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Analytical and experimental studies of dragging hall anchors through rock berm

Shuwang Yan [a], Bingchuan Guo [a], Liqiang Sun [a,*], Wei Guo [b], Zhenming Lei [c]

[a] State Key Laboratory of Hydraulic Simulation and Safety, Tianjin University, 92, Weijin Road, Tianjin 300072, China
[b] School of Civil & Environmental Engineering, Nanyang Technological University, 50 Nanyang Ave, 639798, Singapore
[c] Offshore Oil Engineering Co. Ltd., Tanggu District, Tianjin 300450, China

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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.

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'Neill 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

* Corresponding author.
E-mail address: slq0608@163.com (L. Sun).

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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

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).

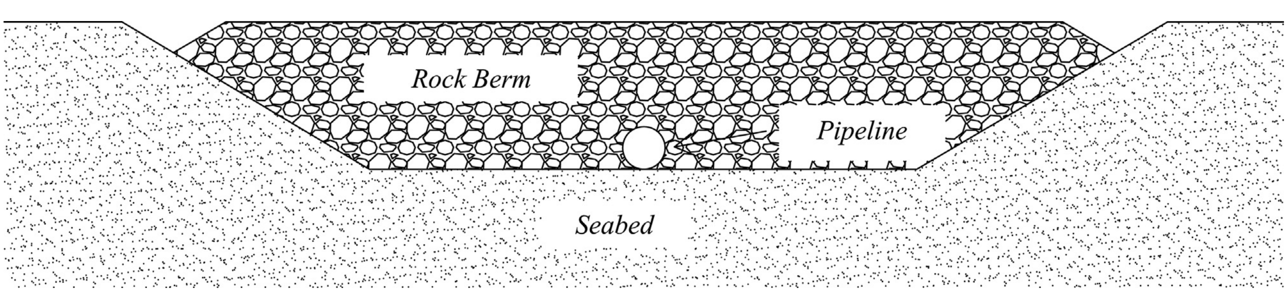

Fig. 1. Construction method of rock berm used to protect pipeline.