3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

Integrating multiple risks to aid the navigation of industrial plant workers during seismic events

Davit Shahnazaryan – IUSS Pavia, Italy, E-mail: davit.shahnazaryan@iusspavia.it

Gerard J. O'Reilly – IUSS Pavia, Italy, E-mail: gerard.oreilly@iusspavia.it

Paolo Dubini – EUCENTRE Foundation, Pavia, Italy, E-mail: paolo.dubini@eucentre.it

Filippo Dacarro – EUCENTRE Foundation, Pavia, Italy, E-mail: filippo.dacarro@eucentre.it

Alberto Gotti – EUCENTRE Foundation, Pavia, Italy, E-mail: alberto.gotti@eucentre.it

Sergio Mascetti – Università degli Studi di Milano, Italy, E-mail: mascetti@di.unimi.it

Emanuele Brunesi – EUCENTRE Foundation, Pavia, Italy, E-mail: emanuele.brunesi@eucentre.it

Annalisa Rosti – EUCENTRE Foundation, Pavia, Italy, E-mail: annalisa.rosti@eucentre.it

Davide Silvestri – EUCENTRE Foundation, Pavia, Italy, E-mail: davide.silvestri@eucentre.it

Abstract: During seismic events, industrial plants are prone to disasters induced by the damage to their components and subsequent release of possibly harmful material. This risk of structural and non-structural element damage, as well as the potential release of toxic materials, compels to safeguard workers within an industrial plant. This study presents an overview of the ROSSINI project demonstrating its objectives towards the implementation of a risk-aware navigation system. Here, structural and environmental health risks are integrated and measured as part of an integrated risk identification and evaluation module. The combined risk is used for the development of risk-aware navigation for the safe egress of workers from a plant. For this purpose, a case-study industrial plant layout is considered for the application and demonstration of the risk-aware navigation system comprising several structural buildings as well as non-structural component groups, including liquid storage tanks, piping systems and chemical storage vessels. The study discusses the component aggregation and distribution inside the plant facility and the importance of safeguarding workers during and following a seismic event through the application of a risk-aware navigation system.

Keywords: risk-aware navigation, industrial plants, structural risk, environmental risk.

1. Introduction

The complexity of industrial plants consisting of multiple buildings, equipment, and components, contributes to their vulnerability to earthquakes. Those components and buildings are generally tied together through various operations, which adds to the complex nature of processes within the plant. Additionally, many processes are carried out in parallel, therefore, if one fails, the rest of the connection can also be at risk. Industrial facilities are thus susceptible to natural hazards triggering technological disasters (NaTech) that can cause fires, explosions, and the release of toxic substances in the industrial facility. Numerous failures leading to casualties in industrial plants have been documented following past earthquakes. Examples include the severe damage to the Tupras refinery because of the Izmit Earthquake in Turkey (Erdik and Durukal 2000), where following the structural collapse of a concrete chimney, a large volume of dangerous substances were released and surrounding equipment was damaged. Similarly, Suzuki (2008) exemplifies destructive damage to industrial areas leading to long-term fires in petroleum refineries following the Niigata Earthquake in 1964 (Figure 1); damage of power stations, lifeline systems following the Tokachi-Oki Earthquake in 1968; damage to piping and large tanks due to sloshing following the Miyagi Ken-Oki Earthquake in 1978, among others. More recently, after the L'Aquila Earthquake in 2009 in Italy, severe damage was documented in a chemical facility located in the industrial area of Bazzano-Paganica, where three silos storing polypropylene beads suffered severe damage (Grimaz 2014); the silos collided with the adjacent warehouse resulting in partial crushing of the concrete walls. Additionally, pipelines transferring gas were damaged, releasing gas, which while not resulting in any harm, are indicative of a potential hazard to life safety in future earthquakes.

Figure 1. The conflagration of the petroleum complex following the 1964 Niigata earthquake (Suzuki 2008).

Similarly, in 2012, following the sequence of Emilia earthquakes in Italy, large damage to industrial facilities and equipment highlighted the risk associated with the release of dangerous substances, like gas or chemicals as a direct consequence of pipelines rupturing or storage tanks damaging. Some of the equipment damage was a direct consequence of structural systems failing, therefore highlighting that simultaneous damage of different components can be amplified leading to the failure of safety systems or the generation of multiple accident chains. Collapsing components, as well as the release of toxic substances, can lead to both significant short term (acute) and long term (chronic) impacts on human health potentially leading to death. As highlighted in Grimaz (2014), despite the moderate intensity of the earthquake in Emilia, the severity of damage to industrial facilities and lifelines, including those within the facility, must not be disregarded.

The observed severity of damage to industrial facilities consisting of structural and environmental consequences of various typologies necessitates the development of safety measures. Passive control techniques may be integrated within the buildings for their seismic protection, such as base isolation or other dissipative systems (Christopoulos and Filiatrault 2006; Spencer and Nagarajaiah 2003). Despite the importance of implementing such systems, following a seismic event the safe egress of workers remains a priority. For that purpose, this study works towards developing a risk-aware navigation system, where the risk is defined as the combination of risks due to structural damage and the potential harm due to release of dangerous substances. The goal of the study will be to introduce a combined risk metric used within a risk-aware navigation system to guide workers towards emergency exits. The navigation system, implemented in a mobile app, computes the best route (i.e., the route that minimises the risk) from the current worker's position to all safe exits and selects the best route among them. The information system is formed by three main components:

sensors; a server; and the mobile client running the navigation app. The risk identification and evaluation (RIE) modules are implemented in the server that updates in real time the client when a change is detected in the estimated risk. The app then computes the route with minimum risk and navigates the user accordingly. For that purpose, a case-study plant layout was devised containing multiple process equipment, non-structural components, as well as buildings of different typologies for the demonstrative purpose.

2. Case study industrial plant

2.1. Plant layout

A case study industrial plant layout was devised to be utilised for the demonstration of the risk-aware navigation system that utilises the integrated risks. Based on past literature analysing the seismic risk of industrial plants (Kalemi et al. 2019; Caputo et al. 2020), several industrial plant processes were identified and considered within the case study plant. Despite providing sufficient details regarding description and component typologies, the relative distribution of the plant's components and equipment was often lacking. Based on available plant layouts of several industrial facilities located in Italy, which were mainly petrochemical processing plants, the relative positions of the selected components and buildings were decided based on engineering judgement to provide a navigable area for a hypothetical worker (Figure 2). Additionally, the vulnerability of all components and buildings was identified as necessary for risk estimation and likely path identification of toxic materials released into the atmosphere. The case study plant consists of several buildings of various processes, multiple liquid storage tanks, storage vessels, piping arrangements as well as an electrical substation, each of which is associated with different vulnerabilities to seismic shaking. The emergency exits have been hypothesised as external environments towards which the worker is navigated to avoid any risk of potential harm within the industrial facility.

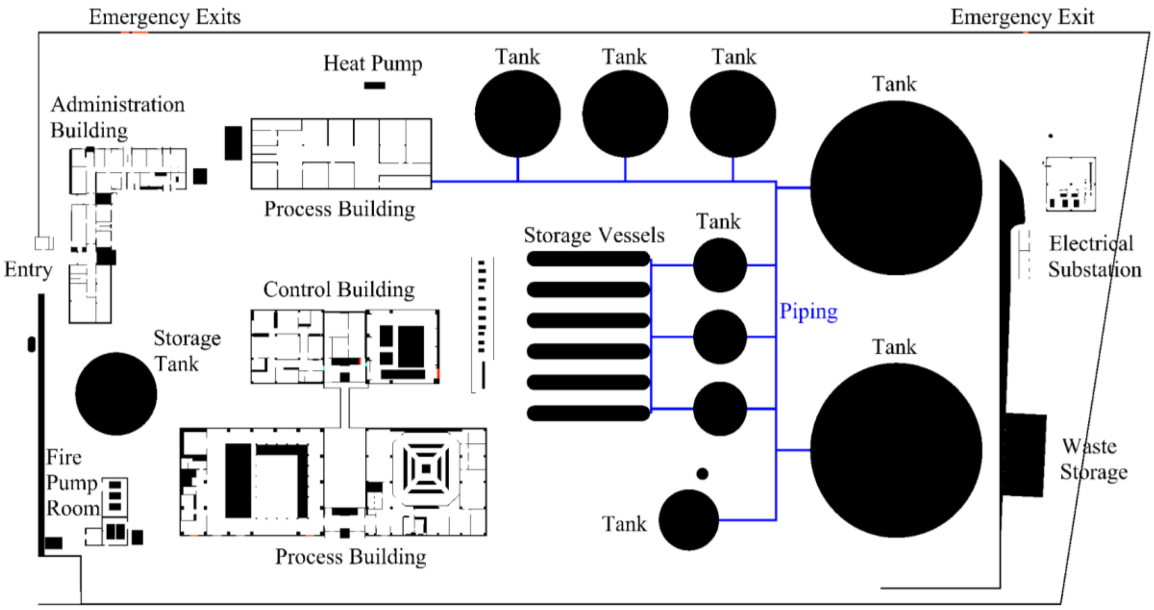


Figure 2. The case study industrial plant layout, where various vulnerable components have been identified.

2.2. Component description

All components and buildings within the plant are sensitive to an intensity measure (IM) of either peak ground acceleration (PGA) or spectral acceleration (SA), which are used for characterising the fragility functions. The damage states, consequences as well as descriptors of fragility functions of liquid storage tanks and buildings are provided in Table 1, for example. Similarly, fragility functions associated with process equipment and pipelines were adapted from the available literature (PEC 2017; FEMA 2003; Di Sarno and Karagiannakis 2020). The consequence descriptors and the estimated level of risk based on fragility functions and input IM associated with the earthquake allows the assignment of risk levels to be utilised within the risk-aware navigation system. Additionally, based on component location, an influence area defined as a vulnerable zone and described through debris fall is identified in the immediate vicinity of the component or the building dependent on its vulnerability. In case of damage, a risk value is assigned to the influence zone, which then also feeds the navigation system. Based on the available literature, debris of a collapsing reinforced concrete building with moment-resisting frames is assumed to be 85% of the total height of the building (Sediek, El-Tawil, and McCormick 2021). Based on engineering judgement, and in absence of available literature, the influence area of equipment and non-structural components, such as liquid storage tanks, was assumed to be 50% of the total height of the component. It is important to note that the assumed value is not meant to be referential but rather a layered demonstration of the complex nature of an application of the navigation system to consider different consequences.

Table 1. Description of damage states and consequences of liquid storage tanks and buildings located within the case study plant.

Component type	Damage state	Consequence
Liquid storage tanks	Excessive sloshing	Spillage of tank content/sinkage of floating roof
	Fracture/Yielding of base plate	Base plate failure/spillage of tank content (local collapse)
	Yielding of structural shell	Panel joint failure as a result of excessive deformities in the structural shell
	Uplifting	Damage to nozzles, causing the release of a potentially harmful substance
	Sliding	Damage to nozzles, causing the release of a potentially harmful substance
	Elephant foot buckling	Damage to structural shell
Multi-storey precast concrete structure (Control-process building)	Extensive damage	Severe damage to structural elements and in-plane damage of horizontal and vertical panels
	Near-collapse	Unseating of precast beam; loss of beam-column connection
	Collapse	Complete collapse of structural system
Non-ductile infilled moment-resisting frame structure (Process building)	Extensive damage	Severe damage to structural elements and in-plane damage of horizontal and vertical panels
	Near-collapse	30% of load bearing capacity attained with out-of-plane failure of infill panels
	Collapse	Complete collapse of structural system
Ductile bare MRF structure (Administration building)	Extensive damage	Severe damage to structural elements
	Near-collapse	30% of load bearing capacity attained
	Collapse	Complete collapse of structural system

3. Risk computation

Estimation of casualties from structures given a seismic event requires knowledge of fragility models relating to the collapse probability of structural and non-structural components within the industrial facility. Coburn and Spence (2002) observed that the number of casualties following earthquakes is related to the number of buildings being fully or partially collapsed. However, empirical fatality models tied to damage states do not explicitly account for the extent of the collapse. In that vein, Crowley et al. (2017) developed a semi-empirical framework for estimating fatality and consequence models for the estimation of a risk metric termed local personal risk (LPR). The LPR is a combination of the probability of dying inside and outside the building given collapse, which identifies the risk the building poses to a single person that is permanently located within or near a building. The risk metric is suggested to be tied to the building type, which is then used to rank buildings in terms of fatality risk. Jonkman et al. (2003) discussed several fatality risk metrics, including the individual risk (IR) defined as the probability of an average unprotected person, permanently present at a certain location, being killed due to an accident resulting from a hazard. The existing literature is predominantly targeted at casualty estimation based on the direct collapse of structural and non-structural components, either based on empirical or analytical models, and dependent on the location of a person with respect to the building. Within this study, the goal was to integrate past knowledge regarding consequence models due to collapse with potentially hazardous environmental factors. Additionally, the navigation system employed must be capable of estimating risk throughout the entirety of the plant at a given time assuming that a person is non-stationary.

The consequence model for fatality risk estimation by Coburn and Spence (2002) considers several factors, including the number of people inside the building at the time of a seismic event, and the percentage of people trapped by collapse, that are unable to escape. For what concerns the external risk, Taig and Pickup (2016) showed that the probability of dying outside is dependent on the debris falling, which is why an influence zone is identified for the components and buildings within the plant layout of this study. Additionally, instead of computing a probability of casualty based on the relative probability of being inside or outside, a more direct risk is computed as the location of a person within the plant is known at a given time. Once an earthquake occurs, the navigation system as an application installed on a worker's mobile phone will devise a least-risk path towards the emergency exits. The combined risk due to structural and environmental impacts will be computed for the entirety of the industrial plant area, as described below.

3.1. Risk levels

Environmental health RIE was developed, which uses risks associated with the possible release of toxic substances and its potential dispersion into the local environment. Before developing a sensible scheme for estimation of risks and their subsequent combination with structural RIE, attention should be directed towards existing literature and methods of computation of environmental and health risks. A recent study by Karagiannakis et al. (2022) developed an analytical framework to be implemented in the risk assessment of vulnerable equipment. The framework uses damage models and limit states for the supporting structure and piping separately. However, both types of components have similar levels of damage and consequence models. Additionally, they argue there is no well-accepted value correlating probability of release with actual damage state, while various studies (Salzano et al. 2003; Fabbrocino et al. 2005) analysing NaTech probability made conservative assumptions that following any substantial damage there is a release. In some cases, a release probability of either 0% or 100% was assigned for all damage states considered. However, as shown in Cooper (1997), a release can occur because of minor damage, and there is not a 100% release occurrence given that the unit has been damaged by an earthquake.

To account for past observations, Karagiannakis et al. (2022) assume discrete values of probability of release associated with different damage limit states of components. Similarly, in this study, 10 different health risk levels, analogous to the structural RIE levels, were devised, which can be grouped into 4 distinct and with increasing health severity consequences with different probabilities assigned to them. This was done to reflect the large spectrum of possible damage states confined within structural and environmental RIE as well as have a larger distinguishable spectrum of risk levels necessary for the risk-aware navigation system as opposed to using fewer risk levels, where a distinction between the risk of 30% and 50% is harder to make.

For the computation of structural risk, the collapse risk is computed for a given IM and collapse fragility function of the building and non-structural components. A choice was made to use specific collapse fragility function rather than using empirical data for the definition of fatality model factors presented in the literature, as the specific risk at any given location and time should be targeted to the safety of a single person, meaning that values related to trapping of workers under debris are irrelevant for the navigation purpose. Effectively, the trapped worker will be unable to escape, and alternative safety objectives and methods should be employed beyond the scope of this study. Analgous to the environmental RIE, ten structural risk levels are identified from 0 (no risk) to 9 (highest probability of risk of death). Risk levels from 1 to 3 are associated with a low to a high probability of risk of minor injury, which is assumed not to be related to the fragility functions of structural components. While levels from 4 to 9 are associated with risk of injury requiring hospitalisation to risk of death with increasing probability.

3.2. Structural RIE

The risk estimation methodology employed is illustrated in Figure 3. The collapse fragility function of vulnerable components follows a typical lognormal distribution function given in Eq. (1):

$$P[ds = DS|im] = \Phi\left(\frac{\ln im - \eta_{DS}}{\beta_{DS}}\right) \tag{1}$$

where η_{DS} is the median value and β_{DS} is the logarithmic standard deviation for a given damage state (DS). This evaluates the risk, or probability P, of the actual *ds* being realised for a given *im* value, which is obtained from accelerometer sensors installed at the plant. Using the collapse fragility function of each component, for a given level of shaking, a real-time estimate of the probability can be obtained within a structural RIE module. In the illustration shown in Figure 3, for a given IM of *iml*, the probability of collapse is around 35%, leading to an associated risk level of 5 and 2 for the inside of the building and the exterior influence zone, respectively. A similar approach is devised for non-structural components, like liquid storage tanks, where a circular influence zone following its shape is assumed. However, instead of considering the inside of a liquid tank, which is untraversable by a worker, the immediate vicinity is considered, and the influence zone is derived further away from the immediate vicinity.

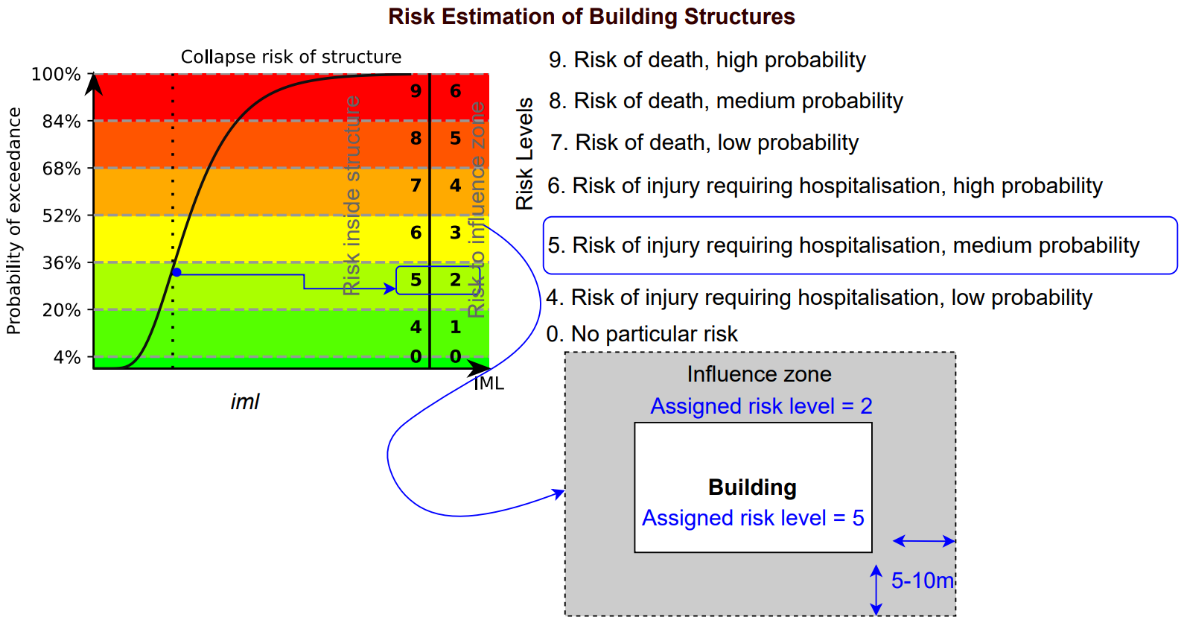


Figure 3. Structural response estimation using a collapse fragility function and associated risk metrics for the inside and outside (influence zone) of a hypothetical building.

3.3. Environmental health RIE

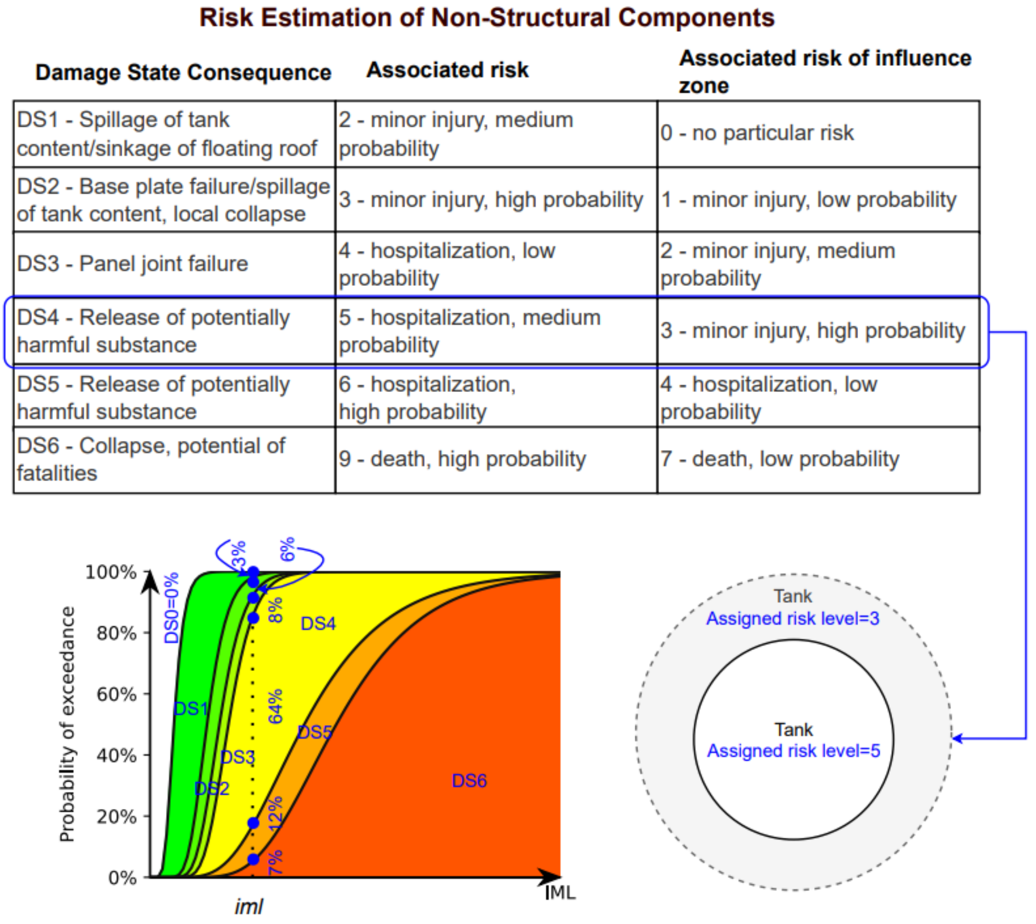
Figure 4 shows the environmental health risks for a liquid storage tank and corresponding consequence descriptions dependent on the release of toxic materials related to any vulnerable non-structural component. Here, instead of using a single damage state as for buildings, all damage states are considered. For a given IM of *iml*, the highest probability of 64% corresponds to damage state 4 (DS4) that the component is most likely to be in, meaning that a risk level of 5 and 3 are assigned to the liquid tank's immediate vicinity and the influence zone, respectively and the associated risk is closely tied to the damage state consequence description.

3.4. Combined RIE

Following the estimation of structural and environmental risk, a combined risk metric is identified and fed into the navigation system. It is important to note that structural and environmental health risk levels are not associated with the same IM level, meaning that depending on IM, the structural risk might be level 4, while due to the level of concentration of toxic substances released, the environmental health risk might be level 6, or the contrary. Additionally, it is highly unlikely to have environmental risks inside the administration building of Figure 2 independent of the IM level. As per the combination rule employed in this study, if health risk was assigned a level of 7, while the structural risk was assigned a level of 5, the combined risk to be used by the navigation system will be level 7, requiring hospitalisation; that is, the highest risk governs. However, the release of toxic materials is still tied to non-structural damage and the relationship should be appropriately defined through fragility functions or otherwise.

It is important to note that this mapping and combination of risks and consequences is not intended to be a novel proposal in terms of the absolute values used, but a general framework for how this can be handled in a simple manner and allow the overall goals of the ROSSINI project to be achieved. Future work should dedicate specific attention to refining this work.

While structural risk is closely tied to the type of building, its functionality and type of collapse mechanism, environmental risk, in addition to all these aspects, is associated with the probability of release of toxic substances. Additionally, the spatial distribution and relative placement of structural and non-structural components play a role in identifying safe pathways for workers to exit. Importantly, the final application is assuming the worker's ability to move freely, as in the case of trapping under debris, the risk is effectively 100% and other methods of safe extractions should be employed, which are not within the goals of the navigation system employed.



Risk Estimation of Non-Structural Components

Damage State Consequence	Associated risk	Associated risk of influence zone
DS1 - Spillage of tank content/sinkage of floating roof	2 - minor injury, medium probability	0 - no particular risk
DS2 - Base plate failure/spillage of tank content, local collapse	3 - minor injury, high probability	1 - minor injury, low probability
DS3 - Panel joint failure	4 - hospitalization, low probability	2 - minor injury, medium probability
DS4 - Release of potentially harmful substance	5 - hospitalization, medium probability	3 - minor injury, high probability
DS5 - Release of potentially harmful substance	6 - hospitalization, high probability	4 - hospitalization, low probability
DS6 - Collapse, potential of fatalities	9 - death, high probability	7 - death, low probability

Figure 4. Environmental risk estimation and risk level consequence descriptions on the example of a liquid storage tank.

4. Summary

This study has presented an overview of a framework needed for the integration of risks to aid the risk-aware navigation system in industrial plants. It uses a combination of structural and environmental health risk to guide workers exposed to harm during seismic events within an industrial facility to safe areas. A case study industrial plant containing multiple buildings, process equipment and non-structural components was described for the demonstration of the navigation system as part of the ROSSINI project. The risks associated with structural collapse and the release of toxic materials were classified into a proposed set of 10 distinct risk levels for integration between structural and environmental risks typically faced in these situations. Additionally, influence zones associated with each building typology as well as non-structural components were identified to account for possible debris fall or leakage. It was seen how the combined risk will then be computed and mapped into the case study layout, and the best route based on minimisation of maximum weight can be computed to guide the worker to a safe area. The navigation application along with a combined risk computation technique highlights an important step towards safeguarding workers in industrial plants during seismic activities.

Acknowledgements

This work has received support from the ROSSINI project, funded by INAIL (Italian national institute for workplace insurance) under the call "BRIC 2019". The contributions of both Alessandra Marino and Mariano Ciucci of INAIL in addition to Denis Sarigiannis, Al-Moauyed Bellah Nafeh and Volkan Ozsarac to the recent developments at various stages of the ROSSINI project are also gratefully acknowledged.

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