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Definition of a short-cut methodology for assessing the vulnerability of a territory in natural–technological risk estimation

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ABSTRACT

Natural disasters may be powerful and prominent mechanisms of direct or indirect release of hazardous material. The main aim of this work was to develop a short-cut methodology for assessing the vulnerability of a territory around an industrial plant in order to evaluate the Natural–Technological (NaTech) risk.

In particular the combined use of a global key hazard indicator with the key vulnerability indicator proposed in this work allows the measurement of the NaTech risk arising from the presence of a plant in a territory with given characteristics.

The proposed methodology was validated by comparing its results with quantitative risk analysis (QRA) results, involving earthquake-related NaTech events. The agreement of the results obtained with the proposed methodology with those arising from a much more detailed QRA carried out with the ARIPAR-GIS software in several case study supports the reliability of the proposed approach.

1. Introduction

Natural disasters may be powerful and prominent mechanisms of direct or indirect release of hazardous material [1]. In fact, when industrial sites are located in naturally hazard-prone areas, loss of containments and technological accidents may be induced by natural events, leading to the so-called NaTech (Natural–Technological) accidents [2].

In recent years, NaTech events have received a significant attention and several reviews on NaTech events have been published [3–11]. Recent examples of NaTech events are reported in the literature [12–15], but only a few works discuss approaches and methodologies necessary to face the problems they cause [2,14,16–18].

The most powerful tool to evaluate the impact that a natural event may have on industrial facilities is an extension of the classical quantitative risk analysis (QRA) to situations wherein an industrial accident is triggered by a natural event [10,19–22]. A limitation of the QRA is that it requires a large amount of resources in terms both of time and expertise; thus, short-cut methodologies for the assessment of industrial risks induced by natural events, easy to handle and capable of taking into account the most important phenomena that occur in a NaTech event, have been developed for screening purposes, i.e., for deciding when it is worthwhile to conduct a QRA [23,24]. However, such procedures do not account for the land use of the territory, giving information in some way similar to the individual risk through the computation of suitable Key Hazard Indicators, KHIs.

In this work, a simple methodology that can assess the vulnerability of a territory considering the characteristics of the population (density and distribution) and the presence of vulnerable centers (hospitals, schools, fire stations and so on) was developed with the aim of complementing the aforementioned KHIs, therefore leading to information in some way similar to the societal risk.

In fact, the combined use of the Global Key Hazard Indicator (KHI_G), obtainable through the methodologies previously developed [23,24], with the key vulnerability indicator (KVI) resulting from the application of the methodology herein presented, allows the measurement of the NaTech Risk level imposed by the presence of the plant in a territory with a given vulnerability. The developed procedure was validated by comparing its predictions with some QRA results involving earthquake-related NaTech events. The main use of the methodology developed in this work is to discriminate between high-risk situations, for which it is necessary to undertake a QRA and to provide risk mitigation measures, and low-risk situations, therefore avoiding wasting of resources using unnecessary expensive methods of Risk Analysis.

Moreover, the KVI can also be used (as a part of a decision support system) as a stand-alone screening procedure for the evaluation of the opportunity to establish a plant in a given territory.

2. Methodology

The seismicity (frequency and force which an earthquake occurs with) is a physical characteristic of the considered territory: the

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seismic hazard is defined as the probability that in a given area and in a certain interval of time an earthquake exceeding a defined threshold of intensity, magnitude, or peak ground acceleration (PGA) can occur. The predisposition of a structure to be damaged by an earthquake is defined vulnerability. The more a structure is vulnerable the more severe the expected consequences will be. The greater or lesser presence of assets at risk and, therefore, the consequent possibility of being subjected to a damage (in human lives, economic and cultural terms, etc.), is defined exposure (of life, of economic assets, of cultural heritage, etc.).

The seismic risk is therefore determined by the combination of these three factors: hazard, vulnerability and exposure; it is a measure of the damages, which, depending on the type of seismic activity, resistance of the structures, and human activities (nature, quality and quantity of exposed goods), can be expected in a given interval of time.

The presence in the considered territory of industrial plants, which hold and use hazardous substances for their activities, exposes the population and the surrounding environment to a given industrial risk. In contrast to the one related to natural events, the industrial risk is associated to human activities.

In particular, the industrial risk is associated with the release of hazardous substances which by their nature, quantity, or processing procedures can cause damage to the population and the environment, trough: fires, explosion and dispersion of toxic substances.

However it has to be distinguished between effects and consequences of an undesired event. For instance, an effect of fires is heat radiation, while a consequence is people burning.

A short-cut procedure should be easy to apply, require a small amount of resources and information and summarize, through a suitable key vulnerability index (KVI), the level of vulnerability associated to a given territory around an industrial plant.

Estimating the value of such KVI requires a simultaneous comparisons among different parameters, ranging from the characteristics of population to the presence of vulnerable centers [25]. Thus, a multi-criteria decision method is necessary to account for the different and often incommensurable effects of various parameters. Among the various approaches available, the analytical hierarchy process, AHP [26] has been used: it can support decision making by establishing alternatives within a framework of multi-weighted criteria. This method allows for choosing among various alternatives through binary comparison, that is, considering only two elements at a time. The idea of using the AHP in the context of NaTech risk analysis has been recently proposed [27], and two practical short-cut procedures for earthquake and flood related NaTech events have been developed [23,24]. In this case, the use of the AHP requires the identification of all the main elements that can determine the vulnerability of the territory; such elements, while covering all the relevant aspects, should be few and easy to evaluate.

All the details of using the AHP for developing a short-cut methodology in the field of risk analysis are not reported in the present paper since they are extensively discussed elsewhere [23]; here it suffices to mention that binary comparisons between elements must be established, and they must be arranged in a suitable hierarchy structured with the goal on top (in this case the KVI), with different branches. At the bottom of the hierarchy there are the alternatives that characterize the given territory. Through simple mathematical manipulations [26], from the normalized values assigned to the alternatives, it is possible to compute the KVI value on a 0–1 scale.

Hierarchy branches (structured at different levels) represent a breakdown into sub-goals. Considering that AHP is used to compare incommensurable elements, the rule used to define which elements could stay on the same level of the hierarchy is that they should answer to the same question.

The hierarchy proposed to evaluate the KVI is summarized in Fig. 1 where we can see that the branches are distributed over two levels, referring to the following two questions:

(1) Which kind of accident could happen into a plant?
(2) What are the elements that mostly influence the vulnerability of the area affected by NaTech event?

Once the hierarchy is defined, it is necessary to compare the relevance of the hierarchy branches at the same level; such comparisons are expressed as qualitative judgments, which can be made quantitative through the semantic scale of Saaty [26]. This procedure results in the definition of the matrix of pair-wise comparison for each level, from which it is possible to compute (through the normalized eigenvector of the matrix) the weight of each branch with respect to the others [26].

The relative importance among the different branches of the same hierarchy was defined on the basis of technical rules-of-thumb. For what concern the first question, we distinguished between two main phenomena, the “fire/explosion” and the “toxic dispersion” event: the assigned relative importance into the matrix of pairs' confrontations is 1, so the importance of the two criteria is equal. This lead to the same weight, equal to 0.5.

For what concern the second question the presence of vulnerable centers is statistically significant only when they involve a high number of people with respect to the population density; the threshold was set at 200 inhabitants per square kilometer. This value is consistent with the information contained in the Italian EPP guidelines [28] and it is obviously a simplification (consistent with the expeditious nature of the method) meaning that for highly populated areas the presence of vulnerable centers does not influence significantly the number of affected people and does not increase significantly the difficulty in managing the emergency. On the basis of this assumption the most important criterion is therefore the number of people present on the considered area which allows to assign the relative importance into the matrix of pairs confrontations equal to 5, “significantly more important”; this lead to weights respectively for the number of people and vulnerable centers equal to 0.833 and 0.167.

After having assigned a weight to each identified criteria, it is necessary to determine the input values of the hierarchy, which are the alternatives.

Due to the expeditious nature of the presented methodology, the choice of using the medium density of population at municipal level for computing the number of people is a reasonable choice if more detailed data are not available.

The elements to be considered as vulnerable can be identified according to the following parameters:

- difficulty of evacuation of weak and needy subjects (sick, children, elderly);
- difficulty to evacuate subjects in buildings higher than 5 floors or large aggregations of people in public places;
- higher vulnerability of outdoor activities respect to the indoor ones;
- lower vulnerability of the activities characterized by a short time of permanence of people, which results in less exposure to risk, compared to activities that require longer time of permanence.

A complete list of main vulnerable sites to be considered can be found in the work of Bonvicini et al. [29]; here just a few are listed for the sake of examples:

- hospitals, barracks
- schools of all levels