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DEPLOYING OF SEISMIC ALERT WARNING SYSTEMS IN INDUSTRIAL FACILITY

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Abstract

In recent years, advancements in employee safety protocols within production facilities have been steadily progressing. However, seismic events pose significant risks to production facilities, potentially disrupting operations, causing structural damage, and endangering the safety of employees. Such a scenario occurred in January 2022, when the Florina earthquake (M5.3) struck an industrial facility in the Bitola region, North Macedonia, triggering both panic behaviour and minor, non-structural damages. Although post-event inspections identified only damage in infill walls, the incident highlighted the facility's vulnerability and emphasized the urgent need for a more robust warning system. To mitigate these risks, the installation of an early seismic alert system was become a critical safety measure.

This paper explores the implementation of such a system in an industrial production facility, focusing on the integration of seismic sensors, real-time data processing, and automated alerting. The proposed system aims to provide early detection of seismic activity, facilitating the immediate evacuation of employees, shut down of critical operations and structural health monitoring. The initial phase involved determining the optimal placement of sensors through comprehensive noise, vibration, and microtremor measurements. Subsequently, two seismic trigger threshold sets were calibrated based on the region's specific seismic hazards and the structural vulnerability. The final system design incorporated an automated earthquake alert that was fully integrated with the facility's existing alarm system. Key components of the system include a seismic sensor, real-time monitoring software, and a LAN-controlled relay that enables the alert to be trigger across various spots within the plant. The system also supports various notification channels such as email, SMS, client monitoring and relay control, ensuring a rapid and coordinated response to seismic events.

This paper is outlining the technical specifications of the alert system, the anticipated benefits in terms of safety and operational efficiency, and its deployment in a high-risk seismic zone.

Keywords: seismic monitoring, earthquake safety, non-structural damage, seismic sensor, monitoring software.

1. Introduction

Every year, various natural hazards, including earthquakes, cause fatalities and property damage by affecting numerous people worldwide. With technological advancements and data processing speed, risk mitigation tools, such as seismic alert systems, have emerged as life-saving guards in many earthquake prone countries. The primary purpose of these systems is to detect an earthquake in the early stage, estimate the shaking intensity in the target regions, and warn the users before experiencing strong ground motion. Unlike other warning systems (typhoons, tsunamis, volcanoes, floods, etc.), hours- or minutes-long warning time is generally impossible.

The main goals of seismic alert systems are guaranteeing personal safety, preventing malfunctions in critical or important public and private facilities, making sure that infrastructure (such as lifelines) remains intact or can be restored quickly, providing the time needed to evacuate the people or to move them and sensitive items to a safe place, and protecting structures, building elements and equipment. Behind all these goals lies, to a varying extent, the need to avert loss of life, minimize injuries, reduce property damage, and shorten interruptions to public life, business, and production processes. Over the

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last five years, significant progress has been made in developing and implementing earthquake early warning systems. [1][2]. Many earthquake monitoring and warning systems have been designed to detect earthquakes and warn individuals to take appropriate precautions [1][2]. Most seismic instruments on the market are small systems built for offline management. Some of them have built-in applications with limited capabilities for real-time data processing. In many cases, those built-in functionalities are not sufficient to make them applicable to broader requirements. For solving those cases, a special algorithm is needed to be developed as external software solution.

To provide seismic monitoring for buildings and other structures, the earthquake monitoring systems have been extended to compute displacements and drift ratios [3][4]. It is designed to perform a near real-time measurement of the building's seismic performance and to monitor the health of the structure.

A modular structure with specialized toolboxes attached to the main module is the optimal approach to design these systems. Therefore, the developed earthquake monitoring and warning systems consist of main module and attachable additional toolboxes. The first installation of such modular monitoring system was installed for seismic monitoring and alerting of the earthfill dam near Zvornik town [5]. To keep up with the most recent demands, new algorithms are always being introduced, and the system is being updated [6]. Several toolboxes have been developed and deployed over the years [7][8][9]. One of them was real-time monitoring toolbox for experimental in-situ testing which can be connected to the main module of the monitoring system described herein [9]. Its main purpose is to obtain the real-time structures' dynamic properties such as natural frequencies, damping and mode shapes. The capabilities of this module were verified by in-situ testing of a 40-storey residential building using both forced and ambient vibration methods [9]. The other toolbox that is ready for connection to this main module is for real-time measurement and assessment of the impact of blast-induced vibration on buildings and humans [7][8]. The latest request of this system was to implement an automated earthquake alert system in production facility in Macedonia. Furthermore, the automated earthquake alert system must be capable of remotely activating the existing central alarm system. To achieve this goal, several improvements and modifications were made to the existing setup. It is designed to contain several units: (1) instrument, (2) software for monitoring and alerting and (3) LAN controlled relay for remote alarm activation. Since the devices are located in different locations, communication between the units is done in real time over a local area network. The improvement of the main module consisted in obtaining better performance for real-time data streaming, processing, and alerting. The additional alert toolboxes were developed for email and SMS notification, as well as relay control.

The first task for successful installation of the monitoring system was selection of the most favourable location of the strong motion instrument. Therefore, the measurements of noise, microtremors, and vibrations in daily working and idle conditions at three locations were performed. After selection of the most favourable location, the trigger level was defined according to the previously determined seismic potential of the considered terrain. As a final step, the automated earthquake alert system was installed and connected to the existing central alarm system.

Such a designed alert system allows facility employees to prepare for and make an appropriate decision prior to the arrival of the seismic peak. This real-time monitoring system provides a solid foundation for future enhancements such as a structural damage monitoring module.

2. Determination of the alarm level for the structure

The structure is located in the Bitola region and consists of three structural parts that represent one functional unit: (1) Production Building with dimensions in the plan of 180m/200m. The principal structural system represents a reinforced-concrete columns on which spatial steel truss roof structure is placed. (2) Social Building with dimensions in the plan of the structure are 180m/15m. It is steel frame structure with steel columns and beams. (3) Technical building is a one-story RC frame with a total area of 5 450m2.

Due to the action of the earthquake with the epicentre in Florina 2022, damage to buildings in the Bitola region has appeared. After the earthquake, a detailed inspection of the building was carried out where

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damages were detected. The damages that appeared were ascertained and an assessment of the stability of the building was carried out.

From the inspection, the following damages were found:

- Technical building: Non-structural damage was observed in the infill walls was observed within this building. Three locations with large cracks within the walls were noticed. Such damage is insignificant and does not have a specific impact of the overall stability of structure.
- Production building: In the second structure, i.e. the production hall, no damage was observed in the structural or nonstructural elements.
- Social building: In this buildings, vertical cracks were discovered in the walls that are adjacent to the production hall. The cracks are likely the result of a construction mistake, as there is not enough clearance between the cantilevered beams of the frames and the wall.

In order to a rapid structural health check after earthquake event, in this investigation fragility functions are used to obtain the damage level. Fragility curves are essential tools to quantitatively assess the physical vulnerability of structures at risk for a given seismic hazard. Since for the reinforced concrete structures there are no existing fragility curves, fragility curves defined with the SP-BELA method for vulnerability class D (buildings designed according to the seismic codes) have been selected (Fig. 1), [10]. The damages are classified according to the EMS98 scale, which is composed of five damage levels, i.e. slight damage D1, moderate damage D2, extensive damage D3, complete damage D4, and collapse D5.

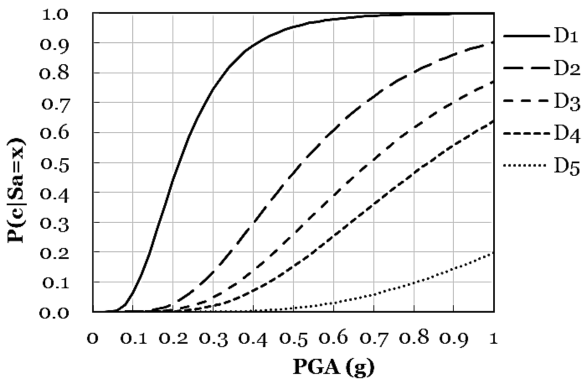

Figure 1. Fragility curves of 2-storey RC frame buildings of vulnerability class D (buildings designed according to the seismic codes)

It is assumed that for peak ground acceleration of 0.21g, there is 50% of probability of exceedance the occurrence the slight damage (D1). This PGA is important parameter that presents the damage level for setting the central alarm system.

3. Trigger level definition

The trigger level is defined in accordance with the previously prepared report for defining the seismic potential of the considered location [11]. Considered location belongs to the Bitola region, which throughout history has been exposed to a large number of earthquakes. The ancient city of Heraclea Linkestis, which is located on the outskirts of Bitola, was destroyed by a catastrophic earthquake. In the last century, the city of Bitola and its wider surroundings were hit several times by earthquakes that occurred in the Bitola-Lerin seismogenic zone: 1920 (M=5.3), 1958 (M = 5.3) and 1994 (M=5.2) (Fig. 1). The Bitola region can be exposed to the effects of earthquakes from neighbouring (Ohrid, Kičevo, Lerin 2022 (M=5.3), Kukuš, Valandovo) and relatively distant (Pehčevo-Kresna) seismogenic zones that might generate significantly stronger earthquakes with seismic intensity in the interval I = 6-7o according to the EMS-98 seismic scale (Fig. 2).

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Neighbouring hotspots are the result of activities on faults of regional character. These hotspots are located within a radius of 40 to 140 km, around the investigated area (Kožani, Ohrid, Kičevo, Lerin, Debar, Valandovo, Pehčevo-Kresna) and the magnitudes of the combined strongest earthquakes in these hotspots in the last 80-100 years are 4-7.8 degrees on the Richter scale. In the last 120 years, only three earthquakes with magnitudes between ML5.2 and ML5.6 occurred in this area. Seismotectonic map of earthquakes from the Bitola-Prespa-Lerin area in the period 1901-2021 (Blue circles are earthquakes from 2022).

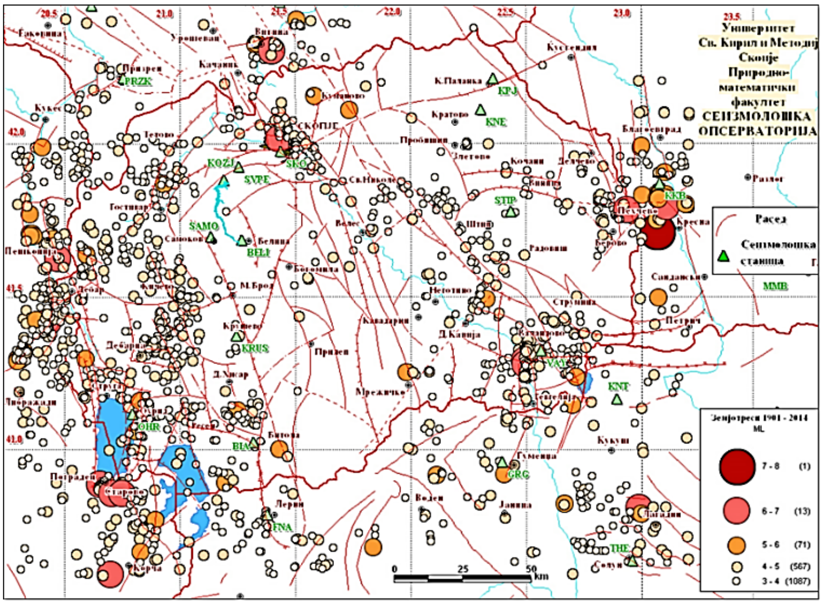

Figure 2. Epicentral map of earthquakes from the territory of the Republic of N.Macedonia and the surrounding areas for the period 1901 – 2014 (source: Seismological Observatory, 2016)

According to the seismic hazard analysis for the considered area [11], the maximum expected acceleration on the bedrock, depending on the return period, ranges between 0.100g to 0.170g. During the earthquake that happened on 09.01.2022, at 21:43, with a magnitude of 5.6 on the Richter scale, the network of instruments for strong ground motion registration installed at the Strezevo dam recorded a maximum acceleration of 22mg on the vertical component to 37mg on the horizontal component, which according to the seismic scale of EMS-98 corresponds to intensity between V and VI degrees.

Following the above data, a trigger level of 1.5% g for the vertical Z axis, and 2.0% g for the X and Y axis, equivalent to a moderate intensity earthquake that would be felt by people inside the buildings, was selected.

4. Determining the location of the instrument

In order to determine the most favorable location for the installation of the instrument, a field survey and microtremor analysis were performed. The Facility Security Officer proposed three possible locations for the device, depending on local technical conditions. The basic technical requirements that the future location would have to satisfy are access to the local area network LAN and power infrastructure. In addition, the site must respond to the absence of an external source of nearby vibrations. The first selected location "Location-1" is located outside the production building and is in the vicinity to "Location-2". The "Location-2" is located in one of the technical buildings, while "Location-3" is located inside the technical room of the production building. For all three locations, microtremor measurements were performed in working conditions.

The results of the measurements are interpretated in the form of frequency-magnitude relationship (Fig. 3 to 5). The conducted visual inspection of the locations and obtained results indicated that "Location-

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2" has the lowest level of noise and it is exposed to the lowest external vibrations. Therefore, it was chosen as the most favorable for the installation of the instrument.

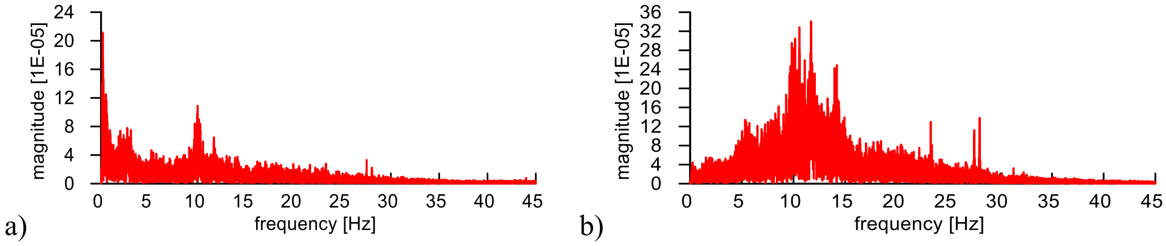

Figure 3. Location-1 a) Horizontal direction b) Vertical direction

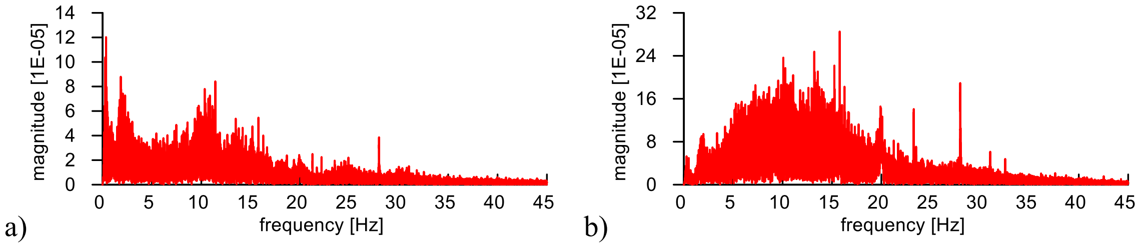

Figure 4. Location-2 a) Horizontal direction b) Vertical direction

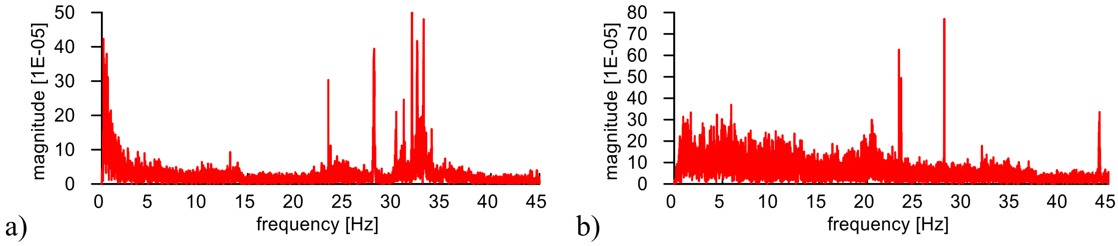

Figure 5. Location-3 a) Horizontal direction b) Vertical direction

5. Description of the seismic monitoring and alert system

The requirement of the safety sector in the industrial complex was to implement a real-time seismic monitoring and warning system that would be connected to the central alarm system. In order to realize this task, it was necessary to create a separate monitoring system, including the purchase of the instrument and developing of special software solution. The basic design parameter was to establish the connection of the newly alert system to the existing local central alarm system. Also, the system needs to be able to perform an automatic real-time activation/deactivation of the central alarm. The input parameters which were taken for the design of the new monitoring system were the locations of the instrument, data center and the location of the central alarm system. Since these three independent connection points are in different locations, the communication is via local area network.

The first step in the implementation of the new alarm system was a review of the existing alarm system and local infrastructure. From the conducted inspection, it was determined that all three proposed locations have access to electricity and LAN. After meeting the project's technical conditions, the design of the seismic monitoring and alert system was completed (Fig. 6).

The monitoring system consists of three devices located in different locations: (1) central alarm system, (2) data center and (3) sensor. The data from the sensor to the software is transmitted in real-time through TCP/IP protocol. The software performs continuous receiving and processing the data and comparing the vibration intensity to the alert threshold. When the alert threshold is exceeded, the software activates the relay and the clients' applications. Clients are additional points (PCs) where the

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current state of the vibration level is presented. By activating the relay, the central alarm system of the industrial complex is activated.

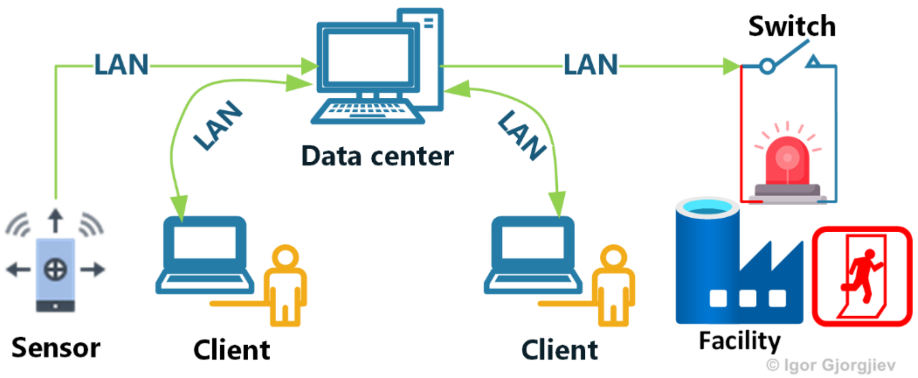

Figure 6. Schematic view of the seismic monitoring and alert system

From the performed site inspection, it was found that the existing alarm system contains a switch that can be used for remote activation/deactivation of the central alarm. Therefore, multi-function LAN/USB two-channel relay controller was used to remotely control the alarm switch. The LAN really uses user datagram protocol (UDP) for communication while USB relay connects to PC using virtual COM port. In order to control the central alarm system, we actually used LAN really, while the client PC uses a USB relay for the local client alarm.

The real-time seismic monitoring and alerting is performed by a tailor-made software solution (Fig. 7). The purpose of the main window is to show the data and status information in real-time (Fig. 7a).

On the right side of the window, the data for all connected instruments is graphically presented. The frequency content of the received data may also be presented. The alert level information along with the reset button are presented on the left side of the main window.

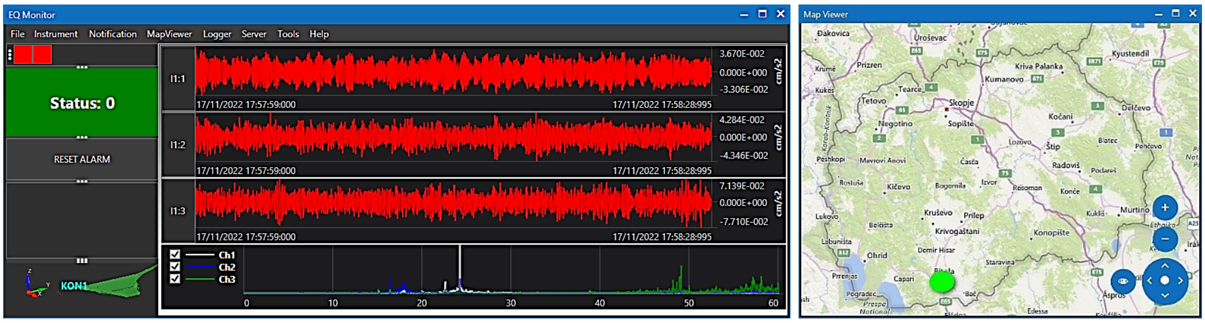

Figure 7. Schematic view of the seismic monitoring and alert system

The intensity of the vibration is presented by four colors. The green color is used for a normal state where no alert level is present. Other colors such as yellow, orange, and red are used for different alert levels. Additionally, a short list of important event messages is also presented in this part of the window. At the button of this window area, a 3D view of the monitored structures and the location with an orientation of the instruments is located (Fig 7a). Furthermore, the alert level of each instrument is presented on a separate map which gives a good quality visualization of multi-instrument monitoring (Fig. 7b). The software package (Fig. 7) consists of several toolboxes (modules): (1) instrument connection, (2) data processing, (3) notification, (4) map viewer, (5) logger and (6) server.

The aim of the instrument connection module is to establish and monitor the connection between the software and the instrument. The automatic reconnection is integrated to handle the connection loss. Also, the alarm reset, retrieving the alert status and the validation of relay connection are part of this module.

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The main purpose of the data processing module is to receive data in real-time and to perform a time synchronization of the data. Additionally, the signal processing and the frequency analysis toolboxes are included (Fig. 8 a, b). The signal processing toolbox contains removing trend together with lowpass, highpass, and bandpass filtering. In the second toolbox, a windowing and frequency analysis are included. As a result of frequency analysis, we can obtain fourier spectra (FS), power spectra (PS), power spectra density (PSD) and singular value of spectral densities (SVD). Additionally, signal averaging can be applied before performing the frequency analysis.

Notification module includes three types of notifications when the alert threshold is reached. The first notification type is sending an email, while the second type is sending an SMS. The last notification type is for controlling the relay status. For each relay type, a different parameter needs to be defined (Fig. 8 c). In the case of LAN relay an IP address and UDP port are required (Fig. 8 c). For USB relay, only COM name is specified. This module monitors whether the alert threshold has been exceeded. In case of alert threshold exceedance, notifications are sent and the central alarm system is turned on. Additionally, an automatic shutdown of the alarm after a particular time interval is supported.

The map viewer module (Fig. 7b) includes real-time graphical presentation of the alert level status on the host PC (data center). There are several view modes: Arial, Roads and Canvas which enable fast and precise monitoring when many instruments are connected.

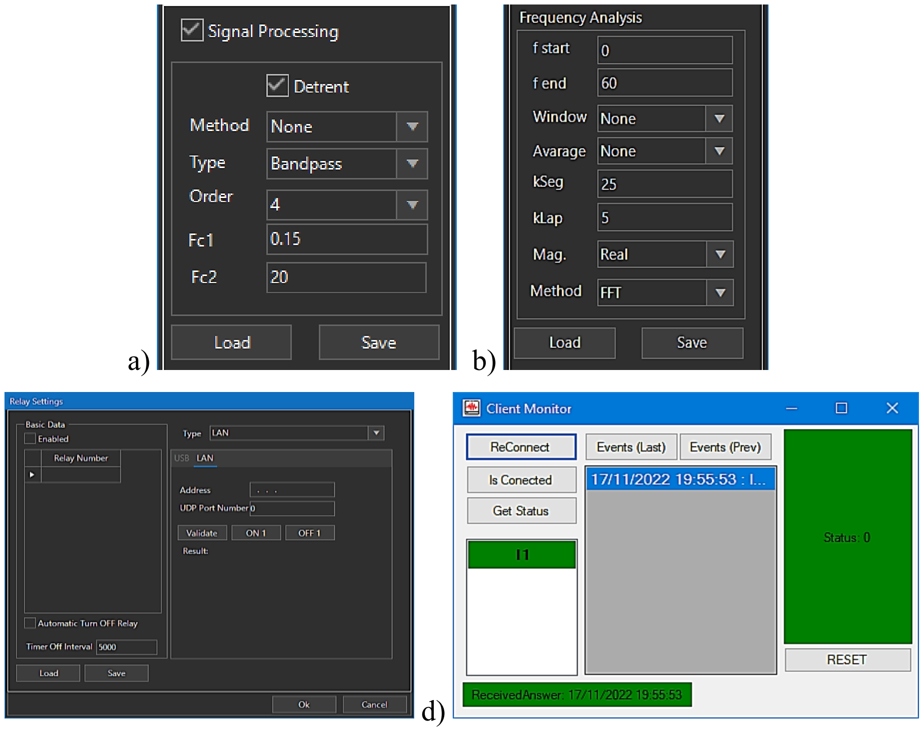

Figure 8. Signal processing (a) and frequency analysis input parameters (b), relay configuration window (c), Client monitor window (d)

The aim of the client monitor module (Fig. 8 d) is real-time monitoring of the alert level status on the client PC side. This module enables viewing the history list of events, getting the alert status on demand, checking the connection of the software to the instrument and doing the reset of the alarm.

The alert module aims to identify the specific earthquake intensity and to activate the notification modules. The alert levels are divided into three earthquake intensities where each earthquake intensity has a threshold for each of the three orthogonal directions. Turning off the alert for any direction is also supported. The control for exceeding the earthquake intensity is set from the highest to the lowest value. When the threshold is exceeded, the central alarm system is turned on and remains active for a defined time interval. The alert level stays active until the higher level is reached or the alert is manually reset. The manual reset can be done from the data center or any connected client.

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Such a designed alert system allows facility employees to prepare for and make an appropriate decision prior to the arrival of the seismic peak. This real-time monitoring system provides a solid foundation for future enhancements such as a structural damage monitoring module.

6. CONCLUSIONS

The Florina earthquake that happened in 2022 with magnitude of 5.3 affected the normal activities of people and lead to uncontrolled crowd panic behavior in the production facility located in the Bitola region. In order to enhance the safety measures, a strong motion instrument has been installed and an earthquake monitoring and warning systems has been developed. The software enables real-time data streaming, processing, and alerting. The alerting consists of three modules: email and SMS notification and remote control of the relay.

A trigger level was defined in each direction separately. The equipment was tested and configured in laboratory conditions, after which it was installed and put into operation. The operability of the strong motion instrument, in laboratory conditions, was confirmed through functional tests, conducted for three trigger levels in each direction individually. In the horizontal direction the alarm level is 2.0%g, while in the vertical direction the level is 1.5%g. The structural slight damage alarm level (D1) was set to 0.21g as the peak ground acceleration.

From the conducted laboratory and field activities, it can be concluded that the installed earthquake alarm system is functional and in working mode. Such alert system designed in this way allows employees to prepare themself and make a proper decision before earthquake peak arrived. Additionally, it presents a good base for adding the next module for structural damage monitoring.

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