INTERNATIONAL JOURNAL OF IJCOE COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

Volume 4 | Issue 3 | Oct 2019

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International Journal of Coastal, Offshore and Environmental Engineering (IJCOE) Vol. 4 / Issue. 3 / Oct 2019 15

International Journal of Coastal, Offshore & Environmental Engineering

Since 2015

ISSN: 2980-8731 (online)

Volume 4 | Issue 3 | Oct 2019

IJCOE

Editor-in-Chief: Prof. Hamid S.Bahai

International Journal of Coastal, Offshore & Environmental Engineering
Since 2015
ISSN: 2980-8731 (online)

In The Name of God

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Volume & Issue:

Volume 4, Issue 3, October 2019

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Content

INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.4/No. 3/Autumn 2019 (1-8)

Available online at: http://www.ijcoe.org

An Analytical Study on the Formation of Submerged Bars in the Southern Coasts of Caspian Sea

Fatemeh Ghanbari[1*], Mehdi Adjami[2], Soheil Ataei H.[3]

[1] *MSc. Student in Coastal Engineering, Faculty of Civil Engineering, Shahrood University of Technology, Shahrood, Iran; ganbari.ftm@gmail.com*
[2] *Assistant Professor, Faculty of Civil Engineering, Shahrood University of Technology, Shahrood, Iran; adjami@shahroodut.ac.ir*
[3] *PhD. Candidate in Coastal Engineering, Faculty of Civil Engineering, Shahrood University of Technology, Shahrood, Iran; ataei.h.s@gmail.com*

ARTICLE INFO

Article History:
Received: 20 May. 2019
Accepted: 25 Nov. 2019

Keywords:
Cross-shore
Profile
Bars
Erosion profile
Geometric shape
steepness

ABSTRACT

Measuring cross-shore profiles is very important in coastal engineering studies, since the cross-shore profile determines the behavior of the sea in the coastal area and determines the process of depth changes in this region. As a result of waves, cross-shore profiles change, which will vary in stormy waves (erosion profile) in compare to normal wave conditions (cumulative profile). Considering the great changes in the Caspian Sea level, the purposes of this study are to investigate and determine the erosion or accumulation of coastal profiles based on Sunamura and Horikawa's studies , determine the number of bars in profiles by Short and Aagaard's equations and also determine the relations between coastal parameters with the wave steepness and changes in water level. The results show that for all the coastal areas in the Caspian Sea, the C-parameter is above 8; in other word a stormy erosional nature is dominant. Also according to B_0 -parameter, for all regions the values are above 100 which means a very high possibility to form multi bars profiles (three bars) very high. As the wave's steepness rises, the location of the formation of the bars moves toward the coast, and the depth of water decreases at the beginning and the ends of the bars; also, in terms of lowering in the water level with the change in the height of the waves, the position and the geometric shape of the bars will not follow a certain trend

1. Introduction

Cross-shore profiles of sandy beaches have a crucial role in design different kinds of port of areas , because the cross-shore profiles will determine the sea's behavior in the coastal zone and will indicate the process of depth changes in this range. As a result of waves, cross-shore change, which will vary in stormy waves compared with the sea normal waves. Storm driven Profiles are called erosion profiles, and while normal wave driven profile are called cumulative profiles. Overview of seasonal changes for the bed profile can be used to design marine structures such as docks, coastal walls and sea-bed pipes that cross the coastal area, as well as to create coastal boundaries and design coastal recovery projects.

In the past, many researchers have done studies on the modeling of cross-shore profiles and cross-shore sediment transport, in order to determine the parameters of storm profiles. Watanable *et al.* (1986) used a three-dimensional model to estimate the amount of cross-shore sediment transport. The results of this three-dimensional model in compare with the formula derived from the transfer of sediments due to the wave and current show that they are in agreement with each other [1]. Larson and Kraus(1989) studied erosion and cumulative profiles and introduced the best criteria for determining the profile of transverse profiles; then geometric parameters of storm profile were calculated using laboratory data and nonlinear regression analysis between geometric characteristics And the characteristics of the wave and sediments [2]. Pruszak *et al.* (1997) examined 81 cross-shore multi bar profile with average slope on the coast of Poland between 1964 and 1994. They calculate and compare the correlation coefficients between two different parameters for each bar and the correlation coefficients between the same parameters for different bars. The results show that the correlation coefficient between the same parameters in different bars decreases with increasing in distance from the coastline, and also by increasing in the height of the bars, the depth of water on the bars will increase [3]. Hsu and silvester (1997) in their studies, coastal profile parameters were determined using experiments and nonlinear regression method. They considered these waves steepness ($\frac{H_0}{L_0}$) and bed slopes (m) as factors influencing the geometric parameters of storm profiles [4]. Hsu (1998) conducted laboratory studies to determine the geometric parameters of a stormy profile. In his experiments, he considered two slopes of the bed and two angles of attack and several different waves steepness. Using the nonlinear regression analysis and the parameter ξ, which determines the relationship between the slope of the bed and the wave velocity, empirical equations to determine Geometric features are considered [5]. Rozynski (2003) explores the bed changes on the coasts of Poland, where they have a gentle slope, dominant wave, multi bars and have no tide. In his study, he used experimental orthogonal functions (EOF) and focal correlation methods (CCA) and by interacting and connecting the results of these two evaluations to a physical model, he describes phenomena and processes [6]. Gunaydin and Kabdasli (2003) conducted laboratory studies to determine the parameters of coastal erosion. By linear regression of the parameters, they provided an empirical relation for each wave state, and by comparing their correlation coefficient they found out that the wave's status is ineffective in determining the parameters of coastal erosion [7]. Hashemi *et al.* (2010) conducted studies in the area of forecasting seasonal changes in coastal profiles; They collected data by examining 19 stations on the coast of the Gulf of Tremodoc, for seven years, such as minimum wind speed, wind direction, number of consecutive winds, number of all winds data, significant wave height, wave period characteristic, wave direction, coastal angle and storm duration and by ANN's (artificial neural network), they predict coastal seasonal variations. The results show that the artificial neural network method is more accurate than other expensive numerical models [8]. Demirci *et al.* (2011) studied sediment transport and the influence of parameters affecting sediment transport during 64 experiments in their studies. In these experiments, the slope of the bed, the average particle size and the wave period were considered as the variables. Based on proposed equation, any increasing in wave steepness (H_0/L_0), lead to more sediment transport, which results in the size and volume of the bars. Also they found that, with increasing sediment transfer to the sea, the amount of erosion of sediments increases from the front of the beach (coastal forehead) and the distance between the coastline and the end of the bar increases. They also discovered that the movement of sediments toward the sea leads to the movement of the bars and hence the place of wave break is also displaced [9]. Kömürcü et al. (2013) provided 80 experiments using the Neural Network (NN) to provide equations for determining the geometric characteristics of the stack. Finally, comparing these results with the regression analysis results, showed that the relations obtained from the neural network are in good agreement with experimental results [10]. Uzlu *et al.* (2014) estimate the bar parameters by conducting the experiment on 31 coastal profiles by nonlinear regression, using TLBO and ABC algorithms to optimize the regression equation coefficients. According to the results, the TLBO algorithm shows better results than ABC [11]. Demirci *et al.* (2015) used artificial neural network model (ANN) and multiple linear regression (MLR) to predict the bar volume. They estimate the errors in these two methods and compare them and conclude that ANN provides a better and more accurate estimate for bar size estimation [12]. Cheng *et al.* (2016) carried out studies on 165 beaches and used two Unibest-TC and S beach coastal profile software to estimate storm coastal changes. They argued that the unibest-TC model could be used to determine the direction of the motion of the sandy bars and the S Beach model can be efficient in determining the exact extent of coastal bars erosion as well as shore line changes [13].

Lopez *et al.* (2017) used an artificial neural network model (ANN) to predict the bar parameters formed in the profile. in order to evaluate the performance of the model obtained from the ANN, errors such as absolute error and average relative error and relative error were used, which by comparing these values with the values obtained from previous relations, they realized low errors in the ANN model [14]. Kankal et al. (2018) examined the cross-shore sediment transport by a coefficient that determines the velocity to the equilibrium of sedimentary deposits. They used laboratory data and artificial neural network models to obtain this coefficient. Also, they used two optimization algorithms TLBO and ABC to optimize these models. Finally, the results showed that TLBO-ANN and ABC-ANN had more accurate results than BP-ANN [15]. Lopez et al. (2018) studied cross-sectional profiles of the western shores of the Mediterranean Sea using artificial neural networks to model cross-sectional profiles. In their studies, they considered the effects of marine plants, in addition to the common parameters that other researchers considered. They also compared the results obtained from the neural network with the results obtained from Religion Formulas (1991) and Aragones (2017), and they found a better performance of the model [16].Ataei et al. (2016) carried out studies on some parts of the southern coast of the Caspian Sea, based on measured data as well as the presented equations. The results of this study show that the Caspian Sea coasts are categorized as stormy type [17]. In addition to the relations found by Ataei *et al.* (2016), Sunamura and

Horikawa (1974), carried out studies on the transfer of sediments and parameters affecting cross-shore profiles, provided the parameter *C* for the classification of coastal profiles. In this equation, H_0, L_0, $\tan\beta$ and d_{50} are the significant wave height, wave length, bed slope and average particle size respectively[18].

$$C = \frac{H_0}{L_0}(\tan\beta)^{0.27}\left(\frac{d_{50}}{L_0}\right)^{-0.67} \qquad (1)$$

the purposes of this study are to investigate and determine the erosion or accumulation of coastal profiles, determine the number of bars in profiles, and also determine the relations between coastal parameters with the wave steepness and changes in water level.

2.Study Area

The Caspian Sea is the largest lake in the world that is not associated with free waters; in recent decades, it has been connected to the Black Sea through the Volga River and the creation of the Volga Channel by Russia. The main source of water entering the Caspian Sea is the Volga River, which accounts for about 80% of the water entering the Caspian Sea. The highest depth of the Caspian Sea is about 1025 meters, and in general the deepest areas of the sea are close to the coast of Iran; the average level of the Caspian Sea water level is 27 meters below the free water level (Shahini, 2006) [19]. In order to investigate the cross-section profiles of the southern coast, necessary information were collected from Anzali and Dastak coastal regions in Gilan province, Namakabrood, Mahmudabad and larim in Mazandaran province and also from Miankaleh in Golestan. The cross-shore profile of the Caspian Sea coastal line is shown in Fig. 1**.**

Figure 1. Cross-shore profiles studied for the Caspian Sea coastal line.

3.Methods

Based on parameter *C*, the type of cross-shore profile can be determined such that if $C < 4$ is the cumulative coastal profile (summer), if $4 < C < 8$ is the equilibrium coastal profile and if $C > 8$ is the coastal profile of the erosion type (winter).

According to the relations provided by Short and Aagaard (1993), the number of bar in the coastal profiles can be found. Based on this, Eq. (2) presents the parameter B_0 for determining the number of bars and X_s and T are respectively the horizontal distance for the closure depth to the coastline and period of wave. In such a way that if $B_0 < 20$ the profile does not have any bar and the profile is a balance one. If $20 < B_0 < 50$ the profile has one bar, $50 < B_0 < 100$ has two bars, $100 < B_0 < 400$ has a three-bar profile, and if $B_0 > 400$, then the profile will have four bars [20].

$$B_0 = \frac{X_s}{gT^2 \tan\beta} \qquad (2)$$

Beach slopes, sediment transport, sea bed, and sea level changes are among the factors affecting cross-shore profiles; In this study, the effect of effective parameters on cross-shore profile deformation has also been evaluated. Fig. 2 shows each of the geometric parameters of coastal profiles.

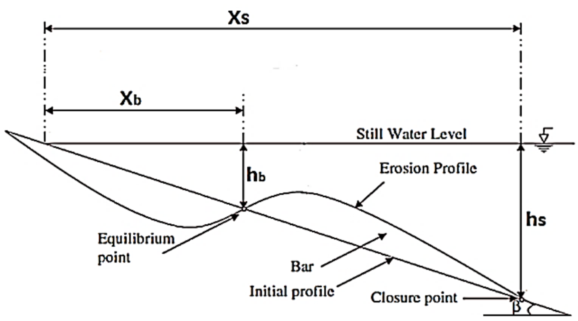
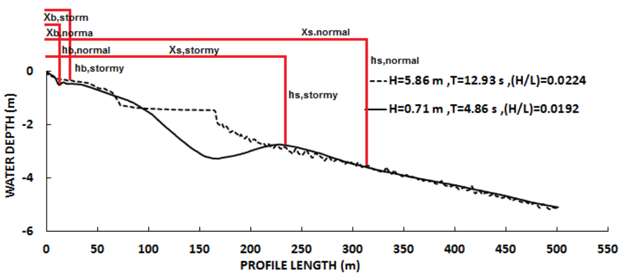


Figure 2. Geometric Parameters of Coastal Profiles (Kömürcü et al. ,2013).

4. Data Analyses and Discussion

Due to the analysis and survey of the southern shores of the Caspian Sea ,in Fig. 3, the profiles of the studied regions are shown. Also in Table 1, the measured parameters are for 12 years Caspian Sea modeling statistics by Ports and Maritime Organization and Caspian Sea National Research Center)[1], include the significant stormy and normal waves height (H_0), wave length (L_0),the significant stormy and normal period of wave (T), water level change (S), average particle size (d_{50}), bed slope ($\tan\beta$), horizontal distance of the starting point for the first bar to the coast line, (X_b) the initial depth of the starting point for the first bar to the water surface (h_b), the horizontal distance for the end of the last bar to the coastline (X_s) and the depth of the end point for the last bar to the water surface (h_s) are shown.



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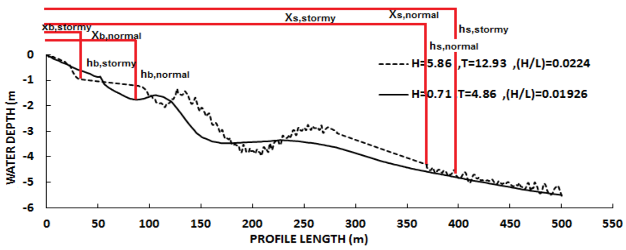

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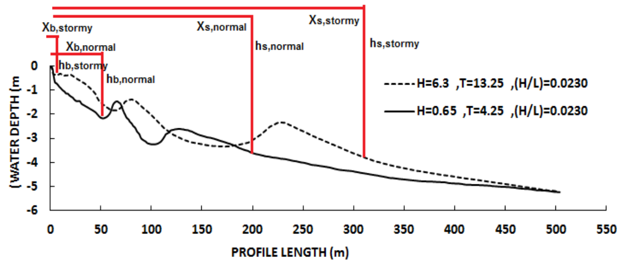

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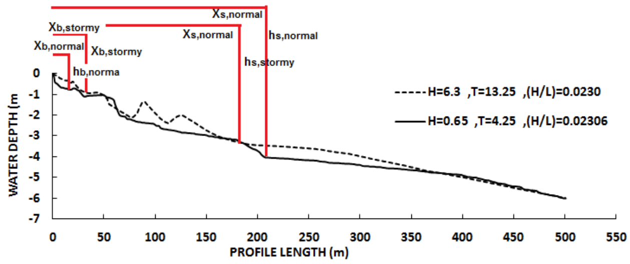

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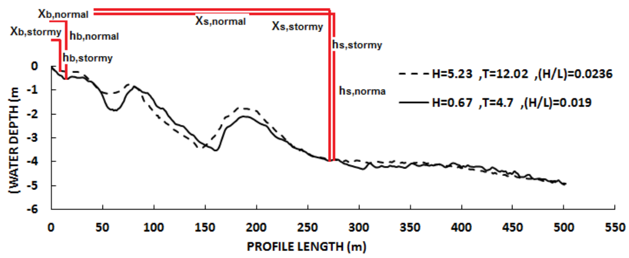

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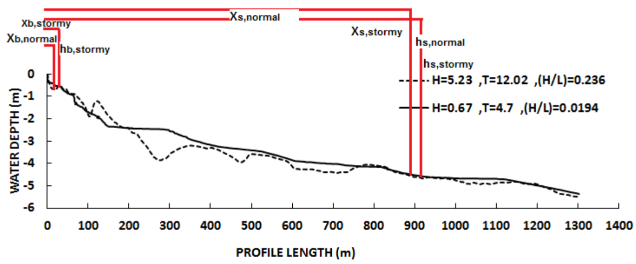

(F)

Figure 3. Profiles of the studied areas; A: Anzali, B: Dastak, C: Namakabrood, D: Mahmudabad, E: Larim, F: Miankaleh (CSNRC Report, 2016 [21]

[1] Data was taken as a text file (x-z) from the Ports and Maritime Organization and Caspian Sea National Research Center (2016).

Table 1. Parameters measured from the southern shores of the Caspian Sea (Ataei et al., 2016 [22]; PMO report, 2016 [23]).

Parameters	Anzali	Dastak	Namakabrood	Mahmudabad	Larim	Miankaleh
$H_{0\max}$ (m)	5.86	5.86	6.3	6.3	5.32	5.32
$L_{0\max}$ (m)	260.81	260.81	273.88	273.88	225.39	225.39
$T_{\max}$ (sec)	12.93	12.93	13.25	13.25	12.02	12.02
H_{0mean} (m)	0.71	0.71	0.65	0.65	0.67	0.67
L_{0mean} (m)	36.85	36.85	28.18	28.18	34.46	34.46
T_{mean} (sec)	4.86	4.86	4.25	4.25	4.7	4.7
x_s (m)	454.43	451.04	327.85	296.80	454.85	885.36
S (m)	-0.132	-0.132	-0.132	-0.132	-0.132	-0.132
D_{50} (m)	0.0002	0.00019	0.00023	0.00019	0.00017	0.00017
$\tan\beta$	0.011	0.011	0.013	0.015	0.010	0.005
$X_{s_{Stormy}}$ (m)	252.82	369.17	318.54	178.67	278.88	891.57
$X_{s_{Normal}}$ (m)	315.42	393.00	198.45	211.77	254.74	891.34
$X_{bStormy}$ (m)	46.68	31.75	6.88	27.67	66.65	48.38
$X_{bNormal}$ (m)	33.48	89.70	53.40	16.08	16.17	17.35
$h_{bStormy}$ (m)	0.26	0.88	0.38	0.43	1.16	0.56
$h_{b_{Normal}}$ (m)	0.5	1.75	2.16	0.75	0.53	0.70
$h_{sStormy}$ (m)	2.97	3.96	4.30	3.14	3.89	4.59
$h_{s_{Normal}}$ (m)	3.43	4.75	3.35	4.05	3.77	4.56

Based on the Eqs (1) and (2), the performance of the coastal areas of the Caspian Sea has been studied and analyzed based on the cumulative, equilibrium and coastal erosion category and the number of bars. The results are presented in Table 2.

Table 2. Calculating parameter C and determining the number of the Caspian Sea bars.

Parameters	Anzali	Dastak	Namakabrood	Mahmudabad	Larim	Miankaleh
C	19.22	19.89	18.32	21.64	20.15	16.71
Type of the cross shore profiles	erosion profile	erosion profile	erosion profile	erosion profile	erosion profile	erosion profile
B_0	177.6	176.3	141.7	111.2	208.2	810.5
Number of the bars	3	3	3	3	3	4

As shown in the calculations, the parameter C in the areas determined on the Caspian Sea coast is always greater than 8 and has values between 16 and 22, so it can be stated that the Caspian Sea behavior has a stormy nature and the coast has erosional nature.According to Table 2, the beach profiles for Dastak, Namakabrood, Mahmudabad and Larim have three bars and the profile of the Miankaleh coastline has four bars. The Anzali cross-shore profile has three bars, according to Eq. (2), but as seen in field data, it has two bars. The reason is the proximity of the location of collection Anzali profiles data to the port, which affects coastal interactions.

To facilitate the use of field data and reduce the error rate X_b, X_s, h_b, h_s and H_0 parameters are converted to dimensionless numbers relative to the wave length, and the change in the water level. In Figs. 4 and 5, the relation between the wave steepness and the dimensionless ratio of the geometric parameters of the profiles and the relation between H_0/S and the dimensionless ratio of the geometric parameters in a situation where the change in water level in all regions are the same is evaluated.

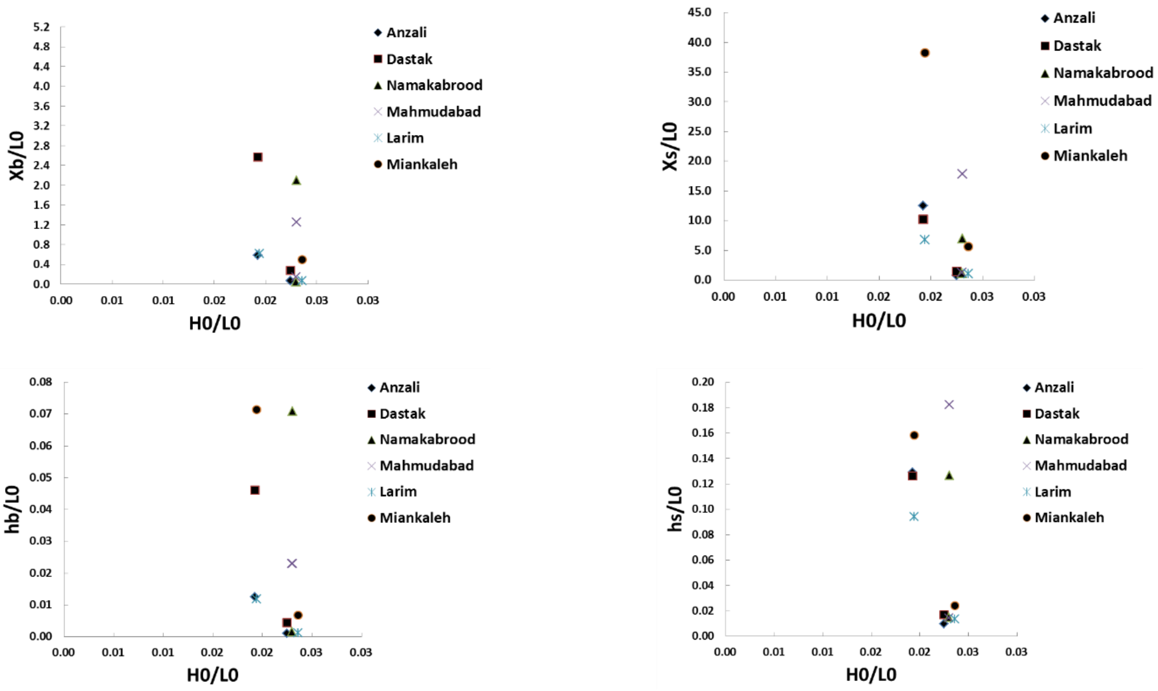

Figure 4. Comparison of the dimensionless parameters of coastal profile with the wave steepness ratio.

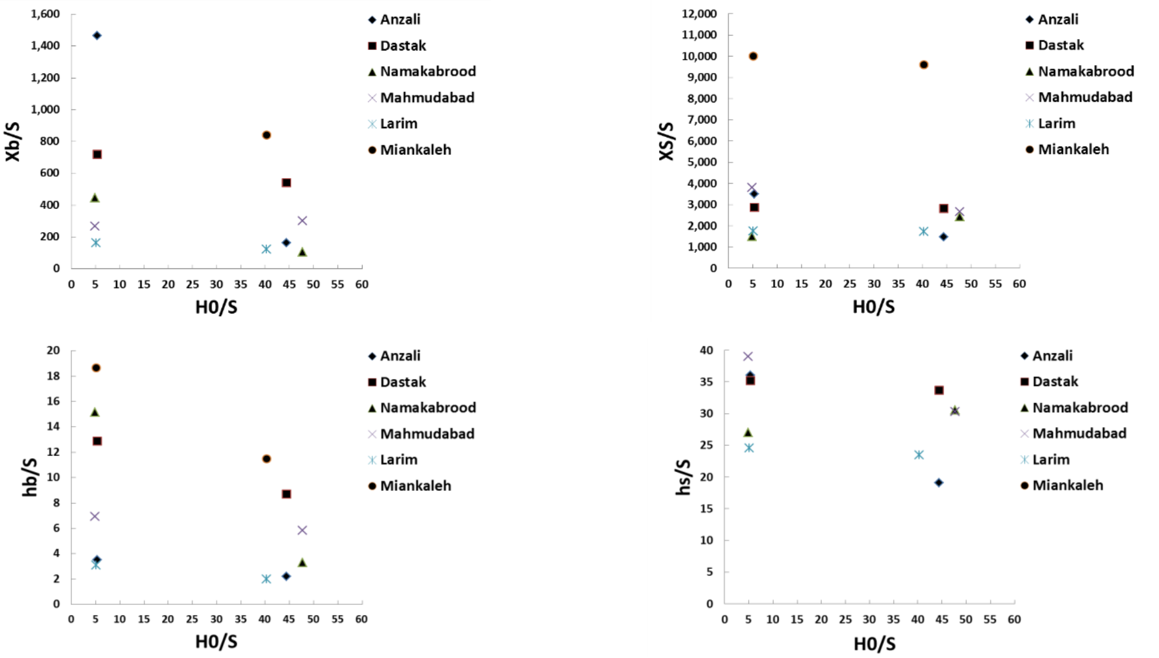

Figure 5. Comparison of the dimensionless parameters of the coastal profile with the H_0/S ratio.

As shown in Fig. 4, with increase in the wave steepness (H_0/L_0), the ratios of x_b/L_0 and x_s/L_0 in the most of the profiles are reduced, thus it can be stated that the coastal bars begin to form at a shorter distance from the coastline and the general displacement of the bars happens toward the coast line. Also, the ratios of h_b/L_0 and h_s/L_0 in most of profiles are also reduced; as these ratios are reduced, the depth of water decreases at the beginning and the end of the bars, which indicates that the erosional beach will be created. King (1972), based on experimental results, modified the location of wave breaking zone due to gradual bars movement, which the results of our studies are consistent with his findings [24].

According to Fig. 5, with constant consideration of water level changes, it is observed that in the conditions of lowering in the water level, by the increase of the wave height, the location of the formation of coastal bars in all regions of the study is not approached to the coast line. As the wave height decreases, the x_s in the coastal profiles of the Larim, Miankaleh, Dastak and Namakabrood areas declines and increases in the coastal profiles of Mahmoudabad and Anzali. Also, with decreasing in wave height, x_b in the Anzali, Mahmudabad and Larim coastal profiles declines and increases in the coastal profiles of the Dastak, Namakabrood and Miankaleh. The geometric parameter of h_s increases with decreasing in wave height in all coastal profiles except Larim and finally for h_b, with decreasing in wave height in the coastal profiles of the Dastak, Namakabrood, Larim and Miankaleh decreases and for Anzali and Mahmudabad coastal profiles increases. This suggests the complexity of the sea's environmental conditions in the state of the water level change, since as water level decreases, the interactions of the wave particles with the bed change, and the type of wave break and its distance to the coast line will be affected.

5. Conclusion

Measuring cross-shore profiles is very important in coastal engineering studies, since the cross-shore profile determines the behavior of the sea in the coastal area and determines the process of depth changes in this range. The purpose of this study is to investigate the southern shores of the Caspian Sea and determine the erosion or accumulation of coastal profiles, determine the number of bars, and also determine the relation between coastal parameters with the wave's steepness and water level changes.

The C parameter in the areas determined on the Caspian Sea coast is always greater than 8 and has values between 16 and 22, so it can be stated that the Caspian Sea behavior has a stormy nature and the coast has erosional nature. The beach profiles for Namakabrood, Mahmudabad and Larim (most of the beach profiles) have three bars and the profile of the Miankaleh coastline has four bars. According to calculations, the Anzali cross-shore profile has three bars, but as seen in field data, it has two bars. The reason for this difference is the proximity of the location of collection Anzali profiles data to the port, which affects coastal interactions.

With increase in the wave steepness, the ratios of x_b/L_0 and x_s/L_0 in all profiles are reduced, thus it can be stated that the coastal bars begin to form at a shorter distance from the coast line and the general displacement of the bars happens toward the coastline. The ratios of h_b/L_0 and h_s/L_0 are also reduced; as these ratios are reduced, the depth of water decreases at the beginning and the end of the bars, which indicates that the erosional beach will be created.

With constant consideration of water level changes, it is observed that in the conditions of lowering in the water level, by the increase of the wave height, the location of the formation of coastal bars in all regions of the study is not approached to the coastline. Also, the process of water depth changes at the beginning and end of the bars is not uniform. This indicates the complexity of the sea's environmental conditions in the state of the water level change, since as water level decreases, the interactions of the wave particles with the bed change, and the type of wave break and its distance to the coast line will be affected. The results show that the behavior of the coastal areas of the Caspian Sea is a stormy nature with a coastal erosion, which makes it possible to form multi bars profiles (three bars) very high. As the wave's steepness rises, the location of the formation of the bars moves toward the coast, and the depth of water decreases at the beginning and the ends of the bars; also, in terms of lowering in the water level with the change in the height of the waves, the position and the geometric shape of the bars will not follow a certain trend.

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INTERNATIONAL JOURNAL OF
COASTAL& OFFSHORE ENGINEERING
IJCOE Vol.4/No. 3/Autumn 2019 (9-15)

Available online at: www. Ijcoe.org

EVALUATION of VORTEX INDUCED VIBRATION EFFECTIVE PARAMETERS on FREE-SPAN SUBSEA PIPELINES

Seyed Mohammad Hossein Sharifi[1*], Mahdi Tasdighi[2]

1 Abadan Faculty of Mechanical Engineering, Petroleum University of Technology, Iran; sharifi@put.ac.ir
2 MSc Student, Department of Offshore Structural Engineering, Petroleum University of Technology, Iran; mahditasdighi@yahoo.com

ARTICLE INFO

Article History:
Received: 20 Jun. 2019
Accepted: 20 Mar. 2020

Keywords:
Upheaval Buckling
Pipeline
ABAQUS
Vortex Induced Vibration
Free Span

ABSTRACT

Subsea pipelines due to the reduction of transfer costs and expedite the offshore operations is one of the all-purpose structures in marine industries. Subsea pipelines are exposed to a variety of hazards, including corrosion and fatigue Etc. Free span exacerbates the fatigue required parameters due to a phenomenon called the Vortex Induced Vibration (VIV). In this research, the influence of the span's length on the free span subsea pipeline has been reviewed with ABAQUS standard code. In this study the previous result has been expanded. The results of the VIV fatigue life are extensible to all of the depth. Achieved Results indicate that the fatigue life of the pipeline even in the worst condition is much higher than the required amount that it represents the upstream design of DNV-RP-F105. In this study the backrest pipeline has been investigated and result show that the pipeline under the different conditions in the backrest, by creating more vibration and displacement on one side of the pipeline reduces the fatigue life of 113 percent compared to snap. The VIV fatigue life has undergone a lot of changes due to span length changes, maximum changes occur between cable and behavioral which the amount of these changes is reduced by 75%. The free span length is another factor in VIV fatigue. VIV fatigue life will be increased by reducing the span length. As well as increasing the flow velocity that is the main factor in creating the VIV is increased fatigue. Therefore, in terms of the accuracy in the choice of the existing conditions of very high importance for the pipeline. Comparison between effect parameters in VIV fatigue life was shown that span length is the most effective parameter.

1. Introduction

In the offshore industries, marine pipelines are widely applicable to reduce the cost of transportation and speed-up in offshore operations. High economic efficiency, adaptation to the harsh conditions of the sea has made pipelines the most important structure in the maritime industry. Different forces are applied to the pipeline, due to the position of the pipeline in the seabed. The dangerous condition made by these forces during operational or hydro test time [5]. Deep waters create more critical conditions for the pipeline.

In the nineteenth century, research was carried out by August Wooler. He found that forces, which is smaller than the static strength, does not have a damaging effect on the structure. Structure's collapse made by frequentative forces during the operational time is possible. Fatigue is one of the most important factors, which reduces pipeline performance and influence on personal safety and the environment.

Free spans made by subsea topology's changes, artificial support and bed roughness [2]. According to the DNV-OS-F101 [6], free span leads to various phenomena such as bursting, fracture and fatigue. Water particles collision with the pipeline's body causes vibrations in the pipeline, which are called Vortex Induced Vibration (VIV) made by free span [7].

The effect of free span on pipeline's fatigue is due to the VIV. If the frequency of VIV is equal to the pipeline natural frequency of the pipeline, the resonance and then fatigue occurs [8].

Span length and effective parameters of VIV play an essential role in determining the fatigue life of free span subsea pipelines. Research has been conducted on the effect of the span length on multi free spans. The impact of the span length has been studied for a single free span with VIVANA and RIFLEX software [9]. Different relation is estimated in fatigue problems which are often lacking in precision [3]. In this study, based on pipeline modeling in ABAQUS standard code and recommended model DNV-RP-F105, the fatigue life of the pipeline has been determined under different conditions and compared to the required value.

2. Pipe Free-Span Fatigue Analysis Methodology

VIV occurs as the result of periodic shedding of vortex around the pipe. Free span induces the pipeline vibration due to vortex shedding which may cause fatigue damage and fracture. Calculation and analysis of fatigue in a pipeline are more necessary due to the possibility of failure in different parts of the pipeline [10].

The VIV fatigue analysis includes several factors such as water depth, current velocity, span length.

Such as multi spans, the pipeline response in a single span is divided into two parts. In the single span, fatigue life occurs in the first response. Hence use the single response to consider fatigue life.

Considering the VIV phenomenon, two directions are determined based on the response frequency. In-Line (IL) and Cross-Flow (CF) are the two directions mentioned. In the ABAQUS standard code, these results are available. Fatigue life can be calculated according to rules and frequencies.

3. Fatigue Damage

Until 2006, in the case of VIV fatigue analysis, there was no comprehensive recipe for all of the free span state. A batch of studies conducted until 2006 only was responsible for a particular case that could not be extended to other states [8]. Other studies of fatigue capacity were obtained laboratory ally [11]. In 2006, DNV provided a general instruction that could be generalized to all modes. The calculations required by DNV-RP-F105 are possible. The fatigue life of the marine pipeline should be greater than the length of time the pipeline is exposed to the fatigue phenomenon.

$$D_{fat\_damage} = \frac{T_{exposure}}{T_{life}} . \eta \qquad (1)$$

The probability of occurrence of the vortex in the direction of IL more than CF direction. Inflexible beams at a velocity below 2.5 with not facing the direction of CF.

Cumulative failure of the free span can be achieved by using the existing equation in DNV-F-105 and the theory of linear cumulative failure.

$$D_{fat}^{cum} = \sum_{i=1}^{k} \frac{n_i}{N_i} \qquad (2)$$

In this equation, n represents the number of repetitions to subsea pipeline's force hit and N represent required repeat number for failure.

The capacity of the VIV fatigue pipeline be obtained from Eq.(3):

$$T_{fat\_life} = \frac{\eta}{D_{fat}^{cum}} \qquad (3)$$

3.1 Evaluation of fatigue for single free span in IL direction

The following steps show the route calculation of the fatigue in the IL direction:

1. Information collected includes soil properties, type of pipeline and ...
2. Calculation of the static fluid frequency.
3. Frequency calculates in IL direction for the different span length and different flow velocity.
4. Calculation of stress incurred from the VIV for each mode figure at different points with different flow velocity and in one span.

$$s_{i,il}(x_j) = 2. A_{i,il}(x_j). \left(\frac{A_{yi}}{D}\right). \psi_{il}. \gamma_s \qquad (4)$$

$\frac{A_{yi}}{D}$ can be found on the IL response model is shown in Figure 1.

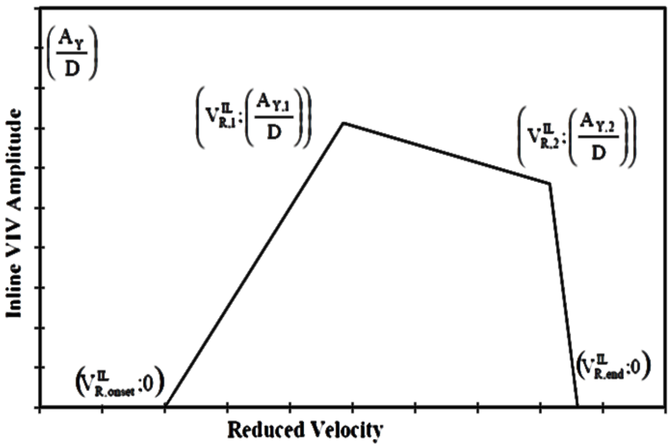

Figure 1. Response model in IL direction

5. Find the active mode at different points during the span and maximum tension exerted.

$$s_{max,il}(x_j) = \max\left(S_{i,il}(x_j)\right) \quad i = 1,2,\dots,n \qquad (5)$$

6. If mode stress less than 10% of maximum tension can be regardless to simplify the model.

$$s_{n,il}(x_j) < 0.01.s_{max,il}(x_j) \qquad (6)$$

7. The calculation of the reduction factor, for each mode.

$$\alpha_{i,i-1} = \begin{cases} 0.05 & if\ f_{i,il_{still}} < f_{i-1,il_{still}} \\ & and\ s_{i,il}(x_j) < s_{i-1,il}(x_j) \\ 1 & else \end{cases} \qquad (7)$$

$$\alpha_{i,i+1} = \begin{cases} 0.05 & if\ f_{i+1,il_{still}} < f_{i,il_{still}} \\ & and\ s_{i+1,il}(x_j) < s_{i,il}(x_j) \\ 1 & else \end{cases} \qquad (8)$$

$$\alpha = \alpha_{i,i-1}.\alpha_{i,i+1}(for i = 1,2,\dots,n)$$

8. The VIV stress in IL direction for different modes is calculated by Eq.(9):

$$s_{i,il}(x_j) = 2.\alpha_i.A_{i,il}(x_j).\left(\frac{A_Y}{D}\right).\psi_{il}.\gamma \qquad (9)$$

9. The combined stress is calculated as follows:

$$f_{cyc,il(x_j)} = \sqrt{\sum_{i=1}^{n} f_{i,il}\frac{s_{i,il}(x_j)}{s_{comb,il}(x_j)}} \qquad (10)$$

10. Calculation of VIV fatigue damage in IL direction with the flow velocity.

$$D_{fat_{IL_k}}(x_j) = f_{cyc.il(x_j)}.\left(\frac{s_{comb_{Il}}(x_j).SCF}{Mpa}\right)^{m(x_j)}.\frac{P_k}{\bar{a}(x_j)} \qquad (11)$$

3.2 S-N Curve for VIV fatigue

Due to the high costs and high time required to do a lot of testing of fatigue and the number of test samples, it is necessary to take into considering statistical fatigue property. In this research has been used the standard fatigue test provided by ASME in the year of 2003 for the determination of a S-N curve with the minimum number of laboratory samples [12]. S-N Curve is one of the ways of calculating fatigue life. S-N curve, based on the input data of the fatigue test. According to the DNV-F-105, the Eq.(12) for the S-N Curve is presented.

$$\log N = log\bar{a} - mlog\,\Delta\sigma \qquad (12)$$

$\alpha\alpha$ is a constant coefficient corresponding to the S-N curve. S is also Standard Deviation compared to. To calculate the fatigue life with SN-Curve, fatigue must be a linear assumption.

$$D_{fatlife} = \sum_{i=1}^{k}\frac{n_i}{N_i} = \frac{1}{a}\sum_{i=1}^{k} n_i\,(\Delta\sigma_i)^m \qquad (13)$$

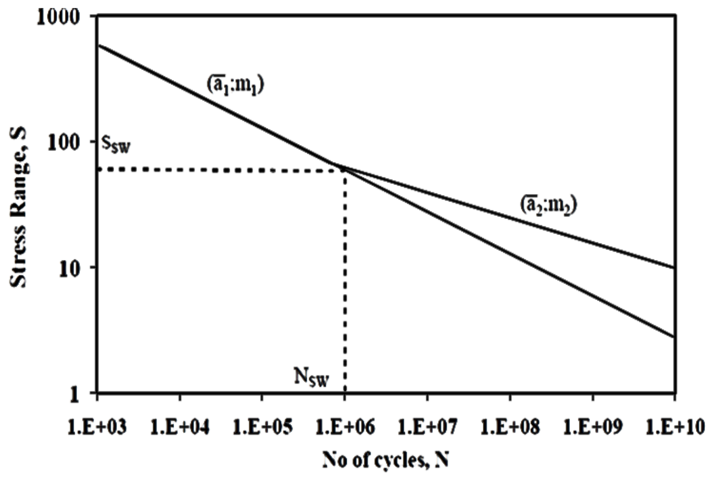

Figure 2. The slope of S-N Curve [6]

4. Modeling

In this study, the pipeline modeled as a two-beam behavior and bending behavior. In order to pass up the question of the marine pipeline balance, the seabed was modeled with a rigid surface. For modeling of a free span, both ends of the pipe were fixed. To phenomenon simulation, the pipeline is located on the surface of the rigid seabed and not buried. In the load steps, the pipe gravity force is applied to the model first, followed by the internal pressure due to hydrocarbon passage, external pressure due to the water column, and temperature to match the effective axial force. Also, it is assumed that concrete coating is not effective on the weight forces and drag forces. The length of the pipeline on both was determined by following the DNV Code.

4.1. Free-Span Fatigue Analysis

VIV fatigue analysis for a single-span pipeline with a single-mode response is performed for a 30-inch gas flow line with 29.7 mm wall thickness at the water depth of 850(m). Studies have been carried out on four span lengths of 80, 100, 180, 250(m) that are exposed to flow at a range of 0.16 to 0.185(m/s) [13].

4.2. Environmental Loads

The sea pipeline is exposed to loads due to current and waves. The wave effect in deep water is neglected and only the effects of the current have been investigated. The effect of the current velocity by the Weibull distribution can be evaluated [14]:

$$F_X(x) = 1 - exp\left(-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right) \qquad (14)$$

In this regard, the estimated coefficients are based on the design.

Reduced current velocity ($V_R V_R$) and stiffness (K) are VIV fatigue parameters.

$$V_R = \frac{U_c + U_W}{D_C f_n} \qquad (15)$$

$$K_S = \frac{4\pi m_e \xi_T}{\rho_w D_C^2} \qquad (16)$$

The approximate amount of raw natural frequencies of structures can be gained from the DNV-F-105 that is:

$$f_1 \approx c_1.\sqrt{1+CSF}\sqrt{\frac{EI}{m_e L_{eff}^4}.\left(1+\frac{S_{eff}}{P_{cr}}+C_3\left(\frac{\delta}{D}\right)^2\right)} \qquad (17)$$

$$P_{cr} = \frac{(1+CSF)C_2\pi^2 EI}{L_{eff}^2} \qquad (18)$$

$$m_e = \left(\frac{\int m(s)\emptyset^2(s)ds}{\int \emptyset^2(s)ds}\right) \qquad (19)$$

5. Case Study

Case studies in this paper are the actual numbers of the Ormen Lange gas field in western Norway in the Norwegian Sea. Free span specification in the case study to be considered according to table 2.

Table 1. Properties of case study

Characteristic	Value
Depth	850 [*m*]
Outer Diameter	762 [*mm*]
Wall Thickness	29.7 [*mm*]
Concrete thickness	8 [*mm*]
Water density	1025[$^{kg}/_{m^3}$ $^{kg}/_{m^3}$]
Steel density	7850 [$^{kg}/_{m^3}$ $^{kg}/_{m^3}$]
Significant Mean Yield Stress(SMYS)	450 [*MPa*]
Significant Mean Tensile Stress(SMTS)	540 [*MPa*]
Young's modulus (E)	207 [*GPa*]
Soil	Firm clay
Fluid density	150 [$^{kg}/_{m^3}$ $^{kg}/_{m^3}$]
Span Length	100 [m]
Span gap	1 [m]
Current velocity	0.16-0.165 [$^{m}/_{s}$ $^{m}/_{s}$]
Current coefficient	α=0.12, β=1.55

6. Results & Discussion

The free-span subsea pipelines with different span lengths were modeled by the ABAQUS standard code. In this paper, the effect of VIV in the direction of CF is not considered due to the dominance of the IL direction. Table 2 shows the fatigue life in the IL direction for four different span lengths.

Table 2. Fatigue life for multi-span length sensitivity analysis

Case No.	L/D	In-line VIV fatigue life (year)	Fatigue life based on DNV (year)
1	80	1614.215	50
2	100	1352.79	50
3	180	209.314	50
4	250	112.752	50

According to DNV, VIV fatigue life is considered to be 50 years in the design of subsea pipelines. Table1 shows that the results of numerical simulations are very different from the DNV, which indicates that rule is over design.

The subsea pipeline has different dynamic behaviors based on the free span length. According to DNV-F-101 for each L/D ratio the pipeline as a modeled beam, cable or combination of beam and cable. In this research, investigated all possible pipeline behaviors across different span lengths. The result of a pipeline with different behaviors is present in figure3. According to figure1 Variations of VIV fatigue life in the pipeline with beam, behavior tends to be steeper than other pipeline behaviors, and as far as full cable behavior proceeds, changes occur with less slope, and VIV fatigue life changes slowly with length increases.

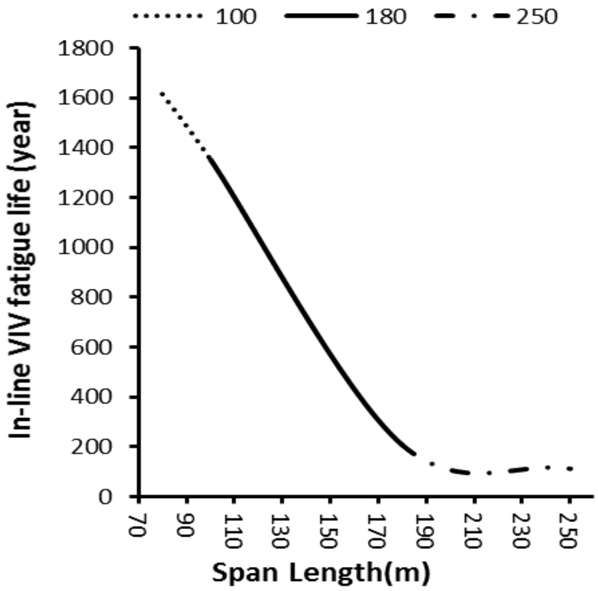

Figure 3. VIV fatigue life of subsea pipelines with different behaviors

The free span first mode frequency of the subsea pipeline depends on the axial force on the pipeline. Different parameters and phenomena are effective to determine the mentioned forces. The free span first mode frequency of the pipeline for different axial forces is shown in figure 4. The change of free span first mode frequency relative to the axial load is linear. In another word free span first mode frequency Independent on VIV parameters.

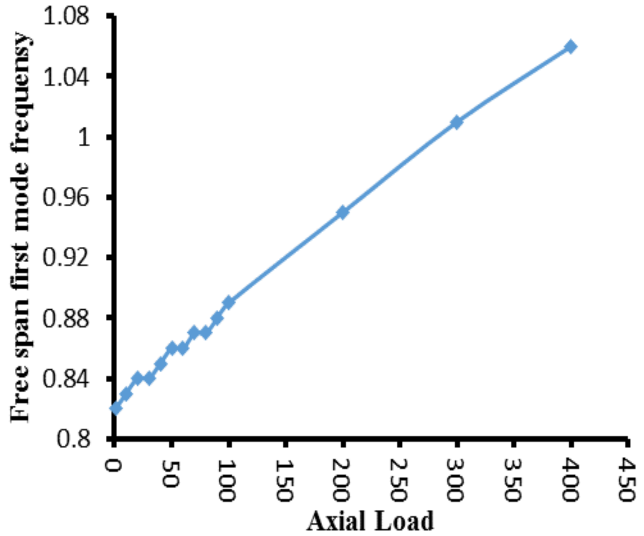

Figure 4. Free span first mode frequency of the pipeline relative to the axial load

Information on the trend of changes in VIV fatigue life with different span lengths exposed to currents with variable values is presented as a curve in figure 5. According to the curves in figure 5, increasing the current velocity increases VIV fatigue life. The rate of fatigue life in different lengths of the span is not the same. The pipeline has been faced with a significant increase in fatigue life by moving away from its beam behavior and moving toward cable behavior.

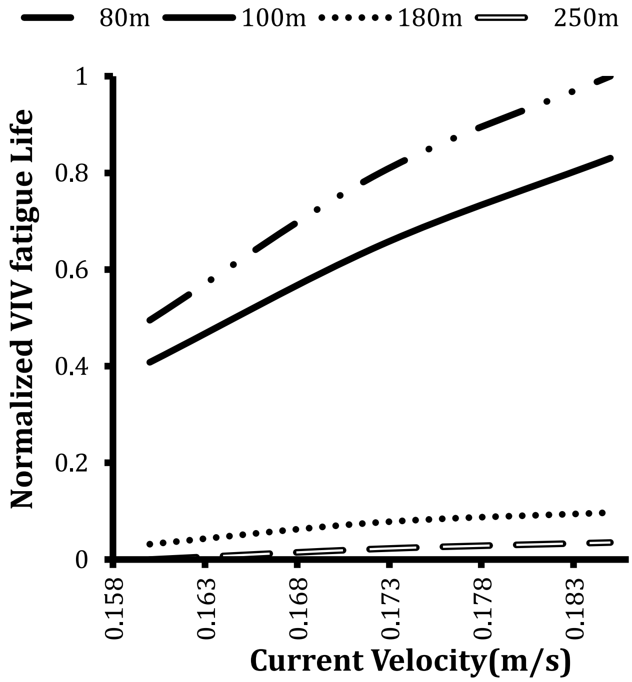

Figure 5. VIV fatigue life for different span lengths in variable current velocity

In this research, fixed supports one of the assumptions to determine VIV fatigue. For pipeline with L/D ratio, less than 80 behaves exactly like the beam.

For the pipeline like a beam, if snap support change to cantilever support, the VIV fatigue life increased 18% and support changes are independent to the current velocity.

Generally, pipeline parameters and environmental conditions that are associated with uncertainty are criteria for the design. Figure 6 illustrates probable failure per different span length and different current velocity. To appear probability results, the negative logarithm of the probability based on different flow rate is plotted in figure 7. 4 curves in the chart represent the increase in the probability of VIV fatigue. Fatigue probability changes greatly due to the pipeline behavior interface from beam to the cable.

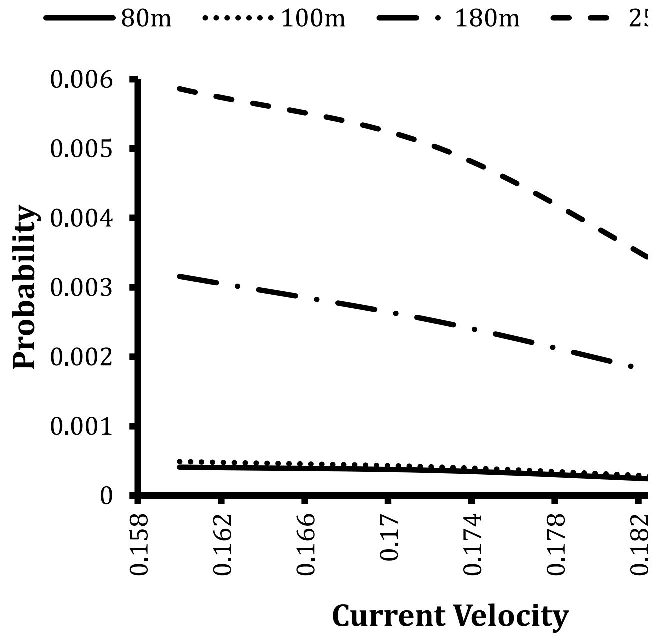

Figure 6. Fracture probability under the effect of VIV fatigue

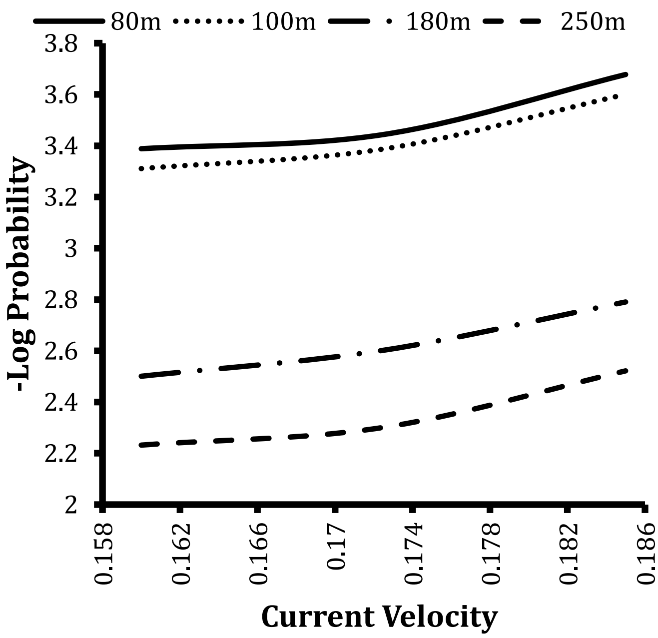

Figure 7. -Logarithm fracture probability under the effect of VIV fatigue

7. Conclusions

In this study, based on pipeline modeling in the ABAQUS standard code and recommended model DNV-RP-F105, the fatigue life of the pipeline has been determined under different conditions and compared to the required value. The obtained results are presented:

- The VIV fatigue damage of the pipeline with vertical displacement at one end is much greater than the pipeline with snap support. In other word by creating more vibration and displacement on one side of the pipeline reduces the fatigue life of 113 percent compared to snap.
- By reducing the span length from 250(m) to 80(m), VIV fatigue life increases by seven times. Maximum changes occur between cable and behavioral which the amount of these changes is reduced by 75%.
- Among the VIV effective parameters that affect pipeline fatigue, free span lengths are more effective and free span first mode frequency is independent of VIV parameters.
- Fatigue probability changes greatly due to the pipeline behavior interface from beam to the cable.

List of Symbols

E	Modulus of elasticity
k	Stiffness
V_R	current velocity
$C_1 - C_3$	boundary conditions coefficient
I	Inertia
CSF	Increase the stiffness factor of concrete
L_{eff}	Effective span length
m_e	Effective mass
D	Outside diameter
P_{cr}	Critical buckle load
Δ	Static displacement
S_{eff}	Effective axial force
Φ	Mode shape of boundary condition
α	Current coefficient
β	Current coefficient

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INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.4/ No. 3/Autumn 2019 (17-31)

Available online at: www. Ijcoe.org

A Systems Engineering Approach to Physical Security of Oil & Gas Installations

Sirous F. Yasseri

Brunel University London; Sirous.Yasseri@Brunel.ac.uk

ARTICLE INFO

Article History:
Received: 25 Mar. 2020
Accepted: 06 May. 2020

Keywords:
Physical Security
Security Assurance
Systems Engineering
Defence in depth
Security threats

ABSTRACT

A fundamental challenge facing security professionals is preventing loss; be that asset, production, or third-party losses. This is not dissimilar to what safety professionals have to face. Techniques and methodologies used by the safety professionals could potentially benefit the security experts. Physical security is about taking physical measures to protect personnel and prevent unauthorized access to installations, material, and documents, which also include protection against sabotage, willful damage, and theft. The characteristics of physical security controls include measures for deterrence, detection, delay, and responses aimed at risk mitigation and enhanced operational effectiveness.

This paper outlines a systems engineering framework for implementing security goals, which are suitable for meeting the challenge of providing physical security for complex systems, which includes oil and gas facilities. The proposed framework builds security requirements into system requirements and moves it in parallel with the system development for the entire system's life cycle; particularly during the concept and design phases. This is a top-down process for use by a multidisciplinary team of security, operations, and industry experts to identify and prevent the system from entering into vulnerable states which could lead to losses. This framework shifts the focus of the security analysis away from threats, being the immediate cause of losses, and focuses instead on the barriers, i.e. safeguards that prevent systems from entering into vulnerable states, which would allow an unfolding event to disrupt the system leading to loses.
The need for such a method comes from the recent experience of the securing complex systems that combine a large amount of hardware, software hazardous materials, and control elements. The method takes advantage of systems engineering and encourages the use of goal-based security requirements instead of using a strict prescriptive approach that is common among security professionals. Using this framework helps both to identify threats associated with the system, as well as weak points within the system. This framework also encourages communication between the security professional, safety engineers, and system designers. This paper draws from the existing literature as listed in the references.

1. Introduction

Physical security is concerned with constructing systems that remain operational despite intentional (willful, malicious) or unintentional (human error, equipment failure,) events [44, 46, and 50]. The objective is to design and build complete systems that proactively and reactively limit vulnerabilities and survive undesirable events; so that the system's mission is assured.

Physical security is an integral part of security engineering. The ISO/IEC 21827 standard [23] identifies the following list of sub-disciplines:

- Operations security
- Information security
- Network security
- Physical security
- Personnel security
- Administrative security
- Communications security
- Emanation security
- Computer security

This paper's focus is on physical security.

The US Department of Defence (DODI5200.44 [12]) defines the term System Security Engineering (SSE) as: "*an element of system engineering that applies scientific and engineering principles to identify security vulnerabilities and minimize or contain risks associated with these vulnerabilities*". A comprehensive survey of the issues and a detailed reference list is provided by Baldwin [6] and Baldwin et al. [7]. DODI5200.44 [12] defines two perspectives for systems security engineering. First, it explains how criticality analysis and security engineering are integral to the technical and systems engineering management as per ISO/IEC 15288 [24] Another perspective of the guide is the overlay of security throughout the life-cycle. It is critical to address security requirements [16] while the largest possible ease of reconfiguration of the system exists, and also to ensure the technical maturity of the security solution throughout the vendor selection, acquisition and construction phases. This understanding should also help with setting and enforcing measures for security.

Security system designers have presented physical security as a tactics problem in the past [53], focusing only on how best to defend assets against threats. While tactics are necessary, this viewpoint misses the primary objective which is the systems' ability to function after an attack, i.e. what is at risk. Defending an asset is not a goal in itself; rather it is a means of safeguarding services and missions against disruptions oe outage. Reframing the problem into one of strategy [53] would produce better outcomes. Such reframing requires to shift most (but not all) of the security analysis away from guarding against attacks (which is tactics) and focus on the broader socio-technical vulnerabilities of a system that allows disruptions to propagate throughout and disable the system (which is strategy) [53]. In other words, rather than primarily focusing the majority of the security efforts on threats from adversary actions, which are beyond the control of the security professionals, focus should be on limiting system's vulnerabilities that are under the designers' control, especially at early phases of a project.

2. The State of the Practice

Security engineering involves several inter-disciplinary requirements, such as stronger physical structures, computer security, tamper-resistant & error-tolerant hardware, psychology, supply chain management, and law [4 and 47]. Security requirements differ greatly from system to system and will primarily depend on the socio-economic and geopolitics of the system environment [50]. System security [40] often has many layers to control entry, authentication of people accessing it, deter & delay, accountability chain, vulnerability, deception, secrecy, and damage tolerance. The challenges are protecting the right items and in the right way [29 and 35]. This paper builds on the idea that the primary objective of System Security Engineering (SSE) should be to minimize, or contain, system vulnerabilities to known or postulated security threats, and to ensure that systems during their entire life cycle are protected against these threats [13 and 27].

The principle idea revolves around the belief that an initial investment in mitigating security vulnerabilities, and the ability to take countermeasures, is cost-effective in the long term. Further, SSE provides a means to ensure adequate consideration of security requirements is made, and those specific security-related requirements are incorporated into the project requirements; not bolted on at a later stage. Security requirements should be identified early in the project (where they can be adequately addressed), implemented, and verified in the course of the system development.

The System Security Engineering Management Plan (SSEMP) is a key document to develop for SSE [27]. The SSEMP focusses on the planning of security tasks for a system, the organizations, and the installation's security. The goals of the SSEMP are to ensure that pertinent security issues are raised at the appropriate points in the project's life cycle, to ensure adequate precautions are taken during the design, implementation, testing, and operation; as well as to ensure that only a tolerable level of risk would be incurred due any introsion during the system life cycle. The SSEMP details the primary tasks required for certification & qualification, preparation of documents, evaluation of the system [15], and detailed engineering. It also identifies the responsible and accountable organizations for each task and presents a schedule for the completion of those tasks.

The SSEMP explains the initial planning of the proposed SSE work scope; detailed descriptions of SSE activities performed throughout the system development life cycle; the operating conditions of the system; the security requirements; the initial SSE risk assessment (including risks due to known system vulnerabilities and their potential impact on continuous operation); and, the verification& validation aproach and results.

An initial system security Concept of Operations (CONOPS) may also be developed [22]. This document explains how system security should operate.

The last step before handing over the system to the client's operations team is the system validation and assurance [14]. NATO AEP-67 [33] defines system assurance as:

"…the justified confidence that the system functions as intended and is free of exploitable vulnerabilities, either intentionally or unintentionally designed or inserted as part of the system at any time during the life cycle... This confidence is achieved by system assurance activities, which include a planned, systematic set of multi-disciplinary activities to achieve the acceptable measures of system assurance and manage the risk of exploitable vulnerabilities."

Since most modern systems rely on software for some of their functionality [24 and 26]; software assurance becomes a primary consideration in system assurance

[3]. The software assurance is a "*level of confidence that software is free from vulnerabilities, either intentionally built into it or accidentally inserted sometime during its lifecycle, and that the software functions as intended*" [11].

This paper draws from the existing literature to build a systems engineering based framework for the physical security of petroleum installations.

Two approaches are commonly used for improving security during the project development and assurance phases before handover to the client, which are prescriptive and goal-based (or performance-based) approaches [1 and 2]. In the first approach all security requirements, analyses and assessments are aimed at ensuring that hazards associated with the system are controlled, removed, or at least mitigated by using predefined scenarios - this is a threat-based approach that is well reflected in the military standards. The second approach focuses on the goals of security, namely what, how, and why we are doing something. As such the focus is on early security requirements [9 & 47] at the conceptual phase of the project. Later, during project development, the system requires verification and validation to prove that it complies with the security requirements; allowing some modifications if needed. With this approach, security goals are set at the select phase and verified during the define phase [51]. This goal-based approach is gradually replacing the prescriptive approach as it becomes more and more irrelevant to modern complex systems.

Security professionals draw heavily on language, metaphors, and models from long standing military approaches. There is a distinction in military doctrine between tactics and strategy. Strategy can be considered as the art of gaining and maintaining a lasting advantage. In contrast, tactics are a prudent means of achieving a specific objective. Tactics are focused on threats, while strategies are focused on outcomes [53]. Means of achieving an objective is tactics, in contrast, the overall campaign plan is termed strategy, which could involve operational plans, actions, and decision-making that shapes the tactical execution. Strategy and tactics are complementary and thus have an intertwined existence. In military terms, tactics are the use of armed forces in engagements, while strategy is the use of engagements to achieve the overall goals. Strategy and tactics are both needed to achieve target goals and objectives. The strategy is the path or bridge for going from where we are today to the destination. It's our general resource allocation plan [53].

Most current security policies generally follow tactics models, namely security analysts will identify some immediate causes that will provide a reason to establish a barrier along the path of a probable event [8]. This type of approach is often described as the "defence-in-depth" concept [21] and is commonly used in security literature as a framework for conceptualizing the goal of security practices. This is a necessary part of securing a system, but it misses other elements of controlling the security risks.

Exploiting vulnerabilities by attackers cause the loss (i.e. a threat); tactics consider threat as the cause of the loss [20]. According to this line of thinking, the loss is when a threat successfully disables several barriers to reach its target [44]. Loss prevention, then, is dependent on how accurately security analysts can identify potential attackers, their motives, capabilities, and strengths. Keeping this point in mind, security analysts will analyse their systems to determine the most likely path that attackers may take to reach their target. Resources can then be allocated to place barriers along that path to prevent losses. This is a causal chain-of-events model which is also used in safety engineering, where the attempt to avoid accidents is focused on breaking the chain, by either preventing individual failure events or erecting barriers to prevent propagation [49].

This threat-based approach [20] is useful for identifying and countering security threats against a single, well-defined, and well-understood attacker or asset. Once an adversary's course of action is identified, the security analyst can provide advice on how best to allocate limited resources to prevent the attack and break the chain. The idea is based on a chain of events, which believes that if one link is broken then the event can't take place. In other words, a high level of threat-understanding enables security analysts to predict not only where an adversary will attack, but also the logical and physical infrastructures required to thwart the attack, which heavily depends on the experts' opinion. Systems designed only based on experts' opinions often lead to unmaintainable, unreliable, and non-rigorous systems. Many methodologies and procedures were developed to counter this viewpoint. Issues addressing this approach are discussed by Plant [38].

The Principle of Defence in Depth [48] for physical protection [11] is built on the idea of building several layers and protection methods (structural or technical, personnel, and organizational), that have to be overcome or circumvented by an intruder to achieve his objectives. The protection of the nuclear power plant is based on the concept of Design Basis Threat (DBT) [20] for the physical protection of a Nuclear Power Plant (NPP), which is protecting a facility against the objectives of an adversary. The physical protection of an NPP is based on many different protection measures, structural and other technical, personnel, and organizational measures, installed and organized in different areas of the facility. The protection measures depend on the consequences for the facility as well as the type of attack. The DBT is based on the maximum credible threat which an organization is expected to control. Beyond that requires government intervention.

3. Defence-in-Depth

The concept of defense-in-depth follows the *Swiss cheese model* for an accident [17]. Each slice of cheese represents a barrier or a control measure which is assumed to be imperfect (i.e. with holes), where each hole represents some bypass (circumvention) or evasion. Employing the Defense-in-Depth concept results in the stacking of barriers, such that each additional stack reduces the exposure and thus reduces the overall risk, Figure 1.

These overlapping layers of protection have been a fruitful approach since it ensures that a "core" set of scenarios is always studied and that the "core" is continually updated by input from the teams studying new emerging threats. The risk of overlooking a potential threat is thus minimized. Success depends on correctly identifying all threats and having barriers in place to impede them all.

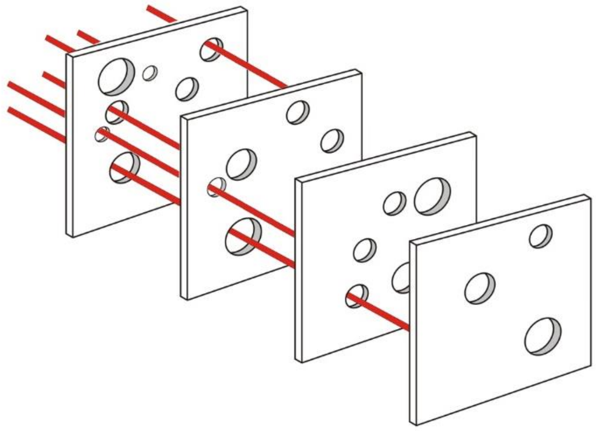

Figure 1. The concept of defense in depth; showing possible flaws in each layer.

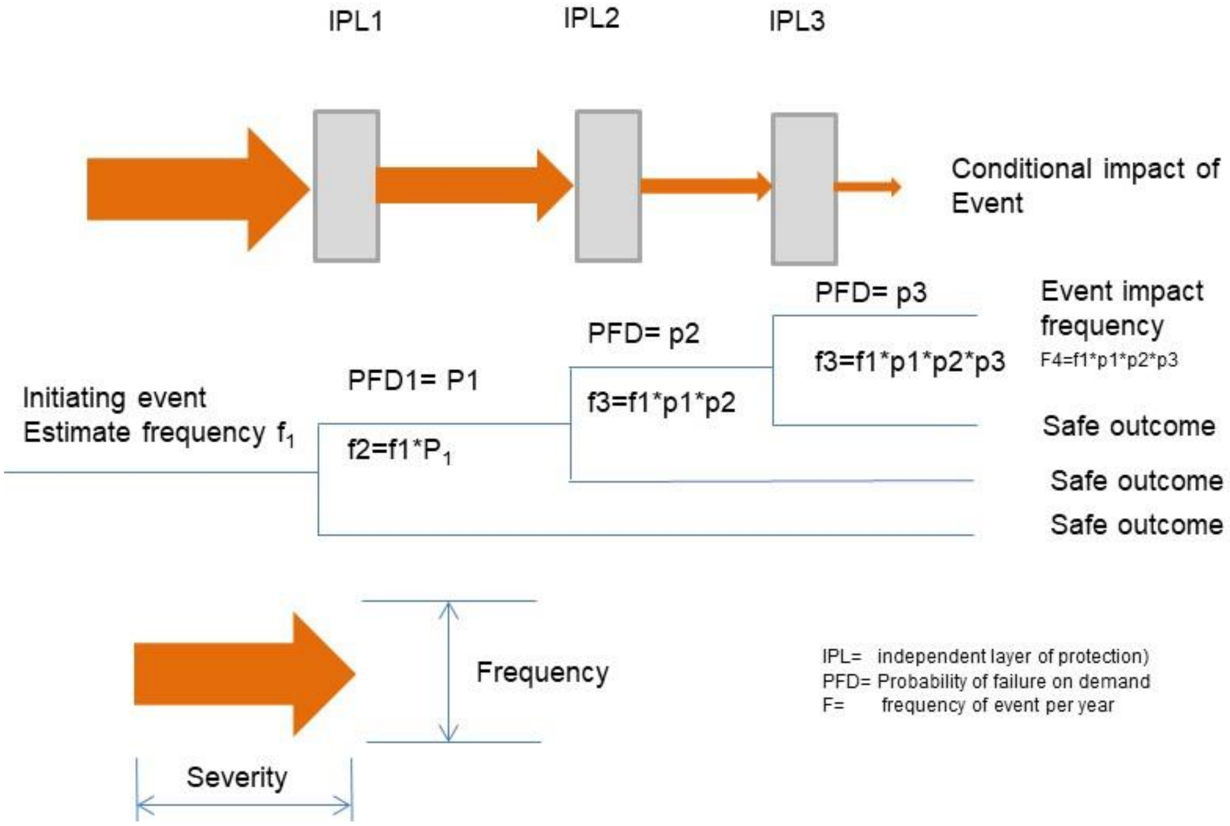

Figure 2. Reduction of severity and frequency of damage using multiple lines of defense (or layers f protection)

When scenarios are compiled, the attack event is coupled with a description of what could happen if an attacker proceeds to the inner domain without being challenged. Each scenario can contain several "attack-consequence" pairs and may have multiple paths to the target. The consequence may be then assessed for severity and frequency. The "bow-tie" [8, 36 & 37] is a suitable method for representation which details the initiating event and the safety barriers which may be present. The "bow-tie" operates as a fault/event tree, taking into account the "ANDs" (events or conditions which must both be true for a hazard to develop) and "ORs" (events or conditions, either of which, if true will allow a hazard to develop) [8].

Lines of defense (or layers of protection) analysis operate as shown in Figure 2. When addressing barriers, it must be assured that its rules are robust enough, and their independence must be guaranteed before they can be considered acceptable. Care needs to be taken when a single consequence can be caused by several different initiating events, or a single event may have multiple paths, thus affecting the cumulative risk. Whilst this might prove to be difficult to reconcile, most practitioners take a very conservative view of threat frequencies and Probability of Failure on Demand (PFD) [17] for independent layers of protection or barriers, which ensures that overall risks are tolerable.

In the example shown in figure 2, the impact event frequency is the product of the original initiating failure event frequency and the PFDs of the 3 lines of defense. As each layer is called upon to function, the failure frequency of the entire system becomes progressively smaller.

4. Security Risk

Risk assessment combines risk analysis and risk management, using a systematic process for hazard identification and determining their consequences, as well as how to cope with these risks. Numerous methodologies were devised for the risk assessment, focussing on different types of risks or different areas of concern. For example HAZard and Operability study (HazOp); Fault Tree Analysis (FTA); Failure Mode and Effect Criticality Analysis (FMECA); Markov analysis (Markov); etc. These methods are to a great extent complementary. They cover all phases in the system development and maintenance process. In general, qualitative methodologies for analyzing risk are effective in identifying risks, but they cannot account for the dependencies between events. Tree-based techniques, however, take into consideration the dependencies between events.

The security risk is defined as:

$$Risk\ (R) = [Threat(T) \times Vulnerability\ (V)] \times Consequence(C)$$

Terms in this equation are defined:

• <u>Threat</u>: a measure of the likelihood that a specific accident or attack will occur.

• <u>Vulnerability</u>: a measure of the likelihood that various types of safeguards fail.

• <u>Consequence</u>: the magnitude of negative effects in case of an accident or successful attack.

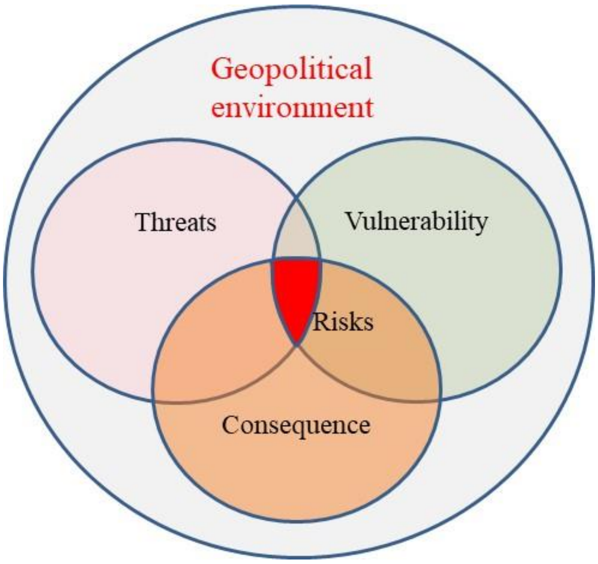

Figure 3. Risk definition as the intersection of threats, vulnerability, and consequences. All three elements may be used to make all risks as low as reasonably practicable (ALARP).

The threat, vulnerability, and consequence analysis [8] is an interactive approach to identify areas subject to high threat levels, extreme vulnerabilities, and high consequences overall, namely the intersection of these causes security concerns (Figure 3). These three elements should be considered in the geopolitics of the facility's location. What should be looked at are summarised below

Threat:

• Understand where terrorists target their activities.

• Typically based on intelligence information.

• Security responses are dependent on available information.

Vulnerability:

• Assessment for critical assets.

• Identify weaknesses/gaps for each attack scenario.

• Identify potential mitigation measures.

Consequences:

• Different types of consequences, i.e. health, environment, economy, and social aspects.

• Short and long-term consequences.

• Economic dimension, e.g. loss of productive capacity and availability

• Political dimension, e.g. stability, geopolitical issues.

The Security Assurance [30, 32, 51, and 52]requires that security measures must be implemented with the intent of providing long-term, continuous protection. New risks and vulnerabilities are introduced at an alarming rate with new technologies being developed and implemented just as fast. The skill, sophistication, and motivation of intruders seem to be increased proportionally. The critical challenge is to keep security configurations current with continual updating. The protection is accomplished by establishing multiple defensive layers (or control measures) around the critical perimeter.

An example of hazards faced by oil & gas[5] facilities is listed in Table 1. The rest of this paper describes how to manage a facility's security concerns during the development phase.

Table 1: Examples of hazards threatening oil & gas facilities [5]

Technological	Natural	Willful (malicious) acts
✓ **Internal** ○ Aging & corrosion ○ Fire & explosion ○ Material failure ○ Corrosion ○ Inadequate design ○ Operator error ○ Excursion beyond design parameters ✓ **External** ○ Domino effect for nearby ○ third party groundwork	Flood Hurricane Earthquake Landslide Ground movemen	Hostile governments Terrorist attack Criminal acts e.g cybercrime of sabotage

5. Systems Engineering V-Model

Systems engineering [31] is an interdisciplinary process that assures the customer's requirements are satisfied. The lifecycle of an oil & gas facility has seven phases: (1) appraise, (2) concept development & selection, (3) front-end engineering, or defining, (4) detailing, fabricating and installing, (5) system integration and testing, commissioning (6) operation, maintenance and modification, and (7) disposal or replacement. The system life cycle may vary from operator to operator, but it would look like the upper section of Figure 4. Whatever form the life cycle takes, requirement analysis is the first step in this process. Concept development, which takes place in the select phase, is the high-level process of determining, understanding, and shaping customer needs.

The V- model describes the activities and results that must be produced during development (Figure 4). The left-hand of the V represents the system specification stream, where the system requirements and the system and subsystem or component designs are specified. The designed components are then fabricated and installed at the bottom of V. Component fabrication is followed by the testing stream in the right-hand of the V, where the gradually evolving and growing system is verified against the specifications defined in the right-hand of the V.

The V-model separates the disciplines of systems and design engineering. This way, top-down and bottom-up development approaches are integrated into the V-model. That is, the system is specified top-down and then the subsystems are integrated bottom-up. Working closely with client engineers, the requirements are elicited, analysed, validated, and documented. At the same time, the security needs of the system must be identified and added to the client's technical needs [34].

Technical, economic, and political feasibility, as well as security issues, are assessed at the appraise phase (Figure 4). In the next phase, known as the select phase, alternative concepts that meet the project's purposes and needs are explored, and the best concept is selected and justified. At this phase, security must be part of decision criteria. The project stakeholders reach a shared understanding of the system to be developed and how it will be operated, maintained, and protected [34 & 52].

Requirement analysis [16] (both technical and security) provides a framework for understanding the purpose of a system, the contexts in which it will be used, and how to keep it secure and safe. In seeking to describe the security requirement of a system, it is necessary to look beyond the system itself, and into the activities that it will support as well as the socio-economic and geopolitics of its environment.

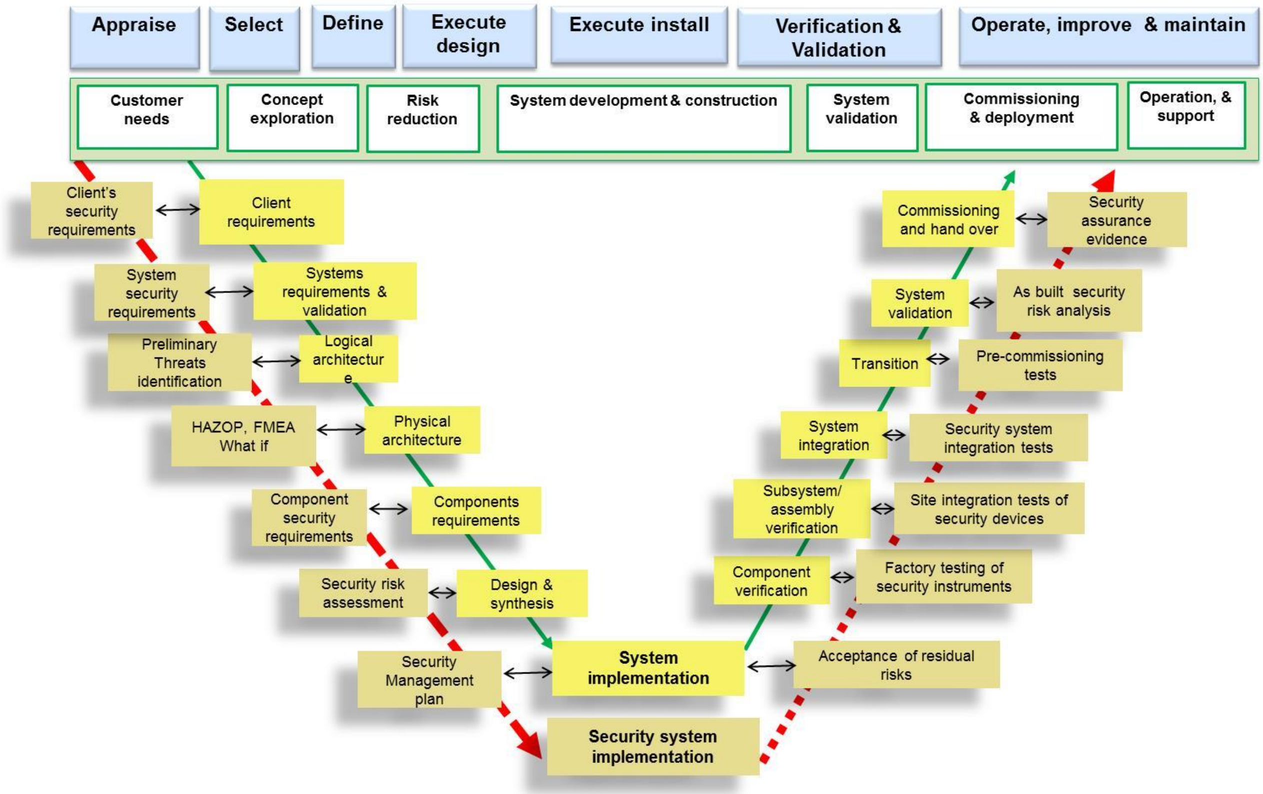

Figure 4. The V-model for the life cycle of an oil & gas project.

Requirements engineering refers to eliciting, specifying, analysing, accepting, validating, and managing the project requirements while considering the user, technical, economic, political, security, and business needs. Ideally, each requirement from the highest to the lowest level of the project must link to a parent

The client's security needs are used to set the initial security requirements. Initial security validation is done to ensure the selected requirements are sufficient and necessary for the protection of the installation. In addition to performance analysis of the security system using risk analysis, such as FMEA, Fault Tree Analyses, and Probabilistic Risk Analyses, to ensure the design will be robust and resilient.

Every security requirement must be traced to the means of its implementation, and every security system must be traced back to one or more of its security requirements. This mapping of security requirements to its implementation may be one to one or one to many [25], which is the traceability analysis.

6. Systems Engineering for Security

The design of safeguards for system protection requires a more formal methodology to support the achievement of objectives and traceability [25]. A systems engineering process can provide a framework within which different technologies can be implemented to design and evaluate the effectiveness of the security systems. Implementing such a process early in the development can save costs and prevent using less effective bolt-on security systems.

The elements of the systems engineering process envisioned for a design for security are shown in Figure 5. The initial step is to determine the security objectives (or security requirements), which includes the client's requirements, regulatory requirements, characterization of the facility, threats analysis, and identifying the targets including system vulnerabilities. The next step is the design of the security system, which includes identifying system elements to perform the detection, delay, and response functions [41]. The final step is to analyse and evaluate the design for all threats. Based on risk analysis results, the system design is modified, by including barriers (or control measures) until a desirable (optimised) compromise is obtained. The following sections describe each step in more detail [27].

Identify Security Objectives: Designing a protection system for a project begins with identifying security requirements, namely what has to be done, why, and how to do it? The security requirements are in addition to the client's operational requirements for the project. The primary focus of a protective system is to detect malicious intention and identify the perpetrators before any harm is done. This step may be complicated due to regulatory requirements and the continually changing nature of the threat. The step addresses four primary areas: regulatory requirements, facility characterization, threat definition, and target identification:

- In addition to the specific client's security requirements, the project must also comply with the regulatory requirements regarding project safety & security [39], public security, and environmental concerns.
- Facility Characteristics i.e. its purpose and general layout are needed to provide the context for more detailed protective system analysis. Characteristics such as schedule and procedures for operations, and the use of employees, among other factors, should be considered.
- The threat definition may be one of the most difficult parts of the design as many different threats exist, and adversary capabilities are constantly evolving. The adversary could be a state or non-state actor(s). Motivations, knowledge, equipment, training, and the number of adversaries are all factors to consider. Threat definition for safeguards should include sabotage.
- Target identification (vulnerable areas or critical equipment) would involve generating a list of items, flow streams, or process areas to be protected (vital zones). This list includes the location, size, and characteristics of the stored material. In principle, this is collectively referred to as the system vulnerabilities

Protective System Elements: The primary function of the protective systems is blocking, delaying, and response. The need exists to develop performance testing and validation of the types of equipment that could be part of an overall protective system. Primary protection measures are:

- Surveillance, detection, and alarm. Detection which centres on surveillance also includes alarms and communication and increasingly surveillance.
- Delay, impede & block paths to the target. Blocking is restricting access of non-authorised people reaching a vulnerable area

Verification and Validation (V&V): The final step is verifying each element of the security system by testing, as well as verification of the integrated system. When the entire system is verified, which ensures that the system is built according to the plan, then it must be validated, i.e. if the as-built security system is the right one for the facility. This is done using scenarios and case studies. Proper engineering design does not rely completely on analytical or numerical models but rather uses people to make sure the design meets the desired objectives.

The V&V strategy consists of sets of actions, each one of which is a kind of trial, test, or inspection. There may be several actions defined against each requirement.

Each action should consider the following aspects:

• The kind of action that would be appropriate for the requirement;

- Response plan (rules of engagement): Means of responding to threats and their state of readiness
- Control of hazardous materials and the type of harm it can inflict.

The following issues are also addressed:

- Operation monitoring, which also provides data regarding material accountability. Loss of material is reported to the security management
- Alarm testing and assessment. Alarm assessment may include lower limits of detection and the detectability of diversion scenarios by attackers. If an alarm is triggered, a method must be in place to recognize false alarms. The possibility of disabling the alarm system by saboteurs must be considered.
- Alarm display and communication – The final part of detection is that the alarm must be reported or communicated to the party of interest.
- Exit Delay – Safeguards are only concerned with exit delay. The plant can be designed to make it difficult or time-consuming to get in and out (except via the designated routes) to give enough time to respond if an event is detected.

Barrier Analysis: There must be at least one barrier or control measure for each threat, physical (e.g. wall) or instrumented, e.g. automatic shutdown. Generally, more than one barrier is needed to reduce the risk to a tolerable [17] level (Figure 5). In this analysis, risk should also be shown to be ALARP, namely as low as practicable, [28 & 36]

Risk Analysis: The purpose of risk analysis is to determine the level of the residual risk and if it is tolerable, as well as the effectiveness of the security system. If unacceptable then go back and rethink

• The stage at which each action could take place – the earlier the better;

• Any special equipment that would be needed for the action;

• What would constitute a successful outcome?

If it proves not to be fit for purpose, then the system designer must go back to make changes as needed until the desired performance objectives are met.

Diversion Path Analysis: An infinite number of diversion scenarios are possible [14], but only a small number may be probable. Diversion path analysis is a difficult step because it depends somewhat on the imagination of those involved in the design. Part of this analysis includes the probability of occurrence and response of the systems.

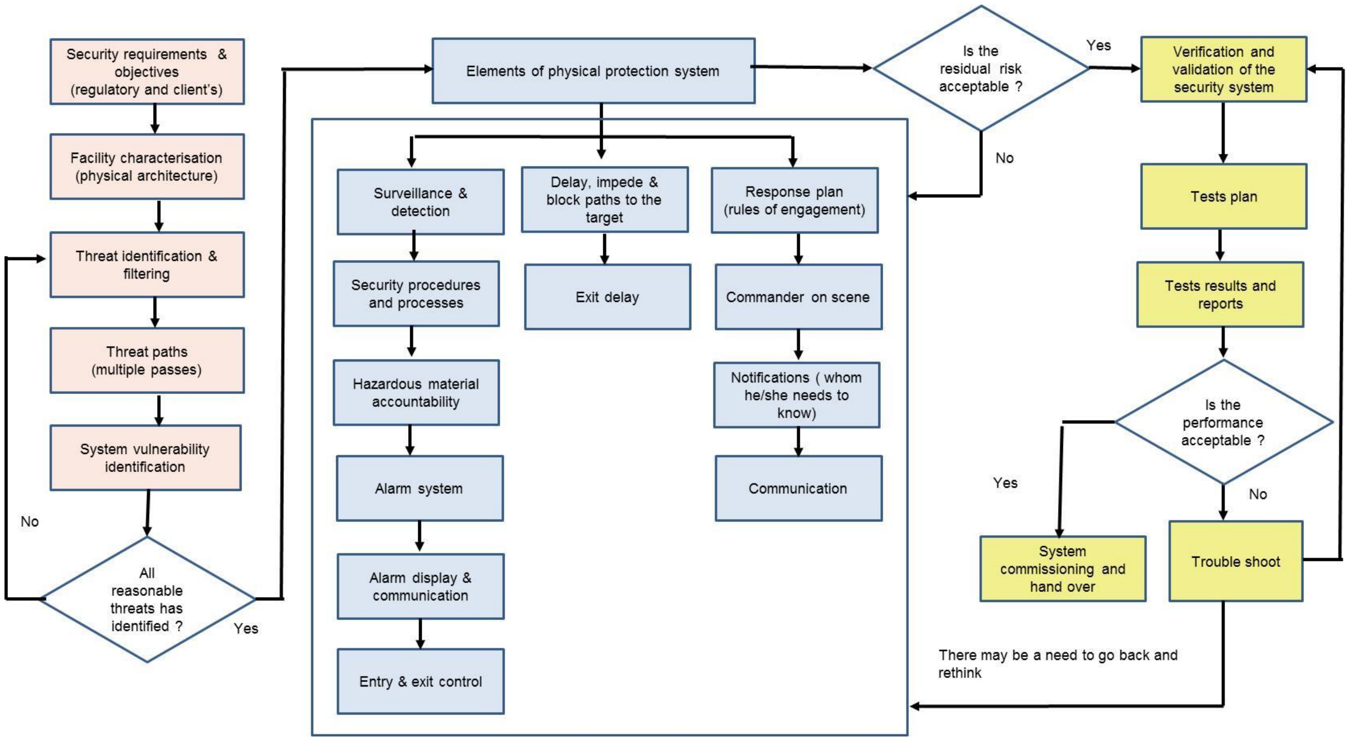

Figure 5. Elements of the systems engineering process envisioned for security design

7. Scenario Selection

There are several methods for selecting scenarios or threats. Hazard and Operability Study (HAZOP), Failure Mode and Effect Analysis (FMEA), and "What if" are just three examples. Some companies have been able to set up libraries of standard scenarios for their studies. This is particularly common where a company uses a similar installation in several different establishments.

FMEA [5 and 42] is based on the concept of the cause-effect chain. Every failure mode is related to a failure cause, and conversely, the effect of each failure is related to a failure mode which causes such effect. A failure effect leads to an unintended situation. The severity defines the importance of the scenario. The frequency relates to failure cause (threat) and effect, and it describes the likelihood of the event (threat).

The Failure Mode and Effect Analysis (FMEA) is a structured technique that is used to investigate security threats and their effects. The aim is to identify potential weaknesses of a system and find means and ways of improving the protection. A system is decomposed to its basic subsystems (or components), and their protection requirements are identified using failure modes to examine their causes and effects [42].

Effective security processes require constant updates to combat the rapid evolution of malicious technology and the ever-expanding range of threats. FMEA originally designed by NASA, and popularized by the automotive industry, has played a key role in helping manufacturers to achieve extremely low fault rates. To achieve similar results in system protection, one should think of security functions as processes, and apply FMEA to prioritize resources towards protecting vulnerable areas whose failure would lead to the worst consequences if damaged.

The advantage of FMEA is the ability in helping to think about all potential failures inherent to the processes or system. FMEA enables leaders methodically to:

•Brainstorm potential failures.

•Evaluate the severity and likelihood of failures.

•Determine the effectiveness of corrective actions in detecting failures.

•Identify appropriate measures to mitigate and prevent failure mode effect severity, as related to the defined boundaries of the system under consideration.

The basic approach (Figure 6) to carry out an FMEA is described in IEC 60812 [19].

Definitions according to IEC 60812 [19]:

•Failure cause: why did the item fail?

•Failure mode: the way that an item fails.

•Failure effect: the consequence of a failure of an item, affecting the operation, function, or state of the item.

•Failure severity: Intensity of the failure effect on item operation, on its surroundings, or the operator.

•Failure criticality: a combination of the severity of an effect and the frequency of its occurrence, or other attributes of a failure such as a measure of the need for addressing and mitigation.

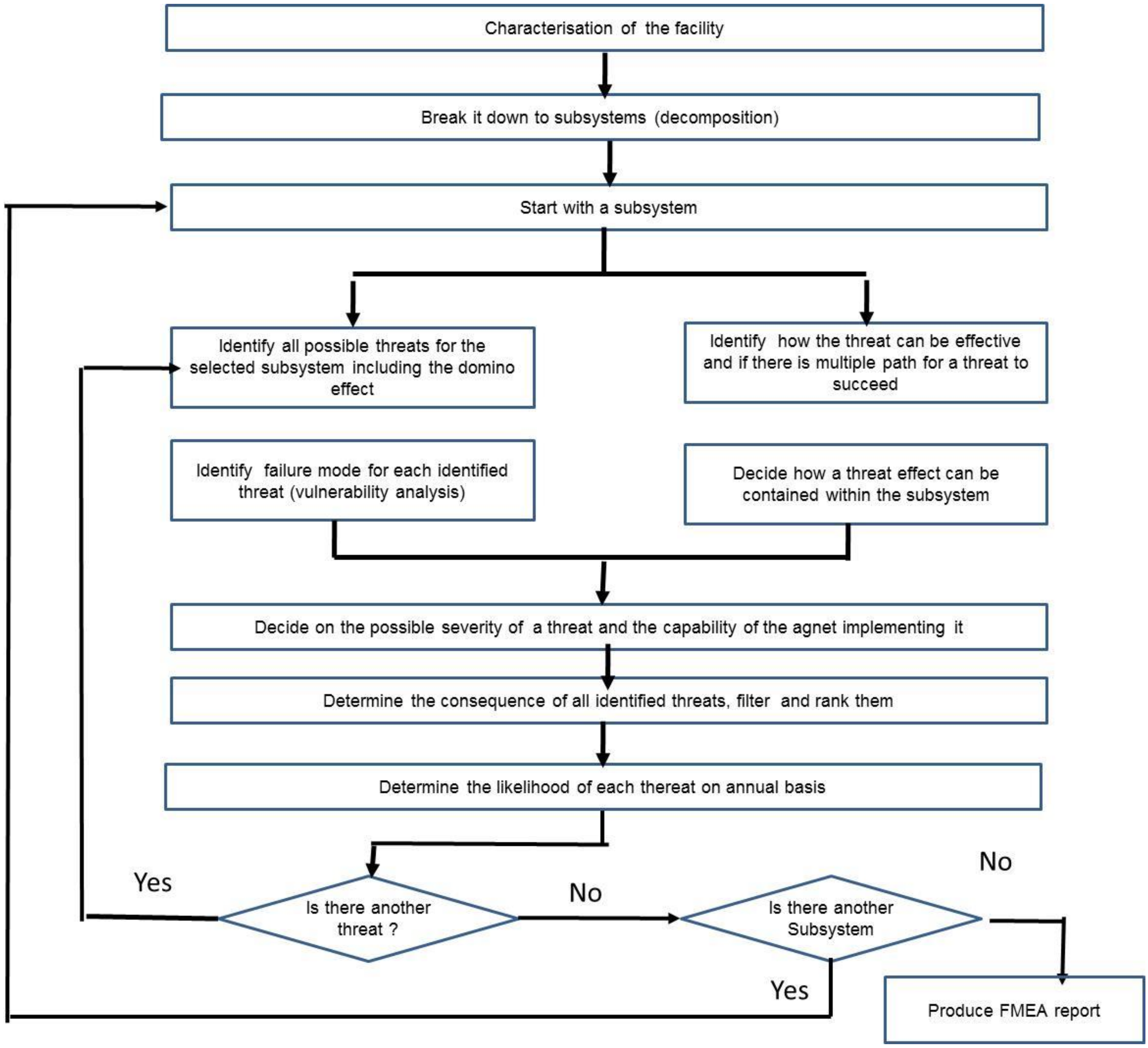

Figure 6. The basic approach to carry out an FMEA as described in IEC 60812 [19].

A similar cause-effect chain is necessary for the inclusion of security, using similar steps for security-critical events. The following elements for security cause-effect chain are a suitable starting point:

- Vulnerabilities
- Threat Agent
- Mode of threat
- Effect of threat
- Attack Probability

Vulnerabilities: The essential precondition for a security breach to succeed is a weak point or vulnerability in the system in which attackers can exploit without impediment. The vulnerability may be considered as a failure cause and should be the starting point of the security analysis. Thus, vulnerability is a weakness that can be exploited by an attacker.

If an attacker (i.e. threat agent) can exploit the vulnerability, then, the system's security is at risk. If there is no threat agent, vulnerabilities on their own do not lead to an effect. For a cause-effect chain, a threat agent is necessary.

While an FMECA usually is very effective when applied to a system, where system failures are most likely the result of single component failures, then Fault Tree Analysis may be a better alternative, especially for systems with a fair degree of redundancy. Qualification of a security system should follow the flowchart shown in Figure 7

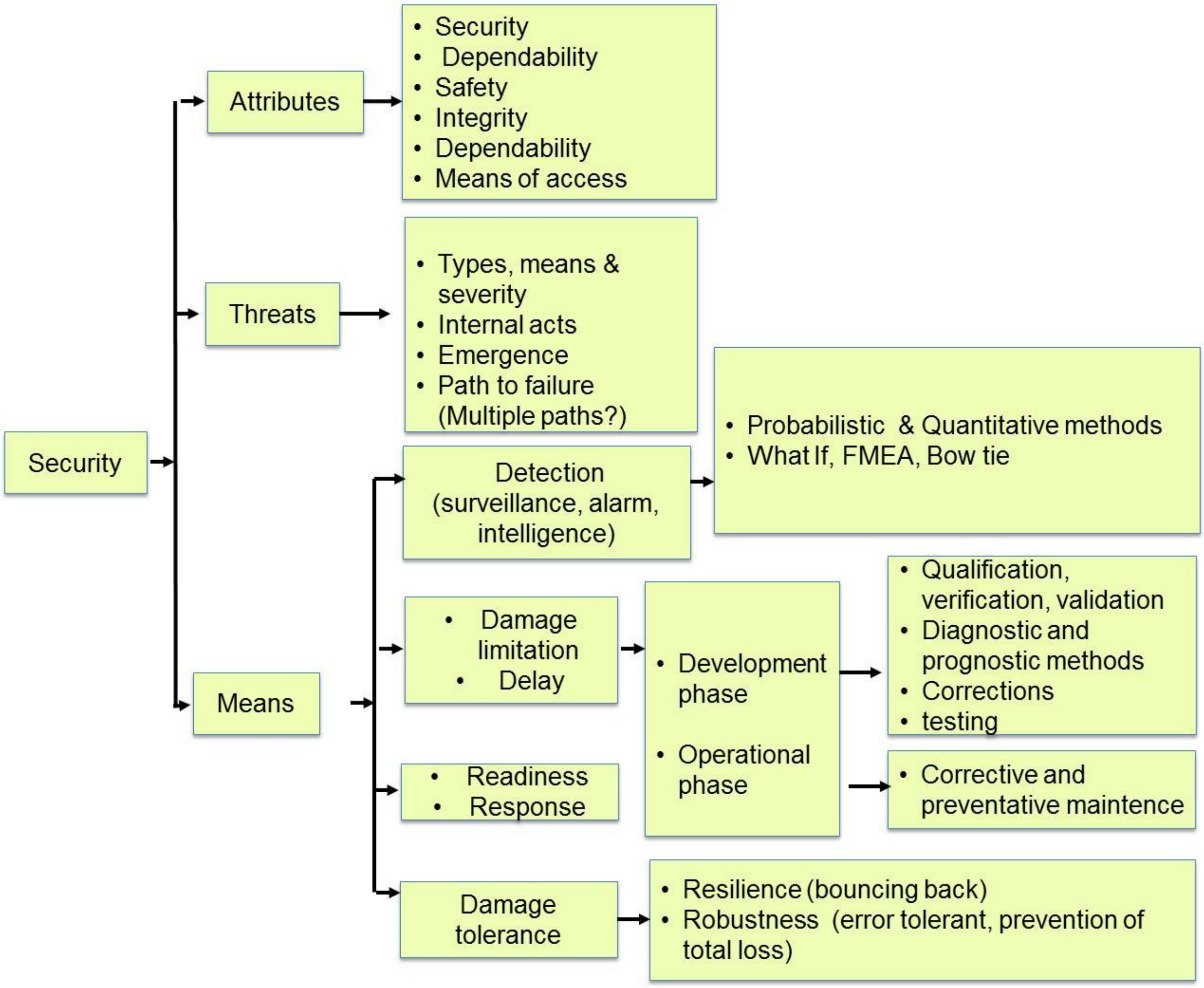

Figure 7. Components of security analysis

8. Barrier Analysis

There are several methods for describing how an incident evolves, and means of blocking (or stopping) its progress. The intention is that the threat should be prevented reaching its target by blocking its path using barriers (physical barrier or by instruments), namely controlling measures [4]

The barrier (which is a control measure in place), is an obstruction, or a hindrance that may either prevent an event from taking place or impede or lessen its consequences (protect the target). The attack succeeds either because the barriers did not serve their purposes or because they were missing. Different barriers will be needed at different stages in the escalation of a hazardous event or malicious act. In recent years, the concept of having several barriers in line has been institutionalised as defence-in-depth or layers of protection.

For the barrier analysis the following elements must be analysed:

Attacker: Attackers or threat agents are elements that are trying to exploit the system's vulnerabilities. For example hacker, terrorists, industrial espionage, or insiders may be such attackers [10].

Threat Mode: Threat mode classifies how vulnerabilities are exploited. There are many ways to exploit vulnerabilities, with different consequences. Potential types of threat (or modes of attack) will depend on system weaknesses, as well as on the capabilities of the attackers.

Threat Effect: "The effect of a threat is described in terms of the consequence on the system's functionality or its operational condition. The threat mode describes the violated security attribute, but the threat effect characterises the violated system quality attribute" [13]. All dependability attributes may be affected by an attack. Which attribute is violated depends on the system, its environment, and the system's operational state.

Attack Probability: To assess the criticality of a security attack, the consequence and probability of the attack must be evaluated. The consequence can be assessed by analysis with assistance from experts. However, the probability of safety and security is determined differently.

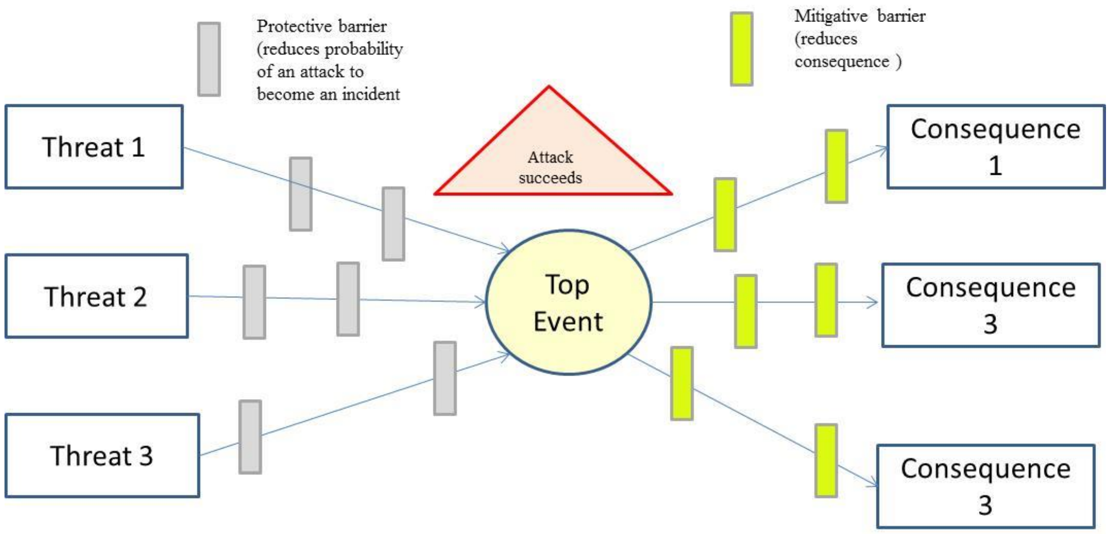

Figure 8. Bow-tie diagram

The concept of defence in depth can be explained with James Reason's "The Swiss Cheese Model", Figure 1 [17].

The holes can arise from active or latent failures. The active failures can be described as errors and violations that have an immediate adverse effect. The latent failures, on the other hand, are the decisions or actions that lie inactive but cause great damage and severe consequences when triggered. A bowtie diagram is a popular approach to describe and analyse the scenarios and to define the critical safety and security elements, Figure 8. A bowtie diagram visualises the barriers that are used to prevent an incident from happening, as well as the barriers that are used to protect vulnerable targets if the incident occurs.

Four types of barriers are defined [18], these are physical or material barriers, functional barriers, symbolic barriers, and incorporeal barriers. The physical or material barriers are barriers that physically prevent something from happening, or protect a target from an incident by blocking or mitigating the effects, e.g. a perimeter wall. Physical barriers are passive and do not need action from an agent. The functional barriers are instruments, e.g. an alarm system or a surveillance system, which have certain pre-conditions that need to be met before the barrier is activated. This activation can be done manually or automatically. The symbolic barrier, on the other hand, needs an intelligent agent who understands how the barrier works for it to achieve its purpose, e.g. a warning sign on the facility's control panel. Finally, the incorporeal barriers are barriers that do not have a material form or substance. Instead, it relies on knowledge by the user to be able to achieve [36 and 37].

9. Discussion

Physical security is defined as the ability of a system to operate in a damaged state, while working under constraints, to best achieve the system's mission. In an oil and gas [45] installations, the goal is to carry on with production while preventing harmful release to the environment, loss of life, and financial loss. The reason for not operating as desired, or for loss of property or life or releasing harmful material may be due to accidental or malicious causes, but the high-level goal of preventing these events is the same.

Applying systems engineering to security requires initially focusing on the security needs as a high-level policy i.e. as a strategy rather than a tactical problem. Certainly, malicious action is a critical consideration in addressing security, but, focusing only on adversaries, diverts attention away from reducing system vulnerability by making it inherently secure and damage-proof. The security goal is not only to guard the physical asset and prevent intrusions, which is threat-focused but also to build a system that is tolerant of all sorts of disruption. The objective is to ensure that critical safety functions and services are maintained if disruptions do take place. Viewing the problem from a strategic vantage rather than tactics, security analysts and defenders can concentrate on the system's vulnerabilities, rather than just continually reacting to evolving disruptions [53].

Resilience must be built into a system to reduce its vulnerability. In a resilient system potential damage to one part of a system is less likely to spread far and wide. Resilience can also be the ability to bounce back from an adverse situation, which is a broad concept with many definitions, but most include the following elements:

● Withstand shock in a time of crisis.

● Quickly recover the functionality of the situation after a disaster or a sudden shock.

● The system should remain functional even if parts of the system have failed/damaged. The objective is to mitigate the severity and/or duration of disruptive events.

The resilience of a system is governed by five elements which are Robustness, Redundancy, Resourcefulness, Responsiveness, and Recovery. The first two are system based properties, and the last three are properties of the organisation running the facility. These elements should be designed into a system to provide inherent resilience capabilities [39].

1-Robustness: Robustness incorporates the concept of reliability and encompasses the ability to absorb and withstand disturbances and errors. That is:

1) If something in the system fails it moves to a safe state, and barriers are added to the system to contain damage escalation.
2) Decision-making chains of command must be responsive to changing circumstances and threats,
3) Designed to prevent unexpected shocks in one part of a system from spreading to other parts of a system, i.e. to localize and contain their impact, - no domino effect (the modular design is a good policy).
4) Damage tolerant.

2-Redundancy: Redundancy involves having excess capacity and back-up systems, which enables the repair of core functionality in the event of disturbances. This element assumes that a system will be less likely to experience a collapse in the wake of stresses or failures of some of its infrastructure if the design of that system incorporates diversity and overlapping alternatives.

3-Resourcefulness: Resourcefulness means the ability of the operators to adapt to crises, respond flexibly, and – when possible – contain the damage spread, protect people both inside and outside of the system boundaries.

4-Responsiveness: Responsiveness means the ability to mobilize quickly and act in the face of crises. This component of resilience assesses whether an organization has good methods for gathering relevant information and communicating the relevant data and information to others, as well as the ability for decision-makers to recognize and resolve emerging issues quickly and act fast.

5- Recovery: Recovery means the ability to regain a degree of normality after a crisis or event, including the ability of the operators to be flexible and adaptable in dealing with the new or changed circumstances after a threat is materialised. This component of resilience assesses the organization's capacities and strategies for feeding information throughout the organization, and the ability for decision-makers to take action to adapt to changing circumstances.

10. Conclusion

A systems engineering framework for the design and evaluation of effective physical security is outlined. This paper argues that in contrast to a bottom-up tactics-based approach, a top-down strategic approach is better. The top-down approach starts with identifying the system losses that are unacceptable, and against which the system must be protected. This will lead to a small and more manageable set of potential losses stated at a high-level of abstraction. A tactics approach starts with how best to protect a facility against disruption, in contrast, a strategic approach concentrates on essential services and functions which must be protected against disruptions and what is considered to be an unacceptable loss.

A chain of events may lead attackers successfully breaching several layers of protection, such as the perimeter walls and the surveillance systems, etc. In almost all such cases, security analysts will identify some barriers that should have served as the last layer of protection (or line of defence) and believe that if only that barrier would have been in the path of attackers, then the attack would have not succeeded. The author believes this is not a correct argument, since the vulnebale element is assumed to have passive role. A tactics-based approach, although necessary, is not sufficient.

A security analyst focussing on tactics would model the threat as the cause of the loss, but it is the vulnerability that leads to the loss event. Based on this concept, then preventing losses, is heavily dependent on the degree to which security analysts can correctly identify the potential attacker and their motives, capabilities, and objectives. With this understanding, security professionals can determine the most likely route (or causal chain) attackers may take to achieve their goal. Then, loss prevention resources is directed to provide "defence-in-depth". However, threat prioritization is challenging given the sheer volume of threats and ever-increasing sophistication and complexity of attackers. If the focuses of the defenders are on the wrong threat, then probably the barriers are not effective. An unstated assumption is that if defence against the more severe and sophisticated threats is implemented, then less sophisticated cases would be covered, which is not necessarily true. Simple requirement errors or operational procedures may allow even unsophisticated attackers from previously ignored or less important adversaries to succeed.

The primar emphasis of this apper isto indetfiy the system's vulnerability first, and then look for the ways and means of protecting against malicious acts.

Acknowledgment

He author wishes to express his gratitude to Mr. Chris Millyard and Dr Jeff Banks for reviewing this paper.

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INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.4/ No. 3/Autumn 2019 (33-42)

Available online at: www. Ijcoe.org

Risk assessment of marine construction projects using Taguchi Loss Function

Amir Reza Valyani[1], Naser Feghhi Farahmand[2*], Soleyman Iranzadeh[3]

[1] *PhD Candidate, Department of Industrial Management, Tabriz Branch, Islamic Azad University, Tabriz, Iran; amirreza.valyani@gmail.com*
[2*] *Associate Professor, Department of Industrial Management, Tabriz Branch, Islamic Azad University, Tabriz, Iran; farahmand@iaut.ac.ir*
[3] *Professor, Department of Industrial Management, Tabriz Branch, Islamic Azad University, Tabriz, Iran; iranzadeh@iaut.ac.ir*

ARTICLE INFO

Article History:
Received: 04 Jan. 2020
Accepted: 10 May. 2020

Keywords:
Marine projects
Construction projects
Risk assessment
Project risk management
Taguchi loss function

ABSTRACT

Today complicated and risky environment makes risk assessment and identification one of the main steps of proper project management and realization of project objectives. Marine construction projects are key and strategic projects, and their specific nature adds to their importance. This study aimed to propose a method for risk assessment and ranking critical risks in marine construction projects in Iran. To this end, the risk assessment team was formed to identify serious marine construction project risks using risk breakdown structure. Afterward, the team defined risk assessment measures. All risks were assessed in each criterion based on the Taguchi loss function. It allowed decision-makers to define a measurable risk threshold for each criterion and assess risks by developing a common language called loss score. Finally, critical risks were determined based on their priority. The results can be used to improve effective risk management, and consequently, project management.

1. Introduction

Maritime, marine exploration and the use of marine food resources have long been of interest to humans. The sea is an essential route for trade, transportation, mineral extraction, energy production, and food supply for humans. It even plays an important role in wars and the security of a country. The largest volume of global trade through the sea, the presence of oil and gas resources in it, and the defense role of the sea have led to the development of knowledge of shipbuilding, maritime, and marine structures. Today, each of these fields is known as a large and advanced industry. They also are taught in universities under different disciplines. Fig. 1 shows activities related to the marine industries [1]. Accordingly, marine affairs and industries play a key and strategic role in many countries.

In recent years, extensive research has been conducted on the risk management of construction and infrastructural projects. . Implementation of construction projects and large marine structures can be considered as important and strategic projects of countries.

Figure 1. Activities pertinent to marine industries

These projects have a special place in the country's economy and security, and recently its importance has increased in Iran. In this research, the main risks of such projects are assessed and ranked based on

previous studies and the opinions of experts and specialists of this field.
By definition, risk is a combination of the severity and the probable frequency of the harm [2]. Risk can be defined as the frequency of a possible event and the consequence of that event`s outcome [3].
Projects are growingly challenged with complexity. In fact, project managers need to deal with several and different deeply interrelated parameters, inside and outside the project. Such complexity results in complex risk interactions and a decrease in the effectiveness of the tools that are normally used for risk management [4]. The effective risk management process begins with an effective risk assessment, and it is not possible to manage the risks without completing these steps [5]. The key step in risk assessment process is to evaluate initial risk using a risk scoring system in particular [6]. In addition, literature review demonstrated that the techniques for risk analysis and assessment are categorized into three major categories: (a) qualitative category, (b) quantitative category, and (c) hybrid techniques category (qualitative, quantitative, and semi-quantitative). The category (a) consists of techniques that rely on analytical estimation processes, and abilities of safety managers and engineers. Based on quantitative techniques, the risk is a quantity that it is possible to estimate and represent it using mathematics based on real accidents data recorded at an operation site. The hybrid techniques create notable complexity given their ad hoc character that limits their usability [7]. In the conventional method of risk analysis, the risk is defined as a function of probability and effect. These two factors are important criteria, but there are unlikely events that occur in many cases. Moreover, many likely events never occur in practice, but, unlikely events often occur at an astonishing rate. Thus, probability and effects alone do not cover all aspects of risk analysis [8].
Several studies have been conducted to evaluate and rank the risks of projects, especially construction projects which is discussed in the next section (literature review).
In this study, considering the importance and significant role of Marin construction projects in Iran, an attempt has been made to identify, evaluate, and rank the large and common risks that these projects face. For this purpose, the Risk Breakdown Structure (RBS) has been proposed as a standard and conventional model for project risk identification as well as Taguchi Loss Function (TLF) as an effective and efficient way to assess and prioritizing the risks.
TLF allowed decision-makers to define a measurable risk threshold for each criterion and assess risks by developing a common language called loss score.
Since the TLF simultaneously relies on the experts' judgments and mathematical relationships in the risk assessment process, we can classify it as hybrid risk assessment techniques. Obviously, by recognizing and prioritizing risks, the risks facing these projects can be managed properly so that such projects can proceed with safe steps towards achieving their objectives.
The rest of the paper is structured as follows: Section 2 reviews the literature. In this section, we studied previous research in order to investigate methods of identifying and classifying risks and techniques used in risk analysis of construction projects. Section 3 presents the research methodology and the proposed framework.
We have made a comparison between the results of the proposed method and one of the most common risk assessment methods known as FMEA in Section 4. Section 5, finally, discusses the results and concludes the paper with recommendations for future research.

2. Literature review

Risk assessment and management as a scientific discipline plays an important role in supporting decision making in practice [9]. Risk assessment, which is an early and crucial stage in the risk management process, involves risk identification and analysis, for which various methods have been introduced [10], [11]. An important key to successful risk analysis is choosing the right risk assessment approach for the considered situation [3].
Jafari and Mohammadi [12], considering the high importance of marine projects as national projects of Iran, assessed the risk of their implementation. They first formed a risk management team and, based on the PMBOK standard and considering EPC contracts, identified and assessed the risk of marine projects in three sections: Engineering, Procurement, and Construction. Mehdikhani [13] by reviewing and comparing project risk assessment and management steps according to PMBOK standard, has proposed a model for the practical implementation of risk management process in marine construction projects and the achievements and experiences of using this model in design, Procurement, and construction stages of marine port projects. He used the FMEA method to identify and rank potential risks in a project and identified five critical risks in marine construction projects. Khatami Firouzabadi et al. [14] determined the main risks within project RBS. Taking into account that project risks have mutual effects on each other, such cause-effect mutual relationships were used to determine the main categories of project risks based on RBS and the fourth edition of project management knowledge guideline using fuzzy DEMATEL method. Their findings indicated that external risk category was the most important category of risks followed by technical, projection management, and organizational categories. Golzar et al. [15] proposed a compromise group decision making model based on hesitant fuzzy sets to assess safety risks in shipbuilding projects. Ship building projects rely on heavy equipment and complicated production process and the industry is one

of the most hazardous industries in the world. Therefore, the authors tried to propose a proper model for safety risks assessment and ranking. These risks are the main causes of main damages to product process and human resources. Lambert et al. [16] provided a quantitative method to rank risk factors and used three indices of probability of incidence, potential effect on project, and efficiency and pace of dealing with risks. Vivian and Shen [17] identified and responded to the critical risks of Hong Kong's maritime projects by focusing on active contractors in the construction sector to reduce and control risk that would improve effective project management. The results of the questionnaire and structured interviews showed that "underwater conditions different from bidding assumptions" are the most common risk factors in marine projects, and lack of access to materials, plants, and labor has the greatest impact on risk exposure.

3. Methodology

After the review of previous studies and based on what was stated in the research literature, the general framework presented in this article is illustrated in Figure 2.

The risk assessment methods based on the opinions and judgments of risk experts fall in the studied area and the results of the risk assessment process are obtained from the data entered by them. In fact, they are the decision makers in the studied field. Thus, it would be of particular importance to employ a limited number of experts to increase the reliability of outputs. Therefore, to improve validity of the proposed method results, improbable and judgmental sampling (purposeful) method was used. In the first step, a risk assessment team consisting of 8 managers and experts with sufficient knowledge and expertise and over 10 years of experience in the field of marine construction projects was formed. During the research, their views were used to identify risks and risk assessment criteria and to complete research questionnaires.

Information from library studies and previous research was then provided to the risk assessment team, during which the risks in marine construction projects were identified. The steps in this research are as follows:

3.1. Identifying the risks and defining the RBS

The main methods to identify the risks were brainstorming, document review, Delphi technique, checklist analysis, and assumptions analysis [9]. In addition, there was a need for a systematic and categorized structure to identify the risks. A common approach to put risk categorization in a structure is RBS, which is a hierarchical representation of potential risk sources [18]. After collecting the data using library and literature review, the RBS of marine construction projects was developed and finalized by experts in 3 levels through Delphi technique which is represented as Table 1.

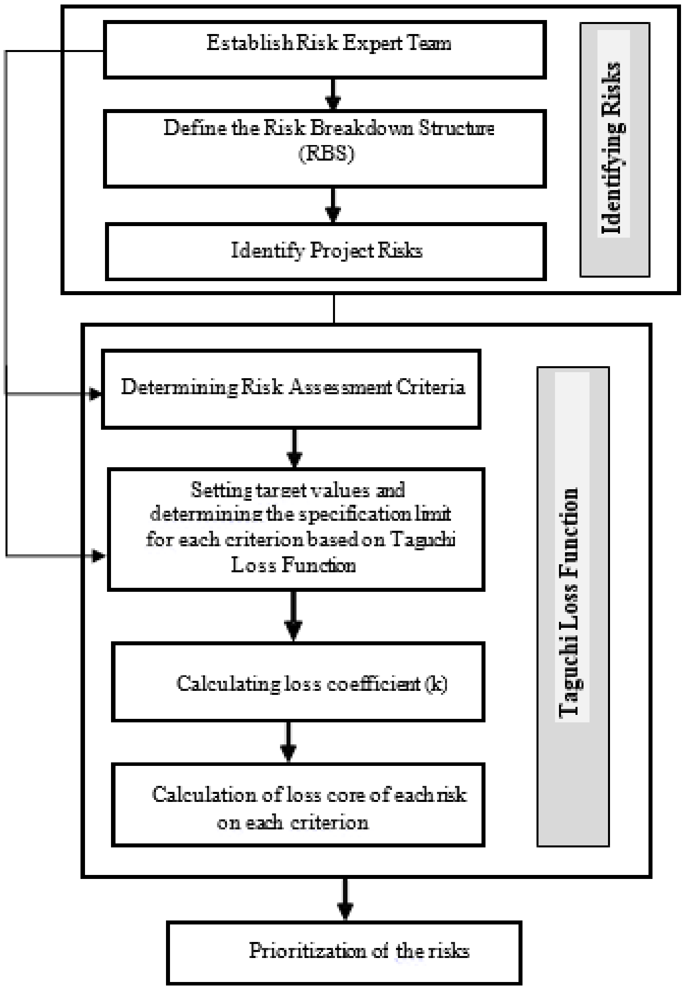

Figure 2. The proposed framework for project risk assessment

3.2. Identification of Risk Assessment Criteria

In order to help with decision-making, risk criteria set standards for evaluating the risks [19]. In conventional risk analysis methods, risk is defined as a function of probability and impact, as two important criteria. However, there exist unlikely events that occur in many cases; yet many probable events never actually happen, and worse is that unlikely events often occur with surprising speed. Thus, probability and impact alone do not cover all aspects of risk analysis [20].

Based on literature review, considering the risk parameters stated in PMBOK 2017, and the risk experts' opinion, the risk assessment criteria were defined in 7 criteria and 3 categories as below:

- Probability: The probability of each risk.
- Impact: The size of impact that puts a risk on one or several project objectives including time, cost, and quality.
  - Impact on Time: The effect of risk is on project timeline.
  - Impact on Cost: The effect of risk is on project planned budget.
  - Impact on Quality: The effect of risk is on expected quality and functionality of project.

Table 1: Marine projects risk breakdown structure

RBS level 0	RBS level 1	RBS level 2	ID
ALL SOURCES OF PROJECT RISK	Technical and Constructional	Changes in project specifications because of inadequate studies	R1
		Design variations	R2
		Complexity of design	R3
		Improper construction methods	R4
		Insufficient experience	R5
		Incompetence sub-contractors	R6
		Poor communication between supervisors and workers	R7
		Inadequate worker safety	R8
	Project Management	Increase in financial and construction costs	R9
		Inappropriate Budget and Financing Plan	R10
		Changes at various levels of management during the implementation of the project	R11
		Inappropriate or inadequate monitoring or control of project activities	R12
		Poor communication between project stakeholders	R13
		Poor site controls	R14
	Resources	Lack of skilled labor	R15
		Exit skilled workers from the project	R16
		Drop in labor productivity	R17
		Equipment breakdown and malfunction	R18
		Unavailability of material and equipment	R19
		Inappropriate storage conditions	R20
	Commercial	Poor performance of suppliers (delivery, transportation, guarantees)	R21
		Slow process of contract	R22
		Customs issues	R23
		Contract disputes	R24
		Fluctuations greater than estimated values	R25
	External	Poor inclement weather conditions	R26
		Increase in costs due to inflation	R27
		Sanctions related issues	R28
		Change in currency rate	R29
		Delay in permits and licenses	R30
		Changes in laws and regulations and code of practices	R31

Table 2. The risk assessment criteria and sub-criteria

The Risk Assessment Criteria

Category	**Probability**	**Impact**			**Manageability**		
Criteria	Risk probability	Impact on time	Impact on cost	Impact on quality	Manageability and controllability	Risk detectability	Risk connectivity
Symbol	RP	IT	IC	IQ	MC	RD	RC

A 9-point Likert scale was used to assess the risks in the criteria. Even numbers represent intermediate numbers.

Table 3. Risk assessment Criteria scales definition

Scale	Very Low		Low		Medium		High		Very High
	1	2	3	4	5	6	7	8	9

3.3. Taguchi Loss Function

Taguchi loss function (quality loss function) is a method to measure the loss caused if a product or service fails to meet the standards [21]. The reason for loss occurrence is to achieve a quantitative evaluation of quality loss due to variation [22]. Quality loss occurs when a product fails to remain within the specification limit and becomes unacceptable [23].

Taguchi demonstrated that deviating from the target value of a feature leads to the occurrence of a loss value and the high quality of a feature occurs when this deviation is minimal and when the feature value is equal to the target value, the loss will be equal to zero. In other cases, the resulted loss can be measured using a quadratic function [24]. As the loss function is nonlinear and quadratic, the loss value increases progressively depending on the deviation rate from the target. This allows larger values to be assigned to metrics that show lower deviation from the target value, which will increase the decision-making accuracy.

Three types of functions can be used in this case, namely nominal-is-best, smaller-is-better, and higher-is-better. To have an appropriate function depends on the magnitude and direction of deviations. When the target is at the center of the specification limit, variation or changes are permitted from the both sides of the target value (known as two-sided equal or nominal-is-best loss function) (see Fig. 2). This can be obtained by Eq. (1), where L(y) represents the loss associated with a particular value of the equality character y, m indicates the nominal value of the specification, and k stands for the average loss coefficient (a constant that depends on the cost at the specification limits and the width (e.g., m ± Δ of the specification, where Δ represents the tolerance limit). The two other loss functions are one-sided minimum and one-sided maximum specification limit functions, also known as smaller-is-better and larger-is-better loss functions, respectively (see Figs. 3 and 4), which are represented by Eq. (2) and (3), respectively.

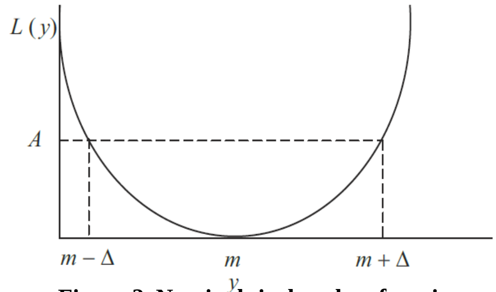

Figure 2. Nominal- is- best loss function

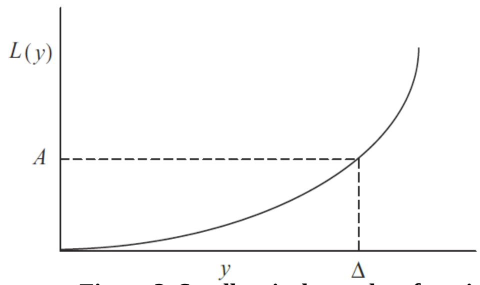

Figure 3. Smaller- is- better loss function

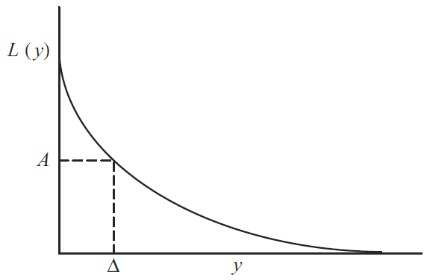

Figure 4. Higher- is- better loss function

We have to specify the optimal value and threshold for each of the criteria in Table 2 to use the TLF in the risk assessment. The range of acceptable deviation from project objectives due to risk effects must be specified for the project team, which is defined by risk thresholds [18].

$$L(y) = k(y - m)^2 \tag{1}$$

$$L(y) = k.(y)^2\ ,\ k = A/\Delta^2 \tag{2}$$

$$L(y) = k/y^2\ ,\ k = A\Delta^2 \tag{3}$$

In this study, we determined the risk thresholds for marine construction projects based on the judgment of experts. It should be noted that the risk thresholds for each of the criteria can vary depending on the requirements and conditions of each project. In general, we tried in this study to make an overall assessment of the risks of such projects by relying on the experiences and expertise of experts in marine construction projects so that the results obtained would be useful for future projects. The risk assessment steps using the Taguchi loss function are fully described in the following.

Step 1. Target values and specification limit were set as decision variables for risk criteria.

All the criteria in Table 2 are considered as the risk assessment criteria. At first, the function type of each criterion is determined. Then, after exchanging the views of the team members and reaching a consensus, the target and threshold values were determined for each of the risk assessment criteria by taking into account the expected project objectives and requirements, as shown in Table 3. For this purpose, the 9-point Likert scale was used according to the scale given in Table 3.

Step 2. The loss coefficient (k) was calculated.

In order to calculate the loss value, we first determined the loss coefficient (k) value for each criterion using Equation (1), where for each criterion, consumer's tolerance and average quality loss were identified by the risk assessment team. Values used to determine the loss score, including consumer's tolerance (Δ), average loss coefficient (k) and average quality loss (A) are shown in Table 3. In order to have consistency between the criteria, the maximum loss was equal to 100. For example, the loss coefficient of "impact on the cost" criterion was found $k = A/\Delta^2 = 100/(3)^2 = 11.11$. and the loss coefficient of the "risk detectability" criterion was found $k = A\Delta^2 = 100 \times (3)^2 = 900$. Values used to determine the loss score, including consumer's tolerance (Δ), average loss coefficient (k) and average quality loss (A) are shown in the following table:

Table 3. The specification limit and loss coefficient of criteria

Criteria	Type of Taguchi Loss Function	Target Value	Specification Limit	Δ	k
Risk Probability	Lower the better	1	5	4	6.25
Impact on Time	Lower the better	1	4	3	11.11
Impact on Cost	Lower the better	1	4	3	11.11
Impact on Quality	Lower the better	1	3	2	25
Manageability and Controllability	Higher the better	9	5	4	1600
Risk Detectability	Higher the better	9	6	3	900
Risk Connectivity	Lower the better	1	5	4	6.25

Step 3. The loss score of each risk was calculated on each criterion.

After defining (k) values, the loss for each risk criterion was calculated using Equations (1) to (3). For example, the loss score of the risk "Improper construction methods" (R4) in "impact on quality" criteria is $L(y) = k.(y)^2 = 25 \times (7)^2 = 1225$. The calculations for the risk loss score are shown in Tables 4 and 5.

Table 4. Data related to each risk in each criterion

Criteria / Risk	RP	IT	IC	IQ	MC	RD	RC
R1	3	5	3	7	3	3	9
R2	5	4	5	8	6	4	8
R3	6	5	5	5	3	7	8
R4	3	7	5	7	7	7	7
R5	4	4	4	7	6	7	8
R6	3	4	7	6	7	9	6
R7	5	6	1	6	7	8	7
.	.	.	.	.	.	.	
. .	. .	. .	. .	. .	. .	. .	
R29	8	1	7	2	4	2	7
R30	7	8	5	1	3	3	4
R31	6	5	4	3	2	2	3

Table 5. The risk loss score

Criteria / Risk	RP	IT	IC	IQ	MC	RD	RC
R1	56.25	277.77778	100	1225	177.77778	100	506.25
R2	156.25	177.77778	277.77778	1600	44.444444	56.25	400
R3	225	277.77778	277.77778	625	177.77778	18.367347	400
R4	56.25	544.44444	277.77778	1225	32.653061	18.367347	306.25
R5	100	177.77778	177.77778	1225	44.444444	18.367347	400
R6	56.25	177.77778	544.44444	900	32.653061	11.111111	225
R7	156.25	400	11.111111	900	32.653061	14.0625	306.25
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
R29	400	11.111111	544.44444	100	100	225	306.25
R30	306.25	711.11111	277.77778	25	177.77778	100	100
R31	225	277.77778	177.77778	225	400	225	56.25

Finally, the average of the loss scores for each risk is being regarded as the final loss score, which in fact, is the risk-ranking criterion. The risks, with higher final loss scores compared to others are more important and ranked higher. The final score and the final ranking of the risks are shown in Table 6. The results show that design variations, lack of skilled labor, improper construction methods, changes in project specifications because of inadequate studies, and unavailability of material and equipment are the five critical risks.

Table 6. The average loss scores and risk ranking

Risk	Final Score	Rank	Risk	Final Score	Rank	Risk	Final Score	Rank
R1	349	4	R12	279	9	R23	238	18
R2	388	1	R13	188	25	R24	172	27
R3	286	8	R14	44	31	R25	245	15
R4	352	3	R15	363	2	R26	276	11
R5	306	6	R16	197	23	R27	236	19
R6	278	10	R17	301	7	R28	182	26
R7	260	12	R18	198	22	R29	241	17
R8	52	30	R19	309	5	R30	243	16
R9	255	14	R20	196	24	R31	227	20
R10	212	21	R21	260	13			
R11	124	29	R22	163	28			

4. Comparing the proposed method with the FMEA method

We made a comparison between the results obtained from the proposed method and one of the most commonly used risk assessment methods known as "Failure Mode and Effects Analysis (FMEA) to evaluate the quality of the results obtained from the Taguchi loss function method. FMEA is a structured method to quantitate the potential effects of error, which makes it possible to prioritize risks aimed at reducing or eliminating the failure modes. To do so, it uses the calculation of a number called Risk Priority Number (RPN), which is resulted from multiplying the three values of the probability of the event occurring, the severity of the event, and the "probability of risk detection". The risks with higher RPNs have a higher priority [26].

We used the same data collected from experts given in Table 4 to make this comparison. Thus, the same numbers were directly used for the criteria of the probability of occurrence and probability of risk detection, and the mean of impact on time, impact on cost, and impact of quality data was considered for the number related to the risk severity criterion. The calculations and rankings of risks based on the FMEA method are shown in table 7. Accordingly, the prioritization of risks is according to Table 8. Hence, the risks of "Increase in costs due to inflation, Poor inclement weather conditions, Complexity of design, Lack of skilled labor, and Sanctions related issues" were identified as 5 high-priority risks, respectively, which are different from the results obtained from the TLF method. The reasons for the differences in the results can be attributed to the use of more criteria as well as employing the risk threshold in the risk assessment process.

Table 7. Data related to each risk in each criterion (FMEA)

Criteria / Risk	Probability	Impact	Detectability
R1	3	5	3
R2	5	6	4
R3	6	5	7
R4	3	6	7
R5	4	5	7
R6	3	6	9
R7	5	4	8
.	.	.	.
.	.	.	.
.	.	.	.
R29	8	3	2
R30	7	5	3
R31	6	4	2

Table 8. The RPN and risk ranking

Risk	RPN	Rank	Risk	RPN	Rank	Risk	RPN	Rank
R1	45.00	27	R12	158.67	10	R23	151.67	12
R2	113.33	18	R13	121.33	17	R24	84.00	22
R3	210.00	3	R14	35.00	30	R25	200.00	6
R4	133.00	16	R15	210.00	4	R26	212.33	2
R5	140.00	14	R16	43.33	28	R27	312.00	1
R6	153.00	11	R17	106.67	19	R28	205.33	5
R7	173.33	8	R18	56.00	24	R29	53.33	25
R8	42.00	29	R19	180.00	7	R30	98.00	20
R9	140.00	14	R20	149.33	13	R31	48.00	26
R10	64.00	23	R21	96.00	21			
R11	26.67	31	R22	168.00	9			

5. Discussion and Conclusion

Given the profound role of marine construction projects in economic development and national security, realization of the objectives of such projects is highly important so that most of these projects are considered strategic ones. The project management team is always faced with several risks and a proper model to identify and assess such risks can guarantee the success of such important projects.

For this purpose, RBS and opinions of a risk assessment team were used to find 31 serious risks categorized in five categories of technical, constructional, project management, resources, commercial, and external risks. Then, the critical and sub-critical risks were defined. Subsequently, they were assessed and ranked using TLF.

The results show that design variations, lack of skilled labor, improper construction methods, changes in project specifications because of inadequate studies, and unavailability of material and equipment are the five critical risks of marine construction projects in Iran.

Also, comparing the results obtained from the proposed method and the FMEA method reveals that the risk prioritization was different in each of them. All experts agreed on the high accuracy and high quality of the results achieved from the Taguchi loss function method due to using further criteria and application of the concept of risk threshold in the risks assessment.

Because of the flexibility of the method and the high collaboration of the risk assessment team during the research process, the results were highly satisfactory and were approved by the experts.

In general, the results can help project managers to achieve project objectives by identifying critical risks of marine construction project which leads to making decisions to prevent, control and respond to them.

It should be noted that in this research, we provided a specific and general framework for the risk assessment of marine construction projects using the Taguchi loss function and its capabilities to achieve more accurate results. Since the definition of the project risk criteria and thresholds varies from project to project, we have to emphasize that the risk assessment process described in this paper should be followed exclusively for each project. Thus, the results obtained from this article are general and can be used to identify important risks in marine construction projects in general without considering the circumstances of a particular project.

Besides, the proposed method is able to be applied to assess and prioritize risks in other projects and sectors. In future research, it is recommended to use theories such as fuzzy logic in order to resolve ambiguity and uncertainty in the views generated by the risk assessment team and thus increase the model accuracy.

Also, risk assessment criteria, depending on the specific conditions and requirements of each project, can have different degrees of importance for the project manager or stakeholders; in such a case, the prioritization of risks will change. Therefore, in future research, we can benefit from the multi-criteria decision-making techniques to determine the importance and weight of the criteria, combine them with the proposed method, and increase the accuracy of the output in prioritizing the risks.

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INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.4/ No. 3/Autumn 2019 (43-46)

Available online at: www. Ijcoe.org

Evaluating semi-empirical wave forecasting method CEM in the Strait of Hormuz

Mahmud Reza Abbasi [1]

[1] Physical Oceanography PhD, assistant professor of Imam Khamenei Marine Science and Technology, Zibakenar, Gilan, Iran; phys.ocean.abbasi@gmail.com

ARTICLE INFO

Article History:
Received: 28 Nov. 2019
Accepted: 11 Jun. 2020

Keywords:
Wind wave
Forecasting
CEM
Hormuz Strait
Numerical modeling

ABSTRACT

Wind waves are one of the most important phenomena that should be considered in coastal and offshore activities. They have many effects on coastal environments such as wave-induced erosion, sediment and pollution transport and even in the worst cases destruction the marine ecosystems. Therefore, knowing the wave characteristics is very important for environmental research. In this paper, the accuracy of CEM semi-empirical method in forecasting the wind-induced waves characteristics in the Strait of Hormuz (SOH) have been studied. Initially, the characteristics of the waves have been calculated by employing the CEM based on wind data from local synoptic stations. Then, the evaluating process have been done by comparing the forecasting values (wave heights and periods) of this method with same recorded value of wave buoys in the SOH. According to the performed study, the accuracy of semi-empirical method in forecasting wave characteristics were in close agreement with measurements values and the SMB method is suitable for determining the wave characteristics in this area. The results show that there is a good correlation coefficient between observations and forecasting data in the CEM and the CEM method has a very small bias error. So, this method is suitable for determination the wave characteristics in this area.

1. Introduction

Knowledge of the characteristics of wind-induced waves is one of the most important issue for every environmental activity on the coast, both in the land and in Water. Damages caused by the waves are as deforming the coasts by erosion, sediment transport and causing changes in natural ecosystems. Since practically the continues monitoring and complete coverage of coasts are generally limited due to the huge costs, a compatible method for determining the wave characteristics is required to ensuring the prosperity of an environmental monitoring system. In order to calculate the waves characteristic, many semi-empirical methods such as SMB [1] ,CEM [2] and SPM [3], numerical models such as Mike 21[4],Wavewatch [5], SWAN [6] and WAM [7] and soft computation methods such as ANN [8], Regression tree[9], fuzzy inference system [10,11] and genetic algorithm [12] have been employed.

Considering the SOH as a habitat for mangrove forests and the presence of environmentally sensitive areas in this area and the impact of sea waves on these environments, accurate knowledge of wave characteristics is very important and very essential for marine researchers. Because of the lake of long-term field wave data and the high cost of field measurements, using the numerical methods and experimental models is preferred to obtain the wave characteristics. Semi-empirical methods because of their simplicity and low cost, the coastal engineers and marine institutions generally use these methods.

Previously many wave studies in different Iranian coastal regions by using various methods have been done [13-16]. In this paper, one of the best significant semi-empirical methods in calculation the wave characteristics known as the CEM has been used to forecast wave characteristics in the SOH.

2. Materials and Methods

2.1. Study area

The SOH as a connectional canal connects the Persian Gulf to the Oman Sea have been located between 24-28˚ N in latitude and 51-56˚ E in longitude (Fig.1). This narrow marine gate with 280 km east-west length and 56 km north-south width is one of the most important waterways in the world. Its depth varies between 40m near the Iranian coasts on the north to 200m near the Omani coasts on the Musandam Peninsula on the south [17]. Approximately 90% of the Persian Gulf oil or on the other hand 40% world's oil exports through this waterway [18,19].

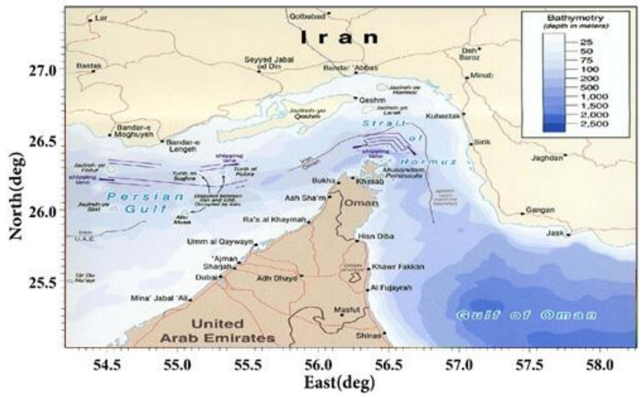

Figure 1. Bathymetry and neighboring regions of SOH

2.2. CEM method

The semi-empirical method CEM is the newest method in wave prediction. In this method the length of fetch in a given direction is determined with plotting through 30 radii (with intervals of 1 Degree) on both sides of the wind direction of blowing from the studied point to the first point of intersection with the coastline [20]. The mean value of these radii is the fetch length.

In semi-empirical methods, wave height and period are calculated based on wind speed, fetch length and wind duration. To determine the wind duration, we used definition of constant wind. In this method the continuity time of wind in the ith-hour is equal to the number of preceding consecutive and acceptable previous hours that should satisfy the following circumstances:

$$|U_i - \overline{U}| < 2.5\, m/s \qquad (1)$$

$$|D_i - \overline{D}| < 15^0 \qquad (2)$$

$\overline{U}$ and $\overline{D}$ are the mean of preceding consecutive and acceptable hourly wind speed and direction, respectively. U_i and D_i are the speed and direction of the wind in the ith hour of the data. The minimum wind duration is computed as follows:

$$t_{min} = 77.23 \frac{F^{0.67}}{U_{10}^{0.34} g^{0.33}} \qquad (3)$$

in which F is the fetch length in meters, U_{10} is the wind speed at a height of 10 meters from the sea surface in meters per second.

For the fetch limited case, the non-dimensional forecast equations for significant wave height and peak period are defined as:

$$H_s = 4.13 \times 10^{-2} \times \sqrt{\frac{U_*^2 F}{g}} \qquad (4)$$

$$T_p = \frac{1}{2.727} \left(\frac{U_* F}{g^2}\right)^{1/3} \qquad (5)$$

Where U_* is the shear velocity and estimated from the following equation:

$$U_* = U_{10} (C_d)^{0.5} \qquad (6)$$

where C_d is the wind drag coefficient, which is calculated as:

$$C_d = 0.001(1.1 + 0.035 U_{10}) \qquad (7)$$

But if the wind duration was not greater than the minimum necessary duration, the duration limited condition is considered and the equivalent fetch length, significant wave height and peak period are computed as below:

$$\frac{gF}{U_*^2} = 5.23 \times 10^{-3} \left(\frac{gt}{U_*^2}\right)^{1.5} \qquad (8)$$

$$H_s = 2.115 \times 10^2 \times \sqrt{\frac{U_*^2}{g}} \qquad (9)$$

$$T_p = 2.398 \times \left(\frac{U_*}{g}\right) \qquad (10)$$

2.3. Wind and wave data

In this study the required wind speed data for forecasting wave height and period in given area were gathered from European Centre for Medium-Range Weather Forecast (ECMWF) database. These data consist of two wind components (u and v) have 0.25*0.25 and 6-hour interval spatial and temporal resolution, respectively. Before applying the coastal area wind data in CEM equations, the correction was carried out by the nearest coastal wind measurement synoptic station (Qeshm Island) (Figure 2).

The wave information including significant wave height and mean wave period were gathered from wave buoy near the northern coast of SOH from 1 July 2002 until 31 August 2002. These data include 1536 discrete records. This Buoy was located by the consultant engineering corporation in the longitude of 55.55^0 east and the latitude of 26.6^0 north (Figure 2).

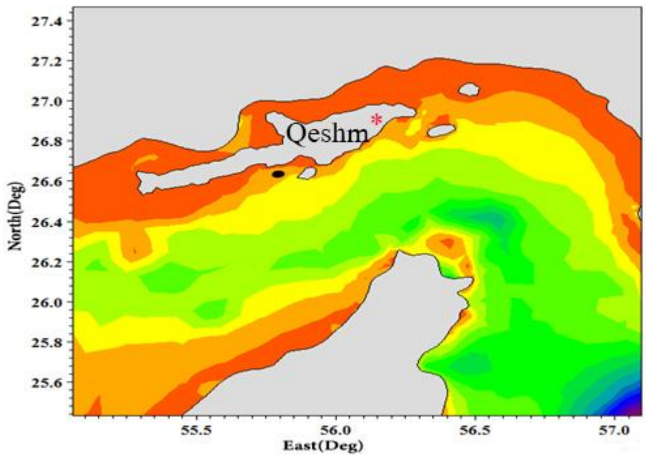

Figure 2. Strait of Hormuz. wave buoy location (black dot), nearest synoptic station (red star).

In this study, in order to evaluating the accuracy of the CEM method and comparing the results of the forecasted wave height with the measurement values, statistical parameters such as the scatter index (SI), correlation coefficient (CC), root mean square error (RMSE) and bias (Bias) were used as follows:

$$Bias = \bar{x} - \bar{y} \quad (11)$$

$$CC = \frac{\sum_{i=1}^{n}\left((x_i-\bar{x})\times(y_i-\bar{y})\right)}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (12)$$

$$\text{RMSE} = \sqrt{\frac{\sum_i (x_i-y_i)^2}{n}} \quad (13)$$

$$SI = \frac{\sqrt{\frac{1}{n}\sum_i (x_i-y_i)^2}}{\bar{x}} \quad (14)$$

Where x, y and n are the observed parameter, the forecasted parameters and the number of observed, respectively.

3. Results and Discussion

In this study, the capabilities of semi-empirical wave forecasting method CEM in forecasting the wave characteristics in the Strait of Hormuz was examined. For this purpose, the scatter plots and time series plots of wave height, wave period and wave direction of CEM and buoy for comparison between them are showed in figures 3,4. Also, four statistical error parameters based on 11-14 equations were computed in order to assess the quantity comparisons between of two data sources (CEM and buoy).

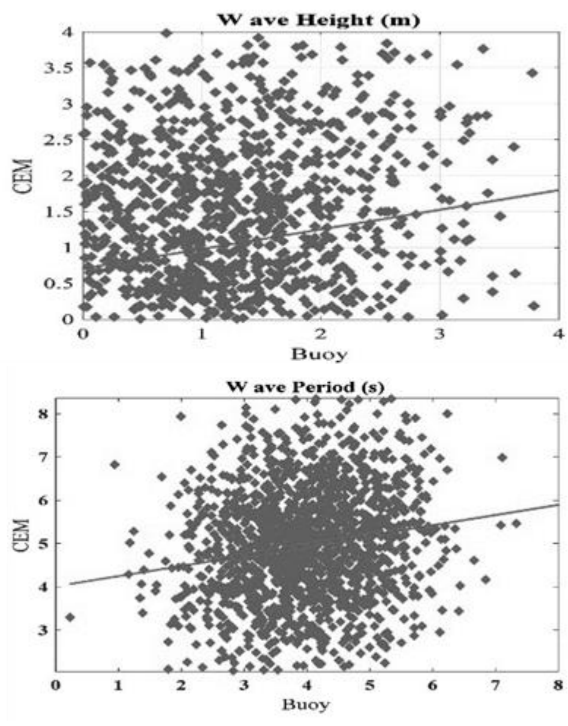

Figure 3. Scatter plot comparison of wave height(up) and wave period(down) from Buoy and CEM

As seen from figure 3, wave height Scatter plot presents a good agreement between the CEM method data and buoy data and the correlation coefficient is %65 for this wave parameter. But for wave period this correlation is not seen as good as wave height and correlation coefficient is %25. The CEM method underestimated both two wave characteristics at SOH region. The bias values are -0.25m and -1.04s for wave height and period, respectively. Also, the CEM wave height forecasting has the lower RMSE value (0.43m) than wave period RMSE (2.25s).

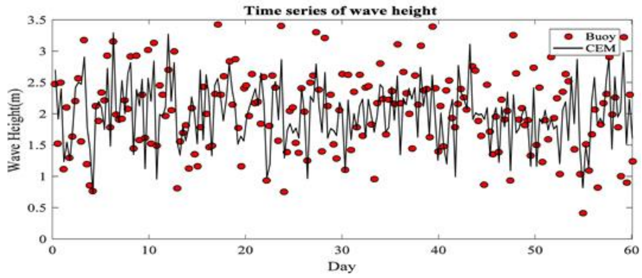

Figure 4. Time series comparison of wave height from Buoy and CEM

Generally, the forecasted and field measured time series of wave height matches but buoy data shows a slight underestimation of this parameter (Fig. 4).

In order to check correctly the directions of the forecasts Wave by semi-empirical methods, the wave roses of SOH buoy and CEM method in time study are presented in Fig. 5.

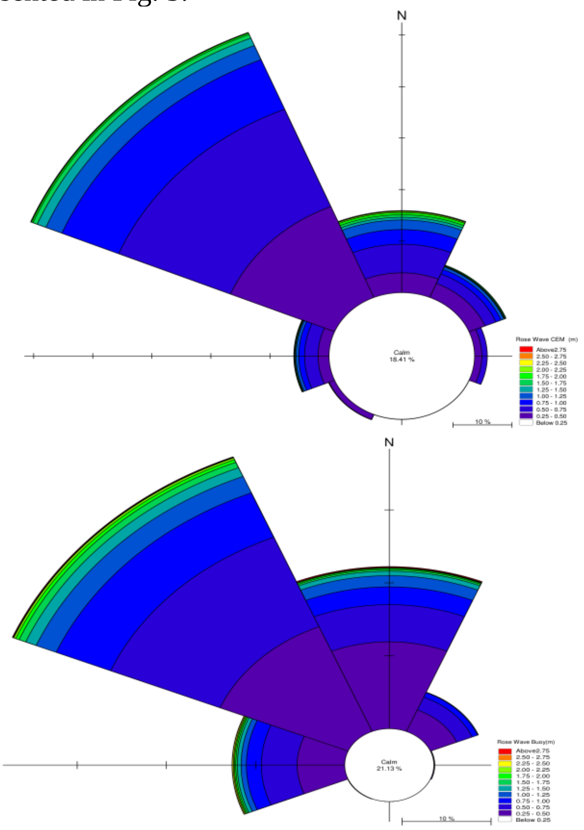

Fig. 5. Wave roses from buoy data(up) and CEM *(*down)

By comparing the wave roses of the CEM and observed data as shown in Fig. 5, although the two wave roses are in good agreement in terms of overall shape and dominant wave directions, but they differ in terms of the frequency of waves occurring in different directions. As can be seen in Fig. 5, the first dominant wave direction is at the northwest direction whose abundances are %65 and %48 for CEM and buoy rose waves, respectively. However, CEM wind rose shows lower value in high speed winds than buoy wave rose. It is worth noting that the difference between two wave roses in calm conditions reaches to its maximum value of %3. The reason of this difference is that when the wind speed is zero, the semi-empirical methods estimate the wave height equal to zero.

For quantitation the CEM model performance the model wave height and period results were comprised with the same local buoy data by calculating the statistical parameters which are presented in table 1.

Table 1. wave characteristics error forecasting by CEM

statistical parameters	Wave Height(m)	Wave Period(s)
Bias	-0.25	-1.04
Correlation Coefficient (%)	65	25
Root Mean Square Error	0.43	2.25
Scatter Index (%)	66	45

4. Conclusions

In the present study, firstly, the characteristics of the waves in Strait of Hormuz forecasted using semi-empirical method CEM and then by comparison between the forecasted value and observed data from local buoy, the errors of this method were determined. The most important results of this study are as follows:

- The CEM method underestimated the wave height and period forecasting in this area.
- By comparison the CEM and buoy wave roses it was showed that the prevailing forecasted wave direction by CEM is in northwest direction in this area in which has a good agreement with buoy data.
- The correlation between the forecasted wave height and observed data was better than the wave period.
- According to the results it seems that the main cause of the error of the semi-empirical method in this region is inappropriate wind input data due to lack of required information in the desired area.
- Due to the error generated by semi-empirical method, CEM is not a suitable method for determining the wave period in this area.

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INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.4/ No. 3/Autumn 2019 (47-52)

Available online at: www. Ijcoe.org

Forecasting Short-term Container Vessel Traffic Volume Using Hybrid ARIMA-NN Model

Negar Sadeghi Gargari [1*], Hassan Akbari [2], Roozbeh Panahi[3]

[1*] *MSc student, Tarbiat Modares University; n.sadeghi@modares.ac.ir*
[2] *Assistant Professor, Tarbiat Modares University; akbari.h@modares.ac.ir*
[3] *Assistant Professor, Tarbiat Modares University; rpanahi@modares.ac.ir*

ARTICLE INFO

Article History:
Received: 20 Feb. 2020
Accepted: 19 Jun. 2020

Keywords:
Forecasting Container Traffic
Neural Network
ARIMA model
Hybrid ARIMA-NN Model

ABSTRACT

A combination of linear and non-linear models results in a more accurate prediction in comparison with using linear or non-linear models individually to forecast time series data. This paper utilizes the linear autoregressive integrated moving average (ARIMA) model and non-linear artificial neural network (ANN) model to develop a new hybrid ARIMA-ANN model for prediction of container vessel traffic volume. The suggested hybrid method consists of an optimized feed-forward, back-propagation model with a hybrid training algorithm. The database of monthly traffic of Rajaee Port for thirteen years from 2005-2018 is taken into account. The performance of the developed model in forecasting short-term traffic volume is evaluated using various performance criteria such as correlation coefficient (R), mean absolute deviation (MAD), mean squared error (MSE) and mean absolute percentage error (MAPE). The developed model provides useful insights into container traffic behavior. Comparing the results with the real data-sets demonstrates the superior performance of the hybrid models than using models individually in forecasting traffic data.

1. Introduction

Forecasting short-term maritime traffic plays a pivotal role in port planning in terms of capacity planning and capacity management [1]. These forecasts enable logistics companies and port authorities to adopt appropriate policies to maintain their international competition by predicting transport lines and port operators. Predicting the throughput of the ports is usually the focus of marine traffic prediction studies. In contrast, there has been relatively little research on traffic prediction in terms of the number of vessels. Thus, a limited number of articles have used artificial neural networks (ANN) and hybrid methods in forecasting marine traffic [2]. Since 1969, many research efforts have been initiated in the field of developing forecasting models. Then, a wide range of approaches was tested to increase the accuracy of forecasting results such as ANNs, ARIMA, Box Jenkins, and so on. Evaluation of prediction results is usually assessed by comparing the forecasted values with real data [3].

In the maritime domain, ANNs are used in various fields such as traffic flow forecasting [4], predicting the impact of a wave on a vessel's diversion [5], and classifying vessels by dividing the vessel's routes [6] into multiple groups based on automatic identification system (AIS) data. Furthermore, ANNs are used in the process of clustering, classifying, and detecting the irregular behavior of vessels [7]. Perera et al. [8] proposed an ANN for identifying and tracking multiple sea routes based on radar/laser tracking data. Abada [9] developed an artificially intelligent system capable of accurately predicting the rotation routes of vessels, in which the physical and operational information of a vessel was used as input to predict rotational maneuvers. In 2009, a study by Simsir et al. [10] aimed to predict the future coordinates of a manually controlled vessel using a trained ANN in which the neural network was trained using position and velocity data.

Predictive methods include qualitative prediction methods, such as visual prediction [11] and quantitative prediction methods, including time series prediction [12], gray prediction model [13], regression analysis [14], neural network model [9] and so on. The visual prediction model mainly relies on experience and comprehensive analysis and creates the judgment for future development, the main form of which is the Delphi method [11]. Primarily for the use of prediction in the absence of historical information and data, these models were based on subjective judgment and expert analysis abilities.

Time series prediction includes moving average method, smooth development method, and trend prediction method. A limitation of these prediction models is that the prediction time cannot be more than one-third of the time for the data as prediction accuracy decreases over time. The regression analysis method shows causal rules between predicted values and their associated coefficients. However, in a complex system, there may be several factors that can affect the predicted values, and it is impossible to list the exact situation accurately [15]. The basic idea of gray prediction is to form a white module dynamically or non-dynamically with known data-sets in accordance with a particular rule and to solve future gray modules with a rule or algorithm [13].

In the maritime traffic domain, Du et al. [16] propose a hybrid deep learning framework for short-term traffic flow forecasting. According to the highly non-linear and non-stationary characteristics of traffic flow data, their framework consisted of Recurrent Neural Networks (RNNs) and Convolutional Neural Networks (CNNs). Eslami et al. [17] developed a hybrid tanker freight rate (TFR) prediction model based on an artificial neural network (ANN) and an adaptive genetic algorithm (AGA). Stepwise regression of TFR variables selected three variables: crude oil price, fleet productivity, and bunker price. Wang et al. [18] proposed a hybrid model and integrating the advantages of ARIMA and ANNs. The hybrid model was tested on three sets of actual data, namely, Wolf's sunspot data, the Canadian lynx data, and the IBM stock price data.

In this article, short-term traffic at Rajaee port is predicted utilizing four models: ARIMA, ANN, Additive hybrid, and Multiplicative hybrid models, and their performance in short-term maritime traffic forecasting are evaluated based on available data-set. Our computational experience indicates the effectiveness of the new combinatorial model in obtaining more accurate forecasting results in comparison with existing models.

In the following, first, the utilized data are introduced. Then, the methodology is described, detailing the ARIMA model, ANN model, and hybrid models. Then, results are stated, and the relevant research implications are discussed. Finally, the results of this research are concluded.

2. Data

Traffic data from 2005-2018 consists of 100,139 observations of vessels referred to the Rajaee Port. In order to predict the number of vessels, the data-set is transformed into monthly data containing 156 rows (each point is the number of vessels referred to Rajaee port in one month). Forecasting performance of different models is assessed by dividing each data-set into two sub-sets, training set, and testing set. The training set is used exclusively for model development, and then, the testing set is used to evaluate the proposed models. The input data, including the number of container vessels, are depicted in figure 1.

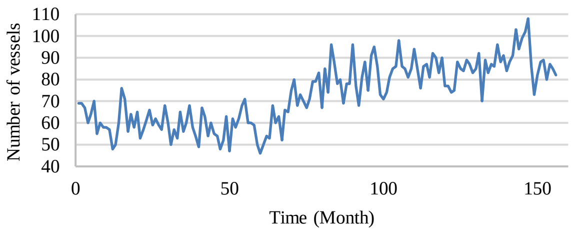

Figure 1. Number of container vessels

3. Materials and methods

In this section, for the sake of clarity, ARIMA and ANN models are discussed as preconditions for the construction of the hybrid model, with a focus on the two models' basic principles and modeling processes.

3.1. The ARIMA model

In an autoregressive integrated moving average (ARIMA) [19] model, the values of future variables are assumed to be a linear function of past observations and random errors; in other words, the basic process that produces the time series is as follows [20]:

$$\begin{aligned} y_t = \theta_0 + \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \cdots \\ +\varphi_p y_{t-p} + \varepsilon_t - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2} + \cdots \\ +\theta_q \varepsilon_{t-q} \end{aligned} \quad (1)$$

where y_t is the actual value, and ε_t are the random errors in the period t; φ_i $(i = 1,2,...,p)$ and θ_j $(j = 1,2,...,q)$ are the model parameters. p and q are integers and are often referred to as the model order. Random errors, ε_t , are independent, with equal distribution, mean of zero, and constant variance of σ^2. If $q = 0$, this equation becomes an autoregressive (AR) model of order p. When $p = 0$, the model is reduced to a moving average (MA) model of q order. The main role of the ARIMA model is to determine the appropriate pattern of the model with order (p, q). Box and Jenkins [21] have developed a practical approach to construct the ARIMA model that has a practical impact on time series and forecasting analysis. The Box-Jenkins method [21] involves three iterative steps of model identification, parameter estimation, and error detection. The basic idea behind model identification is that if a time series is produced from an ARIMA process, it must have some theoretical correlation properties. Box and Jenkins [21] proposed using the samples' automatic correlation function as the main tool for evaluating the ARIMA model. In the identification phase, it is often necessary to convert the time series to static as stability is a prerequisite for building the ARIMA model. Once an experimental model is specified, estimating the model's parameters is simple. The parameters are estimated by minimizing the measurement errors with a non-linear optimization method. The final step in building a model is testing error to know whether the model assumptions about the errors are appropriate or not.

3.2. The NN model

Based on the characteristics of the input data, the structure of ANN is determined. ANN can be classified into static and dynamic categories [22]. The static, or feed-forward network, is a network that does not involve either feedback elements or time delay. The output is computed from the inputs through feed-forward connections [23]. On the other hand, a dynamic network is a network in which output depends on network inputs, as well as on previous inputs and outputs [24].

A multilayer perceptron (MLP) model [25] can be used to model a feed-forward model with a single hidden layer. For a three-layer neural network, the relationship between outputs and inputs is given by the following mathematical formula [26]:

$$y_t = w_0 + \sum_{i=1}^{Q} w_j . f(w_{0,j} + \sum_{i=1}^{P} w_{i,j} . y_{t-i}) \quad (2)$$

Thus, $y_{t-i}(i = 1,2, \ldots, P)$ is the inputs and y_t is the output; $w_{i.j}(i = 0.1.2. \ldots . P; j = 1.2. \ldots . Q)$ and $w_j(j = 1.2. \ldots . Q)$ are the connection weights; P and Q are the numbers of input nodes and hidden nodes. f is a transfer function. The logical function is a common transfer function used in the hidden layer, as follows:

$$f(\xi) = \frac{1}{1 + e^{-\xi}} \quad (3)$$

Some other functions, such as hyperbolic, quadratic, Gaussian, and linear, are also used as neural network transfer functions. Hence, the ANN model practically creates a non-linear relationship between output and input:

$$y_t = F(y_{t-1}, \ldots, y_{t-P}, w) \quad (4)$$

Where w is a vector of weights. F is a non-linear function determined by the structure and parameters of the network. Figure 2 shows the structure of a three-layered neural network.

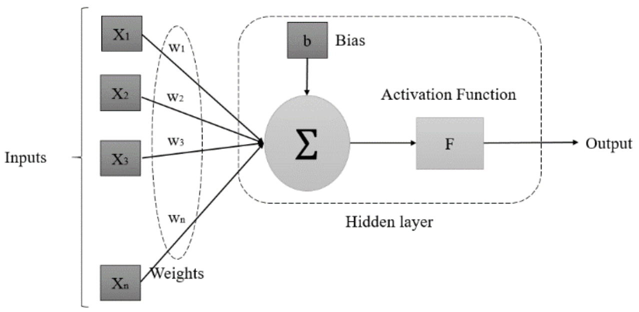

Figure 2. Three-layered Neural Network structure

In this research, the optimal hyper-parameters are found by grid-search method, which results in the most precise prediction [27], and a Network with 5 hidden neurons is selected. The structure of the neural network is shown in Figure 3.

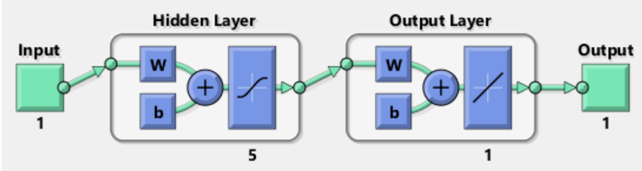

Figure 3. Neural Network structure

In a neural network, data-set are divided into three categories: Training data are used to build a network model, Validation data are used in the training phase to verify if the network capabilities of generalizing solutions are within acceptable levels, and Test data are used to test network performance after training. In this study, according to the recommendation by MATLAB software guide, 70% of the data-set was used as training data, 15% of the data was used as validation data, and 15% of the data was used as test data. Table 1 shows the sample composition for the ANN model. The selection of data is made randomly and automatically each time the program runs.

Table 1. Sample compositions in data-set

Sample size	Training set	Test set	Validation set
156	110	23	23

Training of an ANN model is a process of minimizing the global error function formed by weights. Among various training algorithms, Levenberg–Marquardt (LM) training algorithm is incorporated in this research [28]. The training process initiates with entering the training set into the input nodes. Then, the activation values are weighted and added at each hidden node. Finally, the total result is transformed into the output node's activation value [29].

3.3. The hybrid model

The hybrid method [30] combines the ARIMA and ANN models to produce more accurate results. This process includes five steps, as follows:

1) Data are modeled using the ARIMA method.
2) The residual of the ARIMA method is used as the target variable of the neural network.
3) Two separate neural networks are trained with input and target data.
4) Two neural networks give two predictions in their output.
5) The sum of the average outputs of the neural network model and the ARIMA model is the final output.

The autocorrelation of the input data is modeled by the ARIMA model, and the non-linear relationship between the input and output data is modeled with the neural network. The block diagram of the neural network and ARIMA hybrid model is shown in Figure 4.

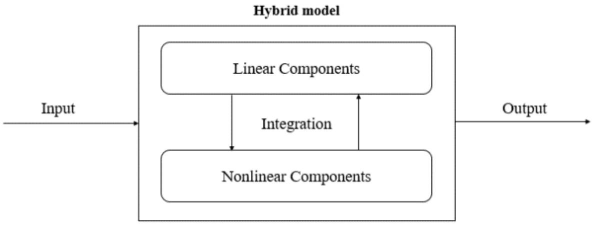

Figure 4. The block diagram of the neural network and ARIMA hybrid model

The precise description of the above operation is that in the first step, ARIMA is used to model the linear relationships in the original time series. $\{e_t\}$ represents the rest of the ARIMA model, respectively, in Additive and Multiplicative hybrid models:

$$e_t = x_t - \hat{x}_t \quad (5)$$
$$e_t = x_t / \hat{x}_t \quad (6)$$

where x_t is the real value and $\hat{x}_t$ is the ARIMA model prediction value.
In the second step, the ANN model is used to model non-linear relationships in AIRMA models. $\{\hat{e}_t\}$ represents the values predicted by the ANN model. The last step combines the predicted values of the two steps above. Two models, additive hybrid model (Linear components + Non-linear components) and multiplicative hybrid model (Linear components × Non-linear components), can be used for evaluating time series. For these two cases, the mathematical expressions are given in Equations (7) and (8):

$$\tilde{x}_t = \hat{x}_t + \hat{e}_t \quad (7)$$
$$\tilde{x}_t = \hat{x}_t \times \hat{e}_t \quad (8)$$

where $\tilde{x}_t$ represents the predicted value of the hybrid model [18].
Artificial neural network models with hidden layers can capture non-linear patterns in time series. So, in time series forecasting, it is advantageous to combine ANN and ARIMA to deal with all interdependent components of the underlying patterns.
To sum up, there are two steps in the proposed hybrid model. An ARIMA model is initially defined, and the corresponding parameters are evaluated, i.e., an ARIMA model is built. As a result, this model is used to calculate the non-linear components. In the second phase, the non-linear components are managed by a neural network model [20].

4. Results and Discussion

Four ARIMA, ANN, additive, and multiplicative hybrid models are used to predict the container traffic of Rajaee port. The prediction accuracy [31] of the four models is investigated by examining the correlation coefficient of R, mean absolute deviation (MAD), mean squared error (MSE) and mean absolute percentage error (MAPE) since using a combination of measures to evaluate the accuracy of the forecast is much better than using a single measure.

$$R = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2]\,[n\sum y^2 - (\sum y)^2]}} \quad (9)$$

$$MAD = \frac{\sum|y_i - \bar{y}|}{n} \quad (10)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (11)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \quad (12)$$

Table 2 shows a comparison of the performance of ARIMA, ANN, and hybrid models.

Table 2. Performance of ARIMA, NN, additive hybrid and multiplicative hybrid model

Method	R	MAD	MSE	MAPE
ARIMA	75.31	7.2128	8.9798	7.2128
ANN	77.50	3.5943	4.8015	3.5943
Additive	80.12	5.2236	6.6733	5.2236
Multiplicative	81.57	5.1636	6.9063	5.1636

Therefore, the results of ARIMA, ANN, Additive and multiplicative hybrid models for predicting the number of container vessels are presented in Figures 5 to 8 in which the values of the predicted vessels are compared with the actual values. Although the errors in the prediction of container traffic do not seem too different between Figs 5 to 8, the comparison of performance criteria (Table 2) indicates that hybrid models reduce the model uncertainty.

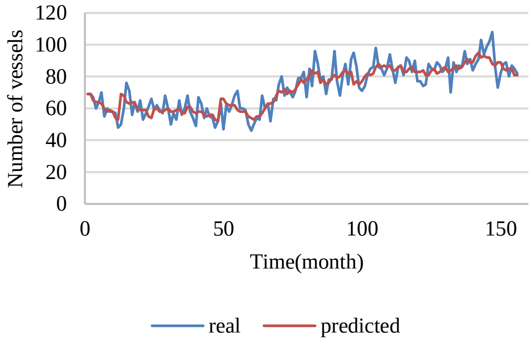

Figure 5. Comparison of the predicted total number of vessels with ARIMA model with real values of vessels' number

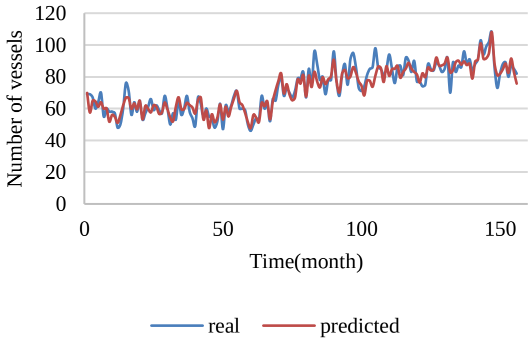

Figure 6. Comparison of the predicted total number of vessels with a NN model with real values of vessels' number

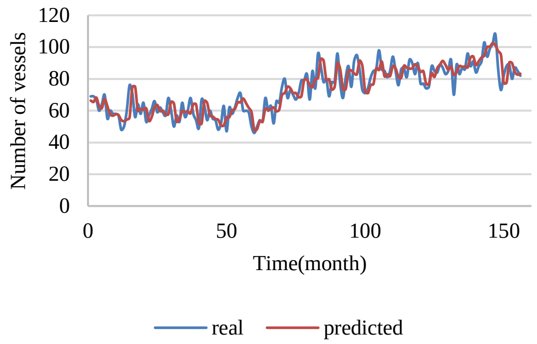

Figure 7. Comparison of the predicted total number of vessels with Additive hybrid model with real values of vessels' number

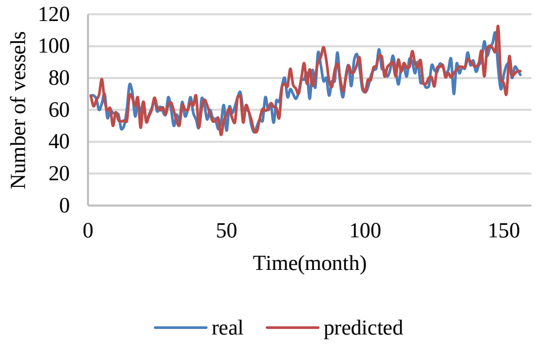

Figure 8. Comparison of the predicted total number of vessels with Multiplicative hybrid model with real values of vessels' number

Based on the results of the four models, the hybrid models provide better performance results for the prediction of the container vessels' number. Also, the comparison of predicted numbers and actual values confirms this result (Figure 5-8).

Figure 9 shows that the annual results of hybrid multiplicative models are closer to the actual data values.

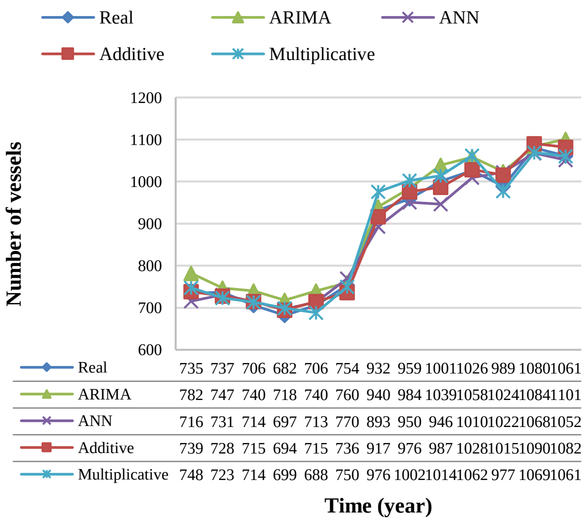

Figure 9. Results of four developed models to predict the number of container vessels

5. Conclusions

Over the past few decades, both ARIMA and ANNs have been widely used in time series analysis and forecasting due to their versatility and usefulness in modeling several issues. However, many researchers have found that none of them are wholly appropriate as a reliable forecasting model regardless of the situation's uniqueness. Some recent studies have focused on building hybrid models to enhance the accuracy and performance of time series forecasting. A hybrid model (additive and multiplicative model) is proposed in this paper, which merged the ARIMA model and the neural network to make predictions with the non-seasonal time series data of Rajaee port.

Additionally, the linear ARIMA model and the non-linear ANNs model are used to capture the various patterns in time series. Throughout the linear and non-linear models, the hybrid model combines the flexibilities of ARIMA and ANNs, and it is an effective way to improve the reliability of forecasted data.

In this paper, we make the first attempt to predict container traffic volume in the Rajaee Port, and the MSE, MAD, and MAPE accuracy tests are used as evaluation criteria. The lowest errors for the multiplicative hybrid model reveals that the introduced model is superior to the ARIMA model, the ANN model, and the additive hybrid model based on the data set of real traffic data. Moreover, indeed, the hybrid method gives more accurate predictions compared to ARIMA and ANN models.

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