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Comprehensive risk assessment and management of petrochemical feed and product transportation pipelines

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ABSTRACT

Complete information is needed for comprehensive risk assessment and management of pipelines. However, obtaining information using quantitative risk assessment (QRA) (probabilistic model) is not readily possible. Thus, in this research, using probabilistic and indexing models, an algorithm is developed, which overcomes most of the limitations of the models, and is an appropriate technique for the comprehensive risk assessment and management of pipelines. For this reason, 60 feed and product pipelines of the Mahshahr Petrochemical complexes were evaluated and chlorine pipeline was selected based on high-hazard distances for risk analysis. Furthermore, the relative risk indices were also determined in all parts of the pipeline. The failure rate of the pipeline was assessed on the basis of different failure causes. Heavy Gas Dispersion Model developed by ALOHA software was used for the consequence analysis of chlorine gas in different concentrations. Subsequently, the results of the relative risk assessment indices were used as an adjusting factor to correct the pipeline failure rate and to develop an algorithm for the comprehensive risk assessment technique. Finally, sensitivity analysis of the algorithm was carried out. The present algorithm enables the identification of most of the pipeline failure causes. Application of historical incident data is not only important in risk management and emergency response plans, but is also helpful in evaluating the risk by using acceptable risk criterion, such as "as low as reasonably practicable" (ALARP).

1. Introduction

The petrochemical special economic zone (PETZONE) that lies in the northern coast of the Persian Gulf and expands over an area of 2000 hectares in the southwestern city of Mahshahr, houses several petrochemical facilities. Feed and product pipelines of the petrochemical complexes have been extensively constructed in this region, to transport very toxic and inflammable chemicals that pose serious hazards to the PETZONE. Therefore, risk analysis of the pipeline networks is essential for emergency response planning (ERP) and risk management.

The three general types of risk assessment models are matrix, probabilistic, and indexing models, each having its own strengths and weaknesses. In this research, quantitative risk assessment (QRA) (probabilistic model), which is the most rigorous and complex risk assessment model, has been employed. Often, clear concise data are not readily available to satisfy the needs of the user of QRA. Accident, releases, and exposure data are representing a wide variety of circumstances. Most often, they do not completely represent the circumstances specific to the situation being evaluated, and modifications may be needed to reflect such conditions (CCPS, 1995). In addition, sometimes, widely differing results may be obtained from "duplicate" PRAs (probabilistic risk assessments) carried out on the same system by different evaluators (Muhlbauer, 2004). On the other hand, indexing models that apply the criterion of strength, such as scoring each pipeline section based on all its attributes, have been employed for determining the adjusting factors and overcoming the problems mentioned earlier.

As risk assessment of all feed and product pipelines for ERP is very difficult, the use of Dow's fire and explosion index (AIChE, 1994b) or the chemical exposure index (CEI) (AIChE, 1994a) is suggested to achieve relative ranking of the pipelines as well as

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selection of hazardous pipelines for additional risk analysis. After selecting the most hazardous pipeline, we calculated the fatal concentrations of the toxic cloud by probit equation (CCPS, 2000), and used the Heavy Gas Model developed by ALOHA software (NOAA, 1999) to determine the fatal length. For the consequence analysis of the pipeline rupture, we used the guidelines for chemical transportation risk analysis (CCPS, 1995). However, as most of the collected data referred to incidents in natural gas and oil pipelines (crude oil and oil products) and only a few referred to releases of ammonia, chlorine, and hazardous liquids and gases (Papadakis, 1999), the generic frequency data for the critical events were used to determine the failure rates (Delvosalle, Fievez, & Pipart, 2004). Finally, to make an accurate assessment of the factors that mostly affect the pipeline failures, the relative risk model (Muhlbauer, 2004) was proposed as an adjusting factor to correct the pipeline failure rate and to develop a comprehensive risk assessment and management algorithm.

2. Description of PETZONE feed and product pipelines

Feed and product pipelines of PETZONE with 285,364-inch diameter and a piping number of more than 60, transport very toxic and inflammable chemicals, such as chlorine, ammonia, butadiene, etc. Majority of these pipelines are placed above the ground on pipe racks in areas near the road or highway. The pipelines transport chemicals between the petrochemical complexes or transfer petrochemical feed and products to and from the jetty or other facilities (Fig. 1). The expansion of the pipelines in the area poses serious hazard to the PETZONE. In the past, few accidents have occurred in the PETZONE pipelines for different reasons—e.g., owing to various activities during the construction stage. Hence, risk assessment of the pipelines is necessary for risk management and ERP.

3. Comprehensive risk analysis of pipelines

The QRA is one of the most credible risk assessment techniques; however, the lack of sufficient historical data adaptable to the present situation requires the adjustment of QRA results. Besides, insufficient information makes the risk management with this technique difficult. Therefore, use of QRA along with relative models is necessary for a comprehensive risk assessment. In this study, we identified the PETZONE feed and product pipelines network for comprehensive risk assessment (Fig. 2). Subsequently,

Fig. 1. View of PETZONE feed and product pipelines.

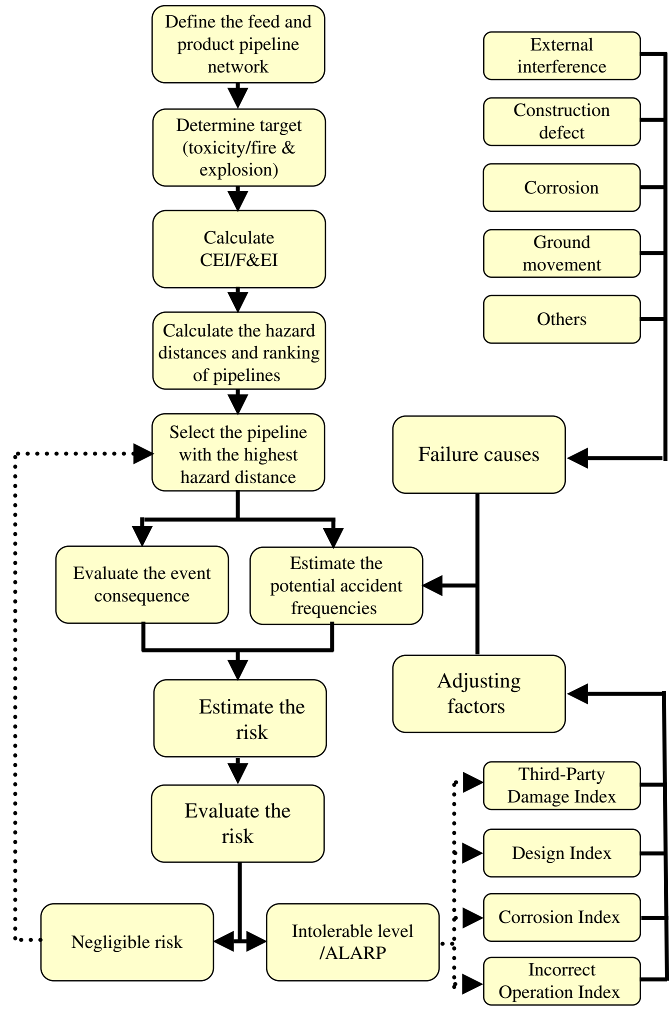

Fig. 2. Comprehensive risk assessment and management flowchart of the feed and product pipeline network.

the CEI was calculated for all pipelines. Pipelines with CEI values > 200 were selected for the determination of hazard distance (HD) and for the ranking of the pipelines. After the ranking, the pipeline with the highest HD was selected for additional risk analysis. Subsequently, we estimated the potential accident frequencies using failure causes and adjusting factors, and then evaluated the event consequence. Comprehensive risk assessment results were determined using accident frequencies and event consequences, and were evaluated with the ALARP criterion.

3.1. Relative ranking of pipelines

As there are more than 60 pipelines in the complex containing hazardous chemicals, the risk analysis of these pipelines is very difficult. Therefore, we used the CEI, developed by the Dow Chemical Company, to determine the longest life-threatening distances and to select the most dangerous pipeline. The CEI is a simple method of ranking the relative acute toxicity hazard threats to people within the chemical plants and neighboring communities from possible chemical release incidents. First, the scenario selection process for determining the airborne release rate was standardized. Airborne quantity (AQ) for a gas release was estimated based on a sonic gas flow-rate equation, while the AQ for a liquid spill was determined by what happens to the liquid as it leaves the pipe. If the liquid flashes to a high degree, then the AQ is the discharge rate from the pipeline. However, if the liquid flash is low enough to allow pool formation, then the AQ is the gas flow resulting from the flash plus the AQ that evaporates from the pool surface. Finally, as the tendency of the liquid to flash becomes small, the AQ becomes the rate of evaporation from the pool surface. The second stage involves the calculation of the CEI value and HD using the determined value of AQ and the Emergency Response Planning Guideline (ERPG) values published by the American Industrial Hygiene Association. In this study, the CEI and HD were calculated for 60 pipelines with different diameter sizes, and a decision was made based on HD for ERPG-3 concentration. Fig. 3 illustrates the HD for 10 pipelines that had CEI $>$ 150 (based on CEI methodology, a CEI $>$ 200 will require a further risk review). The 8-inch-diameter chlorine pipeline characterized by 2.1-bar pressure and 3468-m length showed the highest HD of 1623 m, and this pipeline was selected for further analysis.

3.2. Adjusting factor

Based on the chemical transportation risk analysis guidelines, it is essential that failure rate be adjusted with respect to wall thickness, surveillance system, right-of-way condition, and other related factors. However, there is no specified criterion for determining the different factors on pipeline failure. Hence, in this study, the Relative Risk Model was used, not only for the reasons mentioned earlier, but also to obtain comprehensive information for inspection, maintenance, modification, or risk management of the petrochemical feed and product pipelines. The Relative Risk Model indices from the *Pipeline Risk Management Manual* by Muhlbauer (Fig. 4) were an excellent reference on determining the adjusting factor for pipeline risk analysis. The indices of failure causes used in this figure were the third-party damage index (TPDI), corrosion index (CI), incorrect operation index (IOI), and design index (DI).

3.2.1. Third-party damage index

Third-party damage or outside forces as a failure mode refers to any accidental damage done to the pipe because of activities of personnel not associated with the pipeline. Some possible variables used in assessing the potential for third-party damage on a typical transmission pipeline are as follows:

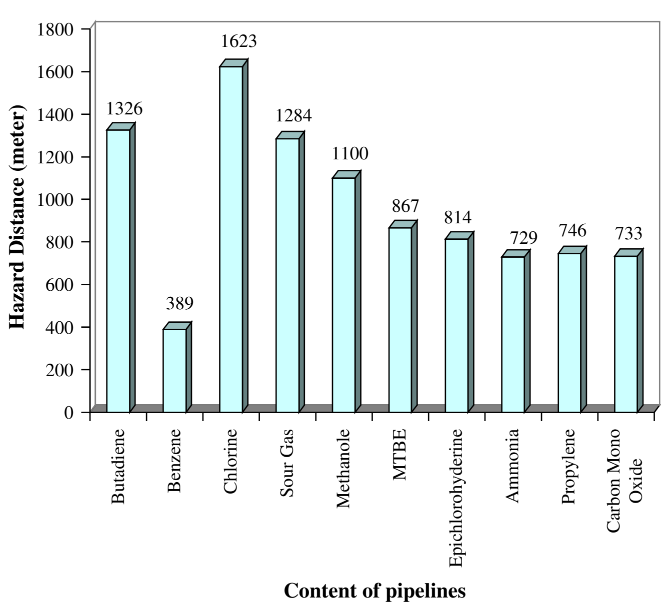

Fig. 3. Hazard distance based on ERPG-3 for 10 pipelines with highest CEI values.

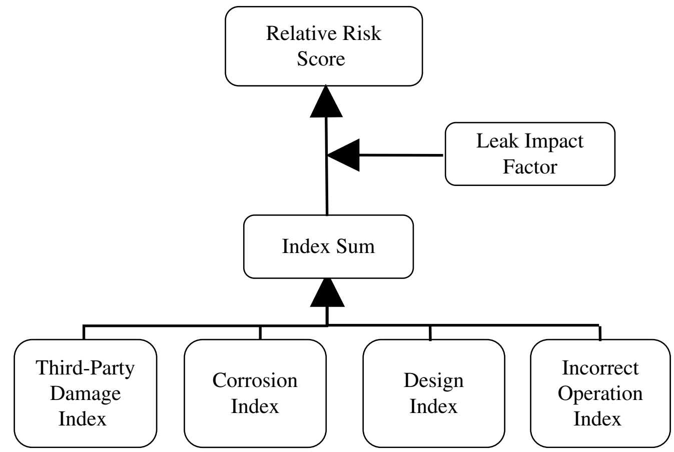

Fig. 4. The relative risk model (Muhlbauer, 2004).

- Minimum depth of cover
- Activity level
- Above-ground facilities
- Line locating
- Public education programs
- Right-of-way condition
- Patrol frequency

3.2.2. Corrosion index

The potential for pipeline failure caused by corrosion is the most familiar hazard associated with pipelines. The CI focuses on the loss of metal from pipe, which also includes various corrosion degradation mechanisms. In this study, the CI values were assessed based on atmospheric corrosion (atmospheric exposure, atmospheric type, and atmospheric coating), internal corrosion (corrosive ability of the product and prevention), and subsurface corrosion.

3.2.3. Incorrect operation index

The IOI (human error potential) assesses the potential for pipeline failure caused by errors committed by the pipeline personnel in all the phases of the project. The phases considered include design (based on hazard identification, maximum operational pressure (MOP) potential, safety systems, material selection, and checks); construction (inspection, materials, jointing, backfill, handling, and coating); operation (procedures, supervisory control and data acquisition (SCADA) or communications, drug testing, safety programs, surveys/maps/records, training, and mechanical error prevention); and maintenance (documentation, schedule, and procedures).

3.2.4. Design index

The DI not only looks at the potential for an active failure mechanism, but also at the ability of the pipeline to withstand failure mechanisms. For assessing DI, the following criteria were evaluated:

- Safety factor
- Fatigue
- Surge potential
- Integrity verification
- Land movement

In this study, the chlorine pipeline with 3468-m length was divided into 100-m sections and the indices mentioned earlier were assessed throughout the pipeline.

In Muhlbauer's Relative Risk Model, the indices were given weights from 0 to 100 (i.e., the greater the score, the better the condition). However, in the quantitative risk analysis, based on CCPS (1995), BG Transco Data (Mather, Blackmore, Petrie, & Treves, 2001), and Tailor (1994), the adjusting factors for pipeline characteristics, such as wall thickness, surveillance system, and right-of-way condition were nearly in the 0–1 range, so that the lower adjusting factor shows better condition and lower risk. Therefore, to use relative risk indices as an adjusting factor, the scores obtained were converted into the adjusting factor range using the following equation:

$$F = 1 - \frac{\mathrm{RRI}}{100} \tag{1}$$

where F is the adjusting factor used for TPDI, DI, and IOI, and RRI is the relative risk index of TPDI, DI, and IOI. On the other hand, based on the accidental risk assessment methodology for industries (ARAMIS) in the framework of the Seveso II directive, the frequencies are provided for an environment where no corrosion is expected. When there is a potential risk for a significant leak (e.g., corrosion), then a multiplicative correction factor of 3–10 is applied, depending on the situation (Delvosalle et al., 2004). To use CI as an adjusting factor, the obtained score is converted to the adjusting factor range according to the equation:

$$F_{\mathrm{CI}} = 10 - \frac{\mathrm{CI}}{10} \tag{2}$$

where F_{CI} is the adjusting factor used for CI. Therefore, if F_{CI} is <3 owing to negligible corrosion, CI is not required as an adjusting factor.

3.3. Failure frequency

Majority of the collected data refer to incidents in natural gas and oil pipelines (crude oil and oil products), and only limited data refer to releases of ammonia, chlorine, and other hazardous liquids and gases (Papadakis, 1999). Thus, this makes it nearly impossible to precisely relate the collected data to the pipelines studied. Therefore, generic frequency data for the critical events in ARAMIS methodology was used, owing to similar condition in the PETZONE pipelines, to determine pipeline failure frequencies, depending on the pipe diameter and hole size. The ARAMIS was a new European project initiated in January 2002, and planned for a 3-year period. In addition, the failure rates based on failure causes and hole sizes were estimated simply from the historical data of the European Gas Pipeline Incident Data Group (EGIG, 1999). Thus, the frequencies of failure depending on hole sizes and failure causes for an 8-inch chlorine pipeline were obtained (Table 1).

Table 1
Frequencies of failure, depending on hole size and failure cause, for an 8-inch-chlorine pipeline (in 1000 km-year) (Delvosalle et al., 2004 & EGIG, 1999).

Hole size	Failure cause				Total failure causes
	External interference	Construction defects	Ground movement	Others	
Small	0.632	0.651	0.087	0.38	1.75
Medium	0.7	0.12	0.04	0.06	0.92
Large	0.087	0.01	0.02	0.001	0.118
Total hole sizes	1.419	0.781	0.147	0.441	2.788

As failure causes presented by the EGIG were not adapted completely with relative risk indices, to obtain the adjusting factor to be used in the algorithm, we used the following equations:

$$F_{\mathrm{EI}} = F_{\mathrm{TPDI}} \times F_{\mathrm{DI}} \tag{3}$$

where F_{EI} is the adjusting factor for external interference, F_{TPDI} is the adjusting factor obtained by the use of TPDI, and F_{DI} is the adjusting factor obtained by the use of DI.

$$F_{\mathrm{CD}} = F_{\mathrm{IOI}} \times F_{\mathrm{DI}} \tag{4}$$

where F_{CD} is the adjusting factor for construction defects, F_{IOI} is the adjusting factor obtained by the use of IOI, and F_{DI} is adjusting factor obtained by the use of DI.

$$F_{\mathrm{C}} = F_{\mathrm{CI}} \tag{5}$$

where F_{C} is the adjusting factor for corrosion and F_{CI} is the adjusting factor with respect to CI.

$$F_{\mathrm{GM}} = F_{\mathrm{DI}} \tag{6}$$

where F_{GM} is the adjusting factor for ground movement and F_{DI} is the adjusting factor with respect to DI.

$$F_{\mathrm{O}} = 1/4(F_{\mathrm{DI}} + F_{\mathrm{IOI}} + F_{\mathrm{CI}} + F_{\mathrm{TPDI}}) \tag{7}$$

where F_{O} is the adjusting factor for others.

Moreover, if corrosion is negligible, then F_{CI} is removed from the equation and the following equation is substituted:

$$F_{\mathrm{O}} = 1/3(F_{\mathrm{DI}} + F_{\mathrm{IOI}} + F_{\mathrm{TPDI}}) \tag{8}$$

3.4. Lethal concentration

The HD determined for ERPG-3 concentrations by the CEI method was very high and was nearly impossible to use it in ERP, especially in an industrial area. However, using fatal concentration was a very practical approach. Furthermore, to estimate the number of people affected, the probit methodology was used. The probit scale is a useful tool for measuring the expected percentage of death at a specified location. For our study, the probit is expressed as (CCPS, 2000):

$$Y = k_1 + k_2 \ln(c^n t) \tag{9}$$

where Y is the probit value; k_1, k_2, and n are the parameters dependent on the toxicity or harmful nature of the hazard (for chlorine gas, $k_1 = -8.29$, $k_2 = 0.92$, and $n = 2$, respectively); c is the concentration in parts per million, and t is exposure time in minutes. Table 2 shows the fatal concentration for the chlorine pipeline.

3.5. Modeling of toxic cloud dispersion

For the modeling of chlorine gas dispersion, the Heavy Gas Model was used with the ALOHA (Areal Location of Hazardous Atmosphere) program prepared by the U.S. Environmental Protection Agency (NOAA, 1999). The ALOHA is an emergency response model primarily intended for rapid deployment by

Table 2
Fatal concentrations for the chlorine gas pipeline.

LC99.9	1299 ppm
LC99	859 ppm
LC50	242 ppm
LC1	68 ppm

responders, as well as for using in emergency preplanning. It incorporates source strength as well as Gaussian and Heavy Gas Dispersion Models, and an extensive chemical property library. More than 700 pure chemicals are included in ALOHA's chemical library. The ALOHA model only releases and disperses pure, non-reactive chemicals. It neither accounts for terrain steering or changes in the wind speed and horizontal direction, nor does it model particulate dispersion. Furthermore, it does not account for the initial positive buoyancy of a gas escaping from a heated source. In this research, we chose "open country" for ground roughness—in this condition, not only threat zone will be longer than "urban or forest" ground roughness, but it will also be better for reliable ERP in PETZONE. Also, the atmospheric data, such as wind velocity, wind direction, and stability classes, which were established by the Bandar Mahshahr meteorological data from 1987 to 2005 (IRIMO, 2006) were used. The results of the data analysis showed that the velocity of the prevailing wind was 6 m/s in the NW direction, while the stability classes were 31.9% in D class, 41.2% in E class, and 26.9% in F class. For the purpose of ERP, the threat zones for the fatal concentrations in D and F classes were prepared (Figs. 5 and 6).

The fatal lengths of the concentrations defined, in this study, by the distance of the lethal toxicity probability in the vicinity of the chlorine pipeline rupture are presented in Table 3.

4. Pipeline comprehensive risk analysis (PCRA) algorithm

The QRA is presented in different forms (such as individual risk and societal risk). The development of pipeline comprehensive risk estimates, such as individual risk contours or societal risk curves, requires a significant number of calculations.

The calculation of individual risk at a geographical location near a plant assumes that the contributions of all incident outcome cases are cumulative. Thus, the total individual risk at each point is equal to the sum of all the individual risks at that point and all the incident outcome cases associated with the plant (CCPS, 2000). Therefore, the total pipeline comprehensive individual risk at the geographical location x, y, $PCIR_{x,y}$, is equal to the sum of the pipeline comprehensive individual risks at that point and each failure cause, l, associated with the pipeline, $PCIR_{x,y,l}$:

$$PCIR_{x,y} = \sum_{l=1}^{w} PCIR_{x,y,l} \quad (10)$$

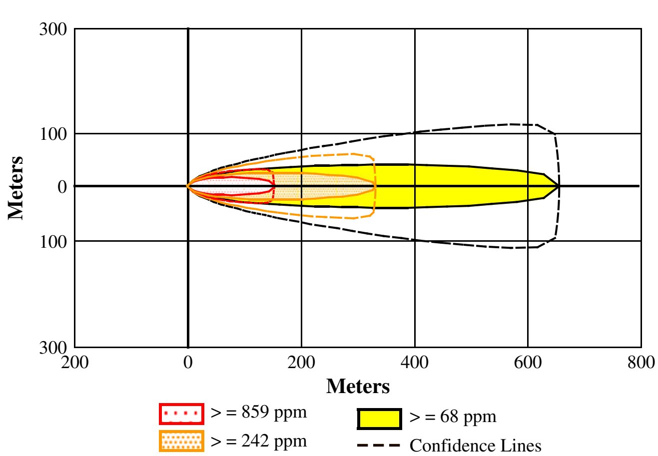

Fig. 5. Threat zone in D stability class for the chlorine gas pipeline.

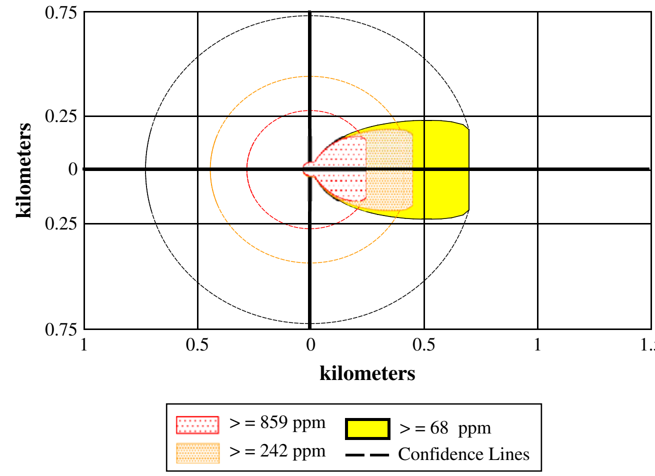

Fig. 6. Threat zone in F stability class for the chlorine gas pipeline.

In other words, by the use of individual risk equation in chemical transportation risk analysis and adjusting factor described earlier, the pipeline comprehensive individual risks at that point of each failure cause will be:

$$PCIR_{x,y,l} = \varphi \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{l=1}^{w} R_{i,l} \cdot F_{i,l} \cdot L_{i,j} \cdot W_j \cdot \sum_{k=1}^{s} P_{i,j,k} \quad (11)$$

where φ is the failure frequency in km-year; $R_{i,l}$ is the release probability for release size i associated with the release cause l; $F_{i,l}$ is the adjusting factor for release size i associated with the release cause l; $L_{i,j}$ is the length of release location zone j for release size i; W_j is the probability that the wind blows in the direction of concern for release location zone j; and $P_{i,j,k}$ is the probability of a fatality at location x,y, given that incident outcome k occurs in release location zone j with appropriate wind direction and a given release size i.

5. Results of comprehensive risk analysis for the chlorine pipeline

The results of comprehensive individual risk for the chlorine pipeline before recommendation are shown in Fig. 7. In this stage, the external interference and other causes of failure were in the ALARP region, but the ground movement and construction defects were in the negligible risk region. As the risks of different pipeline failure causes are cumulative, recommendations for all parts of the pipeline were provided to reduce the risk. Some recommendations for risk mitigation of the chlorine pipeline are as follows:

- Supervisory and control of third-party activities in areas adjacent to the pipeline;
- Protection of the pipeline by the use of appropriate risk mitigation methods, such as distance, barriers, etc.;
- Installation of pipeline indicators, such as product identification signs to prevent possible damage;

Table 3
Fatal length (m) for the chlorine pipeline rupture.

Stability class	Lethal concentration			
	LC1	LC50	LC99	LC99.9
D	654	331	151	116
E	721	354	166	129
F	703	413	248	211

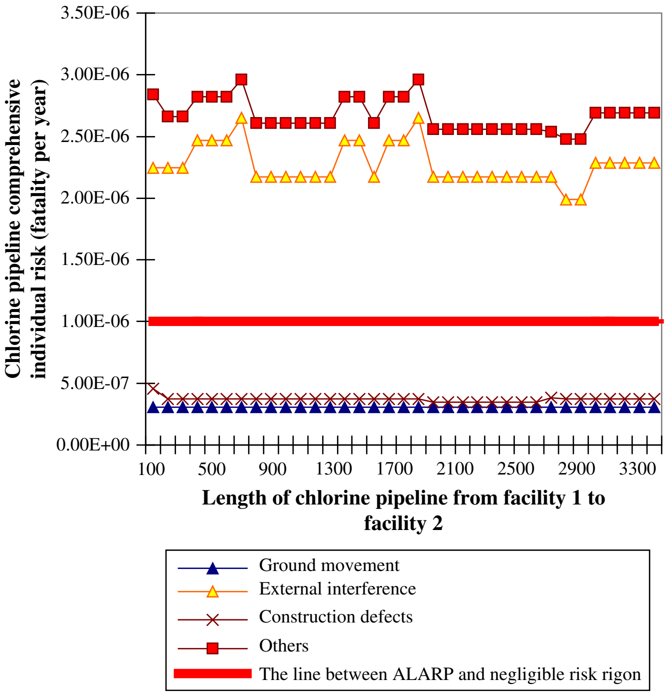

Fig. 7. Changes in PCIR with the length of chlorine pipeline before recommendation.

- Undertaking public education programs;
- Installing safety systems and remote control throughout the length of the pipeline;
- Installing supervisory control and data acquisition (SCADA) systems;
- Preparing operational procedures and enforcing their use in all pipeline activities;

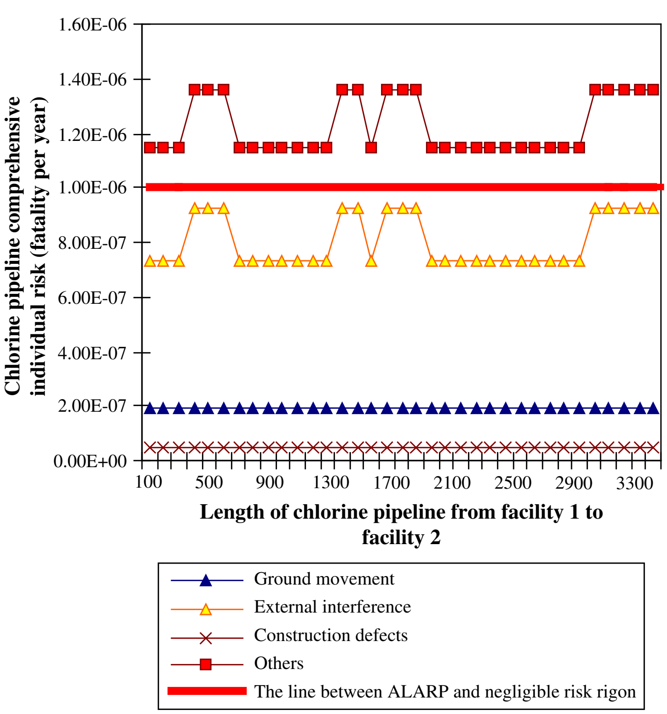

Fig. 8. Changes in PCIR with the length of chlorine pipeline after recommendation.

Table 4
Sensitivity analysis results.

Failure cause	Adjusting factor			Individual risk		Risk mitigation rate (%)
	Index	Before	After	Before	After	
External interference	TPDI	0.61	0.32	2.2467E-06	7.3662E-07	67
	DI	0.08	0.05			
Construction defects	IOI	0.38	0.06	4.5516E-07	4.4917E-08	90
	DI	0.08	0.05			
Ground movement	DI	0.08	0.05	3.0497E-07	1.9060E-07	38
Others	TPDI	0.61	0.32	2.8489E-06	1.1445E-06	60
	DI	0.08	0.05			
	IOI	0.38	0.06			

- Enhancing a safety and health program, and following good housekeeping practices in areas adjacent to the pipeline;
- Preparing appropriate access to inspection and maintenance of pipelines;
- Planning and carrying out complete training courses for pipeline employees.

The outcomes of comprehensive individual risk after recommendation are presented in Fig. 8. In this phase, all the failure causes remain in the negligible risk region and only the other failure causes exist in the ALARP region. In other words, based on ALARP principle, risk-taking is acceptable owing to desired outcomes and benefits.

6. Sensitivity analysis

Sensitivity analysis generally refers to an evaluation of the relative change in results owing to a change in the inputs. This analysis was carried out to determine the effect of incorporating the suggested recommendations on system safety. The results of the analysis are shown in Table 4. It can be observed from the table that the changes in the relative risk indices before and after the recommendations are completely correlated with the changes in the pipeline comprehensive individual risk.

7. Conclusions

The 60 feed and product pipelines in the PETZONE represent non-typical sources of major accident risks. Therefore, we developed a PCRA technique using the relative risk model (index model) and absolute risk model (probabilistic model). The algorithm developed for the identification of the most frequent failure causes of the pipelines and application of historical incident data not only significantly influences the risk management and ERP, but also allows evaluation of the obtained risk using acceptable risk criteria, such as ALARP.

Furthermore, the prepared flowchart for the comprehensive risk analysis of feed and product pipelines network mitigates the risk to acceptable degrees throughout the pipeline network.

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