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Vulnerability Analysis of Harbor Oil Pipeline Affected by Typhoon

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Abstract: The integrity of oil pipelines has received considerable attention. Pipeline leakage accidents cause environmental pollution and casualties. Analysis of accident data in recent years shows that the harbor oil pipeline is prone to natural disasters such as typhoons. The vulnerability analysis of the pipeline was conducted from three perspectives: typhoon grades, windward angles, and operating conditions. The analytic hierarchy is used to build the vulnerability evaluation index system. The vulnerability evaluation score of the pipeline can be calculated by the semi-quantitative method. The results show that the probability of pipeline vulnerability failure increases with the increase of typhoon level, while the change of wind angle has no obvious effect on the pipeline. The full load of the pipeline has a higher evaluation score than that of the empty load, which means the full load is safer. The vulnerability analysis of oil pipelines can effectively improve the safety of pipeline transportation under the influence of typhoons.

Keywords: pipeline transportation; pipeline safety; vulnerability analysis; analytic hierarchy process

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1. Introduction

According to the 2021 China Statistical Yearbook [1], the pipeline length of the oil and gas in 2020 was 144,000 km, and the volume of the oil and gas transported by the pipeline in 2021 was 870 million tons, 3.6% year on year. However, the expansion of the pipeline network is often accompanied by more safety risk issues, such as the increase of the windward area of the pipeline, the greater impact of natural disasters, and an increase in the likelihood of safety accidents. Oil spill accidents occurred in most enterprises not only cause serious economic losses and environmental pollution but also may lead to a series of safety accidents.

On 25 July 2010, in Marshall, Michigan, a pipeline operated and managed by Enbridge Company ruptured due to increased pressure, resulting in the leakage of approximately 3192 m^3 of crude oil. The accident caused no casualties, but caused significant damage to the environment, with direct economic losses exceeding 767 million dollars [2]. Similarly, on 2 October 2021, due to the aging and damage of the oil pipeline, about 3000 barrels of crude oil were spilled from the offshore drilling platform "Elly", which is nearly 5 km away from the coast of California, causing an oil slick of 34 square kilometers in the sea [3]. Pipeline accidents have occurred frequently in recent years, so it is urgent to evaluate the safety of oil pipelines.

Oil pipelines are subject to damaged by various environmental factors. Among them, the special arrangement of harbor oil pipelines is more likely to be affected by extreme weather such as typhoons. Factors such as third-party sabotage, malfunction, line patrol frequency, personnel safety awareness, equipment protection, and emergency rescue capabilities will also affect the performance of the oil pipeline, making the harbor oil pipeline vulnerable to failure and causing major harm. This paper analyzes the vulnerability of the harbor oil pipeline under the influence of typhoons and establishes the threat factors to the oil pipeline. A series of safety measures are proposed to reduce the losses caused by disasters through the calculation and analysis of the evaluation results.

The harbor oil pipeline is affected by the transport process from typhoons. To study the destructiveness of typhoons, Gonzalo et al. [4] developed a hurricane disaster model that helps to assess the vulnerability of construction materials subjected to hurricane threats. Acosta et al. [5] developed a school building retrofitting priority that can be used as a reference by analyzing the damage course of schools after the transit of Typhoon Nina vulnerability curves. To reduce the risk of typhoon disasters, Kim-Anh [6] studied the vulnerability of Vietnam under typhoon conditions. William [7] studied the vulnerability of the mining industry in the Philippines under typhoon conditions.

Pipeline transportation is often accompanied by various risks, and to improve the safety of pipeline transportation, a comprehensive safety assessment of oil pipelines is required and corresponding control and management measures are proposed [8]. Risk analysis of pipelines as well as failure probability calculation are effective measures for improving pipeline safety, such as establishing the reliability of pipelines under different operating conditions through semi-implicit Markov models of port oil pipeline transportation systems under variable operating conditions [9]. Pipeline failure probability is analyzed by fuzzy fault tree analysis (FFTA) [10] and t-norm based fuzzy fault tree analysis [11]. Accidents are analyzed through accident modeling [12] and quantitative risk assessment [13], identifying and analyzing the probability of pipeline failure is identified and analyzed using Bayesian network models [14]. The risk from factors such as third-party failures are identified and analyzed by building different risk management [15] and regression models [16]. The risk analysis of pipelines by vulnerability analysis can greatly improve the safety of pipelines [17].

Oil pipelines are accident-prone when passing through the seafloor, so it is essential to evaluate the service performance of submarine oil pipelines [18]. Due to the huge depth of the seafloor, it is not possible to perform a conventional safety inspection of submarine pipelines. Amna [19] proposed an FBG sensor based on acoustic emission to detect structural damage of pipelines and performed numerical calculations based on the basis of strain measurement. Sutra [20] investigated the applicability of ideal shapes under offshore seabed conditions and their effect on pipeline bulge buckling using a 3D finite element modeling technique. Yu et al. [21] proposed an improved FMEA method based on a cloud model and extensions for assessing the risk of reliability-enhanced submarine pipelines. They have studied the risk assessment and detection of submarine pipeline transportation in depth, but the risk assessment and analysis of pipeline transportation in the port are lacking.

There are many current studies on the safe transportation of oil pipelines, but there are still shortcomings; Iseley [22] analyzed the advantages and disadvantages of current pipeline leak detection techniques and analyzed the future direction of pipeline detection technology to provide a reference for the selection of pipeline detection methods. As the current methods for pipeline failure prediction have major limitations, Zakikhani [23] proposed a maintenance planning process guided by a pipeline availability analysis to address existing gaps and limitations. The above-mentioned study describes the shortcomings of safety inspection during pipeline transportation and proposes improvement measures, but the safety analysis of pipeline transportation under the influence of typhoons is missing. The main objective of this study is to analyze the vulnerability of port pipelines in a typhoon environment and propose corresponding measures to improve the transportation safety.

This paper analyzes the vulnerability of oil pipelines under the influence of typhoons by establishing a vulnerability evaluation index system to obtain the coupling effect of different typhoon conditions or pipeline conditions on the elements of the pipeline vulnerability index, and provides corresponding preventive and control measures. The first section describes the background and significance of the vulnerability analysis of oil pipelines under the influence of typhoons and the current status of domestic and international research on oil pipeline safety, and presents the shortcomings. Section 2 describes the concepts related to vulnerability, conducts the construction of the indicator evaluation system, and analyzes the coupling effect of typhoons on the indicator elements. Section 3 establishes the scheme layer of the vulnerability index system and analyzes three aspects of typhoon intensity, wind angle of attack, and different working conditions of oil pipelines, respectively, to obtain the relative probability of vulnerability failure of oil pipelines under various conditions. Section 4 describes how the impact of typhoons on pipeline vulnerability can be mitigated in the event of a typhoon. Section 5 briefly discusses some of the flaws and shortcomings of this paper. Section 6 briefly discusses the conclusions of this paper, and outlook of this paper.

2. Construction of Vulnerability Evaluation Index System

2.1. The Coupling Effect of Typhoons and Vulnerability Indicator Systems

The coupling effect of the typhoon on the vulnerability index system of the oil pipelines is control coupling. Typhoons generate wind and rain, which makes human behavior and the state of things change, thus affecting the vulnerability of the oil pipeline at the port and having a direct impact on the performance of the pipeline. When typhoon landfall affects port pipelines, it not only poses a threat to the pipeline, but also has an impact on elements such as pipeline corrosion, support damage, equipment protection, emergency rescue response, and safety monitoring. Therefore, when analyzing the vulnerability of port oil pipelines under the influence of a typhoon, it is necessary to consider the impact of typhoons on other index elements and how to better judge the degree of impact of typhoons on other index elements, combining the characteristics of index elements and making more objective judgments on the degree of impact through the results of expert judgment and analytical calculations. For example, under the influence of a typhoon, the possibility of third-party damage, the possibility of non-compliance, the change of patrol frequency, whether the degree of corrosion is affected, the change of personnel safety awareness, the change of emergency rescue capability on the degree of impact on safety monitoring can be judged by experts. Different states of typhoons will have different effects on the index elements. In this paper, we will evaluate which conditions have the greatest coupling effect and the highest probability of vulnerability failure of oil pipelines by targeting three aspects: typhoon strengths, wind attack angles, and operation status, and put forward prevention and control measures.

2.2. Vulnerability Evaluation Index System of the Harbor Oil Pipelines

The vulnerability of oil pipelines in the harbor mainly indicates the possibility of failure or damage caused by external disasters or their adverse effects. In this paper, the comprehensive index method and the hierarchical analysis method are used to study the vulnerability of oil pipelines at the port under the influence of typhoons. The hierarchical analysis method is particularly suitable for analyzing the problem of weight determination and scheme ranking in some multi-objective (multi-criteria) decision problems with more complex structures which are difficult to quantify [24], and the hierarchical analysis method decomposes the relevant elements into multiple levels [25] on which quantitative analysis is performed [26]. Hierarchical analysis treats the research object as a system and makes decisions according to the way of thinking of decomposition, comparative judgment and synthesis. The idea of the system is not to cut off the influence of each factor on the result, and the weight setting of each layer in hierarchical analysis will finally affect the result directly or indirectly, and the degree of influence of each factor in each layer on the result is quantified and very clear and explicit.

The basic steps of the hierarchical analysis are as follows: the first step is to establish a hierarchical model structure, which consists of a target layer at the top, a criterion layer in the middle, and a scheme layer at the bottom, with the basic model shown in Figure 1.

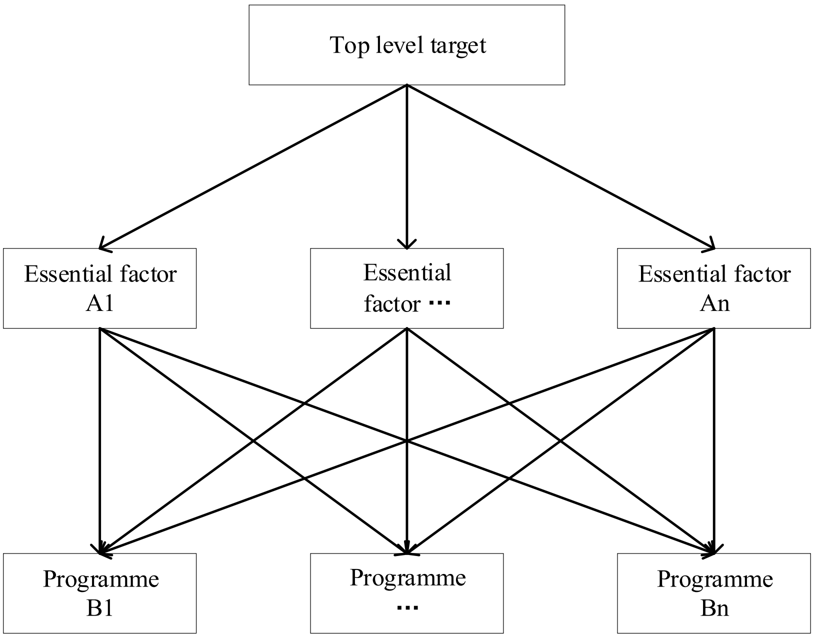

Figure 1. Basic model of analytic hierarchy process.

The second step constructs the judgment matrix, i.e., the comparison of the importance of the elements of this level a_i and $a_j(i, j = 1, \cdots, n)$ relative to the elements of the upper level, and the scales 1–9 are taken when two factors are compared [27], and a_{ij} is used to indicate the result of the comparison of the factor i to the factor j, from which the judgment matrix $\left(a_{ij}\right)_{n\times n}$ is obtained. The 1–9 scale table is shown in Table 1. "2", "4", "6" and "8" indicate an in-between level of influence.

Table 1. Feature Importance Scale.

a_{ij}	Definition	a_{ij}	Definition
1	a_i and a_j are equally important	7	a_i is better than a_j and is obviously important
3	a_i is slightly more important than a_j	9	a_i is better than a_j and absolutely important
5	a_i is better than a_j obviously important		

The third step calculates the maximum eigenvalues of the judgment matrix and the corresponding eigenvectors and does a consistency test on the judgment matrix. When the judgment matrix has consistency, the eigenvector of the maximum eigenvalue $(w_1, \ldots, w_n)^T$ indicates the ranking of the importance of the elements of this level on the elements of the upper level, and w_i indicates the weight of the degree of influence of the factor i of this level on the factors of the upper level. The judgment matrix is considered consistent when $CR < 0.1$ [28].

$$CR = \frac{CI}{RI} \tag{1}$$

$$CI = \frac{\lambda - n}{n - 1} \tag{2}$$

λ is the maximum characteristic root of the judgment matrix and n is the order of the judgment matrix.

The value of RI changes with the change of n, and the specific value is shown in Table 2.

Table 2. The value of RI corresponding to the order of the matrix.

Matrix Order n	3	4	5	6	7	8	9	10	11	12
RI Value	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

In a complex working environment, oil pipelines are not only affected by the internal vulnerability, but also by external threats. Therefore, the selection of vulnerability index elements should be based on the disaster-bearing capacity of the pipeline itself, external environmental impact, safety management, and emergency response capability, etc. The 12 index elements finally derived from the opinions of experts from relevant petrochemical enterprises and technical consultants are third-party damage, malfunction, patrol frequency, personnel safety awareness, equipment protection, emergency rescue capability, support damage, corrosion design defects, service life, safety testing, and deformation. The transmission pipeline vulnerability evaluation system is shown in Figure 2.

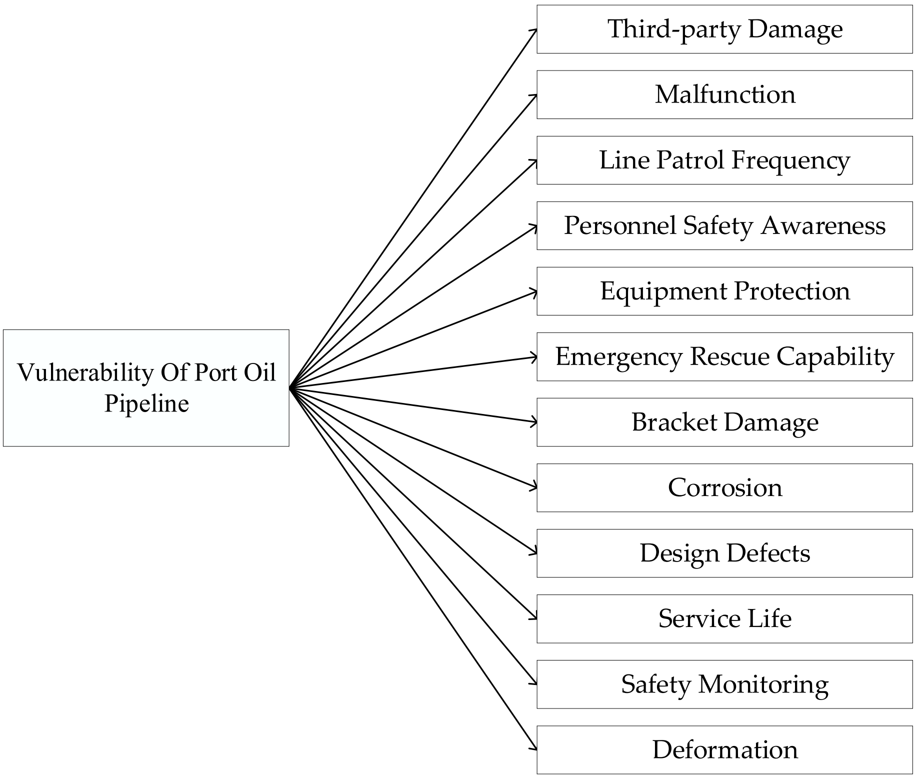

Figure 2. System of evaluation indicators for port Pipeline.

2.3. Calculation of Vulnerability Indicator Elements for Harbor Pipelines

To obtain matrix A of importance judgment of index elements based on importance judgment.

$$A=\begin{bmatrix}
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{5} & 1 & \frac{1}{7} & 1 & \frac{1}{5} & \frac{1}{7} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} \\
2 & 1 & \frac{1}{2} & \frac{1}{4} & 2 & \frac{1}{6} & 2 & \frac{1}{3} & \frac{1}{5} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\
3 & 2 & 1 & \frac{1}{3} & 3 & \frac{1}{4} & 3 & \frac{1}{2} & \frac{1}{4} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
5 & 4 & 3 & 1 & 5 & \frac{1}{2} & 5 & 1 & \frac{1}{2} & 1 & 1 & 1 \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{5} & 1 & \frac{1}{7} & 1 & \frac{1}{5} & \frac{1}{7} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} \\
7 & 6 & 4 & 2 & 7 & 1 & 7 & 2 & 1 & 2 & 2 & 2 \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{5} & 1 & \frac{1}{7} & 1 & \frac{1}{5} & \frac{1}{7} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} \\
5 & 3 & 2 & 1 & 5 & \frac{1}{2} & 5 & 1 & \frac{1}{2} & 1 & 1 & 1 \\
7 & 5 & 4 & 2 & 7 & \frac{1}{7} & 7 & 2 & 1 & 2 & 2 & 2 \\
5 & 3 & 2 & 1 & 5 & \frac{1}{2} & 5 & 1 & \frac{1}{2} & 1 & 1 & 1 \\
5 & 3 & 2 & 1 & 5 & \frac{1}{2} & 5 & 1 & \frac{1}{2} & 1 & 1 & 1 \\
5 & 3 & 2 & 1 & 5 & \frac{1}{2} & 5 & 1 & \frac{1}{2} & 1 & 1 & 1
\end{bmatrix} \tag{3}$$

Normalizing matrix A, the matrix B can be calculated as follows.

$$B = \begin{bmatrix} \frac{1}{47} & \frac{1}{63} & \frac{2}{129} & \frac{12}{611} & \frac{1}{47} & \frac{12}{449} & \frac{1}{47} & \frac{6}{313} & \frac{20}{753} & \frac{6}{313} & \frac{6}{313} & \frac{6}{313} \\ \frac{2}{47} & \frac{2}{63} & \frac{1}{43} & \frac{15}{611} & \frac{2}{47} & \frac{14}{449} & \frac{2}{47} & \frac{10}{313} & \frac{28}{753} & \frac{10}{313} & \frac{10}{313} & \frac{10}{313} \\ \frac{3}{47} & \frac{4}{63} & \frac{2}{43} & \frac{20}{611} & \frac{3}{47} & \frac{21}{449} & \frac{3}{47} & \frac{15}{313} & \frac{35}{753} & \frac{15}{313} & \frac{15}{313} & \frac{15}{313} \\ \frac{5}{47} & \frac{8}{63} & \frac{6}{43} & \frac{60}{611} & \frac{5}{47} & \frac{42}{449} & \frac{5}{47} & \frac{30}{313} & \frac{70}{753} & \frac{30}{313} & \frac{30}{313} & \frac{30}{313} \\ \frac{1}{47} & \frac{1}{63} & \frac{2}{129} & \frac{12}{611} & \frac{1}{47} & \frac{12}{449} & \frac{1}{47} & \frac{6}{313} & \frac{20}{753} & \frac{6}{313} & \frac{6}{313} & \frac{6}{313} \\ \frac{7}{47} & \frac{12}{63} & \frac{8}{43} & \frac{120}{611} & \frac{7}{47} & \frac{84}{449} & \frac{7}{47} & \frac{60}{313} & \frac{140}{753} & \frac{60}{313} & \frac{60}{313} & \frac{60}{313} \\ \frac{1}{47} & \frac{1}{63} & \frac{2}{129} & \frac{12}{611} & \frac{1}{47} & \frac{12}{449} & \frac{1}{47} & \frac{6}{313} & \frac{20}{753} & \frac{6}{313} & \frac{6}{313} & \frac{6}{313} \\ \frac{5}{47} & \frac{6}{63} & \frac{4}{43} & \frac{60}{611} & \frac{5}{47} & \frac{42}{449} & \frac{5}{47} & \frac{30}{313} & \frac{70}{753} & \frac{30}{313} & \frac{30}{313} & \frac{30}{313} \\ \frac{7}{47} & \frac{10}{63} & \frac{8}{43} & \frac{120}{611} & \frac{7}{47} & \frac{84}{449} & \frac{7}{47} & \frac{60}{313} & \frac{140}{753} & \frac{60}{313} & \frac{60}{313} & \frac{60}{313} \\ \frac{5}{47} & \frac{6}{63} & \frac{4}{43} & \frac{60}{611} & \frac{5}{47} & \frac{42}{449} & \frac{5}{47} & \frac{30}{313} & \frac{70}{753} & \frac{30}{313} & \frac{30}{313} & \frac{30}{313} \\ \frac{5}{47} & \frac{6}{63} & \frac{4}{43} & \frac{60}{611} & \frac{5}{47} & \frac{42}{449} & \frac{5}{47} & \frac{30}{313} & \frac{70}{753} & \frac{30}{313} & \frac{30}{313} & \frac{30}{313} \\ \frac{5}{47} & \frac{6}{63} & \frac{4}{43} & \frac{60}{611} & \frac{5}{47} & \frac{42}{449} & \frac{5}{47} & \frac{30}{313} & \frac{70}{753} & \frac{30}{313} & \frac{30}{313} & \frac{30}{313} \end{bmatrix} \quad (4)$$

w_i is derived from the calculation as follows.

$$w_i = \begin{bmatrix} 0.020 & 0.034 & 0.052 & 0.105 & 0.020 & 0.180 & 0.020 & 0.098 & 0.177 & 0.098 & 0.098 & 0.098 \end{bmatrix}^T \quad (5)$$

By calculating $\lambda_{max} = 12.085$, the consistency test results in $CR = 0.00502 < 0.1$, and the consistency test is passed. According to the vulnerability evaluation index system of the harbor oil pipeline, the judgment matrix and weights of the evaluation index system of the harbor oil pipeline are obtained by combining with the hierarchical analysis method, as shown in Table 3 below.

Table 3. The judgment matrix of the evaluation index system of the port pipeline.

	TPD	**M**	**LPF**	**PSA**	**EP**	**ERC**	**BD**	**C**	**DF**	**SL**	**SM**	**D**	**W**
TPD	1	1/2	1/3	1/5	1	1/7	1	1/5	1/7	1/5	1/5	1/5	0.020
M	2	1	1/2	1/4	2	1/6	2	1/3	1/5	1/3	1/3	1/3	0.034
LPF	3	2	1	1/3	3	1/4	3	1/2	1/4	1/2	1/2	1/2	0.052
PSA	5	4	3	1	5	1/2	5	1	1/2	1	1	1	0.105
EP	1	1/2	1/3	1/5	1	1/7	1	1/5	1/7	1/5	1/5	1/5	0.020
ERC	7	6	4	2	7	1	7	2	1	2	2	2	0.180
BD	1	1/2	1/3	1/5	1	1/7	1	1/5	1/7	1/5	1/5	1/5	0.020
C	5	3	2	1	5	1/2	5	1	1/2	1	1	1	0.098
DF	7	5	4	2	7	1	7	2	1	2	2	2	0.177
SL	5	3	2	1	5	1/2	5	1	1/2	1	1	1	0.098
SM	5	3	2	1	5	1/2	5	1	1/2	1	1	1	0.098
D	5	3	2	1	5	1/2	5	1	1/2	1	1	1	0.098

Note: TPD = Third party damage; M = Malfunction; LPF = Line patrol frequency; PSA = Personnel safety awareness; EP = Equipment protection; ERC = Emergency rescue Capability; BD = Bracket damage; C = Corrosion; DF = Design defects; SL = Service life; SM = Safety monitoring; D = Deformation; W = weight.

3. Pipeline Vulnerability Analysis

3.1. Vulnerability Analysis of Typhoon Intensity on Oil Pipelines

Different typhoon intensities have different impacts on the vulnerability of oil pipelines, so the bottom scenario layer is set up with five different typhoon intensities: no typhoon, strong tropical storm, typhoon, strong typhoon, and super typhoon. Combined with the previous section, the complete vulnerability indicator evaluation system is shown in Figure 3.

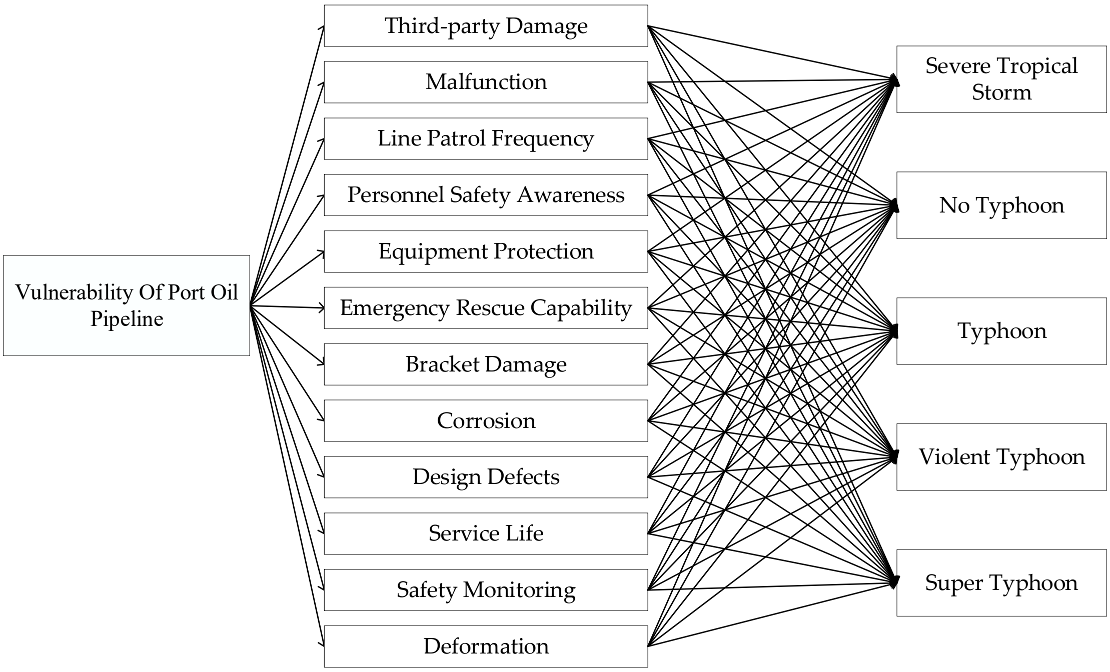

Figure 3. Vulnerability evaluation index system for the pipeline under the influence of different typhoon intensity.

There are 12 influencing factors in the element layer of the harbor pipeline vulnerability evaluation system, which need to be analyzed one by one. Firstly, there is third-party damage, which is a very large part of the cause of pipeline failure, appears more prominent under the influence of typhoon [29], and the judgment matrix of different typhoon strengths relative to third-party damage factors and the eigenvectors are calculated according to the analysis, the maximum eigenvalue is $\lambda_{max} = 5$, the consistency check result $CR = 0 < 0.1$, the consistency check is passed, and the feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 4:

Table 4. Important degree judgment matrix of third-party damage under different typhoon intensity.

Third Party Damage	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	3	3	3	3	0.428
Severe tropical storm	1/3	1	1	1	1	0.143
Typhoon	1/3	1	1	1	1	0.143
Violent typhoon	1/3	1	1	1	1	0.143
Super typhoon	1/3	1	1	1	1	0.143

The second one is malfunction, which is one of the elements of pipeline failure assessment [30], and the judgment matrix of different typhoon intensities relative to the malfunction factor and the eigenvectors are calculated based on the analysis, with the maximum eigenvalue $\lambda_{max} = 5.127$, consistency check results $CR = 0.0283 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 5:

Table 5. Important degree judgment matrix of malfunction under different typhoon intensity.

Malfunction	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/3	1/3	1/5	1/7	0.047
Severe tropical storm	3	1	1	1/3	1/5	0.105
Typhoon	3	1	1	1/3	1/5	0.105
Violent typhoon	5	3	3	1	1/3	0.246
Super typhoon	7	5	5	3	1	0.497

The third one is the patrol frequency, and the judgment matrix and the eigenvectors of different typhoon intensity relative to the patrol frequency factors are calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5.068$, consistency check results $CR = 0.0152 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 6:

Table 6. Important degree judgment matrix of the frequency of the patrol line under different typhoon intensity.

Line Patrol Frequency	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/2	1/3	$\frac{1}{4}$	1/5	0.062
Severe tropical storm	2	1	1/2	1/3	$\frac{1}{4}$	0.099
Typhoon	3	2	1	$\frac{1}{2}$	1/3	0.161
Violent typhoon	4	3	2	1	$\frac{1}{2}$	0.262
Super typhoon	5	4	3	2	1	0.416

The fourth one is personnel safety awareness, and the judgment matrix and the eigenvectors of different typhoon intensity relative to personnel safety awareness factors are calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5.013$, consistency check results $CR = 0.0029 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 7:

Table 7. The important judgment matrix of personnel safety awareness under different typhoon intensity.

Personnel Safety Awareness	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	2	2	3	3	0.368
Severe tropical storm	$\frac{1}{2}$	1	1	2	2	0.206
Typhoon	$\frac{1}{2}$	1	1	2	2	0.206
Violent typhoon	1/3	1/2	1/2	1	1	0.110
Super typhoon	1/3	1/2	1/2	1	1	0.110

The fifth one is equipment protection, and the judgment matrix and the eigenvectors of different typhoon intensity relative to equipment protection factors are calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5.017$, consistency check results $CR = 0.0039 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 8:

Table 8. The important degree judgment matrix of equipment protection under different typhoon intensity.

Equipment Protection	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	$\frac{1}{2}$	$\frac{1}{2}$	1/3	1/5	0.075
Severe tropical storm	2	1	1	1/2	1/3	0.135
Typhoon	2	1	1	1/2	1/3	0.135
Violent typhoon	3	2	2	1	1/2	0.241
Super typhoon	5	3	3	2	1	0.414

The sixth one is the emergency rescue capability, and the judgment matrix of different typhoon intensity relative to the emergency rescue capability factor and the feature vector is calculated according to the analysis, and the maximum feature value is $\lambda_{max} = 5.178$, consistency check results $CR = 0.0396 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 9:

Table 9. Important assessment matrix of emergency rescue capability under different typhoon intensity.

Emergency Rescue Capability	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/3	1/3	1/5	1/9	0.040
Severe tropical storm	3	1	1	1/3	1/7	0.089
Typhoon	3	1	1	1/3	1/7	0.089
Violent typhoon	5	3	3	1	1/5	0.199
Super typhoon	9	7	7	5	1	0.583

The seventh one is bracket damage. Material failure is the most common cause of pipeline safety accidents [31], with the change in typhoon intensity the probability of bracket damage will change, according to the analysis and calculation of the judgment matrix of different typhoon intensity relative to the bracket damage factor and the eigenvector, the maximum eigenvalue is $\lambda_{max} = 5.033$, consistency check results $CR = 0.0074 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 10:

Table 10. Important degree judgment matrix for bracket damage under different typhoon intensity.

Bracket Damage	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/3	1/3	1/5	1/9	0.080
Severe tropical storm	3	1	1	1/3	1/7	0.137
Typhoon	3	1	1	1/3	1/7	0.137
Violent typhoon	5	3	3	1	1/5	0.244
Super typhoon	9	7	7	5	1	0.402

The eighth one is oil pipeline corrosion. Typhoon intensity has little effect on pipeline corrosion, but the high water content of the medium leads to easy corrosion of the pipeline [32], and the pipeline corrosion itself is very damaging to the safe transportation of oil [33]. According to the analysis and calculation of the judgment matrix of different typhoon intensities relative to the corrosion factor of oil pipelines and the eigenvector, the maximum eigenvalue is $\lambda_{max} = 5.033$, consistency check results $CR = 0.0074 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 11:

Table 11. Important degree judgment matrix of corrosion under different typhoon intensity.

Corrosion	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/2	1/2	1/3	1/3	0.090
Severe tropical storm	2	1	1	1/2	1/2	0.158
Typhoon	2	1	1	1/2	1/2	0.158
Violent typhoon	3	2	2	1	1	0.297
Super typhoon	3	2	2	1	1	0.297

The ninth one is the oil pipeline design defect, and the judgment matrix and the eigenvector of different typhoon intensity relative to the oil pipeline design defect factors are calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5.057$, consistency check results $CR = 0.0124 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 12:

Table 12. Important degree judgment matrix for design defects under different typhoon intensity.

Design Defects	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/3	1/3	1/5	1/5	0.056
Severe tropical storm	3	1	1	1/3	1/3	0.130
Typhoon	3	1	1	1/3	1/3	0.130
Violent typhoon	5	3	3	1	1	0.342
Super typhoon	5	3	3	1	1	0.342

The tenth one is the service life, and the judgment matrix of different typhoon intensity relative to the service life factor of the pipeline and the eigenvector is calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5$, consistency check results $CR = 0 < 0.1$, consistency check passes, and feature vector w_i is the weight value. Its weight value is $w_i = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix}^T$.

The eleventh one is safety monitoring. According to the analysis and calculation of the judgment matrix of different typhoon intensity relative to the safety monitoring factors and the eigenvector, the maximum eigenvalue is $\lambda_{max} = 5.010$, consistency check results

$CR = 0.0022 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 13:

Table 13. Important degree judgment matrix for safety monitoring under different typhoon intensity.

Safety Monitoring	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1	1	2	3	0.260
Severe tropical storm	1	1	1	2	3	0.260
Typhoon	1	1	1	2	3	0.260
Violent typhoon	1/2	1/2	1/2	1	2	0.138
Super typhoon	1/3	1/3	1/3	1/2	1	0.082

The twelfth one is the pipeline deformation, and the judgment matrix and the eigenvectors of different typhoon intensity relative to the pipeline deformation factors are calculated according to the analysis, and the maximum eigenvalue is $\lambda_{max} = 5.068$, consistency check results $CR = 0.0152 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 14:

Table 14. Important degree judgment matrix of deformation under different typhoon intensity.

Deformation	No Typhoon	Severe Tropical Storm	Typhoon	Violent Typhoon	Super Typhoon	w_i
No typhoon	1	1/2	1/3	1/4	1/5	0.062
Severe tropical storm	2	1	1/2	1/3	1/4	0.099
Typhoon	3	2	1	1/2	1/3	0.161
Violent typhoon	4	3	2	1	1/2	0.262
Super typhoon	5	4	3	2	1	0.416

Combining the above weights of different intensity typhoons on each indicator element, and then based on the weight values of the 12 elements on the target calculated in Section 2, we finally obtain:

Vulnerability analysis score:

$$\begin{bmatrix} S_{Notyphoon} \\ S_{Severetropicalstorm} \\ S_{Typhoon} \\ S_{Violenttyphoon} \\ S_{Supertyphoon} \end{bmatrix} = \begin{bmatrix} 0.428 & 0.047 & 0.062 & 0.368 & 0.075 & 0.040 & 0.080 & 0.090 & 0.056 & 0.200 & 0.260 & 0.062 \\ 0.143 & 0.105 & 0.099 & 0.206 & 0.135 & 0.089 & 0.137 & 0.158 & 0.130 & 0.200 & 0.260 & 0.099 \\ 0.143 & 0.105 & 0.161 & 0.206 & 0.135 & 0.089 & 0.137 & 0.158 & 0.130 & 0.200 & 0.260 & 0.161 \\ 0.143 & 0.246 & 0.262 & 0.110 & 0.241 & 0.199 & 0.244 & 0.297 & 0.342 & 0.200 & 0.138 & 0.262 \\ 0.143 & 0.497 & 0.146 & 0.110 & 0.414 & 0.583 & 0.402 & 0.297 & 0.342 & 0.200 & 0.082 & 0.416 \end{bmatrix} \begin{bmatrix} 0.020 \\ 0.034 \\ 0.052 \\ 0.105 \\ 0.020 \\ 0.180 \\ 0.020 \\ 0.098 \\ 0.177 \\ 0.098 \\ 0.098 \\ 0.098 \end{bmatrix} = \begin{bmatrix} 0.132 \\ 0.148 \\ 0.157 \\ 0.231 \\ 0.332 \end{bmatrix}$$

Let $s_{no}, s_{Severe}, s_{typhoon}, s_{Violent}, s_{Super}$ be the vulnerability analysis scores of the oil pipeline at the port under different typhoon intensities relative to the typhoon impact, and get $s_{no} = 0.132, s_{Severe} = 0.148, s_{typhoon} = 0.157, s_{Violent} = 0.231, s_{Super} = 0.332$, which shows that the higher the typhoon intensity under the same conditions, the more likely the pipeline failure.

3.2. *Analysis of Wind Attack Angle on the Vulnerability of Oil Pipelines*

Different wind attack angles have different effects on the vulnerability of oil pipelines, so the bottom program layer was set up with four different angles of 30°, 60°, 90°, and 120°, respectively. Four sets of comparisons were established to analyze at what angles of wind the harbor pipeline is more susceptible to vulnerability failure and the overall vulnerability index evaluation system is shown in Figure 4.

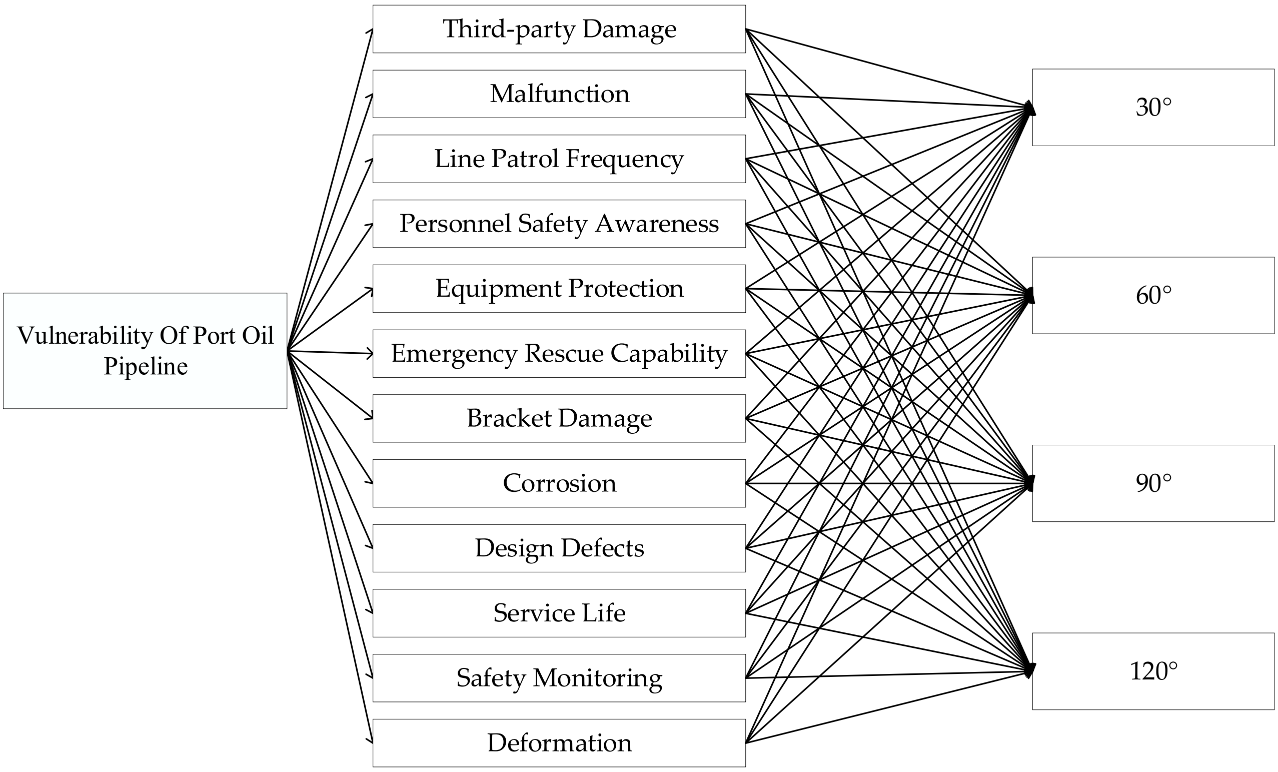

Figure 4. Vulnerability evaluation index system of the pipeline under the influence of typhoons of different wind attack angle.

The typhoon intensity is designated as a super typhoon for the analysis of the impact of typhoons with different wind angles of attack. As the typhoon intensity reaches a certain level, the coupling effect analysis for certain index elements will be dominated by the typhoon intensity, such as third-party damage, malfunction, patrol frequency, personnel safety awareness, emergency rescue capability, corrosion, design defects, service life, safety monitoring, and other index elements. At this time, these elements receive less influence from different wind attack angles and can be considered as receiving equal influence, and the importance matrix is 4th order unit matrix, the maximum eigenvalue of the importance judgment matrix $\lambda_{max} = 4$, the consistency check result $CR = 0 < 0.1$, its weight value is $w_i = \begin{bmatrix} 0.25 & 0.25 & 0.25 & 0.25 \end{bmatrix}^T$.

In addition, there are three elements such as pipeline deformation, equipment protection, and bracket damage, etc. According to the calculation, the judgment matrix and the feature vector of different wind attack angle typhoon pairs and pipeline deformation factors are obtained, and the maximum feature value is $\lambda_{max} = 4.081$, the consistency check result $CR = 0.0304 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 15:

Table 15. Important degree judgment matrix of deformation slower in different wind attack angles.

Deformation	**30°**	**60°**	**90°**	**120°**	w_i
30°	1	1/6	1/4	1/3	0.006
60°	6	1	3	2	0.544
90°	4	1/3	1	2	0.240
120°	3	1/4	1/2	1	0.150

According to the calculation of the judgment matrix and eigenvectors of different wind angles of attack typhoon pairs and equipment protection factors, the maximum eigenvalue is $\lambda_{max} = 4.051$, the consistency check result $CR = 0.0191 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 16:

Table 16. Important degree judgment matrix of equipment protection under different wind attack angles.

Equipment Protection	**30°**	**60°**	**90°**	**120°**	w_i
30°	1	1/5	1/3	1/2	0.085
60°	5	1	3	4	0.542
90°	3	1/3	1	2	0.233
120°	2	1/4	$\frac{1}{2}$	1	0.140

According to the calculation of the judgment matrix and eigenvectors of different wind angles of attack typhoon on the damage factors with the bracket, the maximum eigenvalue is $\lambda_{max} = 4.010$, the consistency check result $CR = 0.0039 < 0.1$, consistency check passes, and feature vector w_i is the weight value. The judgment matrix and the feature vector are shown in Table 17:

Table 17. Important degree judgment matrix for bracket damage at different wind attack angles.

Bracket Damage	**30°**	**60°**	**90°**	**120°**	w_i
30°	1	1/3	$\frac{1}{2}$	1/2	0.123
60°	3	1	2	2	0.423
90°	2	1/2	1	1	0.227
120°	2	1/2	1	1	0.227

Combining the above weights of the typhoon on each index element under different wind angles of attack, and then based on the weight values of the 12 elements on the target calculated in Section 2, we finally obtain:

Vulnerability analysis score.

$$\begin{bmatrix} S_{30} \\ S_{60} \\ S_{90} \\ S_{120} \end{bmatrix} = \begin{bmatrix} 0.250 & 0.250 & 0.250 & 0.250 & 0.085 & 0.250 & 0.123 & 0.250 & 0.250 & 0.250 & 0.250 & 0.006 \\ 0.250 & 0.250 & 0.250 & 0.250 & 0.542 & 0.250 & 0.423 & 0.250 & 0.250 & 0.250 & 0.250 & 0.544 \\ 0.250 & 0.250 & 0.250 & 0.250 & 0.233 & 0.250 & 0.227 & 0.250 & 0.250 & 0.250 & 0.250 & 0.240 \\ 0.250 & 0.250 & 0.250 & 0.250 & 0.140 & 0.250 & 0.227 & 0.250 & 0.250 & 0.250 & 0.250 & 0.150 \end{bmatrix} \begin{bmatrix} 0.020 \\ 0.034 \\ 0.052 \\ 0.105 \\ 0.020 \\ 0.180 \\ 0.098 \\ 0.177 \\ 0.098 \\ 0.098 \\ 0.098 \end{bmatrix} = \begin{bmatrix} 0.226 \\ 0.288 \\ 0.248 \\ 0.238 \end{bmatrix}$$

The analysis scores of $s_{30},\ s_{60}, s_{90}, s_{120}$ for different wind attack angles under the influence of typhoons relative to the vulnerability of oil pipelines in the port are obtained as $s_{30} = 0.226, s_{60} = 0.288, s_{90} = 0.248, s_{120} = 0.238$, which shows that the pipeline failure is most likely to occur when the wind attack angle is 60° under the same conditions, but it is found that the overall difference is not very large, indicating that the difference in the vulnerability of typhoons with different wind attack angles on the oil pipeline at the port is not particularly large.

3.3. Vulnerability Analysis of Oil Pipelines under Working Conditions

Different operating states of the pipeline under the influence of typhoon have different effects on the vulnerability of the pipeline itself, so the bottom scenario layer sets 2 different operating states, no-load state and full-load state, respectively, and the overall vulnerability index evaluation system is shown in Figure 5.

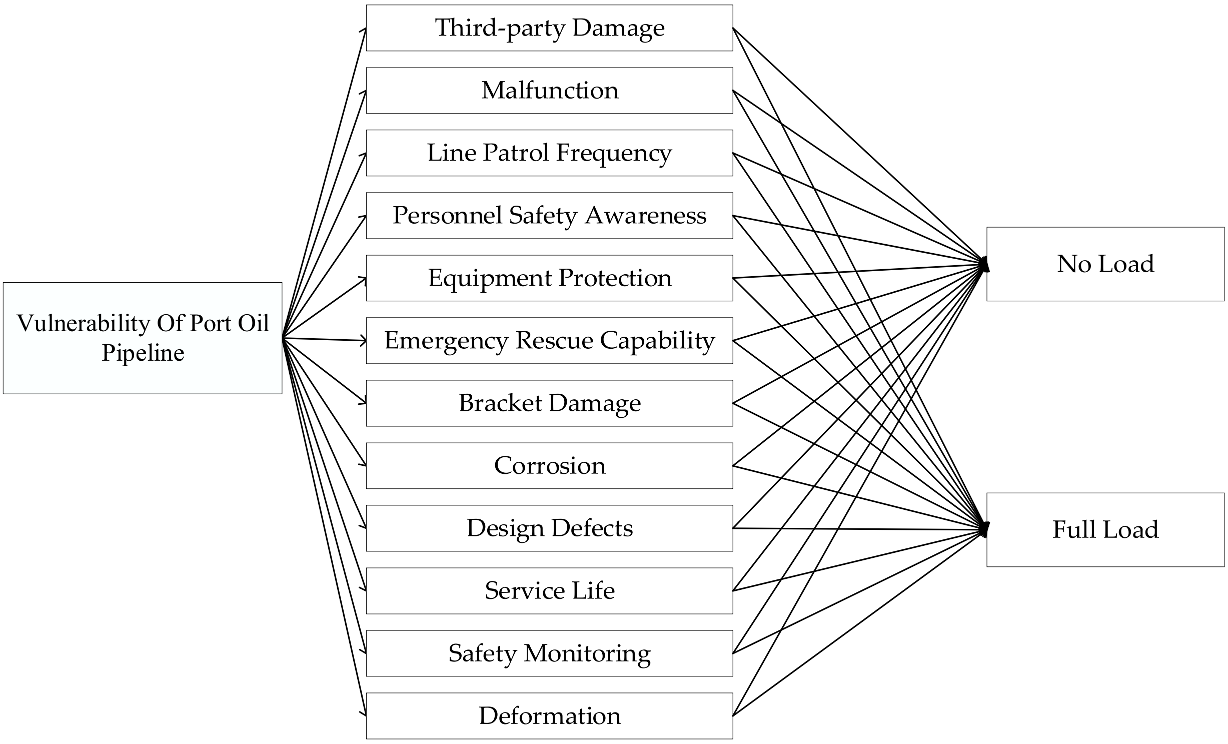

Figure 5. Vulnerability evaluation index system for pipelines under typhoon impact.

When changing the operation state, the influence of third party damage, malfunction, equipment protection, emergency rescue capability, bracket damage, corrosion, and other index elements on the pipeline vulnerability index evaluation system will not change with the change of state, the importance of these index elements in different operating conditions is the same, so the index weights are all $w_i = \begin{bmatrix} 0.5 & 0.5 \end{bmatrix}^T$, which are obtained by calculating the maximum eigenvalue to be $\lambda_{max} = 2$, the consistency check result $CR = 0 < 0.1$, which passes the consistency test. In addition, there are index elements such as patrol frequency, personnel safety awareness, design defects, service life, safety monitoring, and deformation, etc. The importance judgment matrix and maximum eigenvalues of these index elements are obtained after analysis and calculation, as shown in Tables 18–23.

Table 18. Important judgment matrix of patrol frequency under different operating conditions.

Line Patrol Frequency	No Load	Full Load	w_i
No load	1	1/2	0.33
Full load	2	1	0.67

Table 19. Important judgment matrix of personnel safety awareness under different operating conditions.

Personnel Safety Awareness	No Load	Full Load	w_i
No load	1	1/2	0.33
Full load	2	1	0.67

Table 20. Important judgment matrix for design defects under different operating conditions.

Design Defects	No Load	Full Load	w_i
No load	1	3	0.75
Full load	1/3	1	0.25

Table 21. Important judgment matrix for service life under different operating conditions.

Service Life	**No Load**	**Full Load**	w_i
No load	1	2	0.67
Full load	1/2	1	0.33

Table 22. Important degree judgment matrix for safety monitoring under different operating conditions.

Safety Monitoring	**No Load**	**Full Load**	w_i
No load	1	1/2	0.33
Full load	2	1	0.67

Table 23. Important judgment matrix of deformation under different operating conditions.

Deformation	**No Load**	**Full Load**	w_i
No load	1	2	0.67
Full load	1/2	1	0.33

The maximum eigenvalues of the above importance judgment matrix are calculated to be $\lambda_{max} = 2$, and the consistency test $CR = 0 < 0.1$, which passes the consistency test.

Combining the above weight vectors of each index element under different working conditions of the harbor oil pipeline, and then, according to the weight, values of 12 elements on the target are calculated in Section 2.

Vulnerability analysis score.

$$\begin{bmatrix} s_{No\ load} \\ s_{Full\ load} \end{bmatrix} = \begin{bmatrix} 0.50 & 0.50 & 0.33 & 0.33 & 0.50 & 0.50 & 0.50 & 0.50 & 0.75 & 0.67 & 0.33 & 0.67 \\ 0.50 & 0.50 & 0.67 & 0.67 & 0.50 & 0.50 & 0.50 & 0.50 & 0.25 & 0.33 & 0.67 & 0.33 \end{bmatrix} \begin{bmatrix} 0.020 \\ 0.034 \\ 0.052 \\ 0.105 \\ 0.020 \\ 0.180 \\ 0.020 \\ 0.098 \\ 0.177 \\ 0.098 \\ 0.098 \\ 0.098 \end{bmatrix} = \begin{bmatrix} 0.542 \\ 0.458 \end{bmatrix}$$

The vulnerability analysis scores of $s_{No\ load}$, $s_{Full\ load}$ for different working conditions of the pipeline under the influence of typhoon compared with the port pipeline itself are obtained as $s_{No\ load}$ = 0.542, $s_{Full\ load}$ = 0.458, which shows that the vulnerability failure of the pipeline is more likely to occur when the pipeline is empty under the same conditions.

4. Vulnerability Risk Control

The reason for the vulnerability failure of the harbor pipeline is the coupling effect of the typhoon on the relevant indicator elements. Eliminating or reducing the coupling effect of typhoons on relevant index elements will greatly improve the safety of pipelines in typhoon weather. The impact of typhoons on most of the indicator elements is huge, especially those involving personnel operations. Typhoons can affect personnel actions, thus increasing the frequency of malfunction, interfering with the patrol frequency and causing a serious impact on emergency rescue operations. To reduce the impact of the typhoon on the harbor oil pipelines, pipeline managers need to (1) complete some necessary operations in advance, according to typhoon warning information; (2) avoid operating under typhoon weather as much as possible; (3) strengthen the safety inspection of the pipeline before the typhoon; (4) improve the intelligence level of safety management, and (5) at the same time keep the oil pipeline in transportation status. During typhoons, special emergency rescue teams are set up to give responsibilities to people, strengthen the frequency of inspection and protection of key parts of oil pipelines, and make full use of pipeline monitoring and related monitoring equipment to monitor the external and internal changes of pipelines in real-time.

5. Limitations of the Study

Due to the limited time and capacity, we have not conducted a more detailed study of typhoon-affected oil pipelines in the port, and there are still shortcomings and areas for improvement. In this paper, only the influence of typhoon, an external factor, is considered, and the study of the pipeline itself is lacking; more comprehensive consideration of all aspects is needed in future studies. In this paper, only the coupling effect of strong winds generated by typhoon landfall on the vulnerability index elements of oil pipelines is studied, and the coupling effect of heavy rainfall and storm surge accompanying typhoon landfall on the vulnerability index elements of oil pipelines is not considered, and the coupling effect on the index elements needs to be discussed in future studies in conjunction with the three main influencing factors.

In this paper, the hierarchical analysis method is chosen for the vulnerability assessment of oil pipelines. The hierarchical analysis method is a semi-quantitative analysis method, and the importance determination of the index elements mostly relies on the experience of experts, which lacks a certain degree of objectivity. In future research, we will use the big data platform to distinguish the importance of the index elements, which will effectively improve the accuracy of the evaluation results.

6. Conclusions

This paper combines the actual situation of the pipeline with the vulnerability analysis of the harbor oil pipeline. The vulnerability evaluation index system for harbor pipeline was established. Hierarchical analysis has the advantage of simplicity and practicality, which can turn complex decision problems that are difficult quantify in their entirety into multi-level single-objective problems and facilitate the making of judgments. Comprehensive analysis and discussions on the coupling effect of the typhoon on index factors were provided. The conclusions are summarized as follows.

The vulnerability index system was established from three different perspectives. The vulnerability evaluation scores are $s_{no} = 0.132$, $s_{Severe} = 0.148$, $s_{typhoon} = 0.157$, $s_{Violent} = 0.231$, $s_{Super} = 0.332$; $s_{30} = 0.226$, $s_{60} = 0.288$, $s_{90} = 0.248$, $s_{120} = 0.238$; $s_{No\ load} = 0.542$, $s_{Full\ load} = 0.458$.

The arrival of a typhoon will have a large impact on the relevant index elements of the harbor oil pipeline, among which the impact of typhoon intensity on the index elements is the most obvious. The impact of different wind attacks on the pipeline under the same typhoon intensity does not differ much, and the probability of vulnerability failure of the pipeline at no load is relatively higher than that at full load.

Combined with the above analysis, it is recommended that enterprises with oil pipelines near the port should pay attention to strengthening safety protection when typhoons come, especially those involving personnel operations, stop oil transmission operations when typhoons arrive, and keep the pipelines fully loaded.

In future studies we will take into account the material of the pipe itself as well as the aging problem.

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