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Anchor and Mooring Line Analysis in Cohesive Seafloor

해성점토지반에 관입된 앵커 및 닻줄의 변형해석

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요 지

이 연구는 선박을 정착하기 위하여, 해성점토에 관입된 앵커 및 닻줄의 변형, 인장력 및 지반거동을 해석할 수 있는 방법에 대한 연구로써, 앵커와 닻줄을 multi-segment로 나누어, 일차원 유한 요소 해석을 하였다. 각 element와 지반거동에 대한 힘과 모멘트의 평형조건을 만족시키면서, 앵커와 닻줄의 변형과 인장력을 해석하는 방법으로, 앵커 및 선박 상판에서 구할 수 있는 특정경계조건을 구한 후, 지속적인 반복작업을 이용하여 각 element의 변형과 인장력을 구하는 방법을 채택하였다. 이러한 연구결과는 앵커 및 닻줄이 사용된 해양구조물의 설계 및 시공에 반영될 수 있으며, 이 연구의 예측결과는 실제 현장 data와 비교 분석되었으며, 비교를 위한 항목으로는 anchor의 지지력, 닻줄길이, 선박에 연결된 닻줄의 각도 및 인장력 등이 사용되었다. 각 항목의 비교결과, 실제 현장 data와 상당히 일치하여, 이 방법으로 지반 및 선체의 거동을 예측할 수 있다는 것이 증명되었다.

Abstract

An analytical solution method capable of determining the geometric configuration and developed tensile forces of mooring lines associated with fixed plate/pile or drag anchors has been developed. The solution method, satisfying complete equilibrium conditions, is capable of analyzing multi-segmented mooring lines that can consist of either chains, cables, or synthetic wires embedded in layered seafloor soils. The solution method utilizes a systematic iterative search method based on specific boundary conditions. This paper describes the principles associated with the development of the solution for the mooring line analysis. Comparisons of predictions with results from a series of field tests of mooring lines on various types of drag anchors are also described. Comparisons include the tension in anchor, the length of mooring line on the bottom, and the angle of mooring line at the water surface buoy. The results indicate that the analytical solution method is capable of predicting the behavior of mooring lines with high degree of accuracy.

Keywords : Anchor, Cable, Chain, Cohesive seafloor, Mooring line, Tension

1. Introduction

The US Navy developed an analytical solution method that can analyze offshore and deep water mooring lines associated with embedded drag and fixed anchors (Bang, 1996). Mooring lines may be comprised of multi-segments with different material and/or geometric properties and embedded in a general seafloor soil having either cohesion

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or friction or both. Any number of sinkers can also be added to the suspended portion of the mooring line within the water. Solutions can be obtained with a fixed total length of the mooring line, a fixed horizontal length of the mooring line, or a fixed exit angle of the mooring line at the seafloor surface.

The validity of the developed method of analyzing mooring lines embedded in cohesive seafloor soils has been verified through comparisons with laboratory centrifuge model tests (Bang, et. al, 1996; Bang, et. al, 1999).

This analytical solution was also used to compare with the full scale field test results (Bang, et. al, 1996). However, this comparison can only be viewed as indirect, since the developed analytical solution lacks the capability of considering the case when a portion of mooring line lies on the seafloor surface. This paper briefly describes how the analytical solution has been improved to consider cases when a portion of mooring line lies on the seafloor surface.

Results of the field tests conducted in cohesive seafloor soils and the resulting comparisons between the measured and calculated values are described in detail.

2. Mooring Line Analysis

The analysis of the static mooring line geometric configuration is based on the limiting equilibrium method in which the detailed solutions are obtained from the static equilibrium conditions. Figure 1 shows a schematic diagram of a mooring line element embedded in the seafloor. T and ϕ are the axial tensile force and the inclination angle at the ends of the element. N, (f ds), and (w ds) are the normal force, the tangential force, and the buoyant weight of the mooring line element, respectively. From the static equilibrium conditions of forces along the "n" and "t" coordinates and the moment about the point "o"

$$\Sigma F_t = 0$$
$$\Sigma F_n = 0$$
$$\Sigma M_0 = 0, \quad (1)$$

one can solve unknowns, N, T and ϕ. Note that previously published solutions of the embedded mooring line analysis only considered partial equilibrium conditions (Brian Watt Associates, 1983; Degenkamp and Dutta, 1989; Vivatrat, et. al, 1982). The current solution method, which utilizes complete equilibrium conditions, therefore permits an additional degree of freedom in each mooring line element.

In the analysis, it is assumed that the soil tangential forces (f ds) remain at their limiting state at all time, since the dominant mode of the mooring line movement during deployment is sliding. The normal soil forces (N), however, remain as unknowns because of the available additional degrees of freedom and therefore can be less than those defined by the limiting state, i.e., the soil bearing capacity. It is also noted that the assumption of the mooring line element forming a circular arc as assumed in some of the previous solutions is no longer necessary in the current solution.

Eq. (1) forms the basis of recursion formulas for the detailed analysis of the embedded mooring line element in the seafloor, i.e.,

$$T_2 = T_1 - (f + w\sin\phi_1)\,ds$$
$$N = \frac{2T_2 - f\,ds}{\tan\phi_1}$$
$$\phi_2 = \phi_1 + \frac{N - w\,ds\cos\phi_1}{T_2} \quad (2)$$

where T_1 and T_2 = axial forces at the beginning and end of the element

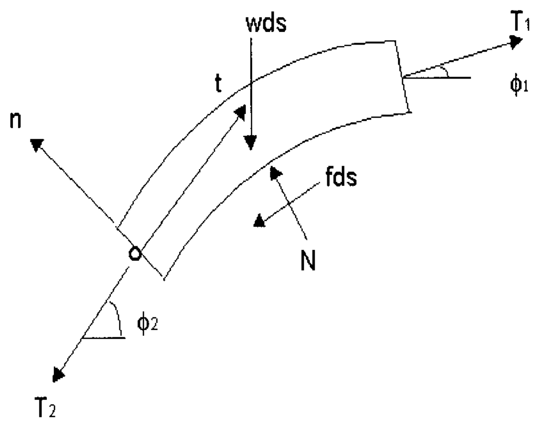

Fig. 1. Mooring line and free body diagram

ϕ_1 and ϕ_2 = mooring line inclination angle to the horizontal at the beginning and end of the element

f = tangential force per unit length of the element

w = buoyant weight of mooring line per unit length

N = normal force at the bottom of the element.

The solution process starts with a known mooring line inclination angle at the seafloor surface (ϕ_1). The catenary and embedded portions of the mooring line are then solved separately and added for the final solution. The following describes the solution details of the embedded portion of the mooring line.

With a known inclination angle at the seafloor surface and the horizontal force at the water surface, the mooring line axial tension at the seafloor surface (T_1) is calculated. Using Eq. (2), the axial tension and the inclination angle at the end of the element, T_2 and ϕ_2, are then calculated. From the compatibility requirement, the values of axial tension and inclination angle at the end of the current element then become those at the beginning of the next element. Concurrently, the coordinates of the elements are calculated and recorded. This process continues until the depth to the element end reaches the specified anchor depth.

In the recursion equations, the element tangential force per unit length, f, is estimated assuming that the soil undrained shear strength is fully mobilized, i.e.,

$$f = e_s \; D \; \alpha \; \beta \; S_u \qquad (3)$$

where e_s = equivalent diameter conversion factor for sliding force to convert mooring line diameter to circumferential area

D = chain link or cable diameter

α = soil adhesion conversion factor

β = contact area conversion factor

S_u = soil undrained shear strength.

For stud link chains, the value of E_s is obtained by converting the chain link diameter to the circumferential area of a cylinder defined by a circle encompassing two perpendicular chain links, i.e., 3.6 times π. For cables, the value of E_s is simply π.

The soil adhesion conversion factor (α) is the ratio of the adhesion between the mooring line and the soil vs. the soil cohesion. The contact area conversion factor (β) is the ratio of the true contact area between the mooring line and the soil versus the surface area of a cylinder defined by the mooring line. In case of chain, the cylinder is defined by a circle encompassing two perpendicular chain links. For cable, the cylinder is simply defined by the cable diameter. The value of β may be less than 1.0, if a separation occurs on the backside of the mooring line while it is deployed.

The value of the normal force, N, is limited to be no greater than the soil bearing capacity, i.e.,

$$N < N_{max} = q \; ds$$
$$q = e_b \; D \; S_u \; N_c \qquad (4)$$

where q = bearing capacity of soil per unit length

e_b = equivalent diameter conversion factor for normal force to convert mooring line diameter to projected bearing area

N_c = soil bearing capacity factor.

For stud link chains, the value of E_b is obtained by converting the chain link diameter to the diametric projectional area of a cylinder defined by a circle encompassing two perpendicular chain links, i.e., 3.6. For cables, the value of E_b is 1.0.

When the calculated total length of the mooring line with zero mooring line inclination angle at the seafloor surface is less than the specified total length of the mooring line, it is evident that a portion of the mooring line lies on the seafloor surface. In such a case, the solution requires an additional step for the determination of the length of the mooring line lying on the seafloor surface. This requires satisfaction of the following two conditions: (1) the mooring line inclination angles at the seafloor surface remain zero, and (2) the mooring line tension at the beginning of the embedded portion is the horizontal tension at the water surface minus the sum of soil tangential force that develops underneath the mooring line lying on the seafloor surface. Since the length of the mooring line lying on the seafloor surface is an unknown, it is determined iteratively by initially assuming that length and comparing the resulting total mooring line length with the specified total length.The details of these solution steps are beyond the scope of this paper. References (Bang, 1996; Bang, 1999) include complete description of the determination of the composition of mooring line segments embedded in the seafloor, calculation of the mooring line geometry and tensile forces, and calculation of the mooring line length lying on the seafloor surface.

3. Field Tests

A series of field tests on drag embedment anchors were performed by the U.S. Naval Facilities Engineering Service Center in Indian Island in Puget Sound, Washington (Taylor, 1980).

The Indian Island seafloor consisted of normally consolidated soft silty clay with shell fragments and was classified as an organic silty clay of high plasticity. The particle size was almost evenly distributed between silt and clay. The liquid limit and water content values were relatively high and approximately equal, varying little with depth up to 8.5 m. Values ranged from 110 to 160 for the water content and 117 to 142 for the liquid limit. The shear strength increased almost nearly from zero at the surface to 8.6 kN/m^2 at 6.4 m.

Figure 2 shows the schematics of the test setup. The mooring line was pulled by the barge, dragging the anchor under the seafloor with its total length remaining the same all the time. Instruments on the anchor, the mooring line, and the barge recorded the movements and tensions of the anchor and mooring line. The details of the anchors and mooring lines used for the tests are listed in Table 1. It describes the anchor type, the anchor weight and the mooring line details.

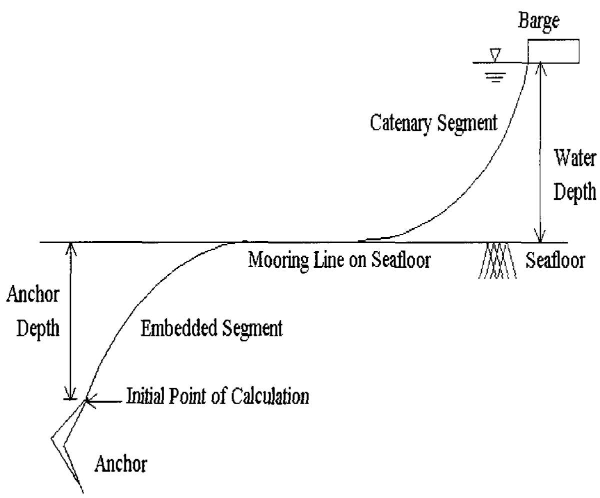

Fig. 2. Anchor - mooring line system

4. Validation

Major input data for the analytical comparison with field test results were the values of the horizontal tension at the buoy, water depth, depth to anchor from seafloor, and friction factor at the seafloor surface, in addition to the material and geometric parameters.

The seafloor soil strength was described by a linearly increasing rate with depth of 1.35 $kN/m^2/m$, starting from zero strength at the surface. The friction factor describes the mooring line - soil interaction behavior at the seafloor surface.

The measured results from the field tests included the anchor force, the mooring line inclination angle at buoy, and the length of the mooring line on the bottom. The length of the mooring line on the bottom is the total length of the mooring line buried in the seafloor and lying on the seafloor surface. These were compared with the results from analytical solutions.

Table 2 indicates the values of input parameters for the analytical solution, excluding the diameter conversion factors that are merely geometric conversion parameters used in the verification with field test results. The values of α, N_c obtained from the previous study (Bang, et. al, 1999) were used for this verification. To obtain α and N_c values, the centrifuges installed seafloor and mooring line system were used. It is noted that the mooring line slide area factors (β) were assumed to remain 1.0 in the analysis. This is mainly because the tangential force developed at the bottom side of the mooring line is influenced by the product of α and β, and no attempt was made during the model tests to separate the effects of these two parameters.

Table 1. Anchors and mooring lines of indian island tests

Test No.	Seafloor Type	Anc. Type	Anc. Weig.	Mooring line Description
170-1	silt	stato	4.76 kN	27 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
172-7	silt	stockless	50.57 kN	27 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
172-8	silt	stockless	50.57 kN	27 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
172-9	silt	stockless	26.47 kN	27 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
172-10	silt	stockless	26.47 kN	27 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
174-13	silt	stockless	26.47 kN	41 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
174-14	silt	stockless	26.47 kN	41 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
176-23	silt	stato	15.57 kN	41 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
176-25	silt	stato	29.36 kN	41 m. 5 cm. c, 108 m. 6.4 cm. c, 122 m. 4.1 cm. w, 105 m. 5 cm. w
208-5	silty clay	two fluke	43.59 kN	55 m. 5 cm. c, 82 m. 7.6 cm. c
209-12	silty clay	stevfix	48.93 kN	27 m. 7.6 cm. c, 55 m. 5 cm. c, 82 m. 7.6 cm. c

Note : c = Chain, w = Wire

Table 2. Constant input data of indian island tests

Parameter	Value
Diameter Factor for Chain Bearing (EWBc)	0.233
Diameter Factor for Cable Bearing (EWBw)	0.0833
Diameter Factor for Chain Sliding (EWSc)	0.733
Diameter Factor for Cable Sliding (EWSw)	0.2618
Chain Bearing Capacity Factor (N_{cc})	14
Cable Bearing Capacity Factor (N_{cw})	9
Chain Slide Adhesion Factor (a_c)	1.4
Cable Slide Adhesion Factor (a_w)	1.4

The surface friction factor between the mooring line and the soil is obtained from the description of the tangential force developed along the mooring line lying on the seafloor surface, i.e.,

$$F = c\, l + N\, \Delta \qquad (6)$$

where F = tangential force

c = soil cohesion

l = mooring line segment length

N = normal force

Δ = surface friction factor.

The magnitude of the surface friction factor can be evaluated from the field test results as follows.

At the beginning of the test, the entire mooring line either lies on the seafloor surface or is suspended in the water. When the mooring line is tensioned, the sum of the force at the anchor and the friction force along the mooring line must equal to the horizontal tension applied at the barge (Figure 3). Since the soil cohesion at zero depth is negligible, the surface friction factor, Δ, can be calculated from

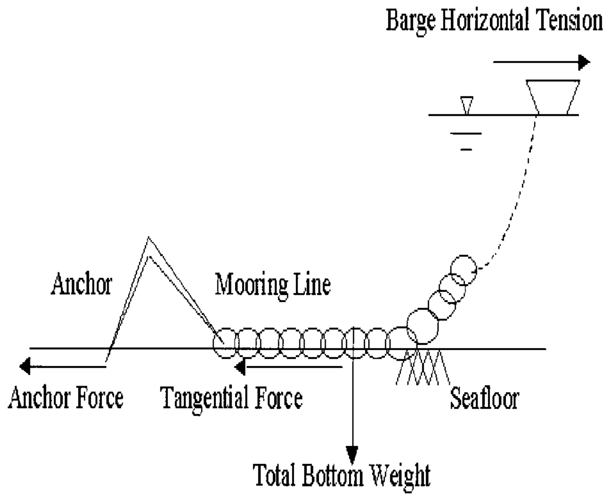

Fig. 3. Anchor and mooring line on seafloor

$$\Delta = \frac{F}{N} \qquad (7)$$

where F = barge horizontal tension minus measured anchor force at zero penetration depth

N = total weight of mooring line on seafloor surface at zero penetration depth.

Using the results of field measurements at given water depth and anchor depth, the surface friction factors at the seafloor surface were obtained as shown in Table 3. Results of field tests, except those whose surface friction factors could not be determined due to insufficient field

Table 3. Surface Friction Factors of Indian Island

Test No.	Anchor Crown Depth (m)	Water Depth (m)	Barge Horiz. Force (kN)	Anchor Force (kN)	Barge Horiz. Force − Anchor Force (kN)	Total Bottom Weight (kN)	Surface Friction Factor
170−1	27.3	26.3	59.6	12.5	47.1	97.2	0.485
172−7	24.6	24	77	11.1	65.8	93.1	0.707
172−8	27.8	27.7	90.3	14.7	75.6	91.8	0.823
172−9	28.4	28.1	77.8	0.9	77	114.8	0.670
172−10	28	28	102.7	3.6	99.2	111.2	0.892
174−13	26.6	26.5	87.2	No Data	***	121	***
174−14	27.2	27.1	98.7	No Data	***	119.6	***
176−23	24.6	25	127.7	2.7	125	102.2	1.223
176−25	28.3	27.2	185.5	No Data	***	104.4	***
208−5	26.8	27.1	61.4	33.8	27.6	90.1	0.306
209−12	26.2	26.8	58.7	0.4	58.3	125.9	0.463

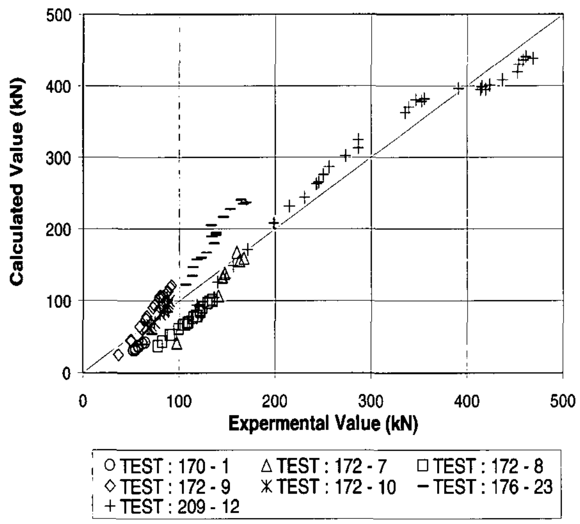

Fig. 4. Comparison of axial force at anchor

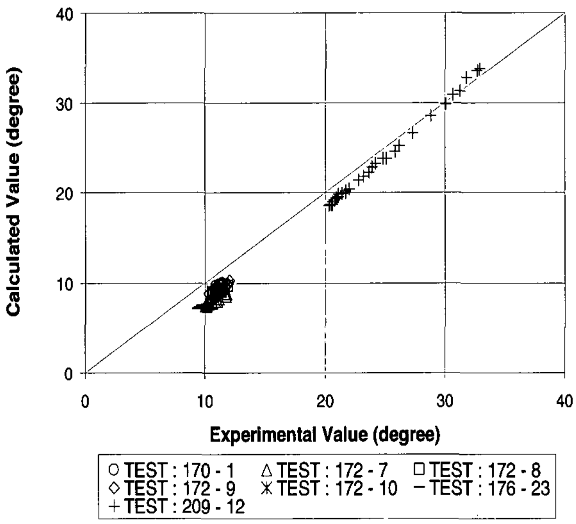

Fig. 5. Comparison of angle at buoy

data, on the axial force at anchor, the mooring line inclination angle at the buoy, and the mooring line length on the bottom have been compared with the analytical predictions. Figures 4 through 6 show the summary of comparisons between the measured and the predicted values. As can be seen from Figure 4, the measured anchor forces agree very well with the analytical solutions. The mooring line inclination angles at buoy also show very good agreement between the measured and the calculated values, as shown in Figure 5, for all tests. Figure 6 indicates that the predicted values of the mooring line on the bottom slightly overestimate the measured values.

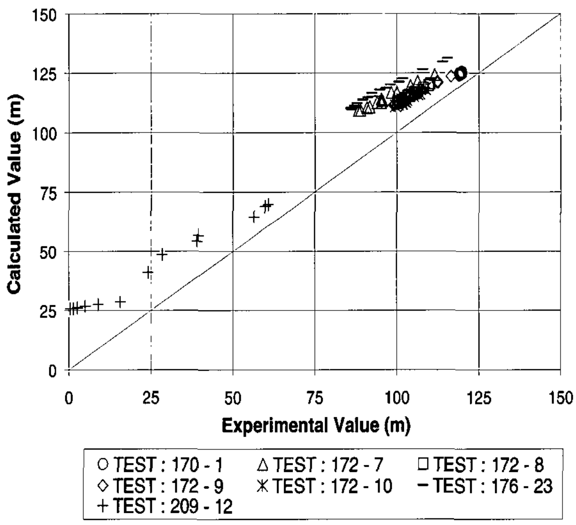

Fig. 6. Comparison of chain length on bottom

5. Conclusion

An analytical solution that can calculate the detailed responses of mooring lines upon tensioning is described. The effectiveness of the solution was validated through comparisons with the field mooring line tests conducted in cohesive seafloor. Comparisons include the anchor force, the mooring line angle at the buoy, and the mooring line length on the bottom.

Although slight deviation exists between the measured and the predicted values, the results indicate that the developed analytical solution is capable of predicting the essential responses of mooring lines with high degree of accuracy. This discrepancy may be in part due to the variation in soil conditions at the test site. The validation of the analytical solution is limited to cohesive seafloor soils as described in this paper. For the analytical solution to be completely validated, it is absolutely essential to expand the validation process with either field or centrifuge test results in sandy seafloor soils.

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