) Initial pulling stage (239N)

(c) Begin to insert into soil (57N)

(d) Buried into the soil (239N)

(e) Depth of the trench after dragging process (705N)

Fig. 6. photographs of pulling anchors in sand.

Before the dragging, the four anchors are slightly placed on the soil surface. The dragging force was horizontal and it was applied by using speed apparatus. The dragging speeds during these tests were maintained at 5.0 cm/min. The photographs of the model tests are shown in Fig. 6.

The movements of the four model anchors are all drawn in

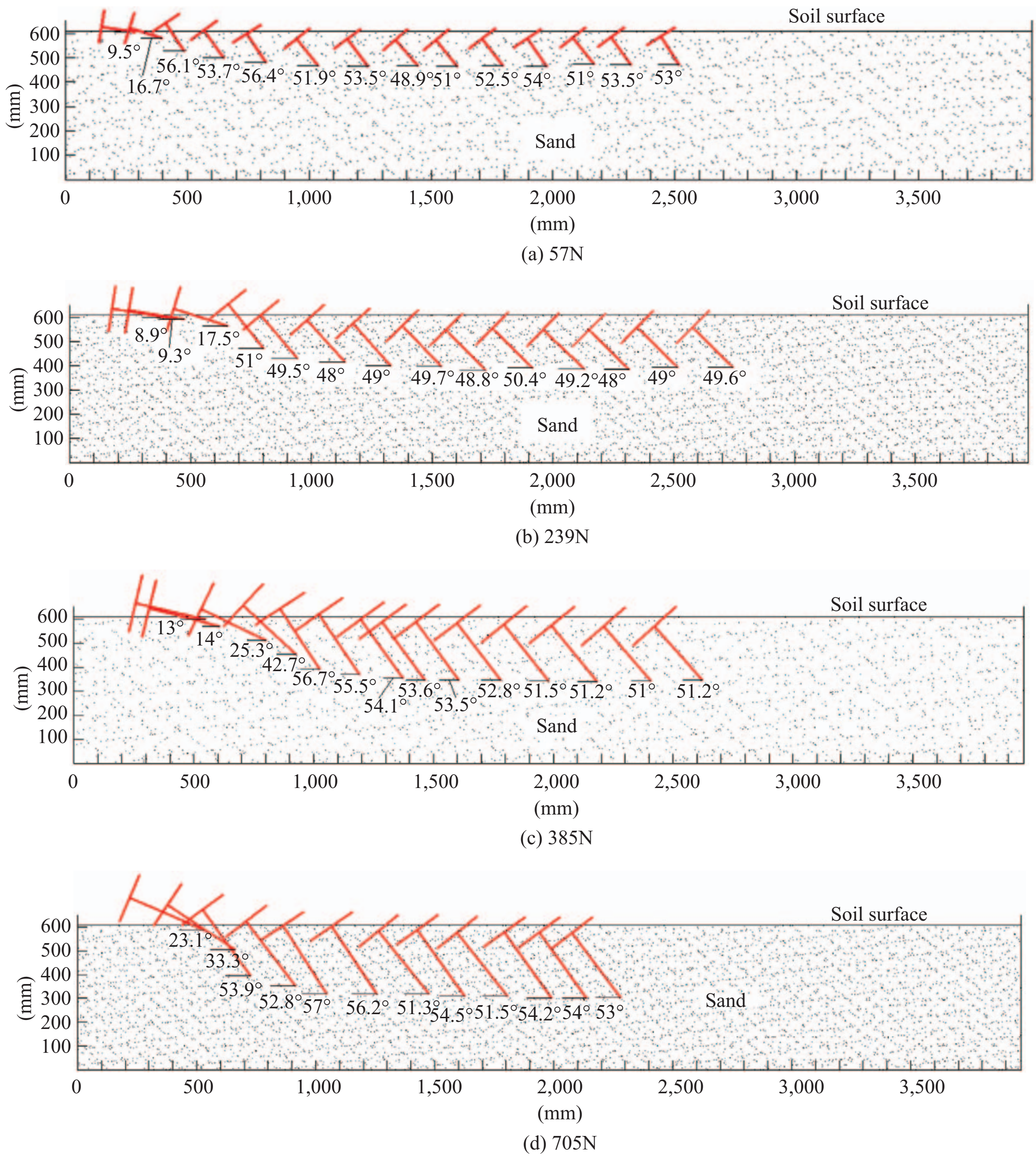


Fig. 7. The movement of the four models in dragging process.

Fig. 7 on the basis of the measured data in the entire dragging process. We can see all the four anchors quickly entered into the soil through continue horizontal dragging, and in the end of the dragging process, the flukes of the anchors were almost submerged in the soil, and the inclination angle of the flukes to horizontal are similar.

After arranging and analyzing the test data of the four model tests, the entire embedment motion of the Hall anchors could be divided into three stages, as indicated in Figs. 8 and 9.

First stage: At the first stage of the dragging process, the angle between the shank and fluke increased gradually, and the anchor began to embed into the soil.

Second stage: The fluke penetrated the soil via continuous dragging. The angle between the shank and the fluke continuously increased. The embedment depth and holding force of the anchor also increased quickly until they reached the maximum value.

Third stage: The embedment and plateau of the holding power were stabilized. The posture of the anchor changed slightly, and the fluke angle in the horizontal direction almost reached 50°.

The relationships between the inclined angle of the fluke in the horizontal direction β and the horizontal position of the fluke tips p_x, as well as the embedment depth of the fluke tips

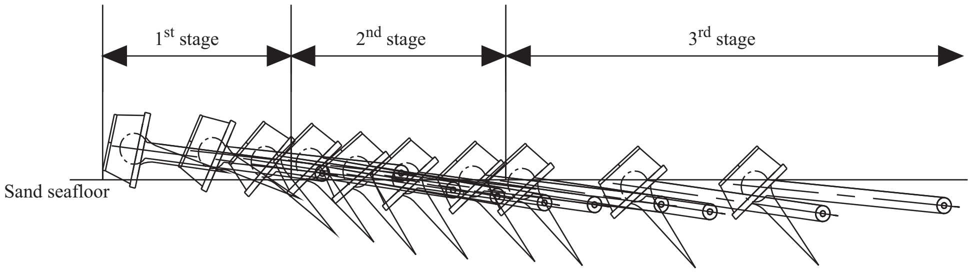


Fig. 8. Anchor embedment process.

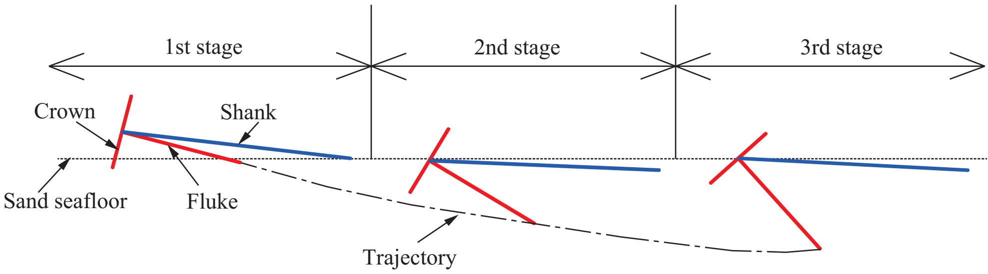
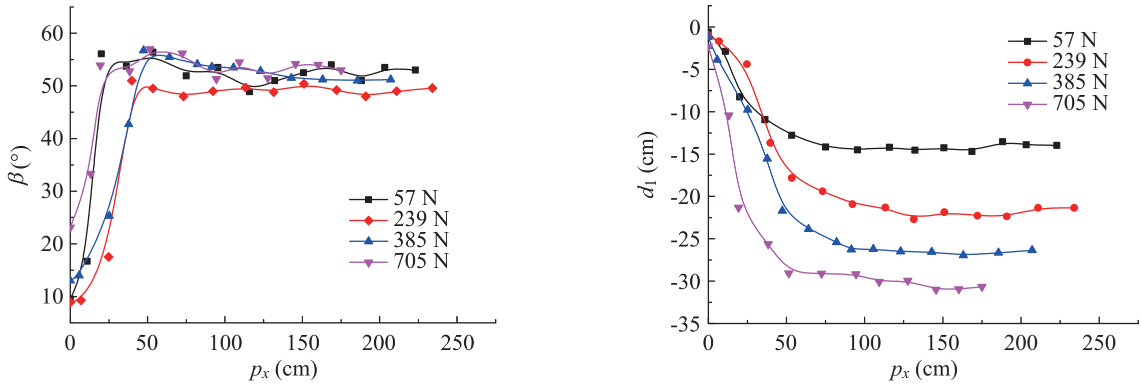


Fig. 9. Simplified embedment motion.



(a) Horizontal inclination of fluke β (b) Embedment depth of fluke tip d_1

Fig. 10. Motion morphologies of model anchors.

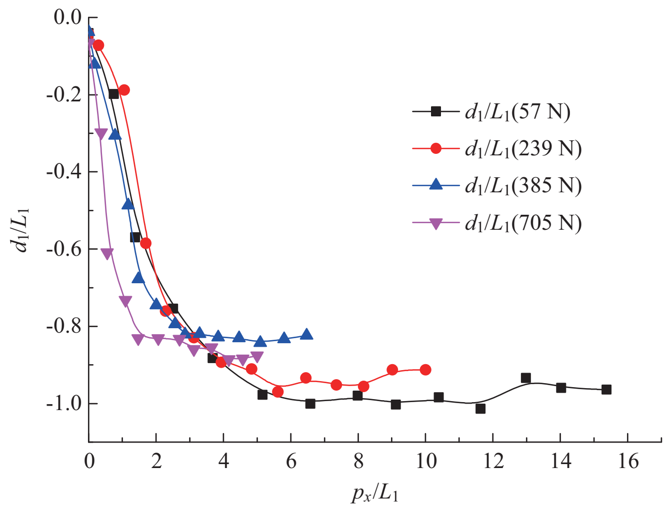
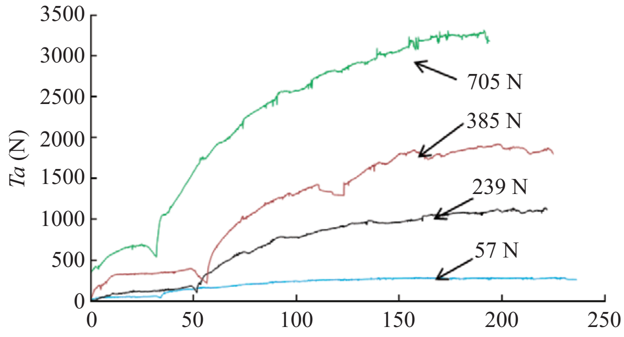


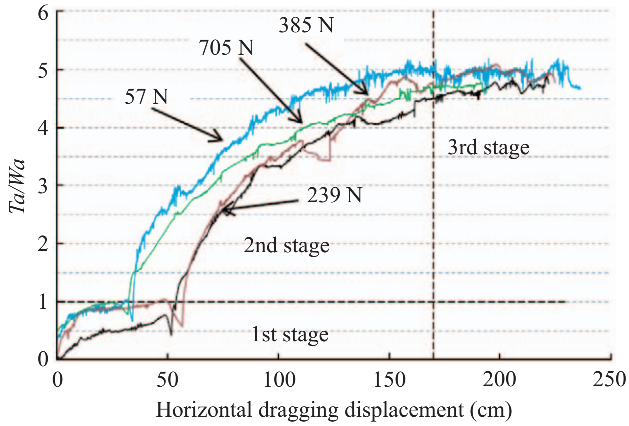
Fig. 11. Motion gestures of the anchor models.

d_1 and p_x, were depicted in Fig. 10. We can see the values of the two parameters (d_1 and β) rapidly increased with dragged distance and then stabilized, which was also shown in Fig. 7. In the final stage, β is close to 50 degree. And the embedment depths of the fluke tip d_1 presented the same regularity. In order to find out the more intrinsic rules the buried anchors, the embedment depths of the fluke tip d_1 were divided by the fluke length L_1, then the relationship between d_1/L_1 and p_x/L_1 was depicted in Fig. 11, the normalization curves of the different anchor models indicated good consistency, and in the final stage, d_1/L_1 was tend to 1.0, which corresponding to Fig. 7. This phenomenon means that the fluke of the anchors would be buried into the soil when the anchors reached the stable stage.

The curves in Fig. 10(a) and Fig. 11 clearly shown the development of the two aforementioned parameters which represent the motion of anchors, they can be diversified by three



(a) *Ta* vs horizontal dragging displacement



(b) *Ta/Wa* vs horizontal dragging displacement

Fig. 12. Measured holding power.

stages and they are corresponding to the three stages of embedment process of anchor: with the increasing of dragged distance, the values grew up quickly, and then kept on a stable value.

The holding power of the anchor models in the test are presented in Fig. 12(a). The abscissa denotes the horizontal dragging displacement of an anchor. The development law of holding power occurs in three stages: initial slow growth stage, rapid rise stage, and the final stable stage.

To determine the inherent development rule of the holding force, a normalization method was adopted in dividing the holding force by the weight of each anchor (T_a/W_a). The curves of T_a/W_a with the dragged distance are illustrated in Fig. 12(b). The curves can also be divided into three stages that correspond to the description above and the three stages provided in Figs. 8 and 9.

The increasing rate of the holding force T_a/W_a shifted from low to rapid after reaching a value of 1.0. This value can be considered as the cut-off point between the first and second stages of anchor motion according to the curves in Fig. 12(b). After continuous dragging, the maximum holding power was achieved correspondingly, and the final holding force coefficient of the anchors was observed within the range of 4.5 to 5 on the basis of the curves of T_a/W_a.

III. CONCLUSIONS

Model tests were operated in sand using four scaled Hall anchor models, and the development rules for the trajectory and holding power in the pulling process in sand were determined. There are some conclusions:

1) The pulling process of a Hall anchor in sand can be divided into three stages. In the first stage, the angle between the shank and the fluke increases. In the second stage, the anchor is quickly embedded into the soil, and the holding power increases rapidly. After entering the third stage, anchor gesture remains stable, the fluke of the anchor almost submerged into the soil entirely.
2) The dragging anchor will eventually entered into a stable state, when the buried depth of the fluke tip tend to one times of the length of the fluke L_1, and the inclined angle of the fluke in the horizontal direction β near 50 degree.
3) The holding power coefficients of the different scaled anchor models in the same sand were almost in the same range of 4.5 to 5.0.

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