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DEVELOPMENT OF A METHOD TO CALCULATE THE PROBABILITY OF A BERTH FAILURE UNDER VERTICAL STOCHASTIC LOAD

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Розроблено метод визначення ймовірності досягнення граничного значення навантажень від вантажу, що зберігається на складах портового терміналу, на вертикальну стінку причалу в умовах невизначеності моментів прибуття суден та їх навантаження. Передбачається, що процес прибуття суден із вантажем описується моделлю складного пуассонівського процесу, а зі складу вантаж вивозиться за допомогою наземного виду транспорту рівномірно із постійною інтенсивністю. За допомогою методів математичної теорії ризику побудовано ймовірнісну модель роботи системи «склад-причал» як складової портового терміналу. Сформульовано критерій безпечної роботи причалу при дії на його конструктивні елементи випадкового навантаження від вантажу, що зберігається на складі у тилу причалу, з метою визначення ймовірності неперевищення гранично припустимого значення тиску на лицьову стінку причалу (згідно закону Кулона), тобто аварії причалу. Для знаходження ймовірності аварії причалу у сталому режимі його роботи виведено інтегральне рівняння типу згортки. Рішення цього інтегрального рівняння дозволило знайти аналітичний вираз для ймовірності безвідмовної роботи причалу для різних функцій розподілу навантаження суден, що дало змогу кількісно оцінити ризик настання аварії причалу. За допомогою знайденої ймовірності аварії причалу сформульовано та вирішено дві практичні задачі. По-перше, визначено значення інтенсивності вивезення вантажу зі складу, яке забезпечує із достатньо малою ймовірністю відсутність аварії. По-друге, сформульовано критерій економічної доцільності страхування збитків внаслідок аварії причалу (його раптової відмови) внаслідок перевищення навантажень від вантажу припустимого значення у даний проміжок часу.

Запропонований у статті методичний підхід до визначення надійності причальної споруди на портовому терміналі, на відміну від існуючих методів розрахунку причальних споруд, дозволяє більш обґрунтовано оцінювати величину реальних експлуатаційних навантажень (вертикальних та горизонтальних), що діють на основні конструктивні елементи причалу

Ключові слова: портовий термінал, судна з вантажем, граничне навантаження, лицьова стінка причалу, ризик аварії причалу, страхування ризику

1. Introduction

The adequacy of the methods for evaluating the reliability of a structure is known to be determined by reliability and accuracy of the models of loading, models of operation of materials, from which the elements of berth structures are made, and the models of occurrence of failures (accidents). Specification of only separate of the listed models is not likely to give any practically acceptable recommendations, unless the level of accuracy of the other remains insufficient.

As regards berth facilities, in the course of formalization and modeling actual operational loads that influence them, the additional difficulty is to take into consideration the probabilistic nature of loads. The models of failures under the influence of different type of operational loads remain particularly insufficiently explored in the theory of reliability of berth facilities. As a result, probabilistic calculation methods have been used over the past three or four decades in the research that addresses the development of methods for qualitative assessment of operational reliability of berth facilities. It was predetermined by the desire to clarify the pre-existing procedures for calculating the indicators of reliability of berth facilities, which did not take into consideration the dynamic and stochastic nature of operational and environmental loads that influence the structural elements of berths and the soils that underlie berth facilities. However, this created specific problems on evaluating the probability of exceeding some critical values by the selected type of a random process, which can lead to the partial or complete destruction of a structure.

In addition, in some major seaports of the world, there has been a tendency over recent years to place too large amount of cargo in the rear zone of berths without taking into consideration the actual technical condition of the berth structure. This can lead to loads exceeding the residual strength of a structure and, as a result, to a berth failure. The practice of operation of docking facilities suggests that it is much cheaper to regularly monitor and predict the loads on a berth and the state of its elements than to overhaul the berth after its complete and even partial destruction.

That is why an important scientific problem is the development of the methods for quantitative assessment of indicators of the reliability of berth facilities, in which the listed three groups of models have the same level of accuracy. This determines the relevance of the examined problem.

2. Literature review and problem statement

The main types of operational loads influencing the berth structures include the following:

a) loads from allision of vessels at their moorings and during their stay during the period of the action of adverse hydro-meteorological factors (wind, waves, etc.);

b) loads transmitted to the constructive elements of a structure through the soil as a result of pressure of the cargo stored in the rear zone;

c) loads from the cordon transshipment machinery and rolling stock (railroad cars, automobiles), located at the berth.

The specified loads under actual production conditions at any moment of time are random by magnitude, by moments of occurrence, points of application, as well as by the duration of exposure. Prediction plays an exceptionally important role for the safe operation of berth facilities. In the operation of berths, residual deformation is accumulated in the elements of a structure, and the berth throughput is generally considered to be constant over its operation period [1, 2].

In the special literature devoted to assessing the operational reliability of berthing facilities, the specified range of problems has not been sufficiently explored so far. Thus, in [3], chapter 10 contains only general information about the "bolverk" type of structures, including schemes of soil pressure, while chapter 13 gives only the general information about port container terminals in general.

Paper [4] proposed the simulation model for the prediction of the wear of the surface of nodes of a concrete berth structure under the influence of sea water and found the distribution of the probability of the beginning of structure destruction due to the formation of cracks. In this case, the limit state is determined as the beginning of steel reinforcement corrosion. Article [5] gives assessment of the effectiveness of the method for reducing the damage to the wall of the berth structure of the gravitational type that is based on the sand compaction at the foundation of a structure. For this purpose, it was proposed to use the method for simulation modeling in conjunction with the finite element method. Numerical simulation and monitoring tests revealed that the displacement of the berth wall occurs mainly near the toe and that the characteristics of the soil of the foundation affect the size of the damage. In paper [6], the method for determining the probability of the first going of the values of the main parameters of a structure beyond the assigned region was developed to assess the reliability of a structure subjected to impacts of stochastic load. External load is described by the multidimensional Gaussian distribution. The method is based on the presentation of an event of "a structure failure" as a sequence of instant failures on the discrete time scale. An analysis of sensitivity of the probability for the first deviation of a parameter vector beyond the assigned region was performed. Paper [7] proposed the stochastic finite element method to estimate the failure probability for various scenarios of the application of external load to a berth structure (the wind load was considered). The probabilistic properties of the damage to berth piles are determined with the use of the proposed method. The general problem of security of marine transportation systems and reliability of their operation is analyzed in [8]. An analysis of stress-strained state of a berth with the use of the finite element method, but without taking into consideration the random character of the influence of operational loads on a berth, was performed in [9].

It should be noted that the methods of stochastic processes have long been proposed for modeling external loads on building structures [1]. However, there have not been enough detailed research into the specificity of forming the operational (that is, unnatural) loads.

At the same time, for the mathematical description of operational loads acting on berths, it is advisable to use special types of stochastic processes applied in the restoration theory, reliability theory, stock theory, and the queuing theory. Article [10] dealt with the basic types of load patterns in relation to the conditions of operation of berths and presented the appropriate formula for the calculation of reliability function for the simplest models of servicing systems. However, these results are based principally on the consideration of the horizontal loads on a berth from mooring vessels, acting instantly. In the actual operational practice, an important role is also played by long-acting horizontal and vertical loads from the cargo stored in the rear part of berths and from reloading machines located at the cordon line of a berth. Accounting for these types of loads in calculation of reliability of a berth structure requires corresponding generalization of the known methods for calculating the probability of occurrence of a failure of a berth structure and performing additional theoretical research.

Thus, an analysis of the special literature that we conducted reveals that the models of failures under the influence of different types of operational loads have not been sufficiently explored in the theory of reliability of berth facilities. For formalized descriptions of this type of loads, it is necessary to model those production processes that occur at a port terminal.

3. The aim and objectives of the study

The aim of this study is to develop a method for determining the probability of a case when the amount of cargo, stored in a warehouse at a port terminal, exceeds the maximally permissible value for the first time. Such an excess could lead to that the maximum value for stresses and deformation of the berth wall is exceeded, which could result in its failure. In the general theoretical terms, we aim to develop a method to control the compliance of the berth bearing capacity to its throughput capacity.

To accomplish the aim, the following tasks have been set:

– to develop a probabilistic model of port terminal opereation for taking into consideration random time-dependent fluctuations in the cargo amount at a warehouse and the corresponding operational load on the main structural elements of berth facilities;

– to state the criterion for safe operation of a berth when it is influenced by a randomly changing load from the cargo, stored in a warehouse in the rear of a berth;

– to find an analytical expression to calculate the probabilility for the absence of a failure (or a failure probability) of a berth when the amount of cargo in a warehouse exceeds the magnitude that results in the excessive pressure on the berth wall;

– to develop a criterion for the expedience of insuring a berth against a premature failure due to excessive operational loads.

4. Key assumptions for the construction of the probabilistic model of a port terminal and statement of the criterion of safe operation of a berth under conditions of fluctuation of loading from cargo

In paper [10–12], a series of models of operational loads influencing the berth, based on using the methods of the queuing theory and the stocks theory were developed. This is explained by the fact that a port is a classic example of a servicing system, and a berth is the main technological element, that is, a service channel. Vessels, trains, cars arriving at a port with cargo or for loading act as requests or requirements to be served.

Consider a port terminal, consisting of berths for accepting and loading the cargo onto the vessels, and a warehouse in the rear part. We assume that the homogeneous cargo is delivered to the terminal by vessels. We believe that the time intervals between successive arrivals of vessels are mutually independent random magnitudes having the exponential law of distribution with parameter λ. In other words, the flow of vessels is described by the model of homogeneous Poisson process with parameter λ. Net loading capacities of all vessels are also assumed to be mutually independent random magnitudes distributed according to the same law of distribution $G(x)$. The total cargo is unloaded from vessels to a warehouse, from where it is transported by road transport (such as motor vehicles or railway trains) evenly with constant intensity equal to W.

Let us introduce the following designations: γ_k is the loading of the k-th vessel that arrived, in this case

$$\mathbf{P}\{\gamma_1 \le x\} = G(x);$$

τ_k is the random time interval between the arrival of the $(k-1)$-th and k-th vessel, in this case

$$\mathbf{P}\{\tau_1 \le t\} = 1 - e^{-\lambda t}.$$

Random sequences $\tau_1, \tau_2, \ldots$ and $\gamma_1, \gamma_2, \ldots$ are assumed to be independent in totality.

For the simplicity of research, we will assume that the mean interval between the neighboring arrivals of vessels $1/\lambda$ is considerably larger than the mean time of cargo reloading from a vessel to a warehouse, that is we will neglect the time of vessels' unloading.

The block schemes of the described port terminal is shown in Fig. 1.

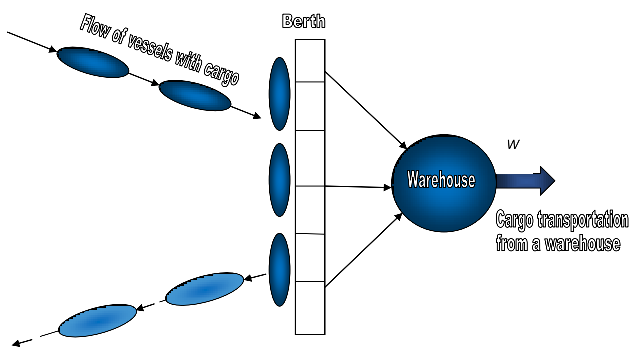

Fig. 1. Block schemes of a port terminal operation

The cargo stored in a warehouse puts certain pressure through the soil of the foundation on the berth wall, which pose a threat of its deformation (that is, failure) and temporary putting a berth out of operation. The maximum permissible magnitude of stress from the side (vertical) pressure σ_0 is determined by the Coulomb law and is calculated from formula

$$\sigma_0 = \lambda_a \sigma_v, \tag{1}$$

where λ_a is the coefficient, determined from formula

$$\lambda_a = \mathrm{tg}^2\left(\frac{\pi}{4} - \frac{\beta}{2}\right);$$

β is the angle of internal friction (Fig. 2); σ_v is the maximum value of vertical stress of the soil, created by the cargo stored in a warehouse. If we consider that the cargo in a warehouse is evenly distributed around its area, it is possible to estimate approximately magnitude σ_V in the following way

$$\sigma_V = \frac{E}{S}, \tag{2}$$

where E and S designate the capacity and area of the warehouse ground of the terminal.

If a berth front of the terminal is an embankment ramp, using formulas (1), (2), it is possible to express the criterion of failure-free operation of a berth wall in case of one berth can be expressed by inequality

$$Z(t) \le S\sigma_0 = \lambda_a E, \tag{3}$$

where $Z(t)$ is the amount of cargo in a warehouse at moment t.

Since cargo shipment from vehicles to a warehouse and loading the cargo from the warehouse onto them generally occur at random times, and vessels arrive at the terminal unevenly in time, amount of cargo $Z(t)$ stored in the warehouse can be considered as a random process.

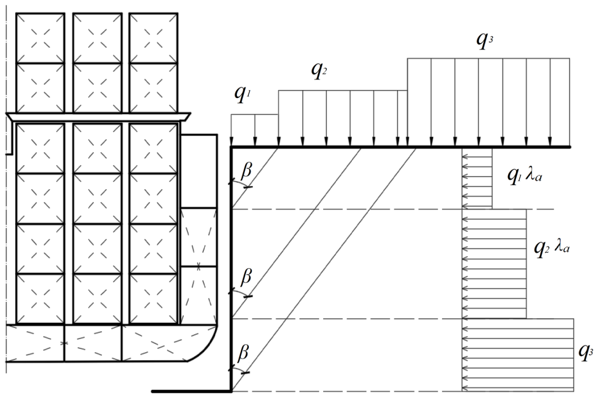

Fig. 2. Block schemes of soil pressure on the face wall considering operational load (q_1, q_2, q_3 are the amount of cargo in a warehouse)

From the point of view of the operational safety of a berth, the moment of the first achievement by process $Z(t)$ of its maximum admissible value $\lambda_a E=Q$ is of the greatest interest (see (3)). This random event can be considered as the moment of occurrence of the risk event that is associated with the damage to a berth structure, as well as losses to the port terminal operator.

5. Development of the method for calculating the probability of a berth failure at exceeding the maximum admissible load from the cargo stored in the warehouse

To solve the specified problem based of the above scheme of modeling the port terminal operation, it is necessary to construct and explore a probabilistic model of the process of the fluctuation in cargo amount in the warehouse of the terminal (berth). As noted above, the probability of the first achievement of a certain maximum value by the cargo stock in a warehouse is primarily of interest. For this purpose, we will use the methods of the risk theory (ruining) [13], with some modification.

Based on above assumptions, it is clear that event $Z(t)>Q$ can occur only at the time of the arrival of a successive vessel with the load. We will write down mathematically the condition that the amount of cargo in a warehouse will first exceed value Q at some point of time at the cargo unloading from a successive vessel (we consider that at the initial time, the first vessel reloaded cargo to the warehouse). This condition takes the following form:

$$\begin{aligned}
&\gamma_1 \le Q,\\
&-W\tau_2+\gamma_1+\gamma_2\le Q,\\
&\dots\dots\dots\dots\dots\dots\dots\dots\\
&-W(\tau_2+\ldots+\tau_n)+\gamma_1+\ldots+\gamma_n\le Q,\\
&-W(\tau_2+\ldots+\tau_{n+1})+\gamma_1+\ldots+\gamma_{n+1}>Q.
\end{aligned}\qquad(4)$$

We will designate through $R_n(Q)$ the probability that the first overloading the warehouse (leading to a berth failure) will happen at time when the cargo is unloaded from the $(n+1)$-th vessel. By definition, when considering condition (4), it can be written down

$$1-R_n(Q)=\mathbf{P}\left(\bigcap_{k=1}^{n}\{\gamma_1+\ldots+\gamma_k\}\le Q+W(\tau_2+\ldots+\tau_k)\right).\qquad(5)$$

We will note, that $1-R_n(Q)$ is the probability that the warehouse will not be overloaded after the arrival of the first n vessels. Subsequently, from the formula of full probability from (5), we obtain

$$1-R_n(Q)=\lambda\int_0^\infty e^{-\lambda t}\int_0^\infty P_n(x,t)\,\mathrm{d}G(x)\,\mathrm{d}t,\qquad(6)$$

where

$$P_n(x,t)=\mathbf{P}\left(\begin{aligned}&\bigcap_{k=1}^{n}\{\gamma_1+\ldots+\gamma_k\}\le\\&\le Q+W(\tau_2+\ldots+\tau_k)\,|\,\gamma_1=x,\tau_2=t\end{aligned}\right).\qquad(7)$$

Provided that $\gamma_1=x<Q$, $\tau_2=t$, the first event under the sign of crossing in the right part of (7) is true.

At $k\ge 2$, event

$$\{\gamma_1+\ldots+\gamma_k\le Q+W(\tau_2+\ldots+\tau_k)\}.$$

Can be rewritten as

$$\{\gamma_1'+\ldots+\gamma_{k-1}'\le Q'+W(\tau_1'+\ldots+\tau_{k-1}')\},$$

where

$$\gamma_i'=\gamma_{i+1},\tau_i'=\tau_{i+1},Q'=Q-x+Wt.$$

Because random magnitudes γ_i, τ_i are independent in totality, sequence $\gamma_1',\gamma_2',\ldots\equiv\gamma_2,\gamma_3,\ldots$ coincides by distribution with sequence γ_1, γ_2,... For this reason, sequence $\tau_1',\tau_2',\ldots\equiv\tau_2,\tau_3,\ldots$ coincides by distribution with sequence τ_1, τ_2,... Therefore,

$$\begin{aligned}
P_n(x,t)&=\mathbf{P}\Big(\bigcap_{i=1}^{n}\{\gamma_1'+\ldots+\gamma_i'\le Q'+W(\tau_1'+\ldots+\tau_i')\}\Big)=\\
&=\mathbf{P}\Big(\bigcap_{i=1}^{n-1}\{\gamma_1+\ldots+\gamma_i\le Q'+W(\tau_2+\ldots+\tau_i)\}\Big).
\end{aligned}\qquad(8)$$

Comparing this probability with the right-hand side of formula (5), we see that it is equal to

$$1-R_{n-1}(Q')=1-R_{n-1}(Q-x+Wt).$$

Then the following recurrent ratio follows from (6) to (8):

$$1-R_n(Q)=\lambda\int_0^\infty e^{-\lambda t}\int_0^Q\left[1-R_{n-1}(Q-x+Wt)\right]\mathrm{d}G(x)\,\mathrm{d}t,\quad n\ge 2,$$

$$1-R_1(Q)=G(Q).\qquad(9)$$

Using ratio (9) and a mathematical induction, it is not difficult to show that

$$R_n(\infty)=0,\quad n=1,2,\ldots\qquad(10)$$

We will consider the terminal operation in a steady mode, that is, at $n\to\infty$. It should be noted, however, that such a mode exists not always and only under certain assumptions. We will assume that average intensity of cargo arrival at the warehouse (it is equal to $\lambda\mathbf{M}\gamma_1$) is strictly lower than the intensity of its removal from the warehouse, that is

$$\lambda \mathbf{M}\gamma_1 < W. \quad (11)$$

Meeting the so-called unsaturation condition (11) for the explored system "warehouse – berth" is necessary to ensure that over time the cargo amount in the warehouse should not increase unlimitedly. In this case, ratio $\lambda\mathbf{M}\gamma_1/W<1$ has the sense of warehouse usage over time.

We will note that $R(Q)$ is the probability of the event "at some point of time the cargo amount in a warehouse will not exceed the value that would lead to the formation of the critical value of stress in the side wall of a berth, that is, to its failure".

From (9) at $n\to\infty$, we derive the following linear integral equation of convolution type to find the probability that a warehouse will never get overloaded, that is $1-R(Q)$:

$$1-R(Q)=\lambda\int_0^\infty\int_0^Q\left[1-R(Q-x+Wt)\right]e^{-\lambda t}\mathrm{d}G(x)\mathrm{d}t. \quad (12)$$

We will note that the equality follows from (10) at $n\to\infty$

$$R(\infty)=0. \quad (13)$$

We will find the solution to equation (12) for some particular cases:

1) Loadings of all vessels are the same and equal to g.

In this case, equation (12) will take the following form:

$$1-R(Q)=\lambda\int_0^\infty e^{-\lambda t}\left[1-R(Q-g+Wt)\right]\mathrm{d}t. \quad (14)$$

After changing a variable by formula

$$y=Q-g+Wt$$

equation (14) is reduced to the form:

$$\left(1-R(Q)\right)e^{-\lambda Q/W}=\frac{\lambda}{W}e^{-\lambda g/W}\int_{Q-g}^\infty\left(1-R(y)\right)e^{-\lambda y/W}\mathrm{d}y,\ Q\geq g. \quad (15)$$

After differentiation of the both parts of the equation (15) by Q, we will come to such linear differential equation of first order with retarded argument:

$$R'(Q)=\frac{\lambda}{W}\left(R(Q)-R(Q-g)\right),\quad Q\geq g.$$

At $0\leq Q<g$ we consider that $R(Q)=1$. The solution to this problem has the form of:

$$R(Q)=e^{-\rho Q},\quad Q\geq g, \quad (16)$$

where ρ is the only positive root of the equation (considering equation (11))

$$\rho=\frac{\lambda}{W}\left(e^{\rho g}-1\right).$$

2) Loadings of all ships are random and distributed by the exponential law, that is

$$G(x)=1-e^{-x/g},\quad x\geq 0,$$

where now $g=\mathbf{M}\gamma_1$ is the mean value of the vessel loading.

In this case, we obtain the following equation from (12):

$$1-R(Q)=(\lambda/g)\int_0^\infty e^{-\lambda t}\int_0^Q\left[1-R(Q-x+Wt)\right]e^{-x/g}\mathrm{d}x\mathrm{d}t. \quad (17)$$

It follows from (17) at $Q=0$ that $R(0)=1$. After substituting the variable of integration in the inner interval in the right-hand side of equation (17)

$$y=Q-x+Wt.$$

After a series of transformations, we will reduce it to the form:

$$e^{Q/g}\ \left(1-R(Q)\right)=(\lambda/g)\int_0^\infty e^{-(\lambda+W/g)t}\int_0^Q\left[1-R(y)\right]e^{y/g}\mathrm{d}y\mathrm{d}t.$$

After two-time differentiation of both parts of the last equation by Q, we will come to the following second-order linear homogeneous differential equation:

$$R''(Q)+\left(\frac{1}{g}-\frac{\lambda}{W}\right)R'(Q)=0.$$

Solution to the last equation under initial conditions (see (10), (13)) $R(0)=1$, $R(\infty)=0$ takes the form:

$$R(Q)=\exp\left[-\left(\frac{1}{g}-\frac{\lambda}{W}\right)Q\right]. \quad (18)$$

Thus, in the explored cases, the probability that a berth failure will ever happen is determined from simple formulas (16) and (18). It is important to note that the specified probability depends on controllable magnitudes, particularly, W and Q, which enables the management of the terminal to control and predict the probability of occurrence of a berth structure failure due to its overloading.

6. Some practical applications of the methods for assessment of the probability of a berth failure

To illustrate the obtained results, consider two practical problems:

1) Assessment of the intensity of the load transportation from the warehouse, guaranteeing a sufficiently small probability of a berth failure.

Probabilistically guaranteed value of parameter W ensuring berth failure ε with low probability is determined from the condition

$$R(Q)=\varepsilon.$$

If we use formula (18), the desired value of parameter W is found from formula

$$W=\frac{\lambda g}{1+\dfrac{g}{Q}\ln\varepsilon}.$$

If we rewrite the last formula in the form

$$W\left(1+\frac{g}{Q}\ln\varepsilon\right)=\lambda g, \quad (19)$$

It is possible to note that expression $(-Wg/Q)\ln \varepsilon$ in the left part of equation (19) has the sense of the reserve of the throughput of a warehouse, providing for meeting the so-called condition of unsaturation of the analyzed "warehouse – berth" system or the condition of its statistically balanced (steady) operation (11), as well as guaranteeing a small probability of occurrence of a berth failure. It should be noted that formula (19) makes sense only under condition that

$$1+\frac{g}{Q}\ln\varepsilon>0.$$

Let us assume, for example, that E=100 thousand tons, g=5 thousand tons, $\lambda=0{,}06$ ships/day, $\varepsilon=0{,}01$, and the backfill soil consists of fine sand with different porosity (characterized by different values of angle of internal friction β). Table 1 gives the probabilistically guaranteed values of the intensity of cargo transporting from warehouse W, guaranteeing the probability of the failure occurrence due to berth overloading ε=0.01, for different values of angle of internal friction.

Table 1

Values of intensity of cargo transportation from warehouse at different values of angle of internal friction of backfill soil

Angle of internal soil friction, degrees	$\lambda_a=\mathrm{tg}^2(45-\beta/2)$	$Q=\lambda_a E$, thousand tons	Intensity of cargo transportation from warehouse W, thousand tons/day
37	0.249	24. 9	3.984
35	0.271	27.1	1.995
33	0.295	29.5	1.367
31	0.32	32.0	1.070
29	0.347	34.7	0.892

Data from Table 1 show that under conditions of considerable fluctuations of loading capacity of vehicles and at using sand with considerable porosity (that is at an increase in angle of internal friction from 29° to 37°) as backfill, to ensure the probability of a berth failure at the level of 0.01, the intensity of cargo transportation from a warehouse should be increased almost by four times.

2) Substantiation of appropriateness of insuring the damage from a berth failure.

The found probability of the failure-free operation of the berth $R(Q)$ also makes it possible to solve the problem of the appropriateness of insurance by the port administration or the terminal operator of the risk of a berth failure due to exceeding the maximum admissible value Q by the cargo amount in the warehouse. In this case, it is assumed that the magnitude of the expected damage from a failure can be evaluated and makes up r. Let the agreement about the insurance of this damage be concluded with the insurance company for period T, and the amount of the insurance premium within this period under the contract be equal to c. We will compose the function of the gain for a port for either of the two variants of solution: to insure or not to insure the risk. Let us designate the value of the gain function for the two specified variants respectively as P_1 and P_2, the event "a berth failure happened within period T" as A. It is not difficult to notice that

$$P_1=-cI(A)+rI(\bar{A}),\;\; P_2=cI(A)=rI(\bar{A}), \tag{20}$$

where $I(A)$ is the indicator of event A. Since the probability of occurrence of event A is equal to $R(Q)$, from (20), we derive the mean gain of the port at every solution:

$$\mathbf{M}P_1=-cR(Q)+r(1-R(Q)),$$

$$\mathbf{M}P_2=cR(Q)-r(1-R(Q)).$$

We will also note that from (20), there follows the equation

$$\mathbf{D}P_1=\mathbf{D}P_2.$$

Thus, insurance will be advisable if the condition is met

$$\mathbf{M}P_1>\mathbf{M}P_2$$

or

$$R(Q)<\frac{r}{r+c}. \tag{21}$$

If loading of vessels obey the exponential distribution law, the condition (21) based on formula (18) will take the following form:

$$\left(\frac{1}{g}-\frac{\lambda}{W}\right)Q<-\ln\frac{r}{r+c}.$$

If, for example, $\lambda g/W$=0.5, Q=5g and c=0.5r, according to this condition, it is not advisable to insure a berth from failure (2.5>0.405), and at $\lambda g/W$=0.8, Q=2g it advisable to insure the risk of a failure (0.4<0.405).

The given examples show the probability of the practical use of the developed method for assessment of probability of occurrence of a berth failure to prevent it.

For the practical use of the above theoretical recommendations, in practice of the port operation, it is necessary not only to conduct periodic inspections of the technical condition of the main structural elements of a berth, in particular its supporting wall, but also to keep statistical account of the fluctuations of the cargo amount in a warehouse, arrival and parking of vehicles along the berth.

6. Discussion of results of studying the assessment of a probability for the occurrence of a berth structure failure

The proposed above methodological approach to determining the reliability of a berth structure of a port terminal, unlike existing methods, makes it possible to estimate more reasonably the magnitude of actual operational loads that influence the main structural elements of a berth. This is achieved through mathematical modeling of the processes of cargo arrival at the terminal warehouse and its transportation from a warehouse by vehicles based on the use of such sections of studying operations as the queuing theory and the stock theory. This approach is the development and continuation of the research previously carried out by the authors related to the assessment of the operational reliability of the port berth facilities. The research resulted into the development of the method for assessing the probability of a berth failure due to exceeding the maximum admissible load on it, which makes it possible to minimize potential losses of a port, associated with the elimination of the berth failure consequences and additional idling of vessels standing at berths for unloading. The method was developed for the case of unloading the cargo arriving on vessels, which is why it is of scientific and practical interest for solving a similar problem for the case when the cargo arrives at the terminal by the land transport, and is transported from a warehouse by seagoing vessels.

The proposed method for the assessment of the probability of a berth failure can be used for subsequent research into this problem, taking into consideration the specifics of the operational and structural features of berths, as well as probabilistic properties of the soil at the foundation of the berth. A more accurate method for assessment of the probability of occurrence of a berth failure will enable the port administration to reduce the losses caused by the liquidation of the consequences of the failure of berth facilities, as well as to improve safety of loading and unloading operations at the port terminal.

7. Conclusions

1. Using the methods of the risk theory, we constructed the probabilistic model of the operation of the "warehouse – berth" system at the port terminal, taking into consideration a random approaching of vessels for cargo loading and even delivery of the cargo to a warehouse by the land transport. This model makes it possible to calculate more reasonably the actual operational loads and can be used as a basis for determining the probability of occurrence of a berth failure as a result of exceeding the maximum admissible magnitude of the stress on the front wall of a berth.

2. We stated the criterion of safe operation of a berth when its structural elements are influenced by random load, stored in a warehouse in the rear of a berth, as the probability of not exceeding the maximum admissible pressure on the front wall of a berth.

3. To find the probability of occurrence of a berth failure due to its overloading, the linear integral equation of the convolution type was derived. The solution to this equation made it possible to find the analytical expression for the probability the failure-free operation of a berth for different functions of distribution of the vessels' loading, which makes it possible to assess quantitatively the risk of a failure.

4. The criterion of economic viability of insuring a berth from a sudden failure due to exceeding the maximum admissible values by operational loads within an assigned period of time was stated. This criterion enables reducing the losses of a port associated with the elimination of the consequences of occurrence of a berth failure.

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