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Hierarchical Process Based Failure Analysis and Application to Marine Pipeline Engineering

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Abstract. For evaluation of subsea pipeline structural reliability, an efficient approach to identify the risk factors is extremely important. In this paper, a more comprehensive and objective methodology, the Hierarchical Energy Expansion Tree (HEET), is achieved by combining the Energy Expansion Tree (EET) with Analytical Hierarchical Process (AHP). First being applied to the useful life phase of a subsea pipeline structure, the new results are shown to be more realistic by comparing the HEET results with the original Full Tree Analysis (FTA)'s and EET's. Also, the HEET has advantages over the conventional combination of FTA & AHP. The evolution from FTA to EET to HEET is explained and demonstrated.

1. Introduction

1.1 Subsea Pipeline Reliability - Importance and Disadvantage of the current methodologies

Subsea pipelines constantly function under complex environmental stresses, such as: current, waves and vortices. They must also survive extremely high energy events like hurricanes, earth quakes, etc. In addition, during their lifetime, the subsea pipeline structures are subject to creep, corrosion, erosion and fatigue which can cause them to fail. The crude oil in these pipelines is toxic and can have a catastrophic effect on the ecology if the oil is allowed to leak out. It is very important to maintain safety and good reliability throughout the designed lifetime of such systems.

Much research has been conducted recently on this subject. This research can be classified into 3 categories: Material Fatigue Analysis[1, 2]; Remaining Strength, [3]; and Reliability Risk Management, [4, 5].

For qualitative analysis, virtually all of the risk factor identifications are developed by subjective ratings derived from brainstorming or logic trees. However, the uncertainties are not readily evident with normal brainstorming methods. The subjective ratings only evaluates the known factors, not the unknown ones. This deficiency has been widely recognized in the field.

1.2 Improvement of Methodology

Quantitative analyses methods should be developed based on a sound and rigorous qualitative analysis. This paper continues with the previous topology of FTA [6] methodology enhancement, Energy Expansion Tree, EET, [7]. Even though the EET presented some improvements for the quantitative analysis, there are several issues which need to be addressed.

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In this paper, the original EET is first modified and refined, then integrated with a simple but powerful data hierarchical tool, Analytic Hierarchy Process (AHP). Applied to a subsea pipeline reliability risk assessment case, the HEET produces both qualitative and quantitative analysis more accurately and efficiently.

2. The establishment of HEET

(1) Expanding EET

i. As previously reported [7], the “basis of split” on the left side of the EET, for locking the physics aspect, must be compromised.

ii. The Mutually Exclusive Collectively Exhaustive (MECE) principles are still valid, but it has been restructured for this presentation.

iii. The energy reference codes are serialized for easy data access.

(2) Regrouping factors

Contributing Energy sources are grouped at different levels and aligned, yet act independently on the pipeline.

(3) Construction of the Matrix

After the EET is converted, the comparison arrays are built based on the layout of the new tree, ready for AHP to plug in. Each judgement matrix is composed with a focus on a single subject, target or relative member.

(4) Calculating

A numerical weight, or priority, is derived for each factor of the hierarchy.

(5) Checking the Consistency Index

The typical method used to check the consistency was created by Saaty[8]. The first step is to calculate the consistency index:

$$C.I. = (\lambda_{\max} - 1)/(n - 1) \qquad (1)$$

Next, calculate the consistency ratio:

$$C.R. = C.I./\ R.I. \qquad (2)$$

$C.I.$ is the maximum acceptable Eigen value and it must be random.

(6) Weight ranking

In the final step, the numerical rank order is calculated for all the decisions.

3. HEET application to the subsea pipeline reliability.

3.1 Qualitative analysis

The qualitative EET for “useful life” regime of the subsea pipeline is converted to be used with AHP without disturbing the logical splits. Based on the design guideline in Section 2, the converted EET is shown in the following Fig.1 (a,b,c,d).

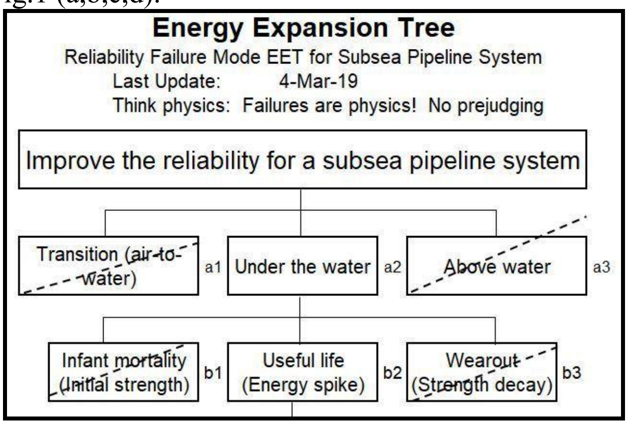
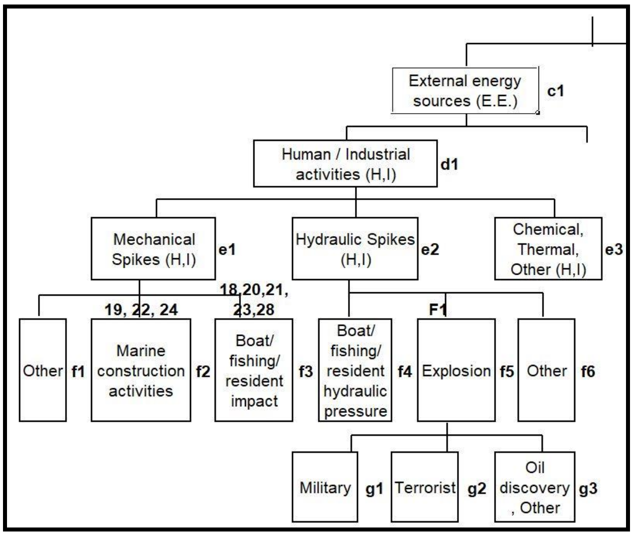
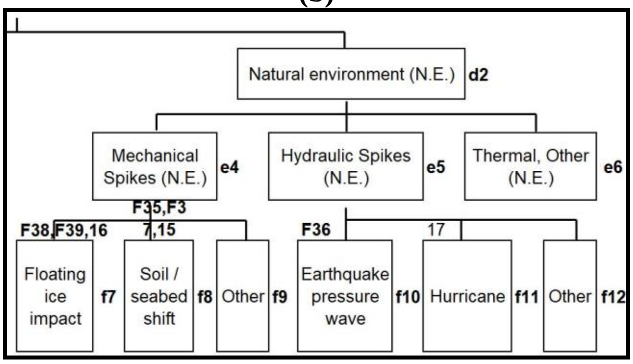


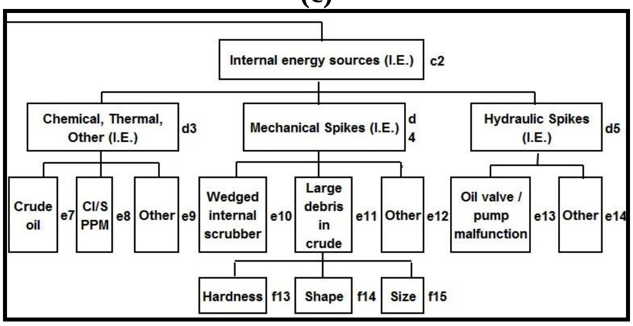
Figure 1(a). The converted EET for energy identification in “useful life” regime of the subsea pipeline figure.



(b)



(c)



(d)

3.2 Quantitative analysis

(1) Matrix setup

The judgment matrix is a positive reciprocal matrix to keep it symmetric. Suppose

$$N = \{1, 2 \cdots n\} \quad (3)$$

$$A = (a_{ij}) \quad (4)$$

A can be setup as the judgment matrix with $n \times n$ entries. The rules to build this matrix are:

$$a_{ij} = 1,\ i \in N,\ a_{ij} = 1/a_{ji},\ i, j \in N \quad (5)$$

The matrix can be symmetric. An $n \times n$ judgment matrix is a constant matrix if

$$a_{ij} = a_{ik} a_{kj},\ i, j, k \in N \quad (6)$$

Combining the existing evaluations from the traditional FTA and the newly discovered leakages from the EET, a more reasonable a_{ij} can be found for further calculations.

(2) Calculations

The AHP fundamental calculation mechanism is: the judgment matrix *A* is a consistent matrix with *n* X *n* elements.

$$w = (w_1, w_2, \cdots w_n)^T \qquad (7)$$

w is the right eigenvector of the principle, then

$$a_{ij} = w_i / w_j,\ i, j \in N \qquad (8)$$

Therefore, *A* is an *n x n* judgment matrix and *w* is the principle right eigenvector of *A*. From this mechanism, we know that *A* is a consistent matrix, then $a_{ij} = w_i / w_j,\ i, j \in N$, the following equation stands:

$$a_{ij} \frac{w_j}{w_i} = 1,\ i, j \in N \qquad (9)$$

Following the mathematical design, each factor in its own level is rated covariently. The overall probability of each factor's occurrence can be recalculated with the weight integration:

$$P_{ij} = a_{ij} \prod_{i=1}^{N} p_{ij},\ i \in N,\ j \in n \qquad (10)$$

In this equation, *P* is the probability factor evaluated by previous studies. *P* is the overall probability taking into account of the weight value using AHP. *i* is the level in the tree, *j* is the sequential number of the rated factor. *N* is the total level number where the rated factor locates. *n* is the total factor numbers at the same level where the rated factor locates.

Feeding the above results to the original EET calculation, a new set of rank order in term of the energy risk factor's weight analysis is also shown in the last column of Fig 2 (a,b) (attached to the end).

Rank Order Calculations

	Tree Layout	Source Reference Codes						
Series	Factor Names Level in FET -->	7	6	5	4	3	2	1
	Under the water							a2
	1-2 Useful life(Energy spike)						b2	
	1-2-1 External energy sources (E.E.)					c1		
	1-2-1-1 Natural environment (N.E.)				d2			
	1-2-1-1-1 Mechanical Sp			e4				
f7	1-2-1-1-1-1 Floating ice impact		f7					
f8	1-2-1-1-1-2 Soil / seabed shift		f8					
f9	1-2-1-1-1-3 Other		f9					
	1-2-1-1-2 Hydraulic Spikes(N.E.)			e5				
f10	1-2-1-1-2-1 Earthquake pressure wave		f10					
f11	1-2-1-1-2-2 Hurricane		f1					
f12	1-2-1-1-2-3 Other		f1					
	1-2-1-1-3 Thermal, Other (N.E.)			e6				
	1-2-1-2 Human / Industrial activities (H,I)				d1			
	1-2-1-2-1 Mechanical Spikes (H,I)			e1				
f3			18					
	1-2-1-2-1-1 Boat/ fishing/ resident impact		20					
			21					
			23					
f2	Marine		19					
	1-2-1-2-1-2 construction		22					
	activities		24					
f1	1-2-1-2-1-3 Other		f1					
	1-2-1-2-2 Hydraulic Spik			e2				
f4	1-2-1-2-2-1 Boat/ fishing/ resident hydraulic pressure		f4					
f5	1-2-1-2-2-2 Explosion		f5					
g1	1-2-1-2-2-2-1 Military	g1						
g2	1-2-1-2-2-2-2 Terrorist	g2						
g3	1-2-1-2-2-2-3 Oil discovery, Other	g3						
f6	1-2-1-2-2-3 Other		f6					
	1-2-1-2-3 Chemical, Thermal, Other (H,I)			e3				
	1-2-2 Internal energy sources (I.E.)					c2		
	1-2-2-1 Mechanical Sp				d4			
	1-2-2-1-1 Large debris in crude oil			e11				
f13	1-2-2-1-1-1 Hardness		f13					
f14	1-2-2-1-1-2 Shap		f14					
f15	1-2-2-1-1-3 Size		f15					
	1-2-2-1-2 Wedged internal scrubber			e10				
	1-2-2-1-3 Other			e12				
	1-2-2-2 Hydraulic Spikes(I.E.)				d5			
	1-2-2-2-1 Oil valve / pump malfunction			e13				
	1-2-2-2-2 Other			e14				
	1-2-2-3 Chemical, Thermal, Other (I.E.)				d3			
	1-2-2-3-1 Crude oil			e7				
	1-2-2-3-2 Cl/S PPM			e8				
	1-2-2-3-3 Other			e9				

Figure 2(a). Rank Order Analysis of Useful Life factors by HEET (left half)

								Result	
Level 6 Raw	g	f	e	d	c	b	a	Contribution	Failure Rank
							33%		
						33%			
					67%				
				33%					
			29%						
0.44								3.14E-03	9
0.11								7.84E-04	20
0.44								3.14E-03	9
			14%						
0.20								7.05E-04	24
0.20								7.05E-04	24
0.20								7.05E-04	24
			57%					1.41E-02	1
				67%					
			29%						
2.70E-03	1.0E-02	71%						9.98E-03	3
2.15E-03									
4.11E-03									
1.48E-03									
1.32E-03	4.3E-03	29%						4.13E-03	8
8.53E-04									
2.15E-03									
0.20								2.82E-03	13
			14%						
0.11								7.84E-04	20
0.44								3.14E-03	9
	0.44							1.39E-03	17
	0.44							1.39E-03	17
	0.11							3.92E-04	27
0.44								1.57E-03	16
			57%					1.41E-02	1
					33%				
				47%					
			26%						
0.17								7.53E-04	22
0.17								7.53E-04	22
0.67								3.01E-03	12
			41%					7.11E-03	4
			33%					5.67E-03	7
				38%					
			50%					6.97E-03	5
			50%					6.97E-03	5
				16%					
			40%					2.32E-03	14
			20%					1.16E-03	19
			40%					2.32E-03	14

Figure 2(b). Rank Order Analysis of Useful Life factors by HEET (right half)

3.3 The results and Discussion

In the HEET results, the ranked order shows the top 10 factors: “Thermal, other (N.E)”, “Chemical, Thermal, Other (H.I)”, “Boat/fishing/resident impact”, “Wedged internal scrubber”, “Oil valve/pump malfunction”, “Other in hydraulic spikes”, “Other in mechanical spikes(H.I)”, “Marine construction activities”, “Floating ice impact”, “Other in mechanical spikes (N.E)”.

In the previous EET study[7], the top 10 ranked factors were “Hurricane”, “Soil/seabed shift”, “Boat/fishing resident impact”, “Hydraulic spikes(H.I)”, “Floating ice impact”, “Boat/fishing/resident hydraulic pressure”, “Other in hydraulic spikes”, “Other in mechanical spikes (N.E)”, “Thermal, other (N.E)”, “Chemical, Thermal, Other (H.I)”, “Chemical, Thermal, Other (H.I)”.

The original FTA analysis[6] concluded the top 5 factors (Only the top 5 factors were considered at the time) were “Third party damage”, “ Corrosion”, “Vortex-induced vibration”, “Management”, “Operation”.

In HEET, 7 out of 10 factors matched the results of EET. The results difference between them comes from the limited availability of the data in EET study. A “0” value was denoted to each data when it’s missing in the original FTA form. In the HEET approach, the problem is solved by integrating the weight analysis of each factor. Place the figure as close as possible after the point where it is first referenced in the text. If there is a large number of figures and tables it might be necessary to place some before their text citation. If a figure or table is too large to fit into one column, it can be centred across both columns at the top or the bottom of the page.

4.Conclusions

A new method to identify the risk factor for subsea pipeline structure, HEET, is established with both qualitative and quantitative analysis. With HEET, significant contribution is made to reduce the subjectivity by integrating the powerful data analysis tool of AHP. The HEET is a method which can be used to evaluate the reliability and quality risk management across a wide range of engineering industries.

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