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General model of critical infrastructure accident consequences application to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. Part 1. Process of initiating events

Keywords

Baltic Sea region, critical infrastructure, sea accident, accident consequences, initiating events

Abstract

In the paper, the process of initiating events at the Baltic Sea area identification is performed. Next, the main characteristics of this process are predicted.

1. Introduction

The General Model of Critical Infrastructure Accident Consequences (GMCIAC) was constructed as a joint probabilistic model [4]-[5], including the process of initiating events [1]-[2] generated either by its accident or by its loss of safety critical level, the process of environment threats [3] and the process of environment degradation (*Figure 1*).

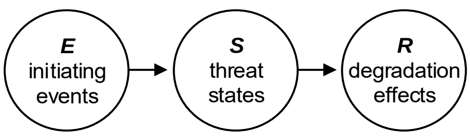

Figure 1. Interrelations of the critical infrastructure accident consequences general model

2. Application of the model of the process of initiating events to the Baltic Sea waters

We assume, as in [6], that the process of initiating events is taking ω, $\omega \in N$, different initiating events states $e^1, e^2, \ldots, e^\omega$. Next, we mark by $E(t)$, $t \in <0,\infty)$, the process of initiating events, that is a function of a continuous variable t, taking discrete values in the set $\{e^1, e^2, \ldots, e^\omega\}$ of the initiating events states. We assume a semi-Markov model [9]-[16] of the process of initiating events $E(t)$, and we mark by θ^{lj} its random conditional sojourn times at the initiating events states e^l, when its next initiating events state is e^j, $l, j = 1,2,\ldots,\omega$, $l \neq j$.

Under these assumption, the process of initiating events may be described by the vector $[p(0)]_{1\times\omega}$ of probabilities of the process of initiating events staying at the particular initiating events states at the initial moment $t = 0$, the matrix $[p^{lj}(t)]_{\omega\times\omega}$ of probabilities of transitions between the initiating events states and the matrix $[H^{lj}(t)]_{\omega\times\omega}$ of the distribution functions of the conditional sojourn times θ^{lj} of the process $E(t)$ at the initiating events states or equivalently by the matrix $[h^{lj}(t)]_{\omega\times\omega}$ of the density functions of the conditional sojourn times θ^{lj}, $l, j = 1,2,\ldots,\omega$, $l \neq j$, of the process of initiating events at the initiating events states.

2.1. Parameters evaluation of the process of initiating events at the Baltic Sea waters

To identify the unknown parameters of the process of initiating events the suitable statistical data coming from realization should be collected. The statistical identification of the process of initiating events was performed on the base on the ship accidents around the Baltic Sea in a period of 11 years (2004-2014). The number of the observed ship accidents that generated the distinguished states of the process of initiating events was $n(0) = 104$. The initial moment

$t = 0$ of the process of initiating event for each ship was fixed at the moment when the ship after an accident generated one of the distinguished states. Unfortunately, the less accurate identification of the process of initiating events is performed for the Baltic Sea waters because of the less sufficiently numerous set of statistical data.

2.1.1. States of the process of initiating events

Taking into account the expert opinion on varying in time process of initiating events, we distinguished 16 states of process of initiating events:
state e^1 – ship transportation process is undisturbed, there are no initiating event,
state e^2 – ship is under collision,
state e^3 – ship is under grounding,
state e^4 – ship is under contact,
state e^5 – ship is under fire or explosion,
state e^6 – ship lost control and drifting,
state e^7 – ship is capsizing or listing,
state e^8 – cargo in the ship is moving,
state e^9 – ship is under grounding, and simultaneously ship is under fire or explosion,
state e^{10} – ship is under fire or explosion, and simultaneously ship lost control and drifting,
state e^{11} – ship lost control and drifting, and simultaneously ship is capsizing or listing,
state e^{12} – ship is under fire or explosion, and simultaneously cargo in the ship is moving,
state e^{13} – ship is capsizing or listing, and simultaneously cargo in the ship is moving,
state e^{14} – ship lost control and drifting, and simultaneously ship lost control and drifting, and is capsizing or listing,
state e^{15} – ship is capsizing or listing, and simultaneously ship is capsizing or listing, and cargo in the ship is moving,
state e^{16} – ship is under fire or explosion, and simultaneously ship is capsizing or listing.

2.1.2. Probabilities of transitions between states of the process of initiating events

On the basis of the statistical data, it is possible to evaluate the following unknown basic parameters of the process of initiating events at the Baltic Sea waters:
- the vector

$$[p(0)]_{1x16} = [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0], \qquad (1)$$

of the initial probabilities $p^l(0)$, $l = 1,2,\ldots,16$, of the process of initiating events at the particular states e^l at the moment $t = 0$,
- the matrix $[p^{lj}]$, $l, j = 1,2,\ldots,16$, of the probabilities of transitions of the process $E(t)$ from the state e^l into the state e^j during the experimental time. The probabilities of transitions that are not equal to 0 are as follows:

$$p^{12} = 0.1731, p^{13} = 0.3558, p^{14} = 0.0481,$$

$$p^{15} = 0.0961, p^{16} = 0.2308, p^{17} = 0.0865,$$

$$p^{18} = 0.0096;$$

$$p^{21} = 0.7500, p^{23} = 0.1000, p^{26} = 0.0500, p^{27} = 0.1000;$$

$$p^{31} = 1;$$

$$p^{41} = 0.8333, p^{47} = 0.1667;$$

$$p^{51} = 0.9000, p^{5\,10} = 0.1000;$$

$$p^{61} = 0.0400, p^{62} = 0.0800, p^{63} = 0.8400, p^{64} = 0.0400;$$

$$p^{71} = 0.5000, p^{73} = 0.4167, p^{7\,13} = 0.0833;$$

$$p^{81} = 1;$$

$$p^{10\,1} = 1;$$

$$p^{13\,1} = 1. \qquad (2)$$

Some of the values of the probabilities existing in the vector $[p(0)]_{1x16}$ and in the matrix $[p^{lj}(t)]_{16x16}$, besides of that standing on the main diagonal, and equal to zero does not mean that the events they are concerned with, can not appear. They are evaluated on the basis of real statistical data and their values may change and become more precise if the time of the experiment is longer.

2.1.3. Evaluation of distributions and mean values of the process of initiating events conditional sojourn times

On the basis of statistical data, the matrix $[h^{lj}(t)]_{16x16}$ of the density functions of the process of initiating events conditional sojourn times θ^{lj}, $l, j = 1,2,\ldots,16$, $l \neq j$, at the particular states, defined by (2.5) in [6], and the corresponding to the matrix $[H^{lj}(t)]_{16x16}$ of the distribution functions of the process of initiating events conditional sojourn times θ^{lj}, $l, j = 1,2,\ldots,16$, $l \neq j$, at the particular states, defined by (2.4) in [6], can be evaluated. In Section 3.2.4 in [7], the forms of the particular density functions $h^{lj}(t)$ and distribution functions $H^{lj}(t)$ of the process of initiating events conditional sojourn times θ^{lj}, $l, j = 1,2,\ldots,16$, $l \neq j$, at the particular states are identified on the basis of statistical data coming from its process realizations at the Baltic Sea waters given in Appendix 2 in [7]. The distribution functions are as follows:

- the exponential distribution function for the conditional sojourn time θ^{13} is

$$H^{13}(t) = \begin{cases} 0, & t < 0 \\ 1 - \exp(-0.0000000112\ t), & t \geq 0, \end{cases} \quad (3)$$

- the chimney distribution function for the conditional sojourn time θ^{31} is

$$H^{31}(t)$$

$$= \begin{cases} 0, & t < 0 \\ 0.000505245t, & 0 \leq t < 1644.29 \\ 0.000014703t & \\ +0.806593305, & 1644.29 \leq t < 13154.32 \\ 1, & t \geq 13154.32. \end{cases} \quad (4)$$

In the case when as a result of the experiment, limited data coming from experts, we only have the number of realizations of the process of initiating events lifetimes at the states and its all realizations are equal to an approximate value, we assume that this conditional sojourn times have the uniform distribution in the interval from this value minus its half to this value plus its half. The uniform distribution functions of the process of initiating events for particular conditional sojourn times θ^{lj} are identified on the basis of statistical data coming from its process realizations at the Baltic Sea waters given in Appendix 2 in [7]. For instance, the process initiating events the conditional sojourn time θ^{18} assumed $n^{18} = 1$ value equals to 1576800, we assume that it has the uniform distribution function given by

$$H^{18}(t) = \begin{cases} 0, & t < 788400 \\ t, & 788400 \leq t < 2365200 \\ 1, & t \geq 2365200. \end{cases} \quad (5)$$

In the case when as a result of the experiment, coming from experts, we have less than 28 realizations of the process of initiating events, we determined this conditional sojourn times have the empirical distributions. The empirical distribution functions of the process of initiating events for particular conditional sojourn times θ^{lj} are identified on the basis of statistical data coming from its process realizations at the Baltic Sea waters given in Appendix 2 in [7]. For instance, the process initiating events conditional time θ^{51} assumed $n^{51} = 9$ values. The order sample realizations θ^{51} is: 20, 20, 60, 60, 120, 120, 150, 240, 680. Thus, we assume that conditional sojourn time θ^{51} has the empirical distribution function given by

$$H^{51}(t) = \begin{cases} 0, & t \leq 20, \\ 2/9, & 20 < t \leq 60, \\ 4/9, & 60 < t \leq 120, \\ 6/9, & 120 < t \leq 150, \\ 7/9, & 150 < t \leq 240, \\ 8/9, & 240 < t \leq 680, \\ 1, & t > 680. \end{cases} \quad (6)$$

We have proceeded with the remaining conditional times at the states of the process of initiating events in the same way and approximately fix they distribution. Further, for distributions identified in this section by application either the general formulae for the mean value or particular formulae given respectively by (2.14) and (2.15-2.21) in [6], the mean values $M^{lj} = E[\theta^{lj}]$, $l, j = 1,2,\ldots,16$, $l \neq j$, of the process of initiating events conditional sojourn times at particular states at the Baltic Sea waters can be determined and they amount to:

$$M^{13} \cong 8928571.43, M^{18} = 1576800;$$

$$M^{21} = 1.00, M^{26} = 1.00;$$

$$M^{31} \cong 1933.68;$$

$$M^{41} = 1.00, M^{47} = 1.00;$$

$$M^{5\,10} = 10.00;$$

$$M^{61} = 120.00, M^{64} = 15.00;$$

$$M^{7\,13} = 1.00;$$

$$M^{81} = 5.00;$$

$$M^{10\,1} = 10.00,$$

$$M^{13\,1} = 10.00. \quad (7)$$

In the remaining cases, when the distributions cannot be identified, it is possible to find the approximate empirical values of the mean values $M^{lj} = E[\theta^{lj}]$, $l, j = 1,2,\ldots,16$, $l \neq j$, of the process of initiating events conditional sojourn times at particular states at the Baltic Sea waters that are as follows:

$$M^{12} = 10249200, M^{14} = 12614400,$$

$M^{15} = 13402800$, $M^{16} = 8694300$, $M^{17} = 5869200$;

$M^{23} = 22.50$, $M^{27} = 5.50$;

$M^{51} = 163.33$;

$M^{62} = 80.00$, $M^{63} = 324.05$;

$M^{71} = 225.83$, $M^{73} = 21.60$. (8)

2.1.4. Prediction of the process of initiating events

Using the identified parameters of the process of initiating events in Section 2.1.2 and 2.1.3, it is possible to predict its characteristics [8]. Namely, considering (2), (7) and (8), the mean values of the process of initiating events at the Baltic Sea waters unconditional sojourn times at the particular states are:

$M^1 \cong 9376491.76$, $M^2 = 3.6$, $M^3 = 1933.69$,

$M^4 = 1.0$, $M^5 \cong 148.0$, $M^6 \cong 284.0$, $M^7 \cong 122.0$,

$M^8 = 5.00$, $M^{10} = 10.00$, $M^{13} = 10.00$. (9)

Since from the system of equations (2.26) in [6] takes the following form

$$\begin{cases} [\pi^l]_{1x16} = [\pi^l]_{1x16}[p^{lj}]_{16x16} \\ \sum_{l=1}^{16} \pi^l = 1, \end{cases}$$

we get its following solution

$\pi^1 = 0.42449$, $\pi^2 = 0.08164$, $\pi^3 = 0.26533$,

$\pi^4 = 0.02450$, $\pi^5 = 0.04079$, $\pi^6 = 0.10205$,

$\pi^7 = 0.04897$, $\pi^8 = 0.00407$, $\pi^{10} = 0.00408$,

$\pi^{13} = 0.00408$. (10)

Then after considering (9) and applying (2.25) in [6] we get the approximate limit values of transient probabilities at the particular states of the process of initiating events at the Baltic Sea waters

$p^1 = 0{,}9998607108$, $p^2 = 0.0000000738$,

$p^3 = 0.0001288857$, $p^4 = 0.0000000062$,

$p^5 = 0.0000015165$, $p^6 = 0.0000072805$,

$p^7 = 0.0000015008$, $p^8 = 0.0000000051$,

$p^{10} = 0.0000000102$, $p^{13} = 0.0000000102$. (11)

Further, by (2.27) in [6] and considering (11), the approximate mean values of the sojourn total times $\hat{\theta}^l$ of the process of initiating events $E(t)$ at the Baltic Sea waters in the time interval θ = 1 month = 43200 minutes at the particular states e^l expressed in minutes are:

$\hat{M}^1 = 43193.98$, $\hat{M}^2 = 0.00319$, $\hat{M}^3 = 5.56786$,

$\hat{M}^4 = 0.00027$, $\hat{M}^5 = 0.06551$, $\hat{M}^6 = 0.31452$,

$\hat{M}^7 = 0.06483$, $\hat{M}^8 = 0.00022$, $\hat{M}^{10} = 0.00044$,

$\hat{M}^{13} = 0.00044$. (12)

3. Conclusion

The results (11) and (12) are main characteristics of the considered process of initiating events that is the first part of the integrated model of critical infrastructure accident consequences [5]. These characteristics are necessary for the prediction of the remaining two parts of the integrated model, i.e. for the prediction of the characteristics of the process of environment threats and the process of environment degradation.

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