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Water-related Risk Assessment of Nuclear Power Plants Based on Simulation

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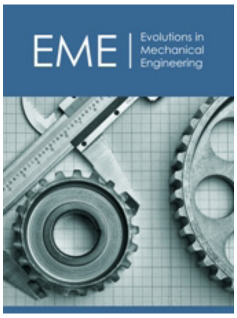

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Abstract

Once a coastal nuclear power station presents a danger, it could have a significant impact on marine ecology. Its safety operation is a concern worldwide. To evaluate the potential threats to the safe operation of coastal nuclear power stations from nearby maritime activities, we conducted this study using a specific coastal nuclear power plant. We focus on the factors affecting water-related risks at nuclear power stations, which include the risks of vessels losing control and colliding, as well as the risk of oil spillage threatening the cooling water supply of the nuclear power plant. Using the DELFT software, the study simulates a two-dimensional tidal current model of the marine area near the nuclear power station. The simulation designs experiments to model the drift of typical vessels under standard and extreme weather conditions, constructs a coastal current fields model to simulate ship oil spillage and applies the OILMAP model in order to simulate the drift, weathering, dispersion, dissolution and shoreline absorption associated with an oil spill. This process results in data relating to oil spill and drift risks under 36 different scenarios during both normal and extreme typhoon weather conditions. The study's findings contribute to defining classified management areas in the waters around the nuclear power station during both regular and typhoon weather and provide suggestions for safety management. The methodology developed by this study can be widely applied to water-related risk management for coastal nuclear power stations, thus ensuring their safe operation.

Keywords: Maritime shipping; Nuclear power plant safety; Oil spill simulation; Ship drifting simulation

Introduction

As of the end of June 2022, there were 441 nuclear power reactors in operation worldwide, spanning 33 countries, with a combined installed nuclear power capacity of 394GW. The International Atomic Energy Agency (IAEA) categorizes the world's nuclear power plant sites into coastal, riverfront and lakeside locations. The safe and stable operation of nuclear power stations is of paramount importance and has garnered significant attention from scholars worldwide [1-3], particularly those situated along coastlines. In the event of a coastal nuclear power plant posing a threat, it could have a substantial impact on marine ecology, as was evidenced by the discharge of nuclear waste water into the ocean following the 2011 Fukushima nuclear power plant incident, which posed a serious threat to marine ecological safety [4,5]. The primary objective of nuclear safety is to establish and maintain effective defenses against radiation hazards in order to protect plant personnel, the general public and the environment. Currently, research on the operational risks of coastal nuclear power stations predominantly focuses on internal operational technologies, including geological disaster risks, nuclear waste disposal risks, nuclear leakage risks and so forth [6-8]. There is a notable gap in the research concerning the potential risks that maritime traffic poses to the safe operation of coastal nuclear power stations.

Through expert consultation and literature review, it has been determined that the main sources of water risk for nuclear power plants stem from ships navigating within the engineering waters [9,10]. Issues such as out-of-control ships, anchoring and oil spills present threats to the safety of nuclear power plants. Specifically, oil spills from ships can impact the safe operation of nuclear power plants. The extensive spread of an oil spill may enter the water intake of the nuclear power plant, leading to decreased water quality of the cooling water, which in turn affects the cooling capacity and could result in nuclear power plant shutdowns and other accidents. Most of China's nuclear power plants have established relevant oil spill protection mechanisms to ensure the safety of the cooling water supply [11,12]. In order to accurately identify the water-related risks for coastal nuclear power stations, including the risks associated with ship adrift and oil spills, specific measures are taken. Regarding the risk of out-of-control ships, the Beijing Institute of Water Science (BIWS) utilizes the V. Dragon 5000 large-scale navigation simulator in conjunction with on-site observations of ship types at nuclear power plants. Using mathematical simulations of ship movements, a mathematical model of ship movements and electronic nautical charts of the waters near the engineering docks are created for representative ship types (test ship types). Through simulated ship maneuvering trials considering the most adverse hydrodynamic conditions in various regions, including normal and typhoon weather, data on the time and speed of ships drifting to within 1 nautical mile of the nuclear power plant are obtained. As for the risk of ship oil spills, DELFT software is employed to simulate and emulate the flow field in the waters near the nuclear power plant to provide an environmental dynamic field for pollutant simulation. The OILMAP model is then used to simulate a series of processes related to oil spills, including drift, weathering, dispersion, dissolution and shoreline adsorption, in order to predict the trajectory of oil film drift and the fate of leaked crude oil and to assess the extent of its harm.

Method

Ship drifting simulation

On the basis of fully considering various factors affecting ship navigation safety, combined with the hydrologic and meteorological conditions of the waters near the project, the ship control simulator is used to simulate the ship runaway drifting in the route, and the influence of the ship runaway drifting on the safety of the nuclear power plant is obtained. The representative ship type is divided into oil tanker and bulk carrier. The purpose of the simulation test is to carry out the ship navigation safety simulation test in the waters near nuclear power plant and study the movement trajectory and safety impact of the navigation representative ship sailing, encountering and overtaking in the waters near nuclear power plant, so as to evaluate the degree of influence of external factors on nuclear power plant. It provides decision basis and reference data for effective protection of maritime traffic risk and formulation of safety zone near nuclear power plant. The simulation uses the navigation simulator of Beijing Institute of Water Science, which consists of a 180° 5-channel projection of the main ship, a 120° 3-channel TV replica ship and a set of two-three-dimensional integration of the port area stereo monitoring system equipment, model V. Dragon 5000. The simulation equipment used for the test is shown in Figure 1 of the Supplementary materials.

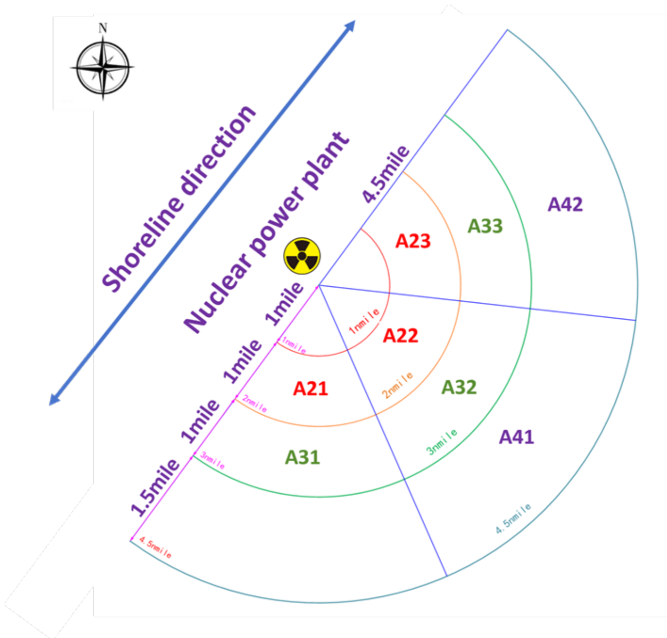

Figure 1: Location and number of the test area.

Ship maneuvering dynamic simulation platform is a two-dimensional simulation system based on electronic chart. Selecting the latest chart to digitize, the electronic chart of the waters near the project wharf is made. On this basis, according to the engineering design drawings and other materials, the hydraulic structure of the engineering platform, water plane layout and other data are added to the electronic chart. Specifically, through the following four steps to carry out experiments

A. According to the real ship data, create a database model and through the debugging data, test the simulation data and real ship data error, so as to get a more accurate ship model;

B. Collect and research the meteorological and hydrological data of the waters near the project, including the wind, currents, tides and other natural environment data and then enter the accurate data into the simulation system or using virtual reality simulation technology

C. According to the main types of ships navigating in the project waters, the degree of influence of the environment (wind, current and tide), the characteristics of the navigating waters and the characteristics of the ship's maneuvering, study and determine the types and number of simulation test programs;

D. Analyse the degree of influence of wind, current and other external factors, and derive the safety spacing and width of waters required for the safe navigation of the ship; analyse the ship's navigational trajectory, and derive the Optimization of engineering platform site selection and recommendations for ship navigation in engineering waters.

Considering that an oil spill may occur after a ship drifts out of control in the waters near the nuclear power plant and drifts to the waters near the outlet of the nuclear power plant under adverse wind conditions, which will cause serious risks to the nuclear power plant, the ship maneuvering simulation test considers that the ship type will lose control under the most unfavourable wind conditions in ordinary weather and typhoon weather in various regions. Obtain the floating time and floating speed of the ship to the 1nmile near the nuclear power plant. Specific test conditions are shown in Table 1 in Supplementary materials.

Table 1: Summary of runaway drift test results.

Ship Type	Working Condition	Placement	Weather	Ship Collision Time (h)	Ship Collision Speed (kn)
Cargo ships	1	A21	General weather	No collision	No collision
	2	A22	General weather	1	0.5
	3	A23	General weather	1.85	0.5
	4	A31	General weather	No collision	No collision
	5	A32	General weather	3.3833	0.5
	6	A33	General weather	No collision	0
	7	A41	General weather	5.6667	0.5
	8	A42	General weather	No collision	No collision
	9	A21	Typhoon weather	0.25	4.3
	10	A22	Typhoon weather	0.1833	4.2
	11	A23	Typhoon weather	0.2167	4.3
	12	A31	Typhoon weather	0.4833	4.4
	13	A32	Typhoon weather	0.3333	4.5
	14	A33	Typhoon weather	0.5667	4.5
	15	A41	Typhoon weather	0.55	4.5
	16	A42	Typhoon weather	No collision	No collision
Oil tankers	1	A21	General weather	No collision	No collision
	2	A22	General weather	1	0.5
	3	A23	General weather	1.85	0.5
	4	A31	General weather	No collision	No collision
	5	A32	General weather	3.3833	0.5
	6	A33	General weather	No collision	No collision
	7	A41	General weather	5.6667	0.5
	8	A42	General weather	No collision	No collision
	9	A21	Typhoon weather	0.25	4.3
	10	A22	Typhoon weather	0.1833	4.2
	11	A23	Typhoon weather	0.2167	4.3
	12	A31	Typhoon weather	0.4833	4.4
	13	A32	Typhoon weather	0.3333	4.5
	14	A33	Typhoon weather	0.5667	4.5
	15	A41	Typhoon weather	0.55	4.5
	16	A42	Typhoon weather	No collision	No collision

In order to facilitate the identification of risks in different water areas, this study divides the 4.5nmile water area centered on nuclear power plant into four fan-shaped areas, each circle being a semicircular area with a central radius of 1nmile, 2nmile, 3nmile and 4.5nmile, and then divides the area into three parts at a 60° Angle. The waters are divided into 11 zones. Among them the nuclear power plant as the center of the 1nmile range of ship navigation is considered to be a high threat to the safety of nuclear power plants and generally non-nuclear power plant working ships or spent fuel transport ships are generally not allowed to enter, pretending to be a prohibited area, and no test research is carried out in this range. According to the relative position of the coastal nuclear power plant and the coastline, we divided the study into 8 regions with the nuclear power plant as the center and the minimum interval of 1 nautical mile, as shown in Figure 1.

Ship oil spill simulation

In order to effectively evaluate the impact on the water intake of the nuclear power plant caused by the possible oil spill accidents of ships sailing and anchoring ships in the waters near the nuclear power plant, this section mainly adopts the numerical simulation of the possible oil spill accidents of ships, evaluates the time of oil spill to the water intake, the amount of pollution and other information, so as to assess the possible risks caused by oil spill. After pollutants enter the water body, their drift and diffusion movement are affected by current and sea surface wind, especially ocean current, which plays an important role. In this study, we use DELFT software to simulate the flow field in study area, so as to provide environmental dynamic field for the simulation of pollutants.

Tidal current model: Tidal current is the basic flow in offshore shallow waters and the numerical calculation of tidal current is the basis to simulate the drift and fate of oil spill. The simulation uses a two-dimensional tidal current model to model the tidal current field in the nearby waters. The two-dimensional tidal current model is used to describe the average depth motion of the barotropic ocean and the equations are composed of the continuity equation and the momentum equation:

$$\frac{\partial \zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial \xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial \eta}=Q \quad (1)$$

Where: ζ-water level; d-Water depth; $G_{\xi\xi}$, $G_{\eta\eta}$-rectangular coordinate system (x y) and orthogonal curvilinear coordinate system (ξ, η) conversion coefficient, $\sqrt{G_{\xi\xi}}=\sqrt{x_\xi^2+y_\xi^2}$ and $\sqrt{G_{\eta\eta}}=\sqrt{x_\eta^2+y_\eta^2}$; The mean velocity component of water depth in the direction of U, V -- ξ and η; Q-outlet of per unit area, evaporation and precipitation's contribution to the traffic, including $Q=H\int_{-1}^{0}(q_{in}-q_{out})d\sigma+P-E$; q_{in}, q_{out} -Source and sink per unit volume.

$$\frac{\partial U}{\partial t}+\frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial U}{\partial \xi}+\frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial U}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial U}{\partial \sigma}+\frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-\frac{V^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}-fV=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\xi)^2}\frac{\partial}{\partial \sigma}\left(V_v\frac{\partial U}{\partial \sigma}\right)+M_\xi \quad (2)$$

$$\frac{\partial V}{\partial t}+\frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial V}{\partial \xi}+\frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial V}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial V}{\partial \sigma}+\frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \eta}-\frac{V^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}-fU=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\xi)^2}\frac{\partial}{\partial \sigma}\left(V_v\frac{\partial U}{\partial \sigma}\right)+M_\eta \quad (3)$$

Where: $G_{\xi\xi}$, $G_{\eta\eta}$ -conversion coefficient between rectangular coordinate system (x, y) and orthogonal curvilinear coordinate system (ξ, η). The mean velocity component of water depth in the direction of U, V -- ξ and η; f -Coriolis force coefficient; Turbulent momentum fluxes in the directions of F_ξ, F_η -- ξ, η; The water pressure gradient in the direction of P_ξ, P_η -- ξ and η; The source or sink of momentum in the direction of M_ξ, M_η -- Δ, ($t-1=t-\delta t$); $t-1$ - Water depth at reference level; $C1$ - Water depth below the reference level; $C1$ -vertical eddy coefficient. Closed boundary condition: the normal velocity of vertical shoreline is 0. Open boundary condition: 8 main component tides M2, S2, K1, O1, N2, P1, K2, Q1 are used to control by harmonic constant. Numerical method: semi-implicit finite difference numerical algorithm.

Simulation and prediction of oil spill accident: OILMAP model was used to simulate and predict the consequences of oil spill accidents. The model simulates a series of processes such as oil spill drift, weathering, diffusion, dissolution and shoreline adsorption to predict the trajectory of oil film drift and the destination of oil spill and to assess its harm degree. The simulation program is shown in Figure 2 of the Supplementary materials.

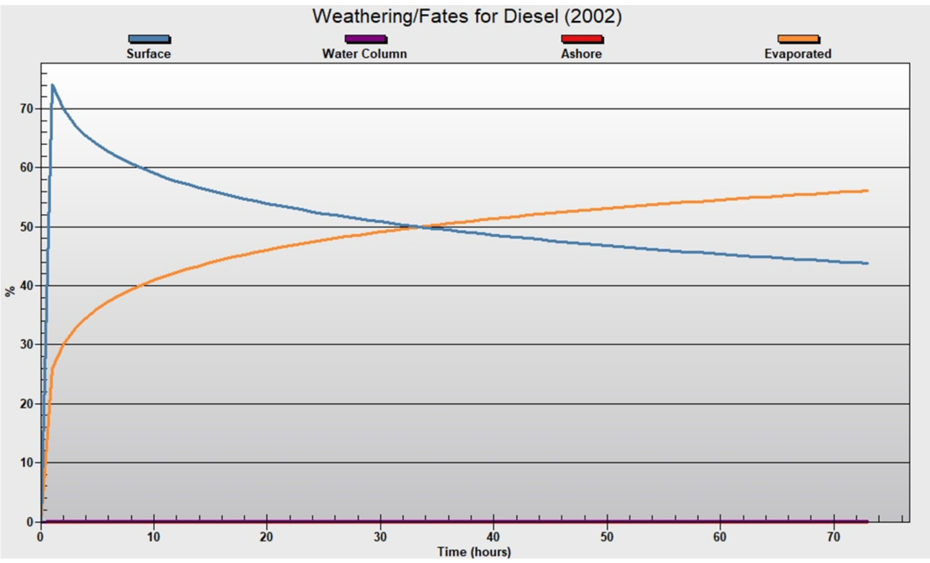

Figure 2a: Incidence diagram of diesel oil in general weather.

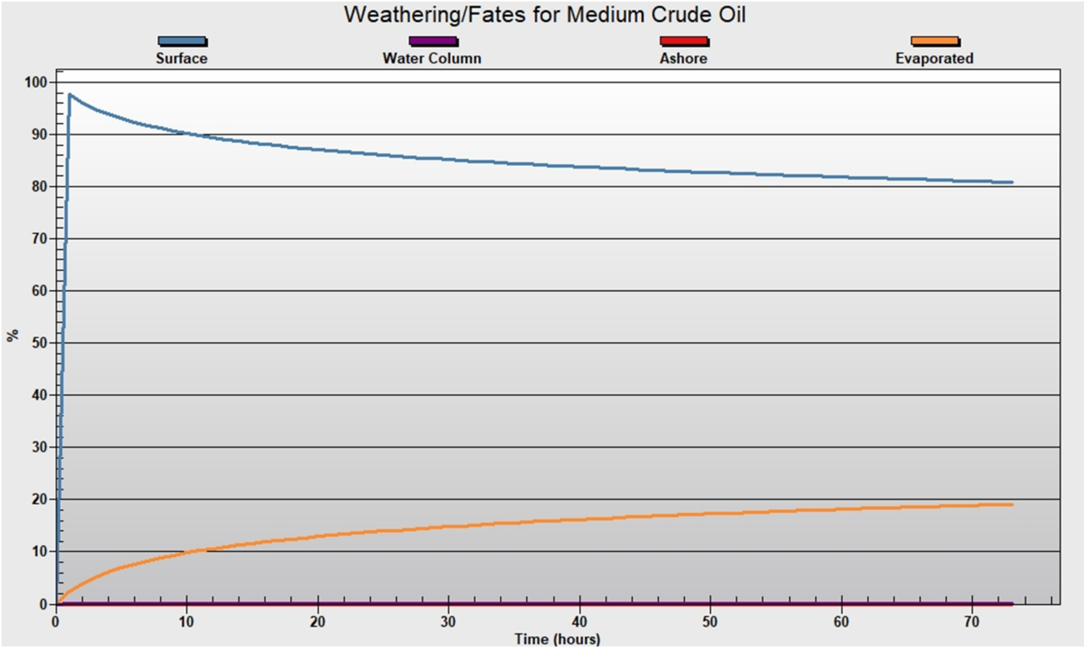

Figure 2b: Incidence diagram of crude oil in general weather.

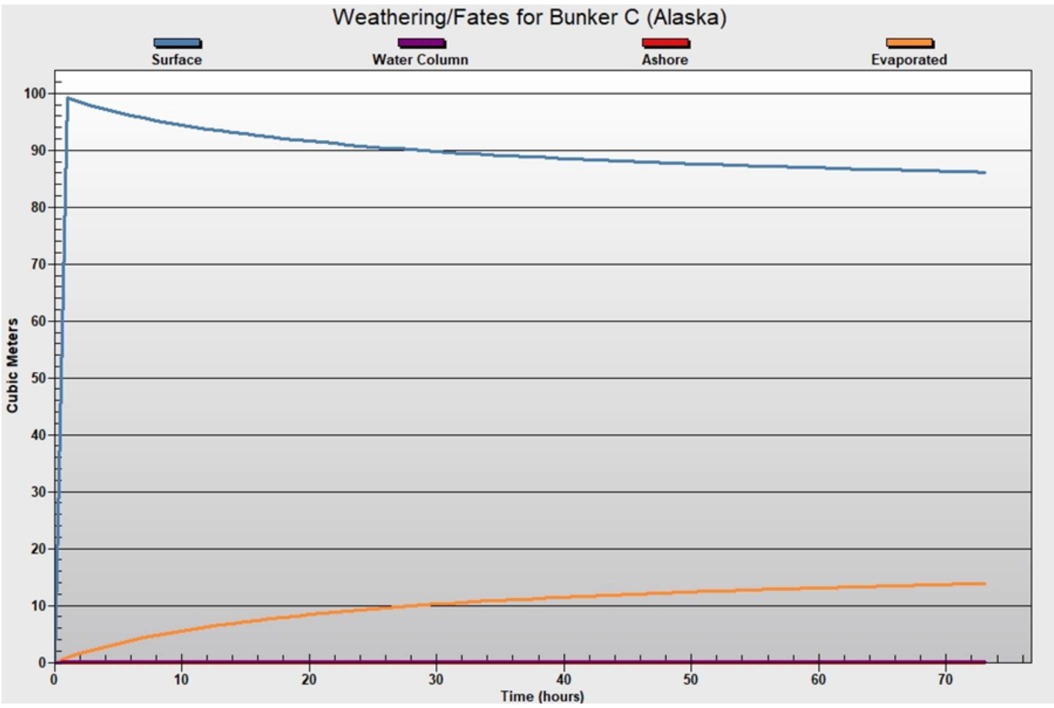

Figure 2c: Incidence diagram of bunker in general weather.

Drift model: Assuming that the oil spill can be divided into many independent oil spills, each oil spill is regarded as a Lagrange particle. The position component of the oil spill particle at time t is represented by X_t.

$$X_t = X_{t-1} + \Delta_t U_{oil} \quad (4)$$

$$(t-1 = t - \Delta t) \quad (5)$$

Where: Δt - time step (s); X_{t-1} - $t-1$ Oil spill spot (m); U_{oil} - Oil particle drift velocity (m/s). Oil spill particle drift velocity U_{oil}(m/s) is defined as follows:

$$U_{oil} = U_t + U_w + U_{disp} \quad (6)$$

Where: U_t -velocity component generated by water flow (m/s); U_w -Velocity component of wind generation (m/s); U_{disp} -The velocity component (m/s) produced by the dispersion process. The flow field is calculated by the environmental fluid dynamics model and output to the oil spill model. The velocity component U_w generated by the wind is determined by the following formula:

$$U_w = C_1 U_{windspeed} \quad (7)$$

The wind drift factor C_1 is a constant, which varies from 1-4.5% and is determined by actual measurements. 3-3.5% is suitable for open ocean. For closed or semi-enclosed seas, C_1 has a smaller value. $U_{windspeed}$ indicates the windspeed.

Dispersion model: U_{dd} (m/s) and V_{dd} (m/s) represent the north and east components of the diffusion velocity, which are defined as follows:

$$U_{dd} = r\sqrt{\frac{6D_x}{\Delta t}} \quad (8)$$

$$V_{dd} = r\sqrt{\frac{6D_y}{\Delta t}} \quad (9)$$

Where D_x is the horizontal diffusion coefficient in the east-west direction (m^2/s);

D_y -- North-South horizontal diffusion coefficient (m^2/s); Δt -Time step (s); r -Random coefficient (-1 to 1). Horizontal diffusion coefficients D_x and D_y are usually equal.

Extended model: The spread area of surface oil spill is calculated by the spread model. The spread area of oil spill directly affects the proportion of oil spill evaporation, dissolution, dispersion and photooxidation. Expansion is caused by the interaction of waves, gravity, inertial forces, viscosity and surface tension. It is assumed that more than 90% of the oil pellets are thick oil films. The change velocity of thick oil film surface area $\overline{A}_{tk}$ (m^2/s) is defined as follows:

$$\overline{A}_{tk} = \frac{dA_{tk}}{dt} = k_1 A_{tk}^{1/3}[\frac{V_m}{A_{tk}}]^{4/3} \quad (10)$$

Where $\overline{A}_{tk}$ -oil film surface area (m^2); k_1 -Expansion rate constant (1/s); V_m -Oil film volume (m^3); t - Time (s). Kolluru adds the correction of the effective radius, and its calculation of the change velocity of the independent oil spill particle surface area $\overline{A}_{tk}$ (m^2/s) is as follows:

$$\overline{A_{tk}} = \frac{dA_{tk}}{dt} = k_1 A_{tk}^{1/3}(\frac{V_m}{A_{tk}})^{4/3}(\frac{R_s}{R_e})^{4/3} \quad (11)$$

Where: $\overline{A}_{tk}$ -- surface area of independent oil spill particle (m^2); k_1 -Expansion rate constant (1/s); V_m -Individual spill particle volume (m^3); R_s -- Independent oil spill radius (m); R_e -Effective radius of surface oil film (m); t - Time (s). The effective radius of the surface oil film is as follows:

$$R_e = [(\frac{1}{\pi}\sum_{n=1}^{N} A_{tk})]^{1/2} \quad (12)$$

Where: A_{tk} -- surface area of independent oil spill particle (m^2); N - The number of oil particles in the surface oil film.

Evaporation model: Evaporation is the process of mass transfer from liquid to gas of the lighter components of petroleum hydrocarbons in water spill to the atmosphere. It is the main part of the oil spill quality transmission process, evaporation can make 20-40% of the spilled oil from the water surface into the atmosphere, especially light crude oil or refined oil products such as gasoline, diesel, etc., evaporation loss can reach more than half of the total amount of spilled oil. Evaporation is related to oil species. The evaporation rate is determined by the oil spill surface area, thickness, steam pressure and mass transfer coefficient. These, in turn, are determined by oil, wind speed and temperature. When oil evaporates, comprehensive factors change, and the density and viscosity of oil also change, thus affecting evaporation. The most volatile hydrocarbons (low carbon number) evaporate the fastest, within a day and sometimes even within an hour. When the oil continues to weather, evaporation will be significantly weakened if part of the water/oil emulsion is formed. The evaporation model is calculated as follows:

$$\frac{dF_e}{dt} = \frac{K_e A_s}{V_0} \cdot exp[A - \frac{B}{T}(T_0 + T_G F_e)] \quad (13)$$

Where: F_e -volume component of oil spill evaporation; T -oil spill temperature; A_s -oil film area; V_0 -initial oil spill volume; K_e -Mass transfer coefficient is calculated as follows:

$$K_e = 2.5 \times 10^{-3} W^{0.78} \quad (14)$$

A, B - experience coefficient; T_0 -initial boiling point; T_G -distillation curve gradient; For crude oil:

$$T_G = 985.62 - 13.597 \cdot API \quad (15)$$

$$T_0 = 654.45 - 4.6588 \cdot API \quad (16)$$

For refined oil products:

$$T_G = 388.19 - 3.8725 \cdot API \quad (17)$$

Emulsion model: Emulsification is formed due to the presence of surfactants, like aromatic hydrocarbon mixtures. Crude oil contains dissolved aromatic hydrocarbons that form stable mixtures. Due to weathering, when the aromatic hydrocarbons are exhausted, the asphalt begins to precipitate. Bitumen reduces the surface tension of oil and water, thus initiating the emulsification process. Water enters the oil phase by breaking or destroying the oil-water interface. Oil spill mixing speed $\overline{F}_{wc}$ can be calculated as follows:

$$\overline{F}_{wc} = \frac{dF_{wc}}{dt} = C_1 U_w^2 (1 - \frac{F_{wc}}{c_2}) \quad (18)$$

Where: U_w -Wind speed (m/s); C_1 -- empirical constant, 2×10-6 for emulsified oils and 0 for other oils; c_2 -Constant, controlled maximum water content, 0.7 for heavy oil and crude oil, 0.25 for home fuel oil; F_{wc} -the maximum water factor in the oil (oil characteristic input value); t - Time (s). Viscosity of emulsified oil μ (cP):

$$\mu = \mu_0 exp\left(\frac{2.5F_{WC}}{1 - C_0 F_{WC}}\right) \quad (19)$$

Where: μ_0 -Initial oil viscosity (cP); F_{WC} -maximum water factor in oil; C_0 -Emulsification constant (0.65). Effect of evaporation on viscosity μ (cP):

$$\mu = \mu_0 \exp(C_4 F_v) \quad (20)$$

Where: μ_0 -initial oil viscosity (cP); C_4 -- constant, light oil is 1, heavy oil is 10; F_v -oil film evaporation coefficient. The exponential increase formula has been used by many oil spill simulators for many years. In this paper, the above model is used to calculate the oil spill emulsification process.

Shoreline sedimentation model: For the purpose of calculating indices of adsorption capacity and removal rates for different types of shorelines, we categorized the shorelines into 11 classes. Included: Open rocky coast, open rocky platform coast, four types of beaches (flat fine beach, medium-coarse sand covered beach, sand-gravel mixed beach, sand-pebble mixed beach), open intertidal zone, sheltered rocky coast, sheltered intertidal zone, sheltered marshland. The fate of oil spills that reach the shoreline depends on the characteristics of oil spills, the type of shoreline and the environmental kinetic energy.

For different types of shorelines (m), the corresponding maximum adsorption capacity $A_{m,max}$ and adsorption leakage rate V_m are defined. The dynamic ability of leakage adsorbed by shorelines is determined by the formula:

$$dA_m / dt = V_m ; A_m \le A_{m,max} \quad (21)$$

Where: A_m is the adsorption capacity of leakage of m type shoreline.

Density change: Oil spill density is determined by the following formula:

$$\rho_e = F_{wv} \cdot \rho_w + \rho_{oil}(1-F_{wv})(1+c_{DE}F_e)[1-c_{DT}(T-T_0)] \quad (22)$$

Where: ρ_e --temperature T density during emulsification; ρ_{oil} --reference temperature T_0 Density of preferred pure oil; ρ_w -water density; c_{DE} and c_{DT} is empirical coefficient. The value for c_{DE} = 0.18 and c_{DT} = 8×10-4.

Viscous change: Viscosity changes with temperature, evaporation and emulsification processes. The effect of temperature on viscosity can be determined by below formal:

$$\mu = \mu_0 e^{c_T(1/T - 1/T_0)} \quad (23)$$

μ -Viscosity of oil at temperature T; μ_0 -Viscosity of oil at reference temperature T_0; c_T --Empirical constant; The recommended value is 5000k; The change in viscosity during emulsification is determined by equation:

$$\mu = \mu_0 \cdot e^{[\frac{c_V F_{Wv}}{1-c_M F_{Wv}}]} \quad (24)$$

F_{wv} -Water content of the emulsion; c_V -Dimensionless empirical constant (recommended value is 2.5); c_M -Append constant to 0.65. The change of viscosity during evaporation is determined by the following equation:

$$\mu = \mu_0 \cdot e^{(c_E F_{em})} \quad (25)$$

F_{em} -Mass number of evaporated oil spill; c_E -Select dimensionless empirical constants between 1 and 10 depending on the oil. For light oil spill at 15 °C, the initial viscous motion coefficient exceeds 38cSt, c_E is 10; for oil spill with low viscous motion coefficient, c_E is determined by the following formula:

$$c_E = -0.0059 \cdot V_{cin15}^2 + 0.4461 \cdot C_{cin15} + 1.413 \quad (26)$$

Design of ship pollution simulation test scheme: In order to quantitatively assess the waters where oil spill may occur, the project divided the main waterways and anchorage waters around the project into eight areas, and carried out simulation tests with the center points of each area representing the possible locations of oil spill accidents. Considering Marine fuel oil and Marine diesel specifically, the main physical and chemical parameters of the leaked oil are shown in the Table 2 & 3 in Supplementary materials. Based on the above related descriptions, the ship oil spill test scheme under seasonal average state and typhoon state of this project is finally determined and shown in the Table 2 & 3 in Supplementary materials.

Table 2: Summary of oil spill hazards in ordinary weather.

Serial Number	Leak Location	Oil Film Arrival Time	Duration of Sustained Harm	Thickness of Oil Film at Arrival
Program A-1	A21	3 hours after oil spill	69 hours	1.6mm
Program A-2	A21	3 hours after oil spill	69 hours	5.5mm
Program A-3	A22	4 hours after oil spill	68 hours	1.5mm
Program A-4	A22	4 hours after oil spill	68 hours	5.0mm
Program A-5	A23	4 hours after oil spill	68 hours	1.6mm
Program A-6	A23	3 hours after oil spill	69 hours	5.6mm
Program A-7	A31	7 hours after oil spill	65 hours	1.2mm
Program A-8	A31	5 hours after oil spill	67 hours	4.5mm
Program A-9	A32	7 hours after oil spill	65 hours	1.3mm
Program A-10	A32	7 hours after oil spill	65 hours	3.9mm
Program A-11	A33	7 hours after oil spill	65 hours	1.4mm
Program A-12	A33	8 hours after oil spill	64 hours	3.5mm
Program A-13	A41	12 hours after oil spill	60 hours	1.1mm
Program A-14	A41	11 hours after oil spill	61 hours	3.1mm
Program A-15	A41	12 hours after oil spill	60 hours	1.4mm
Program A-16	A42	10 hours after oil spill	62 hours	1.1mm
Program A-17	A42	9 hours after oil spill	63 hours	3.4mm
Program A-18	A42	11 hours after oil spill	61 hours	1.5mm

Table 3: Summary of oil spill hazards in typhoon weather.

Serial Number	Leak Location	Oil Film Arrival Time	Duration of Sustained Harm	Thickness of Oil Film at Arrival
Program B-1	A21	45 minutes after oil spill	Sustained impact upon arrival	4.2mm
Program B-2	A21	45 minutes after oil spill	Sustained impact upon arrival	8.7mm
Program B-3	A22	45 minutes after oil spill	Sustained impact upon arrival	4.5mm
Program B-4	A22	45 minutes after oil spill	Sustained impact upon arrival	8.7mm
Program B-5	A23	1 hour 30 minutes after oil spill	Sustained impact upon arrival	2.1mm
Program B-6	A23	1 hour 30 minutes after oil spill	Sustained impact upon arrival	7.4mm
Program B-7	A31	1 hour 30 minutes after oil spill	Sustained impact upon arrival	2.5mm
Program B-8	A31	1 hour 15 minutes after oil spill	Sustained impact upon arrival	7.9mm
Program A-9	A32	1 hour 15 minutes after oil spill	Sustained impact upon arrival	3.4mm
Program B-10	A32	1 hour after oil spill	Sustained impact upon arrival	8.6mm
Program B-11	A33	1 hour 45 minutes after oil spill	Sustained impact upon arrival	1.5mm
Program B-12	A33	1 hour 45 minutes after oil spill	Sustained impact upon arrival	6.9mm
Program B-13	A41	1 hour 45 minutes after oil spill	Sustained impact upon arrival	1.5mm
Program B-14	A41	1 hour 45 minutes after oil spill	Sustained impact upon arrival	6.9mm
Program B-15	A41	1 hour 45 minutes after oil spill	Sustained impact upon arrival	4.5mm
Program B-16	A42	2 hours 15 minutes after oil spill	Sustained impact upon arrival	0.4mm
Program B-17	A42	2 hours 15 minutes after oil spill	Sustained impact upon arrival	6.2mm
Program B-18	A42	2 hours 30 minutes after oil spill	Sustained impact upon arrival	3.8mm

Results

Experimental results of uncontrolled drifting of a ship

The results of the experiment are shown in Table 1: It can be seen from the ship drift simulation test that in ordinary weather, due to a certain deviation between the normal wind direction and the position of the nuclear power plant, Half of the ships tested did not drift Within the 1nmile range of the power station (operating conditions 1, 4, 6, 8); In addition, due to the low wind speed and velocity in ordinary weather, the ship's floating speed is low (average speed is about 0.5kn), and the time is long (average time is about 3h), and the threat to the nuclear power plant is relatively small. Under the influence of typhoon weather, due to the obvious increase of wind power, the time of out-of-control drifting of ships in each test area to the 1nmile of the nuclear power plant is significantly reduced, ranging from 11min (working condition 10) to 33min (working condition 15). At the same time, under the influence of typhoon, the floating speed of ship increases obviously, and under the continuous effect of typhoon, the floating speed of ship continues to accelerate. According to the test results, when the ship enters the 1nmile range of the nuclear power plant, the ship speed can be increased to a maximum of 4.5kn (working conditions 13, 14, 15) and the risk of oil spill is more likely to occur after collision or grounding, which is a high threat to the nuclear power plant.

Oil spill simulation experiment results

According to the above set ship oil spill simulation test scheme, a total of 36 groups of ship oil spill simulation tests were carried out in this study, and the test results are shown in Table 2 & 3:

According to the results of oil spill drift and diffusion, under the influence of adverse wind direction in each region, oil spill will affect the water intake of nuclear power plant. The closer the distance, the faster the arrival time, the fastest about 3 hours (plan A-1, A-2, A-6), the slowest about 12 hours (plan A-13, A-15), and then under the continuous influence of adverse wind direction, the faster the arrival time. Concentrated along the shoreline of the nuclear power plant. The thickness of the oil film at the time of arrival is different due to the difference in the amount of oil spilt. The diesel oil film is thin, the lowest is 1.1mm (program A-13, A-16), while the persistent oil film such as crude oil and heavy fuel oil is thick, the highest is 5.6mm (program A-6) and the impact is greater. According to the results of oil spill drift and diffusion, under the influence of typhoon, the oil spill from ships in various regions reaches the shoreline of nuclear power plant at a faster speed and the closer the distance, the faster the arrival time, the fastest about 45 minutes (plan B-1, B-2, B-3), the slowest about 2 hours and 30 minutes (plan B-18), and then under the continuous influence of adverse wind direction, the oil will gather on the shoreline of nuclear power plant and have a continuous impact. The thickness of the oil film at the time of arrival is different due to the difference in the amount of oil spill and each of them is different. The thin diesel oil film and the high wind speed of the typhoon will further promote volatilizing, and the thickness is only 0.4mm at the thinnest (Plan B-16).

Persistent oils, such as crude oil and heavy fuel oil, are not volatile and have a fast arrival time and a thicker oil film, up to 8.7mm thick (Scenarios B-2 and B-4), which has a greater impact. The simulation results of diesel oil, crude oil and fuel leakage are shown Figure 2-3. As can be seen from the simulation renderings in Figure 2a, due to the strong volatility of diesel itself, and the local temperature is relatively high, so that after 10 hours, diesel volatilization reaches more than 40%, after 30 hours, volatilization approaches 50%, and after 70 hours, it approaches 55%. It can be seen from the simulation effect in Figure 2b that the volatility of crude oil is not strong, which belongs to the persistent oil, when the crude oil first leaked, nearly 98% of the crude oil will float on the water, 10 hours later, the total amount of crude oil volatilized 10%, 72 hours, the evaporation amount is only 20% of the total, about 80% of the crude oil is still floating on the water. It can be seen from the simulation effect in Figure 2c that the fuel oil is also a persistent oil, when the first leak, about 99% of the fuel oil will float on the water, 28 hours later, the fuel oil volatilized 10% of the total, remove the evaporation of the fuel oil, and finally about 85% of the fuel oil is still floating on the water.

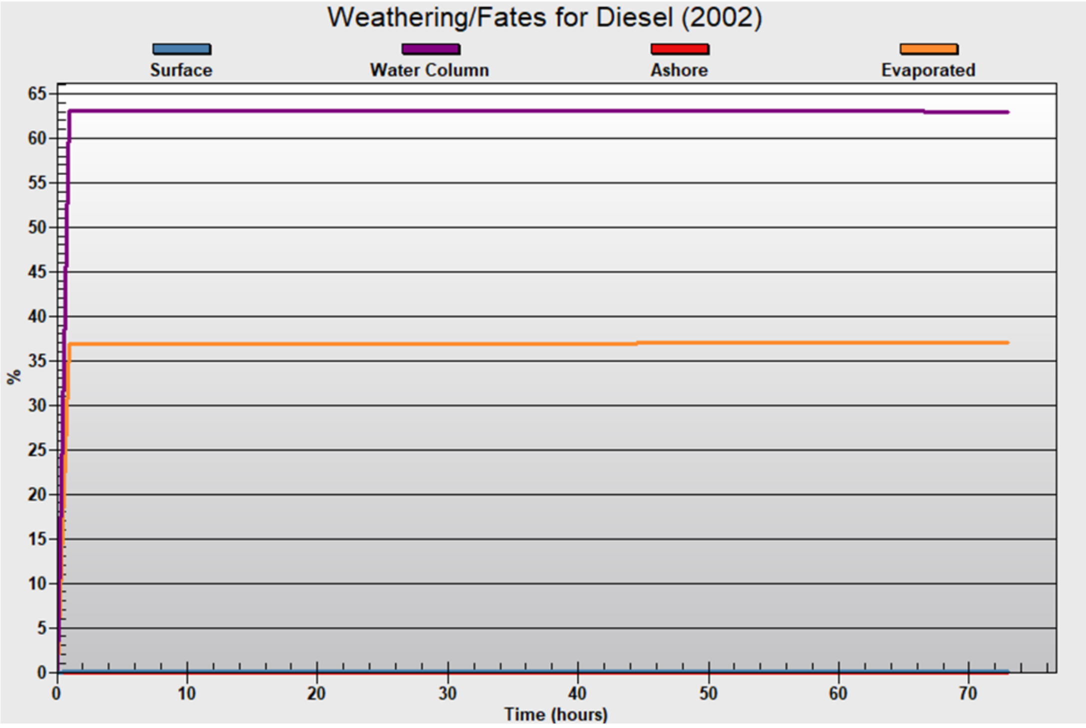

Figure 3a: Incidence diagram of diesel oil in typhoon weather.

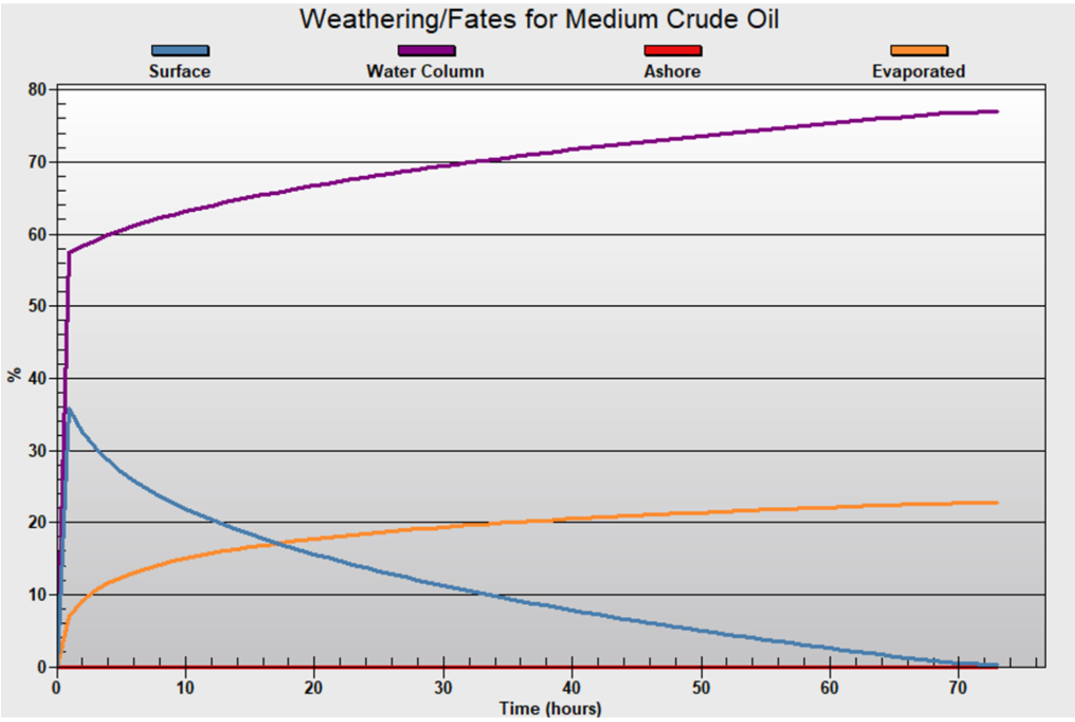

Figure 3b: Incidence diagram of crude oil in typhoon weather.

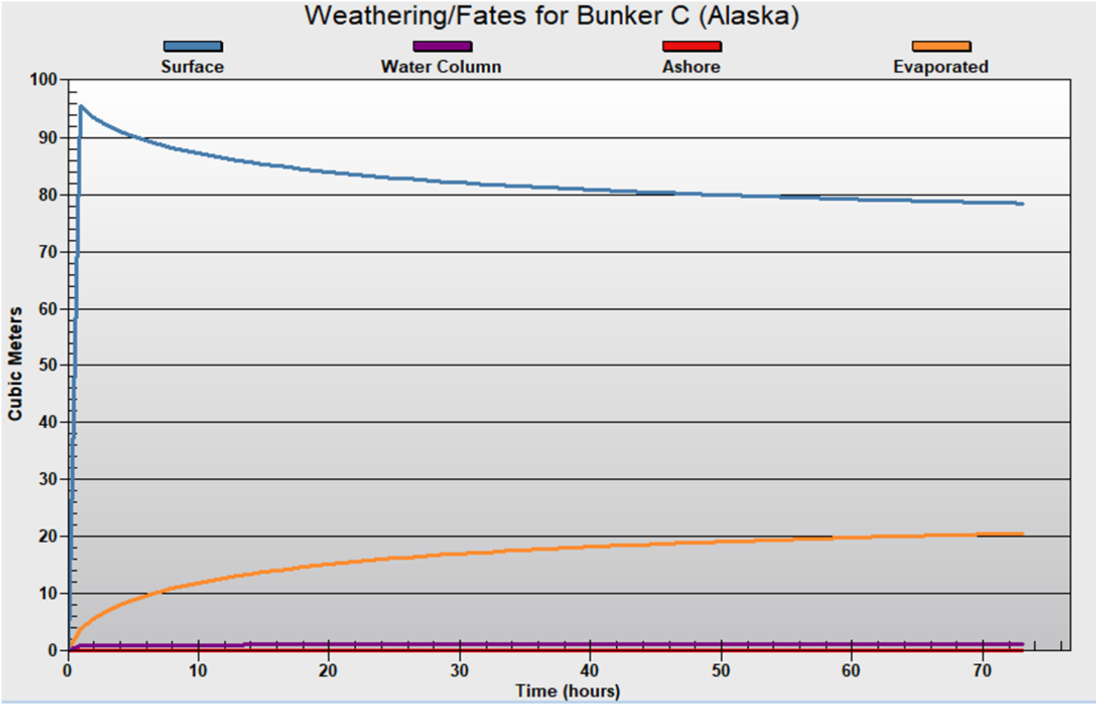

Figure 3c: Incidence diagram of bunker in typhoon weather.

As can be seen from the simulation renderings in Figure 3a, due to the strong volatility of diesel itself and the high sea surface wind speed under the typhoon condition, the volatilization of oil products was further promoted. After about 1 hour, the diesel volatilized 37% of the total amount. At the same time, due to the influence of wind speed, the diesel oil all diffused into the water body at a very fast speed and the oil spill on the sea surface was reduced.

It can be seen from the simulation effect in Figure 3b that crude oil is a persistent oil with low volatility. However, under the strong influence of the typhoon, 10% of the total oil volatilized after 3 hours and 20% of the total oil volatilized after 37 hours. At the same time, when the crude oil first leaked, nearly 36% of the crude oil would float on the water surface, while the oil on the water surface would continue to decrease. At the same time, the strong wind made the crude oil enter the subsurface surface of the water body. About 72 hours later, there was no oil floating on the water surface and a large amount of remaining crude oil entered the water body. It can be seen from the simulation effect in Figure 3c, bunker is also a persistent oil, not volatile, after 6 hours, 10% of the total volatilization, to 70 hours, volatilization reached 20%. At the same time, due to the small proportion and large viscosity, most of the fuel floats on the water, about 96% of the bunker will float on the water within 1 hour, to 50 hours, 80% of the floating on the sea, 72 hours there are still 78% of the bunker floating on the water.

Discussion

This study, based on an in-depth investigation of the coastal nuclear power plants and the surrounding marine environment, achieved comprehensive identification of the water-related risks for coastal nuclear power plants. Two models, namely the ship drifting and oil spillage model, were established to address the risks of ship oil spills and uncontrolled drifting. The research divided the waters surrounding the nuclear power plants into 9 risk zones based on the distribution of coastlines and port functional areas near the nuclear power plants. For cargo ships and ships carrying hazardous materials, the study conducted simulation experiments on ship uncontrolled drifting and oil spillage under normal weather conditions and typhoon weather conditions. The research delved into the level of threat posed by various risk events in each area to the nuclear power plants. Based on the results of the simulation experiments and previous research, the study identified the navigational risks in the waters surrounding the nuclear power plants. When the navigational risks for ships in the waters around the nuclear power plants are excessively high, accidents such as oil spills and uncontrolled drifting will pose significant safety threats to the nuclear power plants. Therefore, based on the simulation results, the study proposed graded control measures and safety management recommendations for the waters surrounding the nuclear power plants under normal weather conditions and typhoon weather conditions. This research fills a gap in the study of maritime transportation risks for coastal nuclear power plants and provides applicable methods for related research to draw upon.

References

1. El-Sefy M, Yosri A, Siam AS, El-Dakhakhni W, Nagasaki S, et al. (2023) A dynamic probabilistic risk assessment platform for nuclear power plants under single and concurrent transients. Journal of Nuclear Science and Technology 60(7): 824-838.

2. Xu P, Xu N, Wan Y, Zhao B, Sun S, et al. (2019) Risk Assessment and case analysis of sea ice dynamic accumulation in water intakes of nuclear power plants. International Journal of Offshore and Polar Engineering 32(2): 186-192.
3. Mercurio D (2011) Discrete dynamic event tree modeling and analysis of nuclear power plant crews for safety assessment. ETH.
4. Chang CC, Chou CC, Shen YH, Huang YN (2013) Development of response-based fragility curves for seismic probabilistic risk assessment of nuclear power plants. IASMiRT.
5. Williams HG, Lee M, Patelli E (2018) Probabilistic risk assessment of station blackouts in nuclear power plants. IEEE Transactions on Reliability 67(99): 494-512.
6. Ritterbusch SE (2000) Nuclear energy research initiative. Risk informed assessment of regulatory and design requirements for future nuclear power plants. Annual report. Office of Scientific & Technical Information Technical Reports.
7. Vera M, Pablo C (2016) Seismic probabilistic safety assessment and risk control of nuclear power plants in Northwest Europe.
8. Ming TD (2016) Study on problems and countermeasures of environmental risk management of inland nuclear power plant in China. Value Engineering.
9. Miller IM (2015) Integrating geographic information systems with the level 3 probabilistic risk assessment of nuclear power plants to advance modeling of socio-technical infrastructure in emergency response applications. Journal of the Juzen Medical Society 111: 348-361.
10. Moilanen P (2000) Risk-informed assessment of regulatory and design requirements for future nuclear power plants. Annual report. Office of Scientific & Technical Information Technical Reports.
11. Zhou T, Modarres M, Droguett EL (2021) Multi-unit nuclear power plant probabilistic risk assessment: A comprehensive survey. Reliability Engineering System Safety 213: 107782.
12. Voggenberger T, Beraha D, Cester F (2005) Nuclear power plant simulation and safety analysis with ATLAS. Proceedings of the IASTED International Conference on Modelling, Simulation and Optimatization pp. 416-421.