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Analytical and Experimental Studies of Dragging Hall Anchors through Rock Berm

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Abstract:

An analytical method is proposed in this paper to calculate the maximum embedded depth of a dragged Hall anchor when passing through rock berm and to thus define a minimum buried depth of pipelines in rock berm to prevent pipelines from being damaged by dragging anchors. The movement of a Hall anchor in rock berm is interpreted based on the equilibrium conditions for resisting and driving moments acting on the anchor. To verify the accuracy of the proposed analytical method, model tests were carried out by using three scaled Hall anchor models and dragging them through rock berm. The comparisons between the two studies show that the average value of their differences for the stable embedded depth of a Hall anchor in sand and in rock berm are only 1.7% and 2.7%, respectively. The good agreements indicate that the proposed method is accurate enough to calculate the minimum buried depth of pipeline in rock berm during pipeline design.

Keywords: Pipeline, Anchor, Anchor Dragging, Rock Berm

1. Introduction

Most offshore submarine pipelines have to pass through the harbor anchorage zone to transfer oil from platforms to the mainland. The mooring force provided by anchors at the harbor anchorage may be inadequate to keep ships stable during severe storms. The anchors will thus be dragged away (anchor dragging) and may consequently threaten the buried pipelines. A field record of submarine pipeline failure due to anchor dragging has been reported by Macdonald et al. (2007). They found an anchor and a piece of 150-m long anchor chain near a damaged EOS20 pipeline in the North Sea Oil Field. The pipeline deviated 14.5 m away from its original location along the anchor chain direction. It is indicated that the dragged anchor was the key reason for this pipeline damage. Some failure records of the submarine cable due to dragging anchors have also been reported in China (Wang and Fan, 2012) and South Korea (Woo et al., 2009). These types of anchoring activities, such as anchor dragging or colliding, are some of the largest causes for submarine cable failure in the harbor anchorage zone (Yoon and Na, 2013a).

Rock berm is widely used to protect the submarine pipelines from damages caused by dragging anchors because it is a relatively easy and cost-effective construction method. The rock berm is usually constructed by digging a trench, filling it with well graded rocks or gravel and embedding the pipeline in it. One typical profile of a rock berm system and its protected pipeline is shown in Fig. 1 (Neubecker and Randolph, 1996a, 1996b; Thorne, 1998; O'Neil et al., 2003). For the effect of rock berms against damage from dropped objects, relatively mature designs and theoretical calculation methods (True, 1974; DNV, 2004, 2011), as well as a field test (Yoon and Na, 2013b), have been carried out. However, compared with dropped objects, anchor dragging is a severe threat to the safety of pipelines. If anchor flukes hook or even touch the pipeline, severe damage to the pipeline may be induced, thus causing ocean environmental problems because of leaking oil.

The effectiveness of rock berm to protect pipelines from damages caused by dragging anchors has been investigated by using numerical methods (Wang et al., 2009, Wang and Chia, 2010) and centrifuge model tests (Gaudin et al., 2007). A

safety assessment of mattress type submarine power cable protectors under dragging forces from a 2-ton anchor was carried out through field tests (Yoon and Na, 2013a). The theoretical solution of the design of dragged plate anchors on sand was proposed by Le Lievre and Tabatabaee (1979) by assuming that the anchor flukes will destroy the front soil wedge during dragging. Neubecker and Randolph (1996a) further improved the theory by considering the dilatancy of sand. A force acting on the end of a fluke was added to balance the free body. In their calculation, the real failure planes and side face of the anchor flukes, as well as the failure plane and direction of anchor movement, presented a certain angle that was assumed to be the dilation angle of the sand. They also found that the soil wedge width in front of the anchor flukes was larger than the width of the anchor flukes. The calculation model was improved from 2D to 3D and thus increased the accuracy of the calculation results.

However, analytical studies of Hall anchors dragged from sand to rock berm have seldom been reported. The Hall anchor is composed of an anchor crown, flukes, and the shank (see Fig. 2). The anchor flukes are similar to two slim rectangles. The width of each fluke is only $1/5$ of the width of the anchor crown. The soil in front of each anchor fluke forms soil wedges with limited equilibrium states, which then widen to a certain extent because of the dilatancy of sand. Two soil wedges present a total of four side friction surfaces. The crown of the Hall anchor is 0.6 times the length of the flukes and 5 times the width of a single fluke. Anchor dragging will destroy the formed soil wedges in front of the anchor crown and will thus impose a strong counterforce to the anchor that cannot be neglected. These characteristics of the Hall anchor make its force analysis significantly different from that of a plate anchor. It is thus necessary to develop a design method to evaluate the behavior of a rock berm under Hall anchor dragging and to acquire the safety assessment of submarine pipelines installed under rock berms.

An analytical method is proposed in this paper based on the method proposed by Neubecker and Randolph (1996a) to calculate the maximum embedded depth of a dragged Hall anchor when passing through rock berm and thus to define a minimum buried depth of pipelines in rock berm that could prevent the pipelines from being damaged by dragging anchors. The calculation method is proposed based on the force equilibrium of the Hall anchor crown and flukes by using the soil wedge limit

equilibrium method. The movement of a Hall anchor through rock berm is interpreted based on the equilibrium of resisting and driving moments acting on the anchor. Model tests are also carried out by using three scaled Hall anchor models and dragging them through rock berm to verify the accuracy of the proposed analytical method.

2. Proposed Analytical Method

The following assumptions are made to derive the analytical method: (1) the anchor is a rigid body; (2) the anchor fluke is fully opened and remains constant during the dragging process; (3) the angles between the failure surface and direction of anchor movement equal to the dilation angle of the sand; (4) the soil wedge in front of the anchor crown remains constant during the dragging process; and (5) the triangular zone in front of the anchor crown is elastic and calculated as a part of the anchor crown. Some of the above hypotheses were also made in the existing theoretical solutions, including Le Lievre and Tabatabaee (1979) and Neubecker and Randolph (1996a).

The simplified calculation model for the Hall anchor is shown in Fig. 3. The shapes of the anchor crown and anchor flukes are assumed to be rectangular. The effective width, B_2 , of the soil wedge in front of the anchor crown equals to the crown width, B , minus the equivalent width of two flukes, B_1 , as expressed in Eq. (1). The anchor shank force on the soil wedge (F_s) is related to its force area (A_s), effective unit weight (γ'), average depth of the shank (d_s) and bearing capacity factor for the shank (N_{qs}), as shown in Eq. (2) (Neubecker and Randolph, 1996a). The factor of N_{qs} will reflect the shape of the shank and the friction angle of the soil. If F_s is assumed to be shared by the soil wedges in front of the anchor crown, it can be separated into the soil wedge counterforce in front of the anchor flukes (F_{s1}) and that in front of the anchor crown (F_{s2}) based on the size of their reaction areas, as shown in Eq. (3) and (4), respectively.

$$B_2 = B - 2B_1, \quad (1)$$

$$F_s = A_s \gamma' d_s N_{qs} \quad (2)$$

$$F_{s1} = \frac{B_1}{B} F_s \quad (3)$$

$$F_{s2} = \frac{B_2}{B} F_s \quad (4)$$

The free body diagram of the soil wedge in front of the anchor crown can be simplified as shown in Fig. 4a. The triangular area (see ABC in Fig. 4a) in front of the anchor crown is assumed to move with the anchor crown and is thus treated as a part of the anchor crown during the calculation. The angle between the counterforce of CDE (R_2) and the vertical surface is assumed to be same as the internal friction angle of the sand embedment (φ). The side area of the soil wedge in front of the anchor crown (A_2) can be calculated as shown in Eq. (5). The increase in the width of the soil wedge in front of the anchor crown (X_2) caused by the dilatancy of sand is calculated by using Eq. (6). Then, the weight, W_{s2} , and side frictional resistance, SF_2 , of the soil wedge in front of the anchor can be calculated by using Eq. (7) and Eq. (8), respectively. A similar method has been proposed by Neubecker and Neubecker (1996a) to analyze plant anchors.

$$A_2 = \frac{H_2^2 \tan \lambda_2}{2} \quad (5)$$

$$X_2 = \frac{H_2 \tan \psi}{\cos(\lambda_2 - \psi)} \quad (6)$$

$$W_{s2} = A_2 \left(\gamma' B_2 + \frac{2}{3} \gamma' X_2 \right) \quad (7)$$

$$SF_2 = \frac{\gamma' L_2 (H_2 + h_2)^2 (\sin \varphi - \sin \psi)}{4 \cos \psi (1 - \sin \varphi \sin \psi)} \quad (8)$$

where L_2 is the length of the anchor crown and h_2 and H_2 are the buried depths of the top and bottom tips of the anchor crown, respectively.

The free body diagram of the soil wedge in front of the anchor flukes can be simplified as shown in Fig. 5. The force on the anchor flukes is analyzed by using methods similar to those used for the anchor crown. The expressions of the side area of the soil wedge in front of the anchor fluke (A_1), the increase in the width of the soil wedge in front of the anchor fluke (X_1), the weight, W_{s1} , and side frictional

resistance of the soil wedge before the fluke, SF_1 , of the soil wedge in front of the anchor fluke can be derived as shown in Eq. (9) to Eq. (12), respectively, which were proposed by Neubecker and Randolph (1996a).

$$A_1 = \frac{H_1^2 - h_1^2}{2 \tan \beta} + \frac{H_1^2 \tan \lambda_1}{2} \quad (9)$$

$$X_1 = \frac{H_1 \tan \varphi}{\cos(\lambda_1 - \psi)} \quad (10)$$

$$W_{s1} = A_1 \left(\gamma' B_1 + \frac{2}{3} \gamma' X_1 \right) \quad (11)$$

$$SF_1 = \frac{\gamma' L_1 (H_1 + h_1)^2 (\sin \varphi - \sin \psi)}{4 \cos \psi (1 - \sin \varphi \sin \psi)} \quad (12)$$

where h_1 is the depth of the back edge of the anchor fluke, H_1 is the depth of the fluke tip, L_1 is the length of the anchor fluke, and λ_1 is the failure wedge angle of the soil before the fluke.

Combining the force analyses for the anchor flukes and crown, the force polygon of the entire Hall anchor could be drawn as shown in Fig. 6. The force system of the entire Hall anchor can be calculated by using the following stepwise manner:

- (1) Assume soil wedge failure angles λ_1 and λ_2 ;
- (2) Calculate F_s , F_{s2} , W_{s2} and SF_2 according to Eqs. (2), (4), (7), (8), respectively, using λ_2 and geometry parameters of the Hall anchor;
- (3) Calculate R_2 and F_{f2} based on the force polygons along the anchor crown (see Fig. 4b) according to their vertical and horizontal force equilibriums;
- (4) Calculate F_{s1} , W_{s1} , and SF_1 according to Eqs. (3), (11), (12), respectively, and then R_1 , F_{f1} based on the force polygons along the anchor fluke (see Fig. 5b);
- (5) Calculate F_{f1} , F_{f2} based on W_a and the force polygons along the anchor body (Fig. 6a) and then T_a , F_{fb} based on the force polygons along the soil wedges (Fig. 6b);
- (6) Repeat step (1) to (5) by changing the value of λ_1 and λ_2 until obtaining a minimum T_a , which is the dragging capacity that the anchor body can support at a given location.

The rotation of the anchor body could also be calculated by using the moment equilibrium on the free body diagram of the Hall anchor (see Fig. 7) when drag force, T , on the end of the anchor shank, point O , is larger than anchor resistance, T_a . The moment arms of forces to point O can be calculated according to their geometric relationship, as shown in Fig. 7. The arm of the force from anchor wedge, L_{Wa} , soil wedge's counterforce against the anchor shank, L_{Fs} , counterforce against the anchor flukes, L_{Ff1} , counterforce against back of the anchor flukes, L_{Ffb} , and the anchor crown, L_{Ff2} , can be calculated as shown in Eq. (13) to (17), respectively. The arm of the drag force is zero because it passes through rotation point O . Then, the total resultant moment of the entire Hall anchor can be calculated by using Eq. (18).

$$L_{Wa} = L_s \cos \omega \quad (13)$$

$$L_{Fs} = \frac{1}{2} L_s \cos \delta \quad (14)$$

$$L_{Ff1} = \frac{2}{3} L_1 \sin \left(\frac{\pi}{2} + \delta \right) - L_s \sin \left(\frac{\pi}{2} - \delta - \alpha \right) \quad (15)$$

$$L_{Ffb} = \frac{2}{3} L_1 \sin \left(\frac{\pi}{2} - \delta \right) - L_s \sin \left(\frac{\pi}{2} + \delta - \alpha \right) \quad (16)$$

$$L_{Ff2} = \left[L_s \cos \omega - \frac{1}{2} L_2 \sin (\alpha - \omega) \right] \sin \delta + \left[L_s \sin \omega + \frac{1}{6} L_2 \cos (\alpha - \omega) \right] \cos \delta \quad (17)$$

$$M = W_a L_{Wa} - F_s L_{Fs} - F_{f1} L_{Ff1} + F_{fb} L_{Ffb} - F_{f2} L_{Ff2} \quad (18)$$

where L_s is the length of the anchor shank, α is the initial opening angle of the anchor flukes, δ is the external friction angle, and ω is the shank rotation angle.

3. Model Tests Apparatus

Model tests were carried out to verify the accuracy of the proposed analytical method. Three steel model anchors, anchor A, B, and C, were fabricated, with weights of 57, 239, and 705 N , respectively. Their geometry scale factors, compared to a 30 kN prototype anchor, were 1 : 8.1, 1 : 5.0, and 1 : 3.5, respectively. A photo of the anchor models is shown in Fig. 8. The dimensions of the three anchor models are listed in Table 1. The fully opened angle between the anchor shank and flukes, α , was 42°.

An I-beam framed container, with dimensions of 3 m (L) $\times$ 1 m (W) $\times$ 0.61 m (H), was used to store sand sediment and thus to simulate the seabed. The photo and dimensions of the tank are shown in Fig. 9. To observe the movement of the sand and gravel embedment, one side of the container was fabricated by using a 1-cm-thick Perspex plate. The sediment used was fine sand with 33 °friction angles. The grain size distribution curve of the fine sand is shown in Fig. 10a. The average particle size of the fine sand was 0.43 mm. The other basic properties of the sand sample are listed in Table 2. The rock berms were constructed by digging a trench and filling it with well graded gravel. The grain size distribution curve of the gravel is given in Fig. 10b. The average particle size of the gravel was 20 mm. As shown in Fig. 9a, the slope of the trench on one side was 1:2.5 and that on the other side was 1:0.6. The cross-section of the trench is in a trapezoidal shape, with its top length of 1.74 m, bottom base length of 0.5 m and height of 0.4 m.

The dragging force was supplied by a winch, wire rope, and pulley block system, as shown in Fig. 11a. The drag force acting on the anchor was recorded by using a tensile sensor (see Fig. 11b), data logger and laptop (see Fig. 11c). The time series of anchor movements were determined and recorded by using a video image correlate-3D (Vic-3D) system supplied by Correlated Solutions, Inc. Columbia SC, USA.

4. Results and Comparisons

Five model tests were carried out in this study. Test 1 to 3 were carried out using anchor model *A* to investigate the effects of the initial buried depth of the anchor fluke, initial opening angles and dragging distance to the rock berm. Test 4 and 5 were carried out using anchor model *B* and *C*, respectively, to investigate the effect of anchor scales. More details of these model tests are summarized in Table 3. A horizontal drag force was applied by using the speed control method. The controlled speed during the test was maintained at 2 cm/min.

The photographs and motion of anchor model *A* during model test 1 are shown in Fig. 12 and Fig. 13, respectively. It can be observed that the anchor flukes gradually open and penetrate into the sand bed (see Fig. 13a). This is because when the anchor is inserted into the soil, the gravitational moment of the Hall anchor is larger than the

counter moments of the soil wedges. However, as the anchor enters the soil gradually, the anchor shank begins to rotate and the counter force of the soil wedge against the anchor increases. The arm of anchor gravity decreases with increasing shank rotation angle and thus decreases the gravitational moment. At a certain depth and rotation angle, the gravitational moment of the anchor and the counter moment of the soil wedge reach a balance when the resultant moment of the anchor is zero. The buried depth in the seabed of the anchor flukes and the drag force of the anchor reach their maximum magnitudes. The anchor fully penetrates into the sand bed with a maximum depth of 127 mm when the opening angle reaches its designed limit of 42° (see point A in Fig. 13). After that, the anchor exhibits a translational motion towards the protective berm with a constant resistance moment.

When the anchor touches the rock berm (see photo in Fig. 12b and point B in Fig. 13), the soil resistance against the anchor increases because of the restraint from the rock berm layer. As there is a slope on the edge of the rock berm, the angled rock berm touches the anchor crown and anchor shank first. However, the anchor will destroy this thin layer of rock and accumulate the gravel particles, further increasing the resistance until the anchor dragging force reaches its peak value (see point C in Fig. 13). Due to the strong resistance from the rock berm to the anchor shank and unbalanced moments in the anchor, the anchor starts to move up and rotate around the end of the anchor shank simultaneously, which lifts the anchor fluke tips (see photograph in Fig. 12c). One more reason is that the larger particles of the rock berm make it hard for the anchor fluke tips to penetrate into them. The lower penetration depth makes the anchor crown emerge from the embedment (see photo in Fig. 12d). These two effects make the drag force decrease suddenly (see point C in Fig. 13b). When the anchor fluke tip is lifted to a certain depth, the force system and moments of the entire anchor reach a new balance state (see point D in Fig. 13). Some main parameters used during the model test are summarized in Table 3.

Fig. 14 shows the test results of model test 1 to 3 using anchor model A when the initial buried depth of the anchor fluke, initial opening angles and dragging distance to the rock berm are different. The depth of the anchor crown tip versus the horizontal movement of the anchor is shown in Fig. 14a. It can be observed that the initial buried depth and dragging distance of the anchor flukes have no effect on their

stabilization positions in sand, which are unique at 135 mm. The dragging forces versus horizontal movements of the anchor curves are shown in Fig. 14b. It can be observed that the initial location of the anchor flukes may affect their forces in sand significantly, but there is no effect on the stable drag force in the rock berm. The rotation angles of the anchor during model test 1 to 3 are shown in Fig. 14c. If the initial buried depth of the anchor flukes in sand exceeds the stable depth, i.e., model test 3, the anchor will rotate to a certain extent in sand because the driving moment is larger than the gravity moment. This condition allows the anchor flukes to be lifted high in the rock berm.

The results of model test 2, 4 and 5 by using the three different anchor models are compared as shown in Fig. 15. To compare the these test data, the horizontal movement of the anchor fluke tip, L_x , and the buried depth of the anchor fluke tip, L_y , are normalized by the anchor fluke length, L_f . The drag force, T_a , is normalized by anchor weight, W_a . As shown in Fig. 15a, although the dimensions of the three anchors are different, they stabilize in the rock berm at a similar L_y/L_f of 0.44. The normalized drag force, T_a/W_a , versus L_y/L_f curves during the three model tests is shown in Fig. 15b. Generally, all three test results fall into a small band and follow the same trend. After the anchors penetrated into the rock berm, the anchors rotated, and their forces changed differently. However, they stabilized at $T_a/W_a = 2.5$. It should be noted that the conclusions are obtained from the specified sand and gravel bed. For other materials, the variation law should be consistent.

The proposed theoretical solutions were also used to analyze the model test data to verify their accuracy. The maximum buried depth of anchor flukes in sand (H_1), maximum drag force of the testing anchor in sand (T_a), maximum drag force when entering the rock berm, stable buried depth of anchor flukes in the rock berm (H_2), rotation angle of the anchor shank (ω), and stable drag force of the anchor in the rock berm were calculated using the proposed method. The measured data and calculated results for model test 2, 4 and 5 are compared and summarized as shown in Table 4. For the stable buried depth in sand and in the rock berm in the three model tests, the maximum percentage of difference between calculated and test results are -13.4% and 16.8%, respectively. However, the averages of differences in the three model tests are only 1.7% and 2.7%, respectively. The results indicate that

the proposed method is accurate enough to calculate the minimum buried depth for pipeline design.

The percentages of difference for the maximum drag force in sand and in the rock berm are also calculated as shown in Table 4. For model test 2, the proposed method underestimates the dragging force in sand by -7.2% but is more accurate when calculating it in rock berm ($< -1.53\%$). For model test 4 and 5, the same trends have been observed, except the maximum difference between the two methods for maximum drag force in sand reached -21.6%. The proposed method also overestimates the maximum drag force in the rock berm, with a maximum difference of 24.5%. The comparisons indicate that the proposed method is safe to use for the estimation of maximum dragging forces. However, the averages of differences of stable dragging force in the rock berm in the three model tests are only 1.0%. The results indicate that the proposed method is accurate enough to calculate the stable dragging force in the rock berm.

The calculated forces were further utilized to calculate the moments of the anchor, as summarized in Table 5. In sand, the dragged anchor will not rotate and basically exhibits translational motion when the driving moment is smaller than the gravity moment as long as the anchor has a balanced force system. However, given that its driving moment is larger than its gravity moment, the dragged anchor will rotate upward around the end of the anchor shank in the rock berm until it reaches a new force and moment balance. This condition verifies the abovementioned protective mechanism of the rock berm against damages caused by dragging.

5. Conclusions

Rock berms are widely used to protect submarine pipelines from damages caused by dragging anchors during severe storms. An analytical method is proposed in this paper based on the method proposed by Neubecker and Randolph (1996a) to calculate the maximum embedded depth of a dragged Hall anchor when passing through rock berm and thus to define a minimum buried depth of pipelines in rock berm to prevent pipelines from being damaged by dragging anchors. The movement of a Hall anchor in rock berm was interpreted according to the moment equilibrium. Model tests were also carried out by using three scaled Hall anchor models to verify

the accuracy of the proposed solutions.

It is found from the model tests that the anchor flukes gradually open and penetrate into the sand bed from the beginning of the test. The anchor fully penetrates into the sand bed when the open angle reaches its design limit. The initial buried depth and dragging distance of the anchor flukes have no influence on their stable position in sand or the rock berm. The dragging force of the anchor achieves its peak value when it reaches the edge of the rock berm. Then, the anchor crown emerges from the rock berm because the anchor fluke cannot penetrate into it, thus making the dragging force have a lower magnitude. Although the dimensions of the three anchor models are different, they stabilize in the rock berm at a similar normalized depth, L_y/L_f , of 0.44 and normalized dragging force, T_a/W_a , of 2.5.

The comparisons between the model tests and analytical results show that the proposed method is accurate enough to calculate the minimum buried depth of a pipeline. The average differences between the calculated and measured results for the stable buried depth in sand and in the rock berm are only 1.7% and 2.7%, respectively. The comparisons also indicate that the proposed method underestimates the stable dragging force in sand, with an average difference of -15.6% but is more accurate when calculating it in the rock berm, with an average difference of 1.0%.

6. Notations

d_s	Average embedded depth of anchor shank
D_s	Diameter of anchor shank
F_{f1}	Fluke force
F_{f2}	Crown force
F_{fb}	Force behind fluke
F_s	Shank force
h_1	Initial buried depth of anchor crown bottom
H_1	Maximum depth in sand
h_2	Initial buried depth of anchor flukes
H_2	Stable depth in rock berm
L_1	Length of anchor fluke
L_2	Length of anchor crown
L_{Ff1}	The arm of counterforce against the anchor flukes
L_{Ff2}	The arm of counterforce against the anchor crown
L_{Ffb}	The arm of counterforce against the back of the anchor flukes
L_{Fs}	The arm of the soil wedge's counterforce against the anchor shank
L_s	Length of anchor shank

L_{Ta}	The arm of drag force
L_{Wa}	The arm of anchor wedge weight
L_x	Horizontal movement of the anchor fluke tip
L_y	Buried depth of the anchor fluke tip
M	The resultant moment of the entire Hall anchor
M_D	Driving moment
M_{f1}	Moment of fluke force
M_{f2}	Moment of crown force
M_{fb}	Moment of force behind fluke
M_{fs}	Moment of shank force
M_{sf1}	Moment of side friction before fluke
M_{sf2}	Moment of side friction before crown
M_W	Moment of resistance (gravity moment)
N_{qs}	Bearing capacity factor for the shank
SF_1	Side friction of soil wedge before fluke
SF_2	Side friction of soil wedge before crown
T	Drag force on anchor
T_a	Total dragging resistance of anchor
W_a	Anchor weight
α	Initial opening angle of anchor flukes
γ'	Effective unit weight
δ	External friction angle
λ_1	Failure wedge angle of the soil before fluke
λ_2	Failure wedge angle of the soil before crown
φ	Internal friction angle
ψ	Dilation angle of the sand
ω	Shank rotation angle

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Table 1 Dimensions of the scaled anchor models

Anchor No.	Weight W_a (N)	Anchor crown and fluke (mm)									Anchor shank (mm)	
		B	B_1	L_1	L_2	e_1	e_2	e_3	e_4	t	L_s	D_s
A	57	210	49	145	85	31	34	93	20	10	350	25
B	239	323	81	234	135	49	54	150	27	16	580	40
C	705	500	120	350	200	75	80	210	45	25	920	60

Table 2 Basic properties of sand and rock berm embedment

Properties	Sand	Rock berm
Internal friction angle φ (°)	33	42
External friction angle δ (°)	22	30
Dilation angle ψ (°)	13	15
Unit weight γ (kN/m^3)	18	22

Table 3 Parameters used in the model test

Test No.	Anchor No.	W_a (N)	Initial buried h_1 (mm)	Initial α (°)	Initial buried h_2 (mm)	Distance to rock berm (mm)
1	A	57	10	10	22	710
2	A	57	50	5	34	320
3	A	57	100	42	171	570
4	B	239	50	8	23	570
5	C	705	200	17	150	330

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Table 4 Comparison between the model test and the calculated results of the three anchor models

	Model Test 2			Model Test 4			Model Test 5			Avg. Diff. %
	Calculated	Measured	Diff %	Calculated	Measured	Diff %	Calculated	Measured	Diff %	
Max./Stable H_1 in sand (mm)	110	127	-13.4	178	161	10.6	261	242	7.9	1.70
Max./Stable T_a in sand (N)	116	125	-7.20	519	662	-21.6	1502	1830	-17.9	-15.6
Max. T_a in rock berm (N)	261	228	14.5	1118	901	24.1	3761	3022	24.5	21.0
Stable H_2 in rock berm (mm)	66	56.5	16.8	109	111	-1.8	151	162	-6.8	2.70
Stable T_a in rock berm (N)	129	131	-1.53	621	602	3.2	1926	1901	1.3	1.00
ω (°)	9	12	-25.0	7.5	6.8	10.3	9.5	8	18.8	1.40

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Table 5 Calculated force and moments of the three anchor models

Model Test No.	In Sand			In Rock berm		
	2	4	5	2	4	5
Fluke force F_{f1} (N)	53.8	225.8	750.3	121.9	516.2	1715.0
Side friction of soil wedge before fluke SF_1 (N)	8.0	33.8	113.0	16.1	67.8	226.7
Moment of fluke force M_{f1} (N)	0.7	2.8	10.8	0.8	2.9	11.1
Moment of side friction before fluke M_{sf1} (N m)	0.3	1.8	8.8	0.5	3.5	17.7
Crown force F_{f2} (N)	21.2	88.4	300.1	125.9	530.6	1793.4
Side friction of soil wedge before crown SF_2 (N)	0.1	0.5	1.6	0.3	1.0	3.3
Moment of crown force M_{f2} (N)	2.8	19.9	99.7	21.6	157.1	781.7
Moment of side friction before crown M_{sf2} (N m)	0.00	0.01	0.04	0.00	0.02	0.08
Shank force F_s (N)	31.9	143.5	474.9	105.6	475.1	1572.0
Moment of shank force M_{fs} (N m)	1.6	12.9	63.0	7.44	58.8	286.0
Force behind fluke F_{fb} (N)	60.2	252.5	744.9	57.6	241.5	712.3
Moment of force behind fluke M_{fb} (N m)	7.9	60.8	252.7	10.5	75.8	276.6
Driving moment M_D (N m)	13.3	98.3	435.0	40.8	298.1	1373.2
Moment of resistance (gravity moment) M_W (N m)	16.8	123.4	535.4	16.8	123.4	535.4
Drag force T_a (N)	55.8	236.9	827.9	261.4	1118.4	3761.2
Failure wedge angle of the soil before fluke λ_1 (°)	61	62	62	70	70	70
Failure wedge angle of the soil before crown λ_2 (°)	82	83	83	86	86	86

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12 Fig. 1 Construction method of rock berm used to protect pipeline

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14 Fig. 2 Profile of stockless Hall anchor for (a) front view, (b) side view, (c) top view

15 and (d) connection bar

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17 Fig. 3 Simplified calculation model of the stockless Hall anchor

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19 Fig. 4 Free body diagram of soil wedge CDE in front of the Hall anchor crown: (a)
 20 front view, (b) top view and (c) force polygons

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22 Fig. 5 Free body diagram of soil wedge KGIJ in front of the Hall anchor flukes: (a)
 23 front view, (b) top view and (c) force polygons

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25 Fig. 6 Force polygon for free body of (a) anchor and (b) anchor plus soil wedge

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27 Fig. 7 Moment arms of forces acting on Hall anchor body

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29 Fig. 8 Photos of scaled anchors models

(a)

(b)

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31 Fig. 9 Model test setup: (a) sketch of setup; (b) photograph of the model test

(a)

(b)

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33 Fig. 10 Grain size distribution of (a) sand and (b) gravel used for rock berm

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35 Fig. 11 Test facility: (a) pulley block and the winch; (b) drag force sensor; (c) data
36 collection and processing system

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38 Fig. 12 Photographs of anchor model (a) while moving in sand, (b) when starting to
39 touch the rock berm, (c) while moving in the rock berm and (d) at the end of the test

Fig. 13 Test results of model test 1: (a) movement trajectory of the anchor and (b) variation in drag force against fluke tip trajectory

(a)

(b)

(c)

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44 Fig. 14 Model test results of anchor model A: (a) anchor movement versus depth of
 45 tip curves, (b) anchor movement versus dragging force curves, and (c) anchor
 46 movement versus rotation angle curves

(a)

(b)

Fig. 15 Test results of scaled anchors models: (a) normalized movement versus depth of anchor fluke curves; (b) normalized movement of anchor fluke versus normalized dragging force curves