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MOORING SYSTEM DESIGN AND OPTIMIZATION FOR FLOATING BRIDGE OF URMIA LAKE

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ABSTRACT

In order to get better understanding on the response of floating bodies, different design aspects of mooring lines has been investigated in this paper. Mooring lines are categerized into two types; the catenary settling on the sea floor (type 1) and the limited one which has no dead-length on sea floor (type 2). It has been observed that the stiffness of both types may be well predicted by Jain's formulation and in the design process of floating bodies the mooring lines may be replaced by uncoupled horizontal and vertical springs. On the other hand, the anchor capacity against sliding and release from the mean still water has been studied in this paper. From the results of a parametric study, using the discrete element method, the block anchor the dimensions for the Urmia floating bridge has been optimized and the behavior of anchor and seabed deposits for release of block anchor indicates that the burial depth and the stress level on the block anchor itself and the sea bed are in the allowable and elastic region, respectively.

KEYWORDS: Floating Bridge, Mooring System, Design, Analysis, Discrete Element Method.

INTRODUCTION

Station keeping of vessels and platforms has always been an important matter to offshore and marine operators. In order to have a better and more reliable mooring system, one should be able to select proper mooring system components. This paper discusses the steps of the mooring system design for the floating bridge of the Urmia Lake in west of Iran. It contains the process of mooring line selection and the procedure of anchor design. To assure a properly operating condition numerical analysis was performed on both the anchor and the mooring line problem and a dimensional optimization was obtained.

Based on how a cable is attached to the sea floor, we can classify the mooring lines into two different categories. One of them is the catenary settling on the sea floor (type 1). The second type is a limited one which can have a nonzero angle at its attachment point to seabed (type2). The difference between these two types is that the former can maintain its zero angle at the bottom just by decreasing its dead-length on sea floor, while the latter's bottom angle is subject to change when the force on its other end alters.

According to Patel [1], O'Brien and the Francis [2] established some mathematical developments on mechanics of hanging catenary. Jennings [3] presented some other studies on this case, considering elastic lines and also the effect of temperature expansion on the catenary. Pryrot [4] worked on a computer algorithm deriving the end force and tension distribution in a catenary by knowing its end co-ordinates, line elasticity and unstretched length. Faltinsen [5] developed some formulations for partly settled mooring lines, which was mentioned above as type 1. He discussed a basic method of mooring line selection with regard to the water depth and cable strength and found a minimum allowable length for the designed cable. Additionally, he suggested a nonlinear horizontal stiffness for mooring line of type 1, which can be used for structural analysis of the vessel and its mooring

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system. For mooring lines of type 2, Jain [6] prepared a technical note discussing the change of horizontal force at the attachment of the catenary to the vessel with regard to vessel movements in two different directions. He developed a two-dimensional matrix for the elastic stiffness of the mooring line, also considering an arbitrary angle at the bottom. Finally, Huang and Vassalos [7] presented a semi-analytic approach for three-dimensional statics of marine cables. Their solution was derived as a function of only three parameters, which could be solved numerically by implementing different kinds of boundary conditions permitting quick parametric studies for optimal selection of the system particulars.

About anchor design, except for some empirical relations as in NAVFAC [8] and MIL-HDBK [9], no particular study was found. For a more exact study of the anchor, we had to model the anchor physically or mathematically. Two aspects were desired to be investigated: block anchor burial depth and the stability problem. Firstly, the block anchor was designed according to empirical relations. Then, the design was analyzed by a numerical method (DEM)[3] and the proper dimensions were obtained. Finally an optimization procedure was performed for this case.

NOMENCLATURE

A	Surface of Interaction between block and seabed
C	Cohesion
$F\phi$	Force due to friction
F_c	Force due to cohesion
F_τ	Shear resistance
h, Y	Sea Depth
H	Height of block anchor
K_H	Horizontal stiffness
K_V	Vertical Stiffness
L	Cable length
L’	Cable length in deformed shape
l	artificial cable length between B and O
l’	artificial cable length between B and O’ (deformed shape)
SF	Safety Factor
Ts	Cable strength
T_H, T_0, Tx	Horizontal force
T_{max}	Maximum tension in mooring cable
T_B	Tension at the bottom of cable
T_A	Tension at the end of catenary
w	Weight per unit length of cable in water
W	Anchor weight
θ_B	Bottom angle of catenary
X	Horizontal distance between catenary’s ends
x_B	Cable dead-length
ΔT_x	Horizontal component variation in force
ΔT_y	Vertical component variation in force
Δx	Horizontal movement in catenary end
Δy	Vertical movement in catenary end
ϕ	Friction angle

CABLE DESIGN AND ANALYSIS

The process of cable design starts with regard to the maximum value of the different horizontal forces produced by the different mooring lines of the ship. Average/maximum of different loading conditions gives different average/maximum values for nodal forces. If we denote the average/maximum of nodal forces by F_{mean}/ F_{max} respectively, then:

$T_s \geq T_{max}$ .S.F. = (F_{max} + wh) (S.F.) (1)

The second step is to analyze the mooring line with regard to its operational condition. In this regard, based on the type of mooring line discussed in earlier section, we may use different formulations. According to Faltinsen [5]:

$$L_{min} = h\left(2\frac{T_{max}}{wh}-1\right)^{\frac{1}{2}} \quad (2)$$

Where L_{min} is the minimum required cable length in case of θ_B =0. Moreover, he has established a relation between X and T_H let.

$$X = x_B + x \quad (3)$$

Where x_B is the length of cable which settles down on the seabed, X is the distance between points A and B in Fig. (1). By considering T_H, equation (3) becomes:

$$X = L - h\left(1+2\frac{a}{h}\right)^{\frac{1}{2}} + aCosh^{-1}\left(1+\frac{h}{a}\right);\ a = \frac{T_H}{w} \quad (4)$$

And the horizontal stiffness for the cable has been represented as:

$$K_{xx} = w\left[\frac{-2}{\left(1+2\frac{a}{h}\right)^{\frac{1}{2}}} + Cosh^{-1}\left(1+\frac{h}{a}\right)\right]^{-1} \quad (5)$$

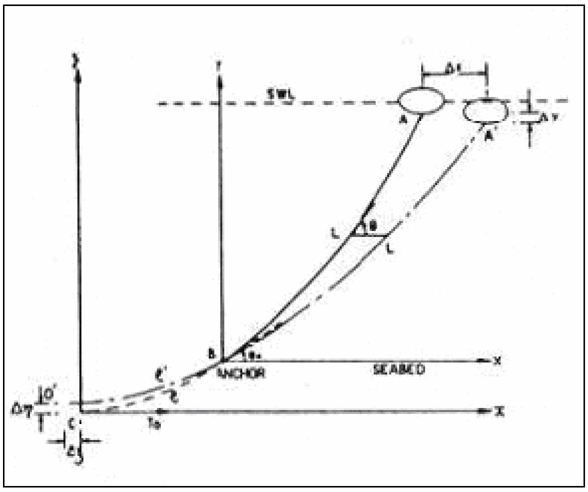


Fig. (1) Schematic of a Cable

If we consider a limited catenary as described in the last section, we have to consider the Jain’s formulations [6]. In this case, the value of the vertical tension and the bottom angle are also subject to change when the vessel oscillates about its position.

[3] Discrete Element Method

By considering $\theta_B = 0$ we find that the result of Jain's formulation is equal to the value obtained by Faltinsen's. This means that Faltinsen's problem is a combination of Jain's problem, also considering a dead-length on the seabed.

From Jain's formulation's we have:

$$\begin{bmatrix} \Delta T_x \\ \Delta T_y \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{6}$$

Where,

$$K_{xy} = K_{yx} = T_0 \left[Y - w \left(\frac{T_B L'^2 - T_A l^2}{T_A T_B} \right) + w \left(\frac{T_B L' - T_A l}{T_A - T_B} \right) \left\{ \frac{X}{T_0} - \left(\frac{T_B L' - T_A l}{T_A T_B} \right) \right\} \right]^{-1} \tag{7}$$

$$K_{xx} = \frac{w}{T_0} \left(\frac{L' T_B - l T_A}{T_A T_B} \right) K_{xy} \tag{8}$$

$$K_{yy} = \frac{w}{T_0} \left(\frac{T_B T_A}{T_A - T_B} \right) \left\{ \frac{X}{T_0} - \left(\frac{L' T_B - l T_A}{T_A T_B} \right) \right\} K_{xy} \tag{9}$$

and $\Delta x = X_2 - X_1$, $\Delta T = T_2 - T_1$

In this regard we establish two observations. First, by assuming $\Delta y = 0$ we find the values ΔT_x by evolving different steps of Δx, so we would be able to find a nonlinear horizontal stiffness, K_H, as:

$$K_H = \frac{\Delta T_x}{\Delta x} \tag{10}$$

Similarly, we can arrange for a nonlinear vertical stiffness, K_v, based on different values of ΔT_y with respect to Δy as:

$$K_v = \frac{\Delta T_y}{\Delta y} \tag{11}$$

These values of nonlinear horizontal and vertical stiffnesses can be entered in the stiffness matrix pertaining bridge structure and mooring lines.

ANCHOR DESIGN AND ANALYSIS

The anchors in this case were assumed to be concrete blocks. From empirical methods as in [8] and [9], the preliminary anchor endurance is estimated by the value of the force at the bottom of the mooring line, in a manner that the anchor's weight in water provides the sufficient balance against the mooring force. In more details one can also consider some geotechnical relations in order to estimate the anchor capacity against sliding. To evaluate the stability of a block anchor against sliding, for an elementary analytical solution, we used the Mohr-Coulomb criterion, which has an acceptable precision for soil mechanics problems [11].

$$F_\tau = F_C + F_\phi \tag{12}$$

The forces, acting on concrete block, are shown in Fig. (2). By force equilibrium in the horizontal and vertical direction we can write the following relation for the safety factor against block sliding:

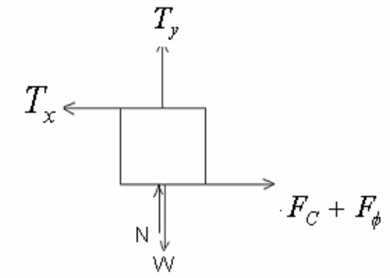


Fig. (2) The forces acting on concrete block

$$S.F. = \frac{F_\phi + F_c}{T_x} = \frac{C.A + (W - T_y).\tan\phi}{T_x} \tag{13}$$

For unit thickness, with regard to Eq. (13) we get:

$$L = \frac{(S.F.)T_x^1 + (T_y^1 - W)\tan\phi}{C} \tag{14}$$

Where L is the block length. On the other hand, by considering the safety factor, the height of a square block for preventing the vertical motion will be:

$$H = \frac{(S.F.)T_y}{L^2.\gamma} \tag{15}$$

Where γ is the weight density of block material. A computer program UDEC is written on the basis of discrete element and is used successfully to model the behavior of discontinuous surfaces (like concrete-soil interface) and behavior analysis of separated blocks. The calculations performed in UDEC are based on Newton's 2nd law, conservation of mass and momentum and energy equilibrium [2].

CASE STUDY

As case study, we tried to use the above stated design and analysis procedure to find a suitable mooring system for the floating bridge of Urmia Lake. Owing to the fact that the structural system was selected as concrete pontoons, it was found that a static analysis would be sufficient for the mooring line. The operational region where the bridge was considered to work had a water depth of 7 meters. Below the seabed the boring hole consists of about 15 meters organic clay and in this paper, the strength of this layer was omitted for safety reasons. Therefore, we considered the water depth as 22 meters for the case study. In this regard after calculating the different values of nodal forces in different loading conditions, the values of F_{max} and F_{mean} was gained as following:

F_{max}= 70.6 tons; F_{mean} =67.5 tons

As for mooring line, with S.F.=3, a wire rope with the following properties was selected:

6×37 Class, IWRC[4], EIPS[5], w=13.9kg/m, d=57 mm, Ts=224 ton.

The cable was considered to operate in a limited form (type 2) with the angle of 30° at the bottom. A numerical investigation was established for this condition, and the results are shown in

4 Independent Wire Rope Core

5 Extra Improved Plow Steel

Figs. (3), (4) and (5). The aim was to find values of the horizontal and vertical stiffnesses for the catenary, which could be used in the structural analysis of the bridge.

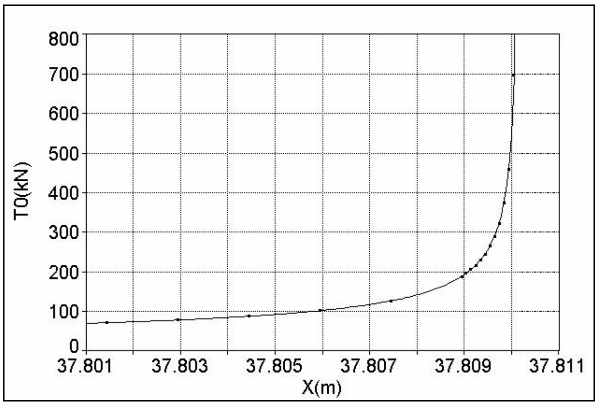


Fig. (3) Relation between T_0 and the distance X for a limited section of the catenary, design angle $\theta_B = 30°$ at the bottom

As mentioned in the previous section, we seek to find the approximate values of K_H and K_v by decomposing the horizontal and vertical stiffness of cable.

The relation between ΔT_0 and Δx was approximated as the following function:

$$\Delta T0=(a+c\Delta X+e\Delta X^2)/(1+b\Delta X+d\Delta X^2)$$

a=0.04605457 b=-201.34133 c=3836.6121
d=9951.6688 e=-409072.92

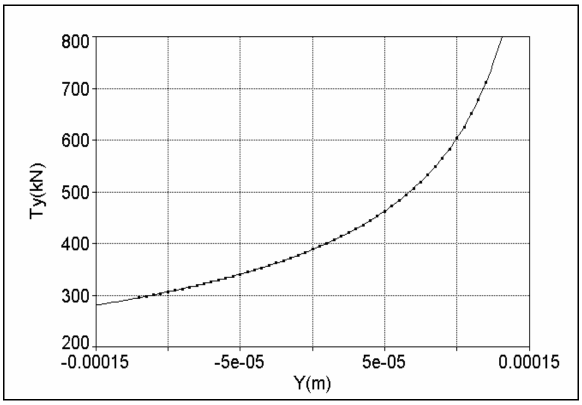


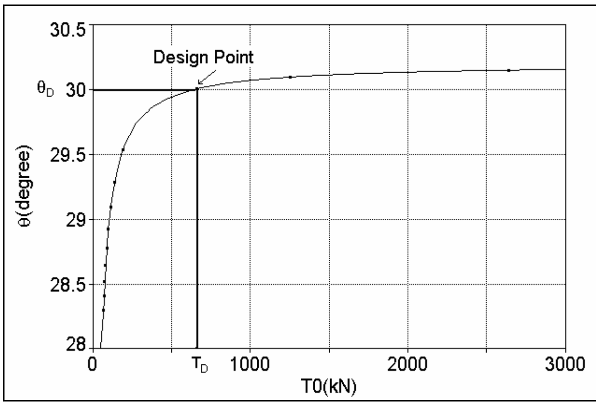
Fig. (4) Graph of vertical position of catenary end in response to vertical force with a bottom angle of 30°

Similarly, for vertical stiffness, a functional relation is fitted for ΔT_y against Δy as:

$$\Delta Ty=(a+c\Delta y)/(1+b\Delta y)$$

a=91.904513 b=-4604.2997
c=751228.34

For catenary of type 2, as shown in fig (5), the angle of θ_B is subject to change when the value of the force at the end changes. The value of θ_B gets stabilized after a definite range of horizontal force. The variation of θ_B at different values of T_0 indicates a continuous and smooth curve, which is less influenced by variation of T_0.



Fig

Fig. (5) Alteration of θ_B with regard to T0

For catenary of type 1, both Faltinsen's and Jain's formulations was investigated. Fig. (6) illustrates the relation of X, x and T_0 based on this idea. It shows that the Jain's analysis for constant zero angle is the same as Faltinsen's if we do not consider the dead-length settled on the seabed in Faltinsen's formulation.

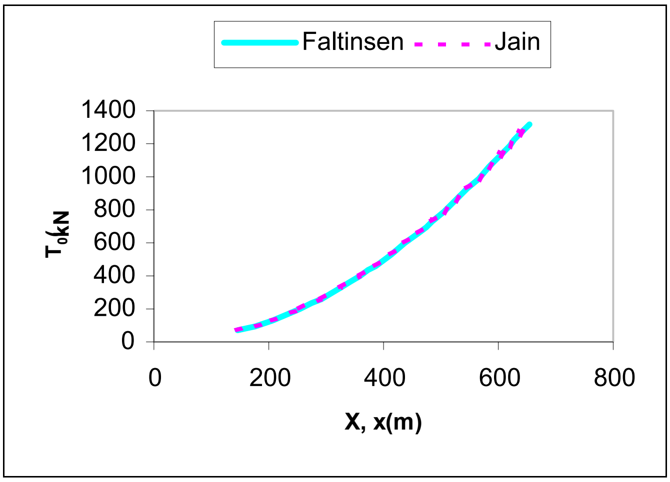


Fig. (6) Comparison of Faltinsen's results with Jain's for catenary type 1

Besides, both type 1 and type 2 catenaries' behavior were investigated using Jain's formula at zero angle at the bottom in Fig. (7).

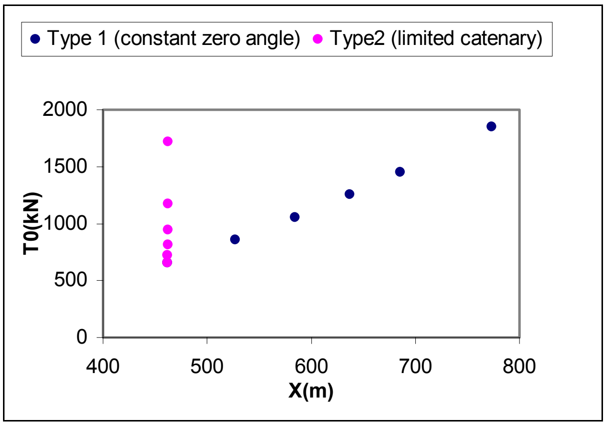


Fig. (7) Comparison of Jain's results for catenaries of type 1 and type 2

For relation between ΔT_y and Δy for θ_B =0°, according to Fig.(8), we find:

$$\Delta Ty^{0.5}=(a+c\Delta y+e\Delta y^2)/(1+b\Delta y+d\Delta y^2+f\Delta y^3)$$

a=0.41278612 b=0.27340152 c=4.5070331

d=-0.73273798 e=-2.1809969 f=0.1739545

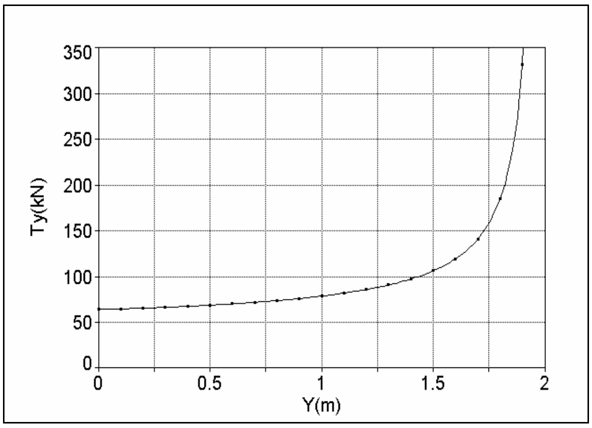


Fig. (8) Graph of vertical position of catenary end in response to vertical force with the bottom angle of θ_B = 0°

For an investigation of the change of the angle θ_B from its initial value, zero, with regard to the horizontal force in type 2 cables we can see from Fig. (9) that it starts to change rapidly by increasing the value of the horizontal force and gets stable at high values of T_0, So selection of catenary type 2 with the angle bottom of zero instead of 30 would not be a suitable design.

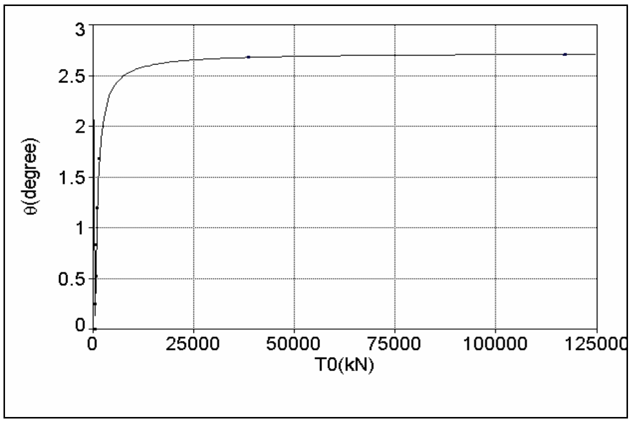


Fig. (9) Change of angle θ_B in type 2 catenary for θ_B =0 as function of T_0

As for the anchor study, by a set of experiments, the following average values were obtained for the soil-concrete interface of the seabed: ϕ =0, C=20 kN/m^2.

Due to the horizontal force, F_{max}=70.6 *ton*, and for a bottom angle, θ_B =30°, with regard to the empirical relations, and a S.F.=2, the preliminary dimensions for the block anchor was found to be as the following (from Eq. 14 & 15):

L=8.32 *m*, B=8.32 *m*, H=1.83 *m*.

To ensure a safe design, we established an analysis for the concrete block by UDEC. Results showed that the block anchor with the above-mentioned dimensions is not able to satisfy the stability condition against sliding. Fig (10) shows the accelerating motion of the block anchor in the horizontal direction. Also it was found that even by increasing the length of the block anchor to a value of 11.5 meters, the block would not be stable against sliding. By an increase in its height by 30 centimeters the block came to equilibrium in this analysis.

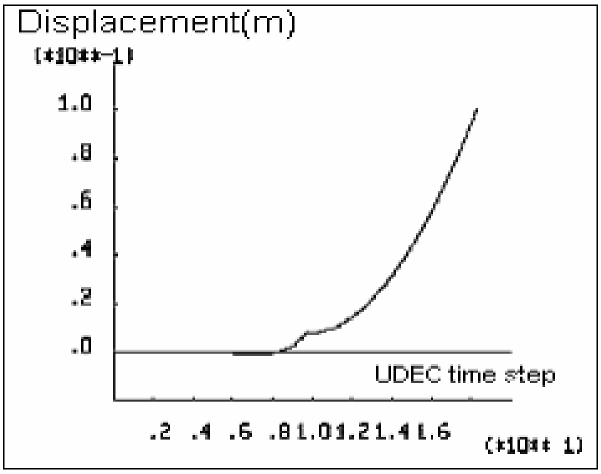


Fig. (10) Diagram of block motion in the horizontal direction

Finally, after a set of iterations in UDEC, the block dimensions were optimized as 9.5×9.5×2.1. The motion diagram for this block has been shown in Fig. (11).

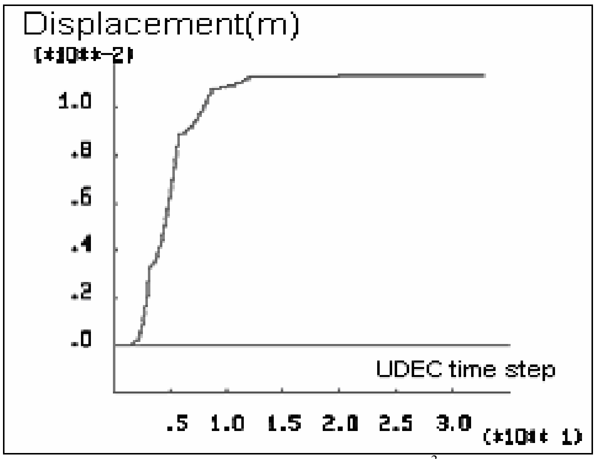


Fig. (11) Motion diagram for a 9.5 × 9.5 × 2.1 m^3 block in horizontal direction

Two types of anchor release, vertical and combined vertical and rotational movement were investigated. The anchor and the soil layer models are shown in Fig. 12. UDEC showed that if this block was released from the water surface, it would not reach the plastic region after hitting the sea floor.
To model the seabed in this part, the material properties including cohesion, internal friction, etc. have been given, considering 6 different layers. Result of hitting moment in the vertical releasing has been illustrated in Figs. (13) to (16). Note that, the tensile and compressive stress shown in Fig. (13) and (14) document that these values are much smaller than the allowable ones. Fig (17) shows the burial depth of block in the seabed in metric units. The burial depth showed no major change in depth, which was considered in the cable design procedure.

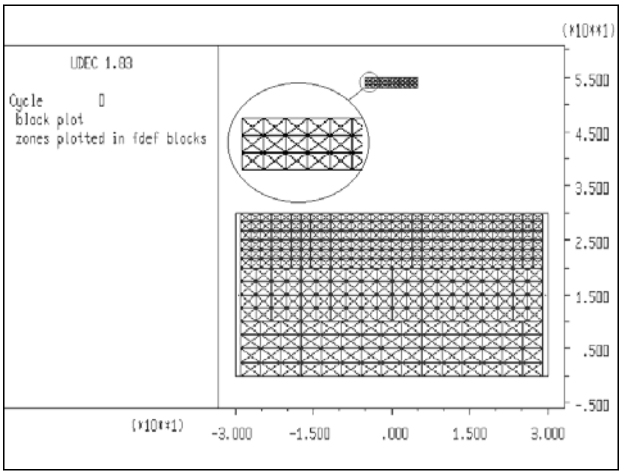


Fig. (12) Lay out of model for release analysis

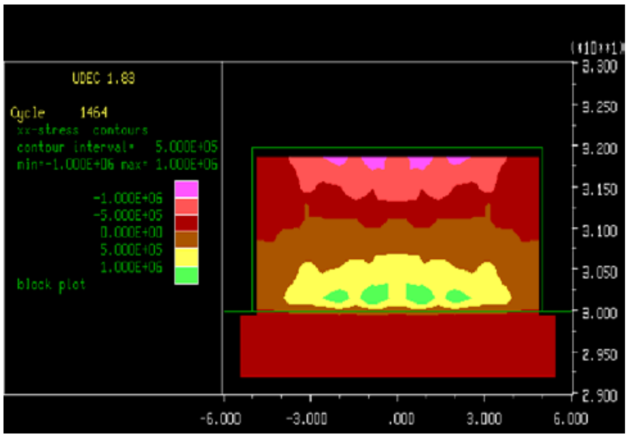


Fig. (13) XX stress contour for block hitting the seabed

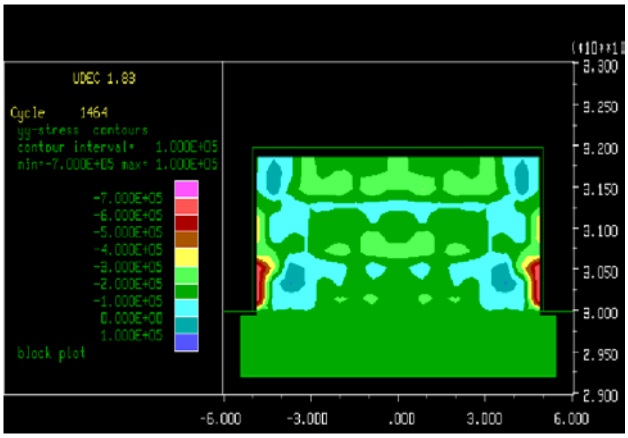


Fig. (14) YY stress contour for block hitting the seabed

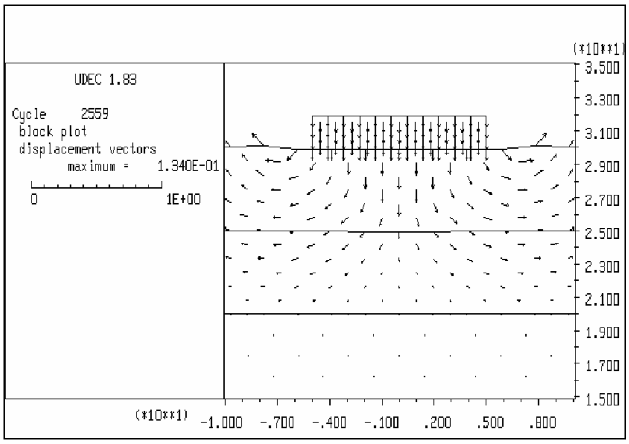


Fig. (15) Schematic of displacements and behavior of block after hitting to the sea floor

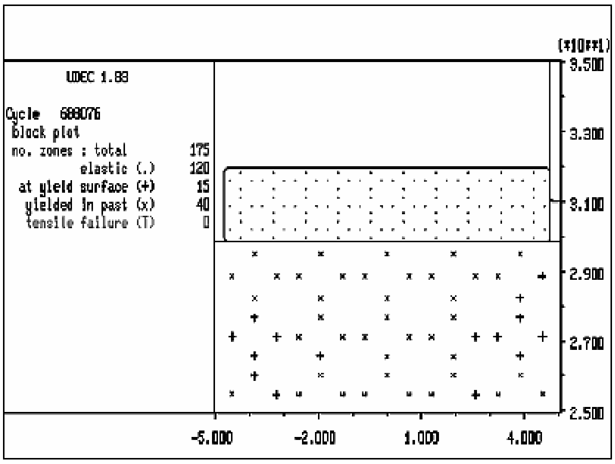


Fig. (16) The block after hitting sea floor

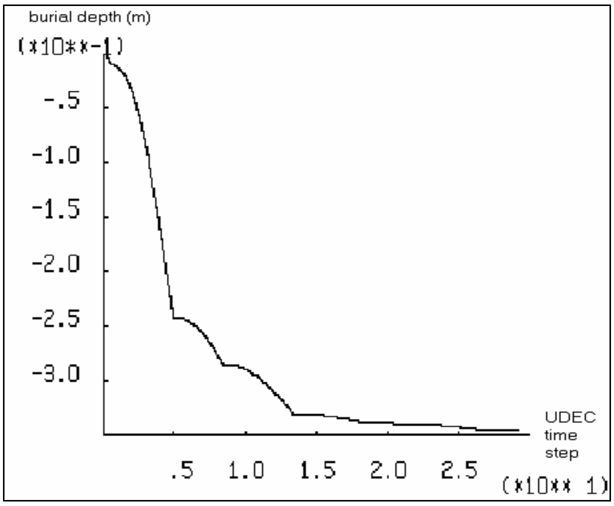


Fig. (17) Diagram showing the burial depth of block

CONCLUSIONS

1. Two nonlinear spring models simplify the stiffness analysis of mooring lines. The horizontal and vertical stiffnesses of these springs were approximated by nonlinear functions of K_{xy} ,K_{xx} , K_{yx} and K_{yy} for K_H and K_v , respectively.
2. A major difference for the stiffness of mooring lines has been found between catenary type 1 and type 2. In the same loading conditions, the value of stiffness in type 2 would be far higher than in type 1.
3. Depending on the operational response expected from the moored structure, one of the catenary types is preferred. For cases similar to floating bridges, using catenary of type 1 would not be rational.
4. In the analysis of catenaries of type 2, it was found that for small values of the bottom angle (θ_B), we face a great change in the value of θ_B when the horizontal force increases. On the other hand, an inverse observation is expected for the decrease in the horizontal force (T_0) in the case of large values of the bottom angle.
5. Analysis for both catenaries of type 1 and 2 can be accomplished by using the formulation represented by Jain. It has been concluded that Faltinsen's formula is a particular case of Jain's.
6. The discrete element method applied in the computer program UDEC has been used in sliding and releasing analysis of the block anchor. Since the empirical methods often neglect the dynamic effect of the sliding problem, a relatively large discrepancy has been found between these methods and the discrete element method.
7. For the parametric case study, the burial depth of the released block anchor on the sea floor is apparently infinitesimal; as a result it will not affect the design water depth that was considered in the preliminary equations considerably.

ACKNOWLEDGMENTS

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REFERENCES

[1] Patel, M. H., 1989, "Dynamics of Offshore Structures", Butterworth & Co. (Publishers) Ltd, England.

[2] O'Brien, W. T. and Francis, A. J., 1964, "Cable Movements under Two Dimensional Loads", *Journal of the Structural Division, American Society of Civil Engineers*, ST3, June, pp. 89-123.

[3] Jennings, A., 1965, "Cable Movements under Two Dimensional Loads – A Discussion", *Journal of the Structural Division, American Society of Civil Engineers*, ST1, Feb., pp. 307-311.

[4] Peyrot, A. H., 1980, "Marine Cable Structures", *Journal of the Structural Division, American Society of Civil Engineers*, Dec., pp. 2391-2404.

[5] Faltinsen, O. M., 1980, "Sea Loads on Ships and Offshore Structures", Cambridge University Press.

[6] Jain, R.K., 1980, "Technical Note, A Simple Method of Calculating the Equivalent Stiffnesses in Mooring Cables", *Applied Ocean Research*, Vol. 2, No. 3.

[7] Huang, S. and Vassalos, D., 1993, "A Semi-Analytic Treatment of Three-Dimensional Statics of Marine Cables", *Ocean Engineering*, Vol. 20, No. 4, pp. 409-420.

[8] (Anon.), 1986, NAVFAC Design Manual 26.4, April.

[9] (Anon.), 1999, Mooring Design, Department of Defense Handbook, MIL-HDBK 1026/4A, July.

[10] (Anon.), 1993, UDEC User's Manual, ITASCA Consulting Group.

[11] Das, Braja. M., 1941, Principals of Geotechnical Engineering.

