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An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure

Zhang Mingguang *, Jiang Juncheng

Institute of Safety Engineering, Nanjing University of Technology, Nanjing 210009, Jiangsu, China

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Abstract

Overpressure is one important cause of domino effect in accidents of chemical process equipments. Damage probability and relative threshold value are two necessary parameters in QRA of this phenomenon. Some simple models had been proposed based on scarce data or oversimplified assumption. Hence, more data about damage to chemical process equipments were gathered and analyzed, a quantitative relationship between damage probability and damage degrees of equipment was built, and reliable probit models were developed associated to specific category of chemical process equipments. Finally, the improvements of present models were evidenced through comparison with other models in literatures, taking into account such parameters: consistency between models and data, depth of quantitativeness in QRA.

Keywords: Overpressure; Process vessels; Damage probability; Damage degrees; Domino effect; Probit model

1. Introduction

In chemical process industry, there are lots of dangerous materials in various equipments. Once domino effect happens between process equipments, leakage of dangerous materials from "target" equipment will make accident consequence more severe. A series of research work has identified overpressure in explosion accident is one important cause of domino effect to chemical process equipments [1–3]. To quantify risk of accidents involving it, some models considering propagation probability and threshold values of the domino effect caused by overpressure have been proposed in previous study. Most of the models related damage to peak static overpressure only, and estimation models reported in literatures almost have limitation because of scarce data and some oversimplified assumption. After revising and analyzing the reference work, improvements have been done to develop more detailed models and more realistic conclusions were achieved.

2. Analysis of previous work

To simplify the problem, most researchers only related damage to peak static overpressure based on "far-field" hypothesis. In previous work, several approaches were reported in the literatures (Table 1), based on damage phenomenon and relevant threshold data of peak static overpressure from past accidents. Bagster and Pitblado [4] assumed the probability of damage decrease with the square of distance, which has not evidenced by any proof. In the work of Gledhill and Lines [5], value of damage probability is simply assumed 0 or 1, which is lack of continuity of probability data. Eisenberg [6] was the first one who proposed a model (Eq. (1)) to assess the damage probability based on "probit analysis", which has been used to assess the dose-effect relationship for human responses to thermal radiation, toxic substances and overpressure

$$Y = a + b\ln(\Delta P) \quad (1)$$

where Y is probit value; ΔP is peak static overpressure (Pa); a and b are coefficients of model. After that, this method was followed by Khan [7] and Cozzani [8,9]. The following development focuses on the accuracy of coefficients (a, b in Eq. (1)) and definition of minimum threshold values with respect to specific model. Comparing with data revised in reference, the

* Corresponding author. Tel.: +86 25 83587422.
E-mail address: zmgnj198173@163.com (Z. Mingguang).

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Table 1
Probit models reported in the literatures [4–9]

Author	Categorization of process plants	Damage Probability model	Threshold values of peak static overpressure
Eisenberg et al. [6]	No categorization	$Y = -23.8 + 2.92\ln(\Delta P)$	
Bagster and Pitblado [4]	No categorization	$F_d = (1 - r/r_{th})^2$, r: distance from explosion center; r_{th}: distance from explosion center at which static overpressure equals ΔP_{th}	$\Delta P_{th} = 36$ kPa
Khan and Abbasi [7]	No categorization	if $\Delta P < 70$ kPa, $Fd = 0$; if $\Delta P > 70$ kPa, $Y = -23.8 + 2.92\ln(\Delta P)$	
Gledhill and Lines [5]	Atmospheric	if $\Delta P < \Delta P_{th}$, $Fd = 0$	$\Delta P_{th} = 7$ kPa
	Pressurized	if $\Delta P \geq \Delta P_{th}$, $Fd = 1$	$\Delta P_{th} = 38$ kPa
Cozzani and Salzano [8–10]	Atmospheric	$Y = -18.96 + 2.44\ln(\Delta P)$	
	Pressurized	$Y = -42.44 + 4.33\ln(\Delta P)$	
	Elongated	$Y = -28.07 + 3.16\ln(\Delta P)$	
	Small	$Y = -17.79 + 2.18\ln(\Delta P)$	

F_d: failure probability; Y: probit values corresponding to failure probability; ΔP: peak static overpressure (Pa).

minimum threshold value used in Khan's model (70 kPa) is too high [5]. Cozzani and Salzano [8–10] took into account different characteristics of different equipment categories. A division of four categories of process plants was suggested. This sort of models is regressed based on data observed from accidents or experiments. Although basic formula (Eq. (1)) has been widely used, the accuracy of model mainly depends on the quality and quantity of data used in the analysis. In Cozzani and Salzano's analysis of data, only four damage probability values were arbitrary assigned (1%, 10%, 30% and 99%) on entire probability range (0–100%) for damage phenomenon, some overpressure values with great deviation were assigned same damage probability value. After calculating mean value and mean square error of the data assigned the same probability value, data whose difference with respect to the mean value exceeded the mean square error was discarded. This approach not only is too rough at assumption of probability value, but also reduces the number of available data for the regression of model. Obviously, the drawback stated before decreased accuracy of models.

3. Method

3.1. Categorization of chemical process equipments

Considering the different characteristics under overpressure, process equipments were divided into different categories to achieve more specific models in previous work. Cozzani and Salzano [8–10] divided process equipments into four categories: (a) atmospheric vessels, (b) pressurized vessels, (c) elongated vessels and (d) small equipment. In domino accidents caused by overpressure, different categories of equipments resist differently to overpressure, due to different material strength, shape, construction method and so on. At this view, this division is accepted in the present study.

3.2. Classification of damage phenomenon

In QRA framework, an important criterion of domino effect caused by overpressure to equipment is structural damage of equipment, followed by loss of containment. In chemical process industry, leakage of dangerous materials may result in various severe secondary accidents. Hence, classification of damage phenomenon is associated to two factors in the present study: damage state (DS) of structure, loss of containment (LOC). The detailed description of factors was introduced in reference [10].

3.2.1. Structure damage state

- *DS1*: light damage to the structure or to the auxiliary equipment;
- *DS2*: intense, or catastrophic damage, or even total collapse of structure, which is certainly followed by an intense loss of containment.

3.2.2. Loss of containment

Three classes of loss intensity (LI) were identified following an approach largely similar to the one proposed in "purple book" [11].

- *LI1*: "minor loss", defined as the partial loss of inventory or total loss of inventory in a time interval of more than 10 min from the impact of the blast wave;
- *LI2*: "intense loss", defined as the total loss of inventory in a time interval between 1 and 10 min;
- *LI3*: "catastrophic loss", defined as the "instantaneous" complete loss of inventory (complete loss in a time interval of less than 1 min).

As stated before, the sequence of accident of equipment caused by overpressure is structure failure, loss of containment and leakage of dangerous materials. DS1 can result in case LI1, and DS2 can result in cases LI2 and LI3. Thus, a classification of damage phenomenon caused by overpressure is made, three degrees are included:

- *DS1LI1*: light damage to the structure of equipment, followed by the partial loss of inventory or total loss of inventory in a time interval of more than 10 min from the impact of the blast wave.

- *DS2LI2*: intense, or catastrophic damage, or even total collapse of structure, followed by the total loss of inventory in a time interval between 1 and 10 min from the impact of the blast wave.
- *DS2LI3*: intense, or catastrophic damage, or even total collapse of structure, followed by complete loss in a time interval of less than 1 min from the impact of the blast wave.

The vessels and containers considered in the present study are characterised by a number of properties such as material strength, shape, and construction method. Therefore a same damage phenomenon does not mean to result in a same damage state for the different categories of equipments (atmospheric or pressurized). In fact, the combination damage state i and loss intensity j ($i = 1, 2$; $j = 1, 2, 3$) will be a comprehensive expression of loss of containment (loss rate and fraction). Loss intensity depends on damage state and states of materials contained in equipments (pressurized or atmospheric). Generally speaking, pressurized material leaks faster through same shape hole. Therefore, in the case of a pressurized vessel a lighter damage state can result in the same time of total loss of containment than that of an atmospheric vessel, assuming they contain the same volume of contents. In the present work, only two states of damage state were defined, but the critical structural damage level was different for different categories of equipments.

3.3. Probability analysis

As stated above, many observed overpressure values with great deviation were assigned to the same damage probability in Cozzani and Salzmann's work, which obviously influenced the accuracy of the final regressed models. To overcome this drawback, a specific probabilistic method is introduced here. According to three damage degrees of structure set above, entire probability range of 0–100% was divided in three correspondent probability ranges.

- The range of 0–30% was assumed to data in DS1LI1 damage state.
- The range of 30–70% was assumed to data in DS2LI2 damage state.
- The range of 70–100% was assumed to data in DS2LI3 damage state.

Table 2
Probability and probit values assigned to observed data (ΔP) for damage to atmospheric vessels

ΔP (kPa)	Damage phenomenon	Damage degree	Probability value (%)	Probit value
5.17	Minor damage, cone roof tank (100% filled)	DS1LI1	3.65	3.21
5.17	Minor damage, cone roof tank (50% filled)	DS1LI1	3.65	3.21
6.10	1% structural damage of equipment	DS1LI1	4.30	3.28
10.00	Failure of atmospheric equipment	DS2LI2	47.00	4.94
14.00	Minor damage of atmospheric tank	DS1LI1	9.88	3.71
18.70	Minor damage, floating roof tank (50% filled)	DS1LI1	13.19	3.88
18.70	Catastrophic failure, cone roof tank (50% filled)	DS2LI3	74.00	5.64
20.00	Deformation of atmospheric tank	DS1LI1	14.11	3.93
20.40	50% structural damage of equipment	DS2LI2	64.00	5.36
24.00	20% structural damage of steel floating roof tank	DS2LI2	70.00	5.53
25.00	Atmospheric tank destruction	DS2LI3	75.50	5.68
27.00	Failure of steel vessel	DS1LI1	19.05	4.12
34.00	99% structural damage of equipment	DS2LI3	77.40	5.75
42.51	Catastrophic failure, cone roof tank (100% filled)	DS2LI3	79.30	5.82
136.00	Structural damage, low pressure vessel	DS2LI3	99.78	7.88
136.05	Catastrophic failure, floating roof tank (50%filled)	DS2LI3	99.79	7.88
136.05	Catastrophic failure, floating roof tank (100% filled)	DS2LI3	99.79	7.88
136.10	99% structural damage of floating roof tank	DS2LI3	99.80	7.88
137.00	99% damage (destruction) of floating roof petroleum tank	DS2LI3	100.00	8.09
7.00	Collapse of atmospheric tank roof	DS1LI1	4.94	3.35
7.00	Partial damage to atmospheric tank	DS1LI1	4.94	3.35
10.00	Fixed roof tank damage	DS1LI1	7.06	3.53
10.00	50% damage to atmospheric tank	DS2LI2	39.52	4.73
20.00	Displacement of steel supports	DS1LI1	14.11	3.93
20.00	100% damage, atmospheric tank	DS2LI3	74.00	5.64
35.00	80% damage of process plant	DS2LI3	78.00	5.77
21.00	Destruction of fixed roof atmospheric tank	DS2LI3	75.00	5.67
42.51	Minor damage, floating roof tank (100% filled)	DS1LI1	30.00	4.47
45.00	Catastrophic failure, floating roof tank	DS2LI3	80.00	5.84
7.00	Failure of connection	DS1LI1	4.94	3.35
20.00	Tubes deformation	DS1LI1	14.11	3.93
22.10	Minor damage, pipe supports	DS1LI1	15.59	3.99
37.42	Catastrophic failure, pipe supports	DS2LI2	65.63	5.40
42.00	Tubes failure	DS2LI2	70.00	5.53

Table 3
Probability and probit values assigned to observed data (ΔP) for damage to pressurized vessels

ΔP (kPa)	Damage phenomenon	Damage degree	Probability value (%)	Probit value
30.00	Failure of pressure vessel	DS1LI1	11.02	3.77
39.00	Structural damage to pressure vessel	DS2LI2	48.79	4.94
39.12	Minor damage, pressure vessel horizontal	DS1LI1	14.38	3.93
42.00	Pressure vessel deformation	DS1LI1	15.44	3.98
52.72	Minor damage, tank sphere	DS1LI1	19.37	4.14
53.00	Pressure vessel failure	DS2LI2	55.54	5.14
53.00	Failure of spherical pressure vessel	DS2LI2	55.54	5.14
55.00	20% structural damage of spherical steel petroleum tank	DS2LI2	56.51	5.16
61.22	Catastrophic failure, pressure vessel horizontal	DS2LI3	86.69	6.11
81.63	Minor damage, pressure vessel vertical	DS1LI1	30.00	4.47
83.00	20% damage of vertical cylindrical steel pressure	DS2LI2	70.00	5.53
88.44	Catastrophic failure, pressure vessel vertical	DS2LI3	94.12	6.57
95.30	99% structural damage of vertical, steel pressure vessel	DS2LI3	95.99	6.75
97.00	99% damage of vertical cylindrical steel pressure vessel	DS2LI3	96.45	6.81
108.84	Catastrophic failure, tank sphere	DS2LI3	99.68	7.73
108.90	99% structural damage of spherical, pressure steel vessel	DS2LI3	99.70	7.75
110.00	99% damage of spherical steel petroleum tank	DS2LI3	100.00	8.09
38.00	Partial damage of pressure vessel	DS2LI2	48.31	5.04
70.00	Failure of pressurized storage sphere	DS2LI2	63.73	5.35
7.00	Failure of connection	DS1LI1	2.57	3.05
20.00	Displacement of steel supports	DS1LI1	7.35	3.53
20.00	Tubes deformation	DS1LI1	7.35	3.53
22.10	Minor damage, pipe supports	DS1LI1	8.12	3.60
37.42	Catastrophic failure, pipe supports	DS2LI2	48.03	4.95
42.00	Tubes failure	DS2LI2	50.24	5.01

In chemical process industry, similar material strength, shape and construction method was applied for designing same category of chemical process equipment. Besides these factors, thickness of the material mainly influences characteristics under overpressure. The thicker the material is, the higher resistance to overpressure the equipment has. Thus, rough linear relationships were proposed to fix specific probability value assigned to each observed data (damage phenomenon and reference overpressure value gathered from literatures [8,9,12], listed in Tables 2–5) in the following equation:

$$P = \begin{cases} 0.3 \times \dfrac{\Delta P}{\Delta P_{\max 1}}, & \text{DS1LI1} \\ 0.4 \times \dfrac{\Delta P}{\Delta P_{\max 2}} + 0.3, & \text{DS2LI2} \\ 0.3 \times \dfrac{\Delta P}{\Delta P_{\max 3}} + 0.7, & \text{DS2LI3} \end{cases} \tag{2}$$

In Eq. (2), P is probability value, ΔP overpressure value and $\Delta P_{\max i}$ ($i = 1, 2, 3$) a threshold value in each linear equation.

Table 4
Probability and probit values assigned to observed data (ΔP) for damage to elongated vessels

ΔP (kPa)	Damage phenomenon	Damage degree	Probability value (%)	Probit value
17.00	Minor damage, distillation tower and cylindrical steel vertical structure. Failure of part of equipment	DS1LI1	11.99	3.82
29.00	Distillation tower and cylinder steel vertical structure	DS1LI1	20.46	4.17
35.71	Minor damage, fractionation column	DS1LI1	25.19	4.33
38.00	Deformation of non-pressure equipment	DS1LI1	26.81	4.38
42.52	Minor damage, extraction column	DS1LI1	30	4.38
45.92	Catastrophic failure, fraction column	DS2LI3	89.75	6.27
47.00	Failure of non-pressure	DS2LI2	70	5.53
69.73	Catastrophic failure, extraction column	DS2LI3	100	8.09
35.00	Damage to fractionating column	DS1LI1	24.69	4.31
14.00	Minor damage of cooling tower	DS1LI1	9.87	3.71
7.00	Failure of connection	DS1LI1	4.93	3.35
20.00	Displacement of steel supports	DS1LI1	14.11	3.92
20.00	Tubes deformation	DS1LI1	14.11	3.92
22.10	Minor damage, pipe supports	DS1LI1	15.59	3.99
37.42	Catastrophic failure, pipe supports	DS2LI2	61.84	5.3
42.00	Tubes failure	DS2LI2	65.74	5.41

Table 5
Probability and probit values assigned to observed data (ΔP) for damage to small equipments

ΔP (kPa)	Damage phenomenon	Damage degree	Probability value (%)	Probit value
25.30	Minor damage, reactor chemical	DS1LI1	9.29	3.68
49.32	Minor damage, heat exchanger	DS1LI1	18.12	4.09
59.52	Catastrophic failure, reactor chemical	DS2LI3	86.41	6.1
59.52	Catastrophic failure, heat exchanger	DS2LI3	86.41	6.1
76.53	Catastrophic failure, reactor cracking	DS2LI3	91.09	6.35
81.63	Minor damage, pump	DS1LI1	30	4.47
108.84	Catastrophic failure, pump	DS2LI3	100	8.09
18.70	Minor damage, reactor cracking	DS1LI1	6.81	3.51
7.00	Failure of connection	DS1LI1	2.57	3.05
20.00	Displacement of steel supports	DS1LI1	7.35	3.55
20.00	Tubes deformation	DS1LI1	7.35	3.55
22.10	Minor damage, pipe supports	DS1LI1	8.12	3.6
37.42	Catastrophic failure, pipe supports	DS2LI2	65.63	5.4
42.00	Tubes failure	DS2LI2	70	5.53

Table 6
Probit models developed in present study

Category of equipment	Probit function	Regression coefficients	Mean square error (%)
Atmospheric vessels	$Y = -9.36 + 1.43\ln(\Delta P)$	0.905	14.1
Pressurized vessels	$Y = -14.44 + 1.82\ln(\Delta P)$	0.844	13.9
Elongated equipments	$Y = -12.22 + 1.65\ln(\Delta P)$	0.786	9.4
Small equipment	$Y = -12.42 + 1.64\ln(\Delta P)$	0.826	11.2

The coefficient values 0.3, 0.4 and 0.3 were decided based on some assumptions stated below:

- In DS1LI1 damage state, a 30% damage probability value was assumed to be correspondent to the highest overpressure value ($\Delta P_{\max1}$) of DS1LI1 damage state.
- In DS2LI2 damage state, a 70% damage probability value was assumed to be correspondent to the highest overpressure value ($\Delta P_{\max2}$) of DS2LI2 damage state.
- In DS2LI3 damage state, a 100% damage probability value was assumed to be correspondent to the highest overpressure value ($\Delta P_{\max3}$) of DS2LI3 damage state.

Through the way discussed before, deviation between overpressure value and probability value were greatly mitigated. After that, probit values can be calculated from probability data. In Tables 2–5, probability values and probit values were calculated from damage data in this way.

At last, probit models for different categories were obtained by least square regression, and listed in Table 6.

4. Assessment of models

The models reported in Table 6 are plotted in Fig. 1. In four categories of equipments, the order of resistance to overpressure is fixed (from higher to lower): pressurized vessels, small equipments, elongated vessels and atmospheric vessels. This conclusion achieves agreement with previous research.

Compared with the latest work (Cozzani [8–10]), more observed data were revised here, and lower errors between observed data and predicted values from models have been obtained (Table 7). Better consistency between models and observed data exists in present models. In Fig. 2, models developed for the same category of equipment were compared to find the difference. In low overpressure value range, same overpressure value can cause higher damage probability to equipment by present models. In high overpressure value range, same overpressure value can cause higher damage probability to equipment by former models. We can explain this difference from probability analysis. For the entire line of former probit models, several overpressure values with obvious deviation were assigned 1% damage probability made the fall of staring part

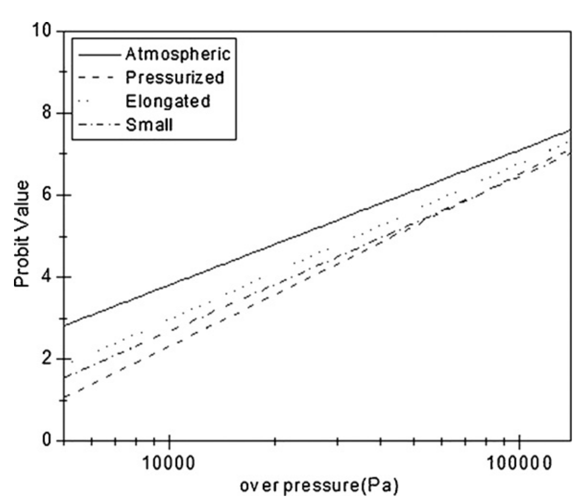

Fig. 1. Probit models developed for damage to different categories caused by overpressure.

Table 7
Comparison of errors of models

Category of equipment	Cozzani and Salzano [8–10]		Present study	
	Regression coefficients	Mean square error (%)	Regression coefficients	Mean square error (%)
Atmospheric vessels	0.573	55.9	0.905	14.1
Pressurized vessels	0.852	52.5	0.844	13.9
Elongated equipments	0.690	5.3	0.786	9.4
Small equipment	0.776	42.8	0.826	11.2

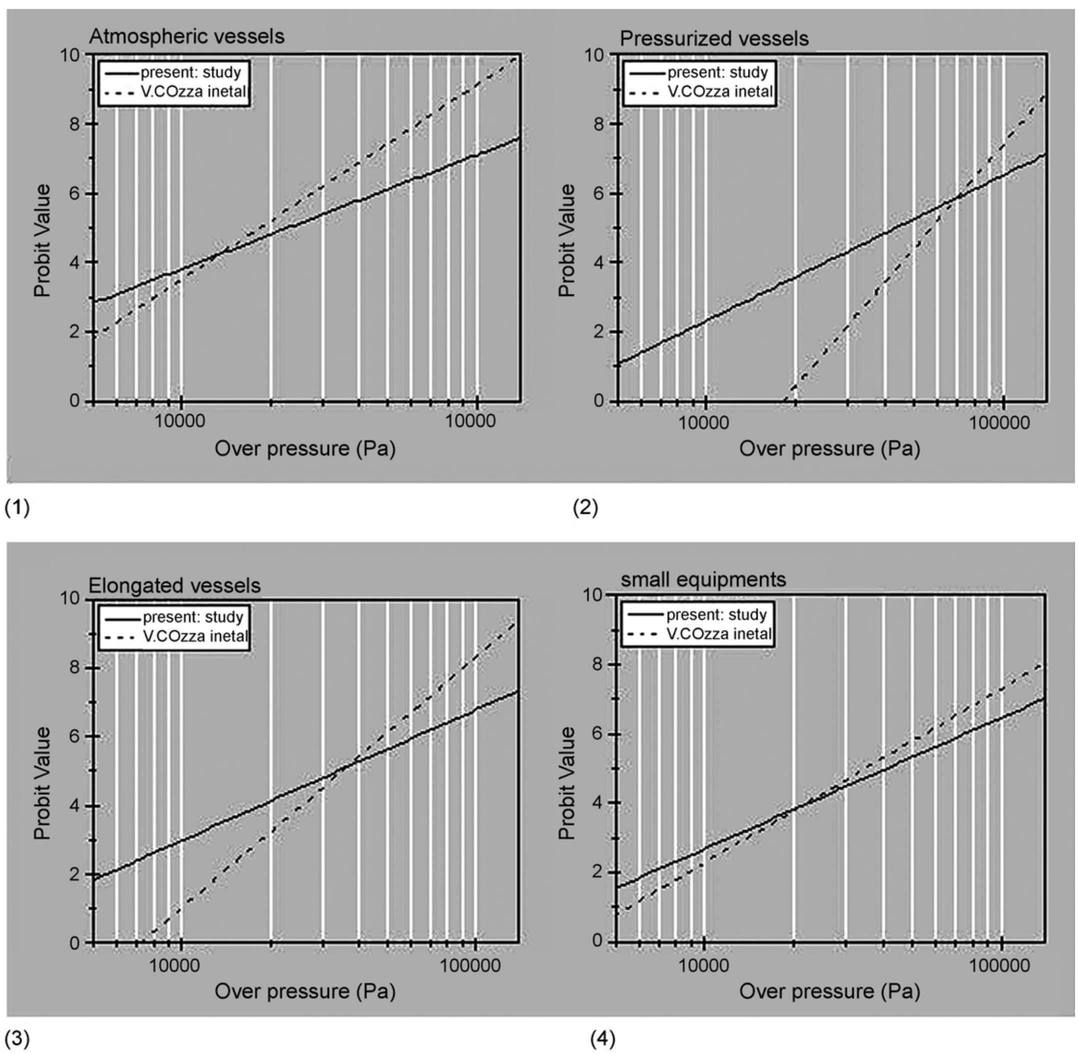

Fig. 2. Probit models comparison: (1) atmospheric vessels; (2) pressurized vessels; (3) elongated vessels; (4) small equipment.

of line, and several overpressure values with obvious deviation were assigned 99% damage probability made rising of ending part of line, which exists in comparison of all four categories, especially for pressurized vessels and elongated vessels. These differences evidence the drawback of fewer observed data used in regression and oversimplification in probability arrangement in former research.

Present models also benefit further QRA of chemical process equipments. Once a certain peak static overpressure works on a type of equipment, damage probability is calculated by models developed here, and the damage degree can be mainly figured out. Thus, a suitable scenario of accident will be predicted in the framework of QRA.

5. Analysis of threshold value

Threshold value for equipment means the minimum overpressure value at which damage is expected at "target" equipment. Some different even contrary conclusion is proposed in literatures about threshold value of overpressure [4,7,10] because of different understanding of "damage" to equipment. A criterion of damage degrees is necessary to achieve widely acceptable

Table 8
Suggested threshold value in QRA of chemical process equipments

Category of equipment	Probit function	Threshold value of 30% damage (kPa)	Threshold value of 70% damage (kPa)
Atmospheric vessels	$Y = -9.36 + 1.43 \ln(\Delta P)$	15	33
Pressurized vessels	$Y = -14.44 + 1.82 \ln(\Delta P)$	32	58
Elongated equipments	$Y = -12.22 + 1.65 \ln(\Delta P)$	24	46
Small equipment	$Y = -12.42 + 1.64 \ln(\Delta P)$	29	56

threshold values. Based on damage probability ranges discussed in forenamed paragraph, 30% damage probability is the critical point of DS1LI1 state and DS2LI2 state, 70% damage probability is the critical point of DS2LI2 state and DS2LI3 state. 30% damage probability value means the state of short time (about 10 min) leakage of the inventory of dangerous materials contained in equipments. 70% damage probability value means the state of instantaneous (about 1 min) leakage of the inventory of dangerous materials contained in equipment. So, threshold values of overpressure which cause 30% and 70% damage probability are suggested to pay more attention in QRA of chemical process equipments. Eq. (3) (Y: probit values correspondent to 30% and 70% damage probability; a, b: coefficients of a particular model) is used for the calculation, and the results are reported in Table 8:

$$\Delta P = e^{(Y-a)/b} \tag{3}$$

6. Conclusions

Probit models for assessment of damage probability of chemical process equipments under domino effect caused by overpressure can be regressed from observed data. But scarce data and oversimplified assumption may lead to poor models. More reliable data were revised in the present study. A more detailed class of damage state and loss intensity was applied to describe the damage phenomenon under overpressure, and ranges of damage probability were proposed, and more reasonable damage probability assignment was made. These two improvements built a more rational relationship between overpressure value and damage probability value, whereas only four single probability values (1%, 10%, 30% and 99%) were arbitrary assigned to overpressure values in previous work. A series of more accurate models were obtained correspondent to chemical process equipment categories, which have much lower errors between observed data and predicted data than the models in literature. A comparison of models for each equipment category was carried out to evidence the improvement of the present study. Finally, threshold values of overpressure were suggested correspondent to specific structure damage degree of each equipment category.

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