



## SI: Natech risk assessment of hazardous facilities

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Industrial plants are prone to be highly damaged when subjected to strong earthquakes. This has been clearly demonstrated in the aftermath of strong seismic events, which may trigger technological accidents usually termed natural-technological (NaTech) events. One of the most famous examples is represented by the Fukushima disaster during the 2011 Tohoku Earthquake. Nevertheless, the effort in developing new design/assessment methodologies is becoming more and more important as clearly proven by the rapid increase of the scholarly contributions on this topic. In this respect, Performance Based Earthquake engineering, which has seen rapid growth in the field of civil structures, can still be considered rather new in the world of industrial facilities because of the neuralgic role of the consequence analysis, necessary to quantify the individual or societal risk. Moreover, the recent activity on the second generation of Eurocodes—and in particular on EN1998:4 dedicated to industrial equipment like silos, storage tanks, chimneys, towers, and masts—makes urgent the identification of the most recent contributions on the topic.

This Special Issue, titled *Natech Risk Assessment of Hazardous Facilities*, promoted by the Guest Editors, Fabrizio Paolacci, Christoph Butenweg and Dimitrios Vamvatsikos, aims to bring together the latest methodologies and techniques for a reliable assessment of NaTech risk and resilience of hazardous facilities. Contributions come from researchers and industry professionals, strongly involved in the activity of Working Group 13 that is working on seismic assessment, design and resilience of industrial facilities within the European Association of Earthquake Engineering. A total 10 papers have been accepted that cover many of the key topics related to NaTech events and consequences in industrial facilities. In particular: (1) hazard issues in NaTech risk assessment, (2) Advanced methodologies for earthquake-related NaTech risk assessment, (3) Seismic analysis of critical non-structural components, (4) Design of safety barriers to control seismic risk of hazardous plants, (5) Performance-based design/assessment of

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hazardous industrial facilities, (6) Resilience of industrial facilities and neighboring communities.

In the first paper, devoted to topic 1 and titled “*The new seismic hazard model ESHM20 of Europe: Investigating the implications of the seismic design and risk assessment of major industrial facilities across Europe*”, by Ptilakis K., Butenweg C., Riga E., Apostolaki S., Renault F., a large-scale study of the impact of the potential adoption of the 2020 European Seismic Hazard model (ESHM20) on the design of new industrial facilities as well as on the potential seismic risk of existing plants at European level with respect to the national seismic codes is presented. Based on the conducted illustrative studies, the consequences of a potential adoption of the revised Eurocode 8 and ESHM20 hazard maps are discussed and summarized in view of the harmonisation process in Europe.

The second paper titled “*Risk-targeted seismic design of the freeboard for steel storage tanks equipped with floating roofs*” by Caprinuzzi S., Žižmond J., Dolšek M., and developed within topic 2, proposes an original method for the quantification of the loss of containment due to seismically-induced liquid overtopping of tanks with floating roofs, which is addressed by introducing a risk-targeted freeboard seismic design. The proposed practice-oriented procedure can be applied to new or existing tanks for which the freeboard was designed based on the tank wall height or liquid height, respectively. It combines the conventional seismic risk equation, and the code-based equation for the maximum vertical liquid displacement at the tank wall corresponding to the seismic action. Parametric studies were conducted to obtain insights into the sensitivity of risk-targeted freeboards to the design input parameters. A design procedure was also used to develop risk-targeted freeboard maps for Slovenia.

Given the attention that the scientific community is paying on topic 3, its growth is accelerating. In the industrial field the role of ancillary elements is recognized to be of vital importance because even a simple (nonstructural) failure could result in severe consequences. In this respect the third paper titled: “*Acceleration-sensitive ancillary elements in industrial facilities: alternative seismic design approaches in the new Eurocode*” by Kazantzi, A. K., Karaferis N. D., Melissianos V. E., Vamvatsikos D., undertakes a comparison study to investigate the seismic performance of ancillary elements in industrial facilities that are designed according to the regulations prescribed by the three design routes offered in the 2022 revised version of Eurocode 8. With respect to ancillary elements in the civil field, the design methodologies offered in Eurocode 8 – Part 4 (prEN 1998–4:2022) are less sensitive to uncertainty in the properties of the supporting structure and the ancillary elements and hence deliver design products that possess consistently safe seismic performance even in cases where a component finds its vibration period accidentally tuned to the period of the supporting structure.

Safety barriers is another critical aspect in designing new industrial facilities or mitigating the seismic vulnerability of existing ones. In this respect the fourth paper titled: “*Seismic vibration mitigation of steel storage tanks by metafoundations endowed with linear and bistable columns*” by Guner T. Bursi O.S., Broccardo M., a new mitigation strategy for seismic mitigation of typical storage tanks is proposed, where extreme loading conditions are considered by safe shutdown earthquakes. To protect the tank from strong earthquakes, finite locally-resonant multiple-degree-of freedom metafoundations were designed and developed; resonator parameters together with bistable columns were optimized by means of an improved time domain multiobjective optimization procedure. The performance of the optimized metafoundations was assessed by means of time history analyses and results were compared with a storage tank endowed with two rigid foundation solutions.

A group of four papers are devoted to topic 5. The fifth paper is titled “*The Generalized E-DVA Method: A New Approach For Multi-modal Pushover Analysis Under Multi-component Earthquakes With Local Variables Maximization*” by Lherminier O., Erlicher S., Huguet M., Civera, M., Ceravolo R., Barakat M.; it deals with a new pushover analysis approach for structures in hazardous plants subjected to seismic NaTech risk. The procedure applies a linear combination of modal load patterns, defined accordingly to the well-established Direct Vectorial Addition (DVA) method. With respect to other existing multi-modal pushover analysis techniques, elliptical response envelopes are employed to calculate the corresponding combination factors.

The sixth paper titled “Do soft soil layers reduce the seismic kinematic distress of onshore high-pressure gas pipelines?” by Makrakis N., Psarropoulos P.N., Sextos A., Tsompanakis Y., recognizes the importance of onshore high-pressure gas pipelines as critical infrastructure that usually cross seismic—prone regions and are vulnerable to permanent ground deformations due to active seismic faults. The study investigates the impact of soft soil layers on the seismic kinematic distress of onshore gas pipelines. An extensive parametric analysis is performed considering different faulting mechanisms and fault dip angles, as well as soil geometry and mechanical properties. The outcome of the paper is a set of design charts and tables for the preliminary seismic design of onshore high-pressure gas pipelines based on the prediction of pipeline deformations.

The seventh paper titled “*Field reconnaissance on seismic performance and functionality of Turkish industrial facilities affected by the 2023 Kahramanmaraş earthquake sequence*” by Sagbas G., Sheikhi Garjan R, Sarikaya K., Deniz D., analyzes the effects the recent catastrophic earthquakes in southeast Turkiye, affecting 15 million-residents and a significant portion of its industrial community. The inspection results show that the earthquake sequence had a significant impact on industrial facilities, resulting in enormous economic losses and business disruptions lasting three months to two years. The most affected facilities were found to be those built before 2000, as well as precast reinforced concrete structures with pin-supported roofs. As a result, these types of facilities in earthquake-prone areas are strongly advised to be re-evaluated. Furthermore, various nonstructural building components, such as infills, claddings and equipment/machinery, were substantially damaged at the majority of the assessed sites, causing lengthy interruptions.

An interesting investigation on seismic performance of slender storage tanks is offered by Holtschoppen B., Knoedel P. in the eighth paper titled “*Seismic response of slender storage tanks on tube feet or skirt support*”. Slender storage tanks on tube feet or skirt support are essential components of industrial facilities and often contain large amounts of hazardous liquids. A procedure is suggested that lowers the overall stress resultants by calculating the hydrodynamic pressure and load components as a function of the geometrical characteristics of the tank. The general concept was developed for flat bottom tanks but can be transferred—with certain adjustments—to the considered slender storage tanks on tube feet or skirts. Its capability for design load reduction in comparison to the simplified calculation method is shown on an example case study.

Papers nine and ten are devoted to quantitative NaTech risk and resilience estimation. The paper titled “*A probabilistic framework for the estimation of resilience in major-hazard industrial plants under seismic loading*” by Kalemi B., Caputo A.C., Corritore C., Paolacci F., presents a probabilistic process flow-based framework for assessment of industrial plant resilience and economic losses in case of seismic events. Uncertainties are considered in the ability of plant equipment to withstand the disruption, and also in the recovery process including equipment recovery durations and recovery costs. Monte Carlo Simulation is used to account for the uncertainties of the model. A black carbon plant is used as a case study to show the applicability of the model. Results and capability of the proposed model shows that it can be a

useful tool for decision makers, plant owners, insurance companies, emergency managers and plant designers in their decision-making process.

The last paper titled “Seismic Risk and Resilience Analysis of Industrial Facilities” by Tabandeh A., Sharma N., Gardoni P., proposes a formulation to model the functionality of interacting industrial facilities and infrastructure using a system of coupled differential equations, representing dynamic processes on interdependent networked systems. The equations are subject to uncertain initial conditions and have uncertain coefficients, capturing the effects of uncertainties in earthquake intensity measures, structural damage, and post-disaster recovery process. The paper presents a computationally tractable approach to quantify and propagate various sources of uncertainty through the formulated equations. The paper illustrates the proposed approach for the seismic resilience analysis of a hypothetical but realistic shipping company in the city of Memphis in Tennessee, United States. The example models the effects of dependent water and power infrastructure systems on the functionality disruption and recovery of networked industrial facilities subject to seismic hazards.

The Guest Editors of this special issue would like to express their sincere gratitude to all authors for their valuable contributions that will certainly represent a reference point for the risk and resilience evaluation of the process industries in the future. Finally, they want to express their appreciation to the Chief Editor Prof. Atila Ansal for embracing and helping this special issue to come to fruition.

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