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ASSESSING LOCAL SEISMIC RESPONSE IN MAJOR-HAZARD INDUSTRIAL PLANTS: IMPLICATIONS FOR NATECH EVENTS

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EXTENDED ABSTRACT

Gli scenari di incidente industriale innescati da eventi naturali sono noti come eventi NaTech (*Natural Hazard Triggering Technological Disasters*). Questi eventi possono portare al rilascio di sostanze pericolose, incendi ed esplosioni, in grado di innescare catene di eventi multipli con conseguenze anche molto gravi per le persone, i beni e l'ambiente.

Il presente lavoro ha l'obiettivo di valutare differenti scenari di pericolosità sismica, tramite studi di risposta sismica locale, nell'area dove risiede uno stabilimento industriale a Pericolo di Incidente Rilevante (PIR, in inglese MHIP), soggetto alla normativa italiana del D.Lgs. 105/2015, in recepimento della Direttiva 2012/18/CE -Seveso III, in grado di generare un evento NaTech a seguito di eventi naturali iniziatori. Come caso di studio è stato scelto lo stabilimento della Società Chimica di Bussi (PE), situato nel comune di Bussi sul Tirino in provincia di Pescara. La scelta di tale area di studio risiede nel fatto che lo stabilimento è considerato MHIP e l'area presenta caratteri geologici – morfostratigrafici - geofisici che la rendono particolarmente pericolosa da un punto di vista sismico, favorendo fenomeni di amplificazione sismica locale.

La progettazione di un geo-database ha permesso di organizzare informazioni geografiche, geometriche, lito-stratigrafiche, e geotecniche provenienti sia da sondaggi geognostici eseguiti nell'area di studio, sia reperite da fonti bibliografiche di archivio. Una successiva implementazione di queste informazioni in un apposito software ha permesso di ottenere un modello geologico-tecnico di riferimento dell'intero stabilimento. La limitata disponibilità di sondaggi profondi ha suggerito l'adozione di sondaggi virtuali estrapolati da sezioni stratigrafiche tratte da dati di archivio. I sondaggi virtuali, implementati a loro volta nel geo-database, hanno ereditato le caratteristiche geotecniche dai sondaggi reali in un processo di trasferimento delle informazioni guidato dal giudizio esperto. I sondaggi virtuali sono stati di indubbio supporto per migliorare il processo di interpolazione dai dati per la realizzazione del modello geologico-tecnico 3D. Ad ogni unità geologica del modello 3D sono stati associati quei parametri fisico-meccanici (γ, Vs) e dinamici (G/G_0, D) necessari per simulare differenti scenari di pericolosità sismica, per alcuni di essi laddove sia stato possibile è stato considerato anche un indice di variabilità (Vs - G/G_0 - D). Il modello geologico-tecnico così realizzato ha permesso di eseguire differenti analisi di risposta sismica locale: lo studio infatti riporta i risultati di tre differenti approcci di calcolo, monodimensionale 1D, monodimensionale 1D con analisi stocastica e bidimensionale 2D. I parametri sismici relativi alla pericolosità sismica di base sono stati definiti mediante l'approccio *Probabilistic Seismic Hazard Analysis* (PSHA), considerando due scenari di pericolosità relativi ad altrettanti tempi di ritorno per lo stato limite SLV e SLC. Mediante l'utilizzo dell'interfaccia grafica REXELweb, per ogni scenario di pericolosità sismica di base, mediante spettro- compatibilità rispetto ad uno spettro target relativo ad una categoria di sottosuolo A e categoria topografica T1 (§ 3.2.2 NTC2018), sono stati selezionati n°7 accelerogrammi (componenti orizzontali) naturali non scalati. Le differenti tipologie di analisi 1D, 1D stocastico e 2D sono state ripetute per ogni scenario di pericolosità sismica di base (SLV - SLC).

Per poter effettuare oggettive considerazioni riguardo i risultati di uno o dell'altro approccio sono stati considerati 3 punti di analisi 1D caratterizzati da differenti profondità del substrato rigido (*seismic bedrock*), la sezione 2D è stata realizzata in modo che tali punti si trovassero allineati lungo la sua traccia. Le simulazioni 1D con approccio stocastico sono state effettuate considerando una colonna sismo stratigrafica 1D "media" che tenesse conto dalla variabilità dei parametri fisico - meccanici e stratigrafici dei tre punti di analisi 1D. I risultati delle analisi permettono di evidenziare notevoli differenze tra gli approcci di calcolo applicati, in relazione anche alle differenti posizioni relative dei punti di calcolo rispetto alla geometria della valle. Al netto dei valori assoluti di pseudo-accelerazione risultano invece simili i risultati tra i differenti approcci in relazioni ai due scenari di pericolosità sismica di base (SLV -SLC).

Gli scenari sismici derivati dai diversi approcci di calcolo, rappresentati mediante spettro di risposta elastico in accelerazione, permettono di evidenziare periodi spettrali dove il segnale sismico subisce le modificazioni più significative, sia in termini di amplificazioni positive che negative (deamplificazioni), rispetto allo spettro di risposta elastico (medio) relativo agli accelerogrammi di input. Per questo motivo, in questo lavoro è stato effettuato il calcolo del fattore di amplificazione entro il range di vibrazione naturale di un serbatoio di H_20_2 presente nello stabilimento di Bussi. La scelta è ricaduta su questa tipologia di struttura in quanto rappresenta un elemento in grado di provocare uno scenario NaTech.

ABSTRACT

Seismic events can trigger a NaTech disaster, leading to the release of hazardous materials, fires, and explosions. These can occur within industrial complexes and along distribution networks as a result of natural disasters. Industrial plants, composed of structural and non-structural components, may be damaged when subjected to earthquakes of a given magnitude. Some examples of these disasters occurred in Kobe (1995), Kocaeli (1999), and Tohoku (2011). This study aims to assess the local seismic hazard by the implementation of different analytical approaches in a Major-Hazard Industrial Plant (MHIP) triggering a NaTech event. For the Bussi MHIP area, a geodatabase has been designed where geometric and geotechnical parameters have been associated with each geotechnical unit. The local seismic hazard has been simulated using 1D and 2D codes, considering two seismic hazard scenarios limit state SLV - SLC according to the National Building Code (NTC2018).

In this study, the amplification factor AF has been calculated within the natural vibration range of an H_2O_2 storage tank located in the Bussi MHIP facility. This type of structure was chosen as it represents an element able to generate a relevant accident and consequently, a potential NaTech event.

Keywords: *NaTech, seismic hazard, engineering-geological model, local seismic response, domino effect.*

INTRODUCTION AND STATE OF ART

Industrial accidents triggered by natural events are known as NaTech events (Natural Hazard Triggering Technological Disasters) and they are identified in the international literature as technological accidents, which can lead to simultaneous damage, triggering multiple releases of dangerous substances with the propagation of domino effects (Mesa-Gomez *et alii*, 2020; Marino *et alii*, 2019). According to Seveso rules, an industrial accident is relevant if "*an emission, fire or explosion widening is identified, due to uncontrolled developments occurring during the operation of a plant*" … "*and gives rise to a danger, immediate or delayed, to human health and the environment, inside or outside the plant, and where one or more dangerous substances are involved*" (D.LGS. N. 105/2015). Since 1 June 2015, the so-called Seveso III, Directive 2012/18/EU, has been in force, whose main objectives are to prevent Major-Hazard Industrial Plants (MHIP) involving dangerous substances and to limit their consequences for human health and the environment. The directive requires a Safety Report (RdS), based on the procedures specified in the NTC 2018 and the Application Circular of 21/01/2019, for any plant that produces or stores large quantities of chemical substances.

The risk analysis must consider all expected accident scenarios resulting from the hazard event-structure-critical elements-dangerous substance interaction that can generate a major accident. The most common approaches in the literature on risk mitigation (*e.g.*, HAZOP, FTA, ETA) allow the transition between the identification of the event, the subsequent risk analysis and, in the end, the analysis of consequences, through appropriate techniques and linkages (Shahriar *et alii*, 2012; Misuri *et alii*, 2021; Ricci *et alii*, 2021).

NaTech risk assessment identifies accidental sequences triggered by earthquakes, because they can generate an increase of the frequency of occurrence of accidental events associated with critical elements and extend their damage areas. The consequences must be adequately considered both for structural aspects, mainly related to the structural stability of the buildings and the containment of hazardous substances in the plant, and for non-structural aspects, such as the failure of safety devices or critical components. The earthquake affects the entire facility at the same time, and it can cause the collapse of the structure as a direct consequence of seismic activity and lead to various damage degrees resulting in the loss of containment.

A comprehensive cycle encompasses the phases of preparedness, mitigation and response. Notably, until now there is no systematic method for the transition from natural hazard assessment to risk analysis and management, which deserves further exploration and integration to enhance industrial safety.

CASE STUDY

The selected case study is the Bussi Chemical Company plant, identified as MHIP. It is located near the village of Bussi sul Tirino (Central Italy) (Fig.1). This area is marked by high seismic hazard due to the role of the proximity to seismogenic fault planes of the Central Apennines, such as the Gran Sasso Unit to the north and by the Morrone Unit to the south (Conese *et alii*, 2001; Galadini & Galli, 2000). In addition, local geomorphological and geological settings can cause seismic amplification phenomena where alluvial

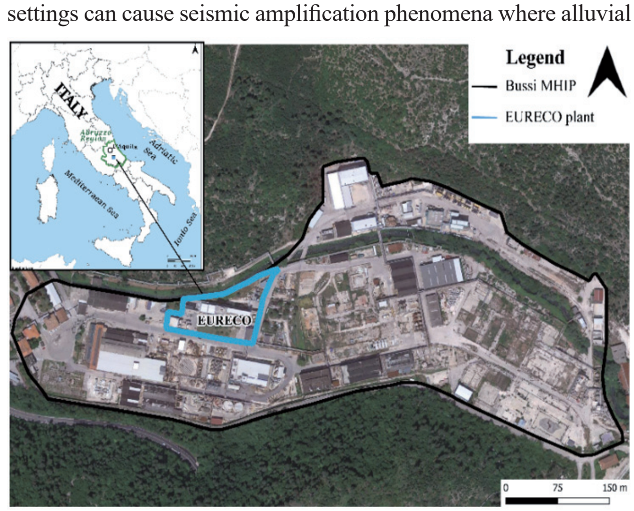

Fig. 1 - Satellite image of the Bussi MHIP, delineated by the black line, with a focus on the EURECO plant, indicated by the blue line

deposits of Tirino River are thicker than 50 m laying on the stiff bedrock, and the buried geometry of sediments is typical of a narrow valley. We refer to the stiff bedrock as seismic bedrock, composed by limestones. The industrial complex covers an area of approximately 2 km^2 and includes several production units. The analysis is focused on the EURECO facilities, which are known for the synthesis of phthalimido peroxycaproic acid (PAP). This compound is produced through the synthetic interaction of phthalic anhydride and caprolactam, followed by peroxidation with hydrogen peroxide of the resulting intermediate.

METHODOLOGY

The assessment of seismic hazards has a key role in the identification of potential NaTech accidents. This study aims to investigate 1D - 1D stochastic - 2D local response (Kramer, 1996; Fabozzi *et alii*, 2021; Pasculli *et alii*, 2023) studies through a high-resolution 3D engineering-geological model of the subsoil by using seismic input data (time history) derived from probabilistic seismic hazard analysis PSHA (Bazzurro & Cornell, 1999; Cornell, 1968). Our approach aims to have a detailed definition of the geometry of the valley to understand how a seismic event can trigger a NaTech event and produce domino effects in the industrial plant, assessing the seismic amplification.

The proposed methodology contributes to re-evaluate the rate of occurrence, modifying accident scenarios already predicted and indicating new scenarios that could occur during an earthquake. This approach implies the updating of the risk assessment, through HAZOP or Fault Tree Analysis (Kotek & Tabas, 2012; Yuhua & Datao, 2005). For instance, the occurrence of an earthquake can produce an unintentional LOC (loss of containment) from the storage tank; therefore, it is necessary to re-evaluate its rate of occurrence (Salzano *et alii*, 2003; Mocellin *et alii*, 2019). Various elements, such as reactors, pipelines and storage tanks, have different fundamental frequencies of vibration and will be stressed in different ways due to earthquake frequencies.

Reference engineering-geological modelling

A comprehensive geodatabase was implemented to store information from bibliographic surveys and log boreholes of the Bussi site, encompassing details such as location, total depth, lithology, water table, and stratigraphy. A total of 125 boreholes were incorporated into the geodatabase. Other stratigraphic logs, also called "virtual boreholes" (Antonielli *et alii*, 2023), were extracted from six geological cross sections (three longitudinal and three transverse to the valley) of the Bussi site, giving a preliminary geological model. Along the cross-sections, lithostratigraphic information was extracted through virtual boreholes, where real ones were missing, establishing a dense irregular grid of boreholes (Fig. 2). This strategic approach allows to validate the thickness and the continuity of all the lithological units, from geological sections, geological maps, and literature information. Data associated with these virtual log stratigraphies were stored in multiple Excel spreadsheets, which constitute a relational database of geo-referenced data that was employed for processing and editing operations through RockWorks 16 software. Project data was georeferenced by integrating geospatial coordinates with associated borehole information, to conduct advanced spatial analyses and modelling. This approach allows us to integrate and combine objective data with virtual data, merging lithologies through expert interpretation. Borehole distribution was non-uniform across the study area, with the highest density observed in proximity to the EURECO facility (Fig. 2). The virtualised geological information is more extensive at the EURECO facility, where we aim to conduct a seismic response study. We extracted multiple virtual boreholes from the geological sections along this facility, in order to accurately reproduce the geological and geometric characteristics of the site. To enhance the spatial representation, a 20×20 grid was overlaid on the study area. The density of boreholes significantly influences this grid: areas with a high density of boreholes have more than four boreholes in a single grid pixel. During the implementation process, we attribute more weight to the data from the real boreholes than to the virtual ones. This is due to the information from these boreholes was synthesised from the geological sections.

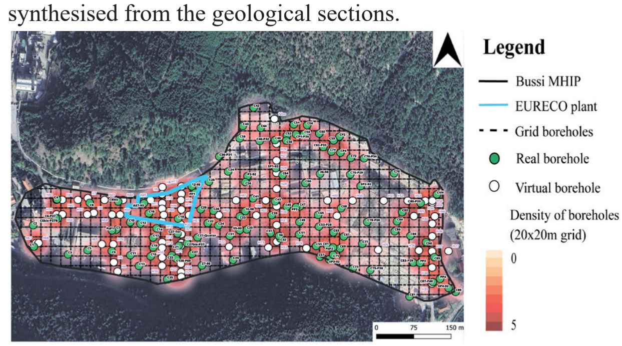

Fig. 2 - Density of virtual and real log boreholes on the Bussi MHIP. The red scale indicates the graduality of the borehole distribution. The black points represent the total boreholes, the dark red areas indicate a high concentration of boreholes, while the light red areas indicate a low concentration of boreholes. EURECO plant is marked with a blue line

Physical and dynamic characterization of soils

Soil properties are natural parameters and vary from site to site (Wang *et alii*, 2016), determining a significant role in geotechnical analyses and designs and, consequently, in the simulation of seismic scenarios. The properties of the site for each soil type were collected from a review of relevant literature (Lanzo *et alii*, 2019; Pagliaroli *et alii*, 2019; Totani *et alii*, 2016) and Seismic Microzonation studies of geologically compatible areas, available at the web link: 10.5281/zenodo.813497927.

The collection has public databases and published works, according to European Commission principles 28 (Gaudiosi *et alii*, 2023). From these studies, we derived the physical (*e.g.*, *g*, *Vs*) and dynamic (*e.g.*, shear modulus G, damping D) properties for each soil type. More in detail, the shear modulus and damping curves proposed by Darandeli (2001) and modified by Gaudiosi (2023) were applied to each soil type.

We assigned the soil code to each geological unit, classified according to the Unified Soil Classification System (USCS), *e.g.* by attributing GW-GM classes to backfill deposits. The average value for each parameter in the associated row of the table is presented in Table 1. Experimental data of G/G_0 (γ) and D (γ) curves obtained from different types of geotechnical laboratory tests: Double Specimen Direct Simple Shear, DSDSS; Resonant Column, RC; Cyclic Triaxial, TXC; Cyclic Torsional Test, CT; Cyclic Torsional Shearing, CTS; Resonant Column and Cyclic Torsional Test, RCT (Gaudiosi *et alii*, 2013).

The different physical and dynamic characteristics of the soil allowed geotechnical units to be identified and compared with geological ones. Understanding the seismic stratigraphy of areas covered by geological investigations and geotechnical parameters allows us to assess the degree of homogeneity of the study area.

Seismic analysis

Differences in the mechanical properties and stratigraphy along the path from the seismic bedrock (Kramer, 1996) to the free surface cause modification in the seismic input, defining the contribution to the seismic hazard of the site (Fig. 3). These modifications include differences in the acceleration, frequency and duration of the seismic signal. Seismic scenarios were considered with the *Probabilistic Seismic Hazard Analysis* (PSHA) approach. It gives, for any location, the seismic hazard curves from multiple sources in terms of Poissonian probability of exceedance. In the probabilistic approach, it is possible to choose earthquake scenarios with associated probability of occurrence values. The approach is empirically based on statistical observations of earthquake catalogues (McGuire, 1995).

Seismogenic sources, active faults and their seismic history were analyzed for the identification of the seismic hazard of the area. The disaggregation (Barani & Spallarossa, 2007) analysis provides relevant indications for the determination of the intervals to be used in the selection of records. In our case, the selection of accelerograms was oriented towards the definition of the optimal Mw-Distance interval deduced from the disaggregation analysis. In compliance with the Italian Building Code (NTC2018), we select seven unscaled horizontal natural records from the REXELweb interface (Felicetta *et alii*, 2023), registered at rock (soil type class: A) and flat topography (topographic class: T1), assuming two different Ultimate State conditions. In the first case, analyses were conducted at the Safe Life State (SLV) with a 10% exceedance probability in 50 years, while in the second case, a more severe scenario was considered at the Collapse Limit State (SLC) with a 5% exceedance probability in 50 years. In the first case, we assume a magnitude-distance couple (4-7 Mw - 30 km) representative of the site seismic hazard. In the second case, the selected magnitude-distance couple is 4.5-7.5 Mw - 55 km. The database of strong motions stored in REXELweb returns a list of site-compatible combinations according to the chosen period interval and the predicted tolerance, providing also the target average spectrum.

Local seismic response simulations were performed using the equivalent linear approach (Kramer, 1996) through 1D-1D stochastic-2D simulations (Kottke & Ellen, 2008; Idris *et alii*, 1973), considering two different basic seismic hazard scenarios (SLV - SLC). To make objective considerations regarding the results of either approach, n°3 1D analysis points characterized by different depths of the seismic bedrock were considered. The 2D section was designed so that these n°3 points were aligned along its trace. Stochastic 1D simulations were conducted, taking into account a 1D seismic stratigraphic column that considered the variability of the physical-mechanical and stratigraphic parameters across the n°3 1D analysis points

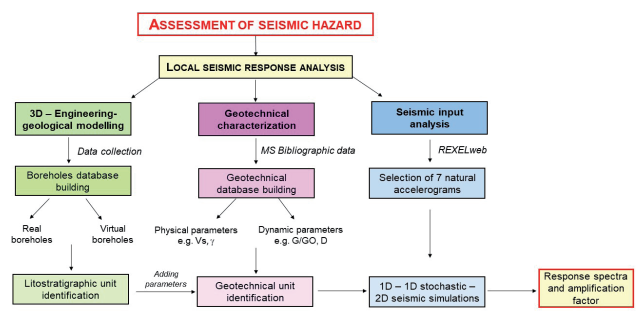

Fig. 3 - Flow chart of the methodology adopted for seismic hazard analysis in the MHIP

Storage tank vibration period

EURECO plant is characterised by different structural and non-structural components with different fundamental periods of vibration. The influence of the amplification factor (AF) on the different types of equipment present in MHIPs can be assessed, identifying possible damage scenarios. More in detail, rates of occurrence are assumed for each type of component capable of triggering a major accident, eventually developing a domino effect (Campedel *et alii*, 2008). By correlating the acceleration spectra of the input and output signal, we can graphically highlight the amplification factor (AF) for the vibration interval of interest of a storage tank of H202 at Bussi MHIP, *i.e.* between 0.21 ÷ 0.51 s. It is a vertical cylinder in stainless steel, with a geometric capacity of 24 m^3. The correlation enables the identification of the specific regions of the accelerogram where the structure is more stressed, and it allows to modify the accident scenarios already predicted in the risk analysis. Several cases may occur about the AF storage tank position on the acceleration spectra: *i*) the set of storage tank vibration frequencies falls within the seismic amplification zone, increasing the rates of occurrence to generate a major incident; *ii*) the set of storage tank vibration frequencies does not fall within the seismic amplification zone, maintaining the rate of occurrence, *iii*) the sets of storage tank vibration frequencies are placed where the seismic signal is de-amplified, reducing the rate of occurrence. Similarly, the described analysis is also applicable to pipelines, which represent critical elements in industrial plants and transport hazardous materials, such as oil products, and natural gas (Yuhua & Datao, 2005). Pipelines are used for the more efficient transport of these fluids within the plant, connecting different production or storage units. They are designed to ensure safe and efficient transport of materials, preventing loss, damage or contamination (Girgin & Krasussman, 2016).

RESULTS

The lithological units of the study area were reconstructed by merging the lithologies crossed by the boreholes (125 real, 110 virtual) under an expert judgment approach and following the information from the literature. A high-resolution 3D engineering-geological model was obtained by integrating lithological and geotechnical data in order to perform local seismic response analyses.

More than 60 boreholes reach a depth of 50 meters, located at the centre of the valley, while, towards the sides, the bedrock is located at lower depths, less than 30 metres. The geodatabase facilitated the identification of six lithological units (Fig. 4) with locally complex contacts, represented in Fig.4: 1) Backfill, 2) Slope Debris, 3) Lacustrine silts and clays, 4) Travertine, 5) Fractured and partially cemented gravel and 6) Seismic bedrock. The valley morphology appears to be narrow and deep, filled

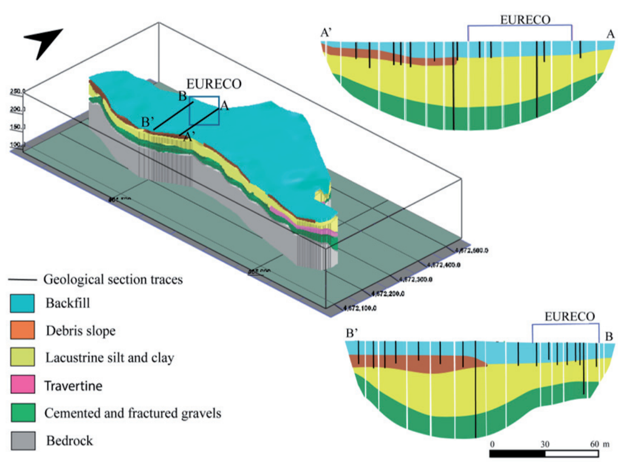

Fig. 4 - 3D Engineering-geological model of Bussi MHIP where we underlined the EURECO plant through the blue line. The cross section A-A' is shown above, where real (black) and virtual (white) boreholes are displayed

with alluvial deposits. The reconstructed model reveals that the debris unit on the slopes is only present at the foothills of the surrounding slopes, with maximum thicknesses of 8 meters toward NW of the MHIP. Moving towards the centre of the valley, the debris unit gradually diminishes until it disappears.

Interpolation of the geological parameters associated with the virtual boreholes allowed the reconstruction of the lithological contacts, to generate a 3D engineering-geological model. It enables the monitoring, analysis, and manipulation of informations, revealing a wide variability of geotechnical properties. The properties of the EURECO site for each unit are summarized in stratigraphic order. in Table 1.

Unit	Mean thickness	Min thickness	Max thickness	Mean Vs	Min Vs	Max Vs	Mean Vp	γ	ν ratio
-	*m*	*m*	*m*	*m/s*	*m*	*m/s*	*m/s*	*kN/m³*	-
Back fill	8	5	11	350	240	470	625	18,7	0,38
Debris slope	5	4	6	450	300	600	830	18	0,30
Lacustrine silt and clay	21	11	31	400	300	500	680	17	0,43
Cemented and fractured gravels	10,5	6	15	750	700	800	1050	22	0,30
Bedrock	-	-	-	1160	900	1250	2500	24	0,27

Tab. 1 - Geotechnical characterization of each unit identified for the EURECO plant

The geotechnical parameters assigned to each unit showed different soil behaviour. The analysis of the G/G0 curves contributed to detecting variations in stiffness and energy dissipation between different geological units, providing a detailed perspective on the geotechnical characteristics of the Bussi MHIP subsoil. The reconstruction of the curves was performed by statistically analysing the collected data, where each USCS geotechinical unit identified in the Aquila site is represented by the average values of the shear modulus degradation and damping, and by the Darendeli confidence levels (± 95 %) (Darandeli *et alii*, 2001).

The reconstruction of the morfo - seismo - stratigraphy of a soil column located below the EURECO plant reveals that the lowest Vs values are measured in the backfill deposits (350 m/s) and lacustrine silts and clays (400 m/s), in contrast with gravels (750 m/s) and bedrock (1160 m/s). The geological model reveals that travertine is not present in the EURECO plant, but it extends into the southern sector of the system. Therefore, the parameters for travertine were not included in Table 1.

The 2D section used for local seismic response analyses emphasizes the geometric characteristics of the valley and the buried seismic units, allowing for the assessment of the combined effects of morpho-stratigraphic factors (Bard & Bouchon, 1999) on the modification of the input seismic signal.

For each of the accelerograms used in the local seismic response analyses, the main ground motion parameters have been identified (Table 2). Among the parameters considered most important for this specific study, where the aim is to highlight the

SL	ID	Name	PGA	PGV	PGD	Arias	RMSa	RMSv	RMSd	CI	SED	PP	MP	Time
SLV	1	0001_3A.MZ102..HNE.D.EMSC-20161030_0000029.ACC.MP.ASC	0.3724	0.04431	0.01454	0.01797	0.03814	0.0043	0.0018	0.0654	0.0014	0.18	0.44568	77.15
	2	0002_HI.ARG2..HNN.D.EMSC-20140203_0000008.ACC.MP.ASC	0.26196	0.03356	0.008722	0.00599	0.02884	0.0032	0.00127	0.0329	0.00045	0.46	0.47284	45.01
	3	0003_IT.TLM1.00.HNN.D.IT-1976-0002.ACC.MP.ASC	0.35232	0.02268	0.003877	0.00822	0.03755	0.0029	0.00089	0.0439	0.00032	0.25	0.39698	36.39
	4	0004_IV.EVRN..HNE.D.EMSC-20181226_0000014.ACC.MP.ASC	0.30057	0.02839	0.005492	0.00368	0.01991	0.0026	0.00079	0.0214	0.0004	0.38	0.64324	57.905
	5	0005_IV.T1201..HNE.D.EMSC-20161030_0000029.ACC.MP.ASC	0.34594	0.02082	0.009893	0.00952	0.03136	0.0035	0.00172	0.0432	0.00075	0.11	0.41722	60.48
	6	0006_SM.109.00.HN2.D.IS-2000-0053.ACC.MP.ASC	0.43489	0.04134	0.023363	0.0117	0.03645	0.0053	0.00332	0.0516	0.00155	0.1	0.36358	55
	7	0007_SM.112.00.HN3.D.IS-2008-0054.ACC.MP.ASC	0.33417	0.03498	0.009552	0.0054	0.02163	0.0026	0.00146	0.027	0.00047	0.36	0.51687	72
SLC	1	0001_3A.MZ102..HNE.D.EMSC-20161030_0000029.ACC.MP.ASC	0.3724	0.04431	0.01454	0.01797	0.03814	0.0043	0.0018	0.0654	0.0014	0.18	0.44568	77.15
	2	0002_3A.MZ19..HNE.D.EMSC-20161030_0000029.ACC.MP.ASC	0.36311	0.03528	0.012805	0.01195	0.03835	0.0041	0.00185	0.0535	0.00086	0.27	0.48103	50.755
	3	0003_HL.AIGA.00.HN2.D.GR-1995-0047.ACC.MP.ASC	0.49834	0.04045	0.008488	0.01033	0.04026	0.0042	0.00135	0.051	0.00069	0.41	0.51112	39.79
	4	0004_IT.AMT.00.HGN.D.EMSC-20160824_0000006.ACC.MP.ASC	0.37565	0.04232	0.008713	0.00751	0.04101	0.0044	0.00141	0.0439	0.00054	0.22	0.54108	27.895
	5	0005_IT.AQG.00.HNE.D.IT-2009-0009.ACC.MP.ASC	0.44605	0.03157	0.006108	0.01376	0.02932	0.0027	0.00066	0.0502	0.0007	0.21	0.44742	100
	6	0006_IV.T1214..HNE.D.EMSC-20161030_0000029.ACC.MP.ASC	0.60489	0.05501	0.021708	0.03995	0.0572	0.0046	0.00285	0.1195	0.00163	0.09	0.28198	76.24
	7	0007_SM.106.00.HN2.D.IS-2000-0048.ACC.MP.ASC	0.32031	0.07206	0.01817	0.01309	0.04179	0.0071	0.00368	0.0584	0.00233	0.39	0.65341	46.8

Tab. 2 - Flow chart of the methodology adopted for seismic hazard analysis in the MHIP

variability of the amplification factor in relation to the vibration period of a component of the system, the predominant period (PP) and the mean period (MP) are emphasized. Considering that the vibration range of the tank is between 0.21 ÷ 0.51 seconds, it is observed that the majority of accelerograms have predominant energy content within the same interval.

We identified 3 logs of H18 - H19 - H20 boreholes, which represent the northern, central and southern limits of the EURECO plant, respectively. Each log is characterised by the mean Vs shear waves, bedrock depth, and geotechnical properties associated with its seismic unit. This approach enabled 1D seismic simulation and 1D stochastic seismic simulations, by modelling a 1D column averaged between H18 - H19 - H20. The 2D simulation was carried out by reproducing a model with the geological cross-section of the EURECO plant, including the positions H18 - H19 - H20 as control points for the output results. For both SLV and SLC scenarios, we compare the acceleration spectrum calculated at the ground surface (Output) obtained through numerical simulations with those derived from a *simplified approach* (§3.2.2 NTC2018). We use the last one to assess the seismic response of the site for a subcategory of soil type D (Output), as indicated in the RdS, with the bedrock acceleration spectrum (Input).

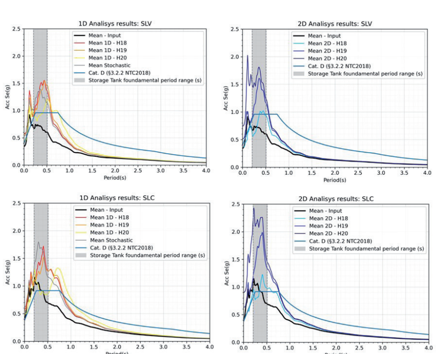

Fig. 5 - Comparison between acceleration spectrum response obtained from 1D – 1D stochastic – 2D in the SLV (top) and SLC (bottom) conditions. The right column shows the results obtained from 1D and 1D stochastic analyses, while the left column shows the site response from the 2D analysis

The seismic analyses conducted for SLV and SLC conditions reveal a notable variability in terms of site response along the same verticals at least in terms of absolute difference of acceleration. The acceleration spectra obtained from the 1D analyses (deterministic and stochastic) amplify the seismic signal differently from what is derived from 2D analyses. The 1D results showed for H18 column indicate the highest acceleration of the spectrum, in contrast with the H20 column which shows the lowest amplification, even de-amplifying the seismic signal around 0.3 s in SLC conditions. Differently, the results obtained from 2D analysis for the H18-H20 columns highlight different site responses, where the seismic signal is de-amplified to the mean input along the H18 column (SLV interval: 0.2-0.3 s, SLC interval: 0-0.3 s). On the other hand, the 2D seismic response of the H20 column shows the highest acceleration spectrum on the EURECO plant. The 1D stochastic results for the SLV condition are similar to those obtained for the H19 column., i.e. at the mid-point of the plant. In addition, the 1D analyses reveal an opposing AF trend to that observed in the 2D analyses. Specifically, in the one-dimensional case, AF decreases from H18 towards H20, while in the two-dimensional case, AF increases from H18 towards H20, as shown in Fig. 6.

The results of the 2D analyses clearly show how the AF is primarily influenced by the seismic impedance contrast due to the shallower layers (Fig. 6 unit: 1 - 2 - 3) and by the approximately symmetric

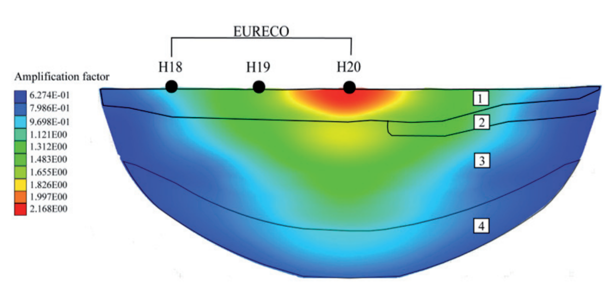

Fig. 6 - 2D distribution of the amplification factor (AF) along the A-A' geological section, for the SLV conditions. Lithological unit: 1) Backfill; 2) Debris slope; 3) Lacustrine silt and clays; 4) Cemented and fractured gravels

shape of the bedrock relative to the axis of the valley, which focuses seismic energy at the center of the 2D section (H20). The maximum values of AF calculated at point H20 are 2.28 and 2.25 respectively for SLV and SLC conditions. The comparison between different calculation approaches highlights that the 1D approach is not suitable for the morpho-seismo-stratigraphic conditions characterizing the site. Simultaneously, the results of the 2D analyses show a significant variation in AF throughout the entire EURECO plant area.

CONCLUSIONS AND FUTURE PERSPECTIVES

The seismic hazard assessment contributes to the identification of potential NaTech accidental scenarios that may occur at an MHIP plant. Our approach proposes the development of the engineering-geological model and 1D-1D stochastic-2D seismic analysis of Bussi MHIP to provide a solid basis for further studies of local seismic response and for the planning of risk mitigation measures.

The local seismic response analysis shows how the geometric and geotechnical characteristics of buried soils significantly and variably influence the hazard conditions of the area where the EURECO plant is located. Along the analyzed 2D section, there are areas characterized by local de-amplification of the seismic signal (AF < 1) to maximum values exceeding a factor of 2, located at the centre of the alluvial plain. For all analyses AF value has been calculated within a spectral range between 0.21 ÷ 0.51 seconds, this interval represents the vibration range of an H_2O_2 storage tank.

These analyses were performed assuming only the storage tank vibration period, so it would be necessary to perform a subdivision of micro-zones within the plant, extracting the vibration periods of other components, in order to simulate multiple site seismic hazard scenarios. Based on a seismic hazard map "*at the scale of component*" it would be possible to perform a risk mitigation or maintenance program of each plant component.

In the case of design of a new facility, the proposed methodology involves creating a mapping of seismic hazard where the calculation of AF is carried out based on the characteristics of individual components. The aim is to maximize the ratio between seismic risk mitigation and the cost for the construction and subsequent maintenance of the facility, in order to reduce the risk of a NaTech event triggered by a seismic event. In conclusion, this approach can be applied to investigate accident scenarios at Bussi and all other MHIP.

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