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Application of an Integrated CRITIC-EDAS Method in Optimal Anchoring Operations of Horizontally Loaded Offshore Structures on a Medium Clay Seabed

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Abstract

Floating offshore structures are dynamic structures influenced by environmental loads. This study entails optimization of anchoring operations on horizontally loaded offshore structures on a medium clay seabed location. In view of this, an integrated CRITIC-EDAS method is employed. The anchor alternatives considered in this study are the drag-embedment, dead weight, piles and the vertical load anchor types. The considered anchor types are analyzed using four basic criteria such as cost, ultimate holding capacity of the anchor, suitability for the loading direction, and the seabed suitability. A CRITIC method is used as a tool for assignment of weights to the criteria, while the EDAS method is utilised in evaluation and ranking of the anchor alternatives. The result obtained, showed that the drag-embedment anchor is the best alternative with an appraisal score of 1.

Keywords: Anchor, Load, Offshore structure, CRITIC, EDAS, Seabed,

1. Introduction

Metocean conditions can affect optimal operations of floating offshore structures. Horizontal loads on offshore structures are wind and wave induced loads, creating horizontal moments and forces on the structures. Anchors is used toposition mooring lines of floating offshore structures on a seabed. The fundamental requirements for anchors are to be able to resist horizontal and vertical loads on soft or hard seabed; and easy installation in a cost effective manner. Complexity of technologies in deepwater moorings, has made anchor behaviors in the seabed to become more complicated and pose a great challenge to the analytical methods (Zhao & Liu, 2016).The commonly used anchor types are the drag-embeded, dead weight, piles, and the vertical load anchors. Anchor optimization is one of the most vital activities in the marine and offshore industry. The ultimate goals of anchor optimization are to maximize profit; and contribute significantly in provision of safe marine environment for various operations.Anchor optimization for horizontally loaded structures mounted on any given seabed location is a complex task and requires the consideration of many technical, environmental and economical factors. The appropriate anchor type is the type that is technically viable for the seabed conditions in a cost effective manner.

Deployment of an anchor type utilised in a marine and offshore engineering operations for another operations tends to lead to disaster without considering the characteristics of the seabed and metocean conditions. Effective decisions on the choice of an anchor can usually be perceived only through a detailed analysis of the seabed and the loads that will act on it.Analysis of different anchor alternatives have been conducted in various publications (VanZwieten et al., 2014; Diaz et al., 2016; Ming &Aggidis, 2008; Zhao & Liu, 2016; Rao et al., 2006; Ehlers et al., 2004; O'Loughlin et al., 2018., Harris et al., 2006; and Qiao et al., 2020).In VanZwietenet al. (2014), anchoring systems such as deadweight, plate, pile and drag embedment suitable for ocean current turbines were compared.They utilised numerical simulations of single point moored marine hydrokinetic devices toextract anchor loading at a likely deployment location for mooring scopes from 1.25 to2.0 and turbine rotor diameters between 3–50m.

In Diaz et al (2016), examination of different anchor types that can be used for floating offshore wind towers (FOWTs) was conducted, within the context of their traditional usage in securing a single mooring line to the seabed. Anchor types such as driven piles, dynamic piles, suction caissons, drag embedded, vertically loaded, pile driven plate, dynamically embedded plate, and suction embedded plate anchors were the ones examined. Ming & Aggidis (2008) discussed anchors in relation to the behaviour and performance of wave energy converters and their comparisons were conducted with similar offshore operations. Thus, revealing typical and desirable features of anchors for effective wave energy converter operations. In the works of Zhao & Liu (2016), a large deformation finite element (FE) analysis that utilised the coupled Eulerian–Lagrangian technique is performed to simulate the installation/mooring line, so as to reveal the analysis of anchor behaviors in the seabed. In Rao et al. (2006),tests were carried out on single pile, 2-pile, 4-pile anchors made out of pipe piles of 25.4 mm dia with length to diameter ratios of 10, 14 and 18; and model suction anchors of 113 mm dia. The impact of parameters such as consistency of the clayey soil in the seabed, mooring chain inclination, and anchor embedment ratios on pullout capacity were revealed. Ehlers et al. (2004) discussed two relatively proven anchor concepts such as the suction caisson and the vertical loaded (drag embedment plate) anchor, and two developmental anchor concepts such as suction embedded plate anchor and the torpedo/deep penetrating anchor.The authors demonstrated how the suction caisson is the preferred anchor for taut-leg mooring systems, irrespective of the economic issues associated with the fabrication and installation processes.

In O'Loughlin et al. (2018), the follower-embedded plate anchors are examined andways of refining their current design basis as articulated in design codes to reduce cost and risk are explained. Harris et al. (2006) reportedvarious types of wave energy converters. The designcriteriaof the mooring systems are also revealed.They discussed the varieties amongst conventional mooring systems and how they can be suitable for wave energy converter. In Qiao et al. (2020), drag anchor is classified as ananchorage foundation type. In their works, finite element analysis method was used to calculate the ultimate anchor holding capacity in the seabed soil. The incremental calculation method was used to predict embedded motion trajectory.The novelty of this study lies in the application of CRITIC-EDAS model in the optimization of an anchor type suitable for horizontally loaded structures on a medium clay seabed location.

1.1. Anchor System Description

The general anchor types evaluated in this study are the drag-embedment, dead weight, vertical load and pile anchors. Anchors have design variations and deployment methods(VanZwieten et al. 2014).The loading directions and the characteristics of the seabedare considered in anchor optimization in most studies (VanZwieten et al. 2014). The performances of anchors are evaluated in the study based on their ultimate holding capacities, the loading direction considered, seabead suitability and their cost implications.The drag embedment anchor is the most popular type of anchors in use today. They arefit for purpose in temporary and permanent station keeping of floating structures (Moharrami and Shiri, 2018).During the installation processes, the anchor, tensioned mooring line and anchor-handling vessel usually interact with each other (Wang et al. 2014).It has been designed to either fully or partly penetrate the seabead. Its holding capacity is generated by the resistance of the seabed infront of the anchor. The necessary parts of the drag embedment anchor are the fluke, shank and padeye. The connection between anchor andmooring line is termed padeye, while the fluke supports anchor's holding capacity at its utmost embedment depth. The design of the shank is made in a way that the soil resistance that is perpendicular to the anchor's embedment trajectory is reduced. The vertical load anchor is similar to drag embedment anchor. They utilised similar installation procedurewiththe drag embedment anchors. The only difference is that its shank is released to boost pull out capacity after the initial drag installation. Pile anchorhas hollow steel structure. It is driven into the seabed with the aid of a piling vibrator or hammer. It's holding capacity is generated by a combination of the lateral seabed resistance and the friction of the seabed along the pile. The pile is usually installed at a very deep depth that is below the seabed, so as to obtain the desired holding capacity. Deadweight anchoris probably the oldest type of anchor in use today. The holding capacity of this anchor type is generated by the weight of the deadweight material and partially by the friction between the seabed and the dead weight. Steel and concrete are the common materials in use for dead weight anchors.

1.2 Descriptions of Criteria

The criteria that will be considered for selection of the anchors are:

- Ultimate holding capacity: This refers to the ability of an anchor to withstand the load mounted on it effectively without failure.
- Loading direction: This is the ability of an anchor to withstand a load from a given direction.
- Seabed suitability: This refers to the compactibility of the seabed characteristics and the considered anchor type towards achieving the desired objective.
- Cost: This refers to the total cost of purchasing and installing an anchor alternative.

2. Methodology

An integration of the Criteria Importance Through Intercriteria Correlation (CRITIC) method and the Evaluation based on Distance from Average Solution (EDAS) method are employed in this study for the optimization exercise. Their respective functions are:

- A CRITIC method is used to estimate weights of the criteria for the considered anchor alternatives.
- An EDAS method is employed for the evaluation and optimization of the different alternatives considered.

2.1. CRITIC Method

The CRITIC method is a tool use to determine the objective weights of criteria (Diakoulaki et al., 1995). It induces the intensity of the contrast and the conflict in the structure of the subject under investigation (Diakoulaki et al., 1995). In this method, the contrasts between criteria are determined using correlation analysis (Yilmaz & Harmancioglu, 2010). The decision matrix is analyzed and the criteria contrasts are obtained using the correlation coefficients of all pairs of columns of the normalized criteria values and the standard deviation of the normalized criteria values (Madić& Radovanovic, 2005). The steps of CRITIC method are:

Step 1: The normalization of the decision matrix using the formula below.

$$T_{ij} = \frac{T_{ij} - T_j worst}{T_j best - T_j worst} \qquad 1$$

Step 2: Obtain the standard deviation (σ_j) for each criterion

Step 3: Obtain the symmetric matrix with element, γ_{jk}, which is the linear correlation coefficient of paired criteria.

Step 4: Obtain the measure of the conflict created by criterion j based on the decision situation defined by the rest criteria usingEquation 2.

$$\sum_{k=1}^{n} (1 - \gamma_{jk}) \qquad 2$$

Step 5: Quantity of the information in respect to each criterion using Equation 3.

$$C_j = \sigma_j \sum_{k=1}^{n} (1 - \gamma_{jk}) \qquad 3$$

Where, $C_j =$ Criteria contrast

Step 6: Obtain the objective weights of each criterion using Equation 4.

$$W_j = \frac{C_j}{\sum_{k=1}^{n} C_j} \qquad 4$$

Where, $W_j =$ the objective weight of criterion

2.2.EDAS Method

Keshavarz Ghorabaee et al. (2015) proposed EDAS method in 1995. EDAS method is very practical in problems with contradictory attributes. The alternatives are prioritize based on their distance from average solution. Two distances measures which are the Positive Distance from Average Solution (PDA) and the Negative Distance from Average Solution (NDA) are used to evaluate the alternatives. The alternative with the lower value of NDA and higher values of PDA is seen as the desirable alternative. The procedures for the computation of EDAS method are defined below:

Step 1: Selection of the available alternatives, and the basic criteria that describe the alternatives. A decision-making matrix x is then constructed as shown in Equation 5.

$$X = \left[X_{ij}\right] n \times m \begin{bmatrix} X_{12} & X_{12} & \ldots\ldots & X_{1n} \\ X_{12} & X_{22} & \ldots\ldots. & X_{2n} \\ X_{1n} & X_{2n} & \ldots\ldots.. & X_{mn} \end{bmatrix}$$

5

Where X_{ij} indicates the performance rating of the alternative i on the criterion j; assuming that all X_{ij} are positive real numbers.

Step 2: Determination of the average solution based on all criteria using Equation 6.

$$X_j^* = \frac{\sum_{k=1}^{m} X_{ij}}{m} \qquad 6$$

Step 3: Calculate the positive distance from average (PDA), denoted as d_{ij}^{+} and the negative distance from average (NDA), denoted as d_{ij}^{-}, based on benefit and non-benefit criteria as follow:

$$d_{ij}^{+} = \begin{cases} \dfrac{max(0,(x_{ij} - x_j^*))}{x_j^*}; & j \varepsilon \Omega_{\max} \\ \dfrac{max(o,(x_j^* - x_{ij}))}{x_j^*}; & j \varepsilon \Omega_{\min} \end{cases} \quad 7$$

$$d_{ij}^{-} = \begin{cases} \dfrac{max(0,(x_j^* - x_{ij}))}{x_j^*}; & j \varepsilon \Omega_{\max} \\ \dfrac{max(o,(x_{ij} - x_j^*))}{x_j^*}; & j \varepsilon \Omega_{\min} \end{cases} \quad 8$$

Where Ω_{max} and Ω_{min} indicates the set of the benefit criteria and non-benefit criteria respectively, and X^*_j is a positive number.

Step 4: Assuming that a vector $w = (w_1, w_2, \ldots w_n)$ of non-negative weights is given. The determination of the weighted sum of PDA, Q_i^{+} and the weighted sum of NDA, Q_i^{-} for all alternatives is obtained in Equations 9 and 10 respectivelyas follows:

$$Q_i^{+} = \sum_{ji=1}^{n} w_j d_{ij}^{+} \; 9$$

$$Q_i^- = \sum_{ji=1}^{n} w_j d_{ij}^- \quad 10$$

Where $w_j$indicates the objective weight of criterion

Step 5: Normalization of the values of the weighted sum of the NDA and the weighted sum of the PDA for all considered alternatives as follows:

$$S_i^+ = \frac{Q_i^+}{Max_i Q_i^+} \qquad 11$$

$$S_i^- = 1 - \frac{Q_i^-}{Max_i Q_i^-} \qquad 12$$

Where S_i^+ and S_i^- indicates the normalized weighted sum of the PDA and the NDA respectively.

Step 6: Calculation of the appraisal score,S_i, *for* all considered alternatives using Equation 13.

$$S_i = \frac{1}{2}\left(S_i^+ + S_1^-\right) 13$$

Step 7: Ranking of alternative based on decreasing values of the appraisal score. The alternative with the highest S_i value is rated as the best alternative.

3. Results and Discussion

3.1 Illustrative Case Study

In this research, the CRITIC-EDAS method is utilized in enabling optimal anchoring operations of horizontally loaded offshore structures on a medium clay seabed location.The mechanism of CRITIC-EDAS method is used to facilitate identification of the most effective anchor type in offshore environment.The anchors under investigation are drag embedment anchor, vertical load anchor, pile anchor and deadweight anchor, while the criteria that will be used to optimise them areultimate holding capacity, loading direction, seabed suitability and cost as evidenced in Sections 2 and 3 respectively.The step-by-step procedures of the CRITIC-EDAS model is systematically applied in the anchor optimization exercise.

3.2Application of CRITIC Method in Weight Estimation of the Anchor Optimization Criteria

Wrong decision making in selection of anchor type criteria at the planning stage of marine and offshore engineering operations have contributed significantly insystem failures.To address this problem in anchor optimization, three experts with equal experience of anchor installation and operations are employed in the numerical ratingsof the associated criteria, during weight estimation exercise. The three expertsnumerically rate each criterion and take the mean as the actual one, since they have equal experience of the subject under investigation. The CRITIC method is utilized in the estimation of the weights ofthe anchor selection criteria. The step by step approach of the CRITIC methodology. Available data provided by three experts in Table 2, using Table 1 as guideline in their engineering judgement are utilised in facilitation of the estimation of the weights of criteria such as ultimate holding capacity, loading direction, seabed suitability and cost. Equations 1-4 and Tables 1-10 are used to facilitate the weights estimation of the anchor optimizationcriteria. The mean of numerical ratings of the criteria are presented in Table 3.

Table 1: Criteria Rating Scale (Dantsoho, 2015)

0 1 2 3	4 5 6	7 8 9 10
Low	Medium	High

Table 2: Experts' Alternatives Ratings

Anchor Alternatives	Expert 1				Expert 2				Expert 3			
	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost
Dead weight	1	7	9	5	1	6	9	3	1	8	9	4
Drag-embedment	9	9	7	5	9	9	9	6	9	9	8	4
Piles	6	9	8	7	4	9	6	8	5	9	7	9
Vertical load anchor	7	9	6	8	8	9	7	8	6	9	8	8

Table 3:Mean of Experts' Criteria Numerical Ratings with Associated Best and Worst Value

Anchors	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost
Dead weight	1	7	9	4
Drag-embedment	9	9	8	5
Piles	5	9	7	8
Vertical load anchor	7	9	7	8
Best value	9	9	9	4
Worst value	1	7	7	8

The decision matrix in Table 3, is normalised using Equation 1 and the result obtained is presented in Table 4. The standard deviation for each criterion is calculated and results obtained are demonstrated in Table 5. The correlation coefficients of all pairs of columns are obtained, thus a systemmetric matrix is constructed as demonstrated in Table 6. The measure of the conflict created by each criterion based on the decision situation is defined by the rest criterion is calculated using Equation 2 and results presented in Table 7. The criteria contrasts are calculated using Equation 3 to obtain the results presented in Table 8.

Table 4: Normalized Rating Values

Anchors	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost
Dead weight	0.00	0.00	1.00	1.00
Drag-embedment	1.00	1.00	0.50	0.75
Piles	0.50	1.00	0.00	0.00
Vertical load anchor	0.75	1.00	0.00	0.00

Table 5:Normalized Rating Values

Anchors	**UltimateHolding Capacity**	**LoadDirection**	**Seabed suitability**	**Cost**
Dead weight	0.00	0.00	1.00	1.00
Drag-embedment	1.00	1.00	0.50	0.75
Piles	0.50	1.00	0.00	0.00
Vertical load anchor	0.75	1.00	0.00	0.00
σ_j	0.4270	0.50	0.4787	0.5154

Table 6: System Matrix

Anchors	**Ultimate HoldingCapacity**	**Load Direction**	**Seabed suitability**	**Cost**
UltimateHolding Capacity	1.00	0.8783	-0.5606	-0.3550
LoadDirection	0.8783	1.00	-0.8704	-0.7276
Seabed suitability	-0.5606	-0.8704	1.00	0.9711
Cost	-0.3350	-0.7276	0.9711	1.00

Table 7: Measure of the Conflict

Anchors	**Ultimate Holding Capacity**	**Load Direction**	**Seabed suitability**	**Cost**	$\sum_{k=1}^{n}\left(1-\gamma_{jk}\right)$
Ultimate HoldingCapacity	1-1.0 = 0	1-0.8783=0.1217	1-(-0.5606) = 1.5606	1-(-0.3550)= 1.355	3.0373
Load Direction	1-0.8783 = 0.1217	1-1.00 = 0	1-(-0.8704) = 1.8704	1-(-0.7276) = 1.7276	3.7197
Seabed suitability	1-(-0.5606) = 1.5606	1-(-0.8704) = 1.874	1-1.0 =0	1-0.9711 = 0.0289	3.4599
Cost	1-(-0.3350) = 1.3350	1-(-0.7276) = 1.7276	1-(0.9711) = 0.0289	1-1.00 = 0	3.0935

Table 8: Criteria contrasts

Anchors	σ_j	$\sum_{k=1}^{m}\left(1-\gamma_{jk}\right)$	C_j
Ultimate Holding Capacity	0.4270	3.0373	1.2969
Load Direction	0.5	3.7197	1.8599
Seabed suitability	0.4787	3.4599	1.6563
Cost	0.5154	3.0935	1.5944
$\sum_{j=1}^{m} C_j$			6.4075

The weights of the criteria are calculated using Equation 4 and the obtained are presented in Table 9.

Table 9: Weights of Criteria

Anchors	$\frac{C_j}{\sum_{j=1}^{m} C_j}$	W_j
Ultimate Holding Capacity	$\frac{1.2969}{6.4075}$	0.2024
Load Direction	$\frac{1.8599}{6.4075}$	0.2903
Seabed suitability	$\frac{1.6563}{6.4075}$	0.2585
Cost	$\frac{1.5944}{6.4075}$	0.2488

3.3 Utilization of an EDAS Method in Estimationof Appraisal Score for Ranking of Anchor Types

The steps of EDAS method is logically applied in anchor optimization. Average solution of criteria is estimated using Equation 6 and the results obtained are presented in Table 10. ThePDAis determined for each alternative using Equation 7, and the obtained results are demonstrated in Table 11. The weighted sum of PDAis determined for each alternative using Equation 9, and the results obtained are presented in Table 12. The NDA for each alternative is determined using Equation 8, and the obtained results are presented in Table 13.The weighted sum of NDA is determined for each alternative using Equation 10, and the calculated results are presented in Table 14. The normalization of the values of the weighted sum of the PDA and the NDA are determined using Equations 11 and 12 respectively. The appraisal score (Si) for all considered alternatives are obtained using Equation 13 and the results presented in Table 15. The alternatives are ranked using their respective appraisal score, as presented in Table 15. The best alternative is associated with highest score and vice- verse.

Table 10: Average Solution of Criteria, X_j^*

Anchors	**Ultimate Holding Capacity**	**Load Direction**	**Seabed suitability**	**Cost**
Dead weight	1	7	9	4
Drag-embedment	9	9	8	5
Piles	5	9	7	8
Vertical load anchor	7	9	7	8
Average	5.5	8.5	7.75	6.25

Table 11: Positive Distance from Average (PDA), d_{ij}^+

Criteria’s weight	0.2024	0.2903	0.2585	0.2488
Anchors	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost
Dead weight	0.0000	0.0000	0.1613	0.3600
Drag-embedment	0.6364	0.0588	0.0323	0.2000
Piles	0.0000	0.0588	0.0000	0.0000
Vertical load anchor	0.2727	0.0588	0.0000	0.0000

Table 12: Weighted Sum of PDA, Q_i^+

Anchors	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost	$Q_i^+ = \sum_{ji=1}^{n} w_j d_{ij}^+$
Dead weight	0.0000	0.0000	0.0417	0.0896	0.1313
Drag-embedment	0.1288	0.0171	0.0083	0.0498	0.2040
Piles	0.0000	0.0171	0.0000	0.0000	0.0171
Vertical load anchor	0.0552	0.0171	0.0000	0.0000	0.0723

Table 13: Negative distance from average (NDA), d_{ij}^-

Criteria's weight	0.2024	0.2903	0.2585	0.2488
Anchors	Ultimate Holding Capacity	Load Direction	Seabed suitability	Cost
Dead weight	0.8182	0.1765	0.0000	0.0000
Drag-embedment	0.0000	0.0000	0.0000	0.0000
Piles	0.0909	0.0000	0.0968	0.2800
Vertical load anchor	0.0000	0.0000	0.0968	0.2800

Table 14: Weighted Sum of NDA, Q_i^-

Anchors	**Ultimate Holding Capacity**	**Load Direction**	**Seabed suitability**	**Cost**	$Q_i^- = \sum_{ji=1}^{n} w_j d_{ij}^-$
Dead weight	0.1656	0.0512	0.0000	0.0000	0.2168
Drag-embedment	0.0000	0.0000	0.0000	0.0000	0.0000
Piles	0.0184	0.0000	0.0250	0.0697	0.1131
Vertical load anchor	0.0000	0.0000	0.0250	0.0697	0.0947

Table 15: Alternative's Appraisal Score, S_i

Anchors	Q_i^+	Q_i^-	S_i^+	S_i^-	S_i	Rank
Dead weight	0.1313	0.2168	0.6436	0.0000	0.3218	3
Drag-embedment	0.2040	0.0000	1.0000	1.0000	1.0000	1
Piles	0.0171	0.1131	0.0838	0.4783	0.2811	4
Vertical load anchor	0.0723	0.0947	0.3544	0.5632	0.4588	2

3.4 Decision Making on Optimal Anchoring Operations

This study targeted optimization of suitable anchor type that can influence anchoring operations of floating offshore structures on a medium clay seabed location using a CRITIC-EDAS method. The first phase of the methodology utilised the CRITIC method in determination of the anchor optimization criteria weights. The method showed that the anchor’s suitability for the load direction as a criterion with the weight of 0.2903 and it’s suitability for the seabed condition criterion with the weight of 0.2585 are the two most salient criteria respectively as shown in Table 9. The cost criterion and the ultimate holding capacity criterion have the weights of 0.2488 and 0.2024 respectively. The obtained weights of the criteriaare used to facilitate application of the EDAS method in the evaluation and ranking of alternatives. The obtained results are presented in Table 16. The drag embedment anchor is ranked as the best with an appraisal score, S_i of 1, followed by the vertical load anchor, dead weight and piles with appraisal scores of 0.4588, 0.3218 and 0.2810 respectively.

Conclusion

A CRITIC-EDAS method was employed for the optimization of the anchor alternative suitable for anchoring horizontally loaded floating offshore structure on a medium clay seabed location. The obtained results revealed that the drag embedment anchor is the most feasible choice. The appropriate anchor type selection enhances the safety of moored offshore structures and also plays a vital role in the minimization of offshore structural failure.Based on the obtained result, practitioners should focus more on the anchor’s suitability for the loading direction and seabed condition in terms of decision making. The drag embedment anchor is seen as the most suitable anchor type for horizontally loaded floating structures on a medium clay seabed location. This study is useful for researchers and practitioners in Marine and Offshore industry as bases to facilitate researches and decision making. This multi-criteria correlation model has the ability to effectively address complex decision problems in the aforementioned industry because it accommodatesintegration of practical experiences in form of qualitative and quantitative data.

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