5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Valencia, Spain
DOI: http://doi.org/10.4995/JISDM2022.2022.13753

Integrated survey approaches for monitoring procedures during yard phases

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Key words: *deformation measurements*; *structural monitoring*; *sensors*; *topographic survey*; *construction site*

ABSTRACT

Buildings, construction sites and civil structures need an accurate, continuous, and real time monitoring system. This necessity arises to detect dangerous situations for the structures and any occupant, especially during natural or anthropogenic events such as earthquakes or delicate phases of invasive operations such as excavations for piling. During these situations, the static and dynamic conditions of a structure and everything related to it could be impaired. The analysis and evaluation of significant displacements and deformation parameters, which are fundamental for structural controls and health monitoring, can be approached following different exchangeable procedures. Among the non-destructive monitoring techniques used in recent years, such as in this research, wireless sensors, are having a remarkable development in detecting anomalies. The acquisition of significant deformation parameters is obtained starting from the traditional topographic survey by total station and using static and dynamic sensors. Monitoring equipment concerns three-axial wireless tiltmeters which allow to measure accurately any angle of inclination in the points where they are installed in order to monitor kinematic movements during yard phases. The main purpose of this experiment is to compare data collected by tiltmeters with those obtained by the robotic total station. Three-axial accelerometers are also installed to obtain the acceleration value of the different reference points. By processing the collected data, it is proved that the final results are comparable, despite using different and completely independent monitoring systems. These integrated survey approaches demonstrate the effectiveness and efficiency of designing a monitoring system based on sensors that are installed to observe changing phenomena over the time, especially during delicate phases of invasive operations, which may represent a more widespread low-cost and reliable solution.

I. INTRODUCTION

Monitoring of the impact of the high-risk works on the environment is one of the most important elements enabling the safe implementation of projects. So, it is necessary to strengthen monitoring during the construction period, especially if it concerns the risk of structural failure of adjacent existing structures (Zhang, *et al.,* 2020). The trend of a health monitoring system started getting attention in the last decades of the previous millennium after catastrophic events, like the Japanese earthquakes, which damaged and destroyed thousands of buildings (Mita, 1999). Monitoring operations are then necessary to guarantee health and safety conditions by detecting instabilities or controlling the evolution of deformation patterns (Di Stefano *et al.*, 2020). After the most recent drastic events in Italy, such as the collapse of the Morandi Bridge in Genoa, there is a growing attention to prevention, so an increasing focus on preventive maintenance (Morgese *et al.*, 2020; Domaneschi *et al.*, 2021; Petito *et al.*, 2019). In order to increase the investments dedicated to prevention, several Italian engineering companies are allowed to take benefits from bonuses for buildings rehabilitation. One of these is the Decreto Rilancio n. 34/2020, so-called Superbonus 110%, which aims to relaunch the building sector by favoring the anti-seismic requalification of the building heritage and favoring the economy with its advantages (Artese *et al.*, 2021). For this reason, it is possible to integrate construction works with a monitoring system that gives information on the structural performance during the various stages of work by taking advantage of the existing tax reduction. For this reason, and because of the high risk for structures and infrastructures, an elaborate monitoring system can allow a careful predictive and preventive analysis of structural damage, so as to direct the authorities towards more adequate and timely interventions. A network of sensors for the displacement and deformation's monitoring of various engineering infrastructures is a nowadays very important issue (Antunes *et al.*, 2012).

Recent Structural Health Monitoring (SHM) applications in civil infrastructures pointed out the uniqueness of each structure and the importance of long-term evaluation of the structural performance (Aktan *et al.*, 2000). Furthermore, the effectiveness of a monitoring procedure is better when it is supported by the continuity and the accessibility of performance's data collected in real time (Brownjohn *et al.*, 2008; Brownjohn *et al.*, 1998).

Given the above, the proposed monitoring system was executed by using three non-destructive techniques: i) a topographical survey, ii) wireless tiltmeters and iii) triaxial accelerometers. The first two systems were paired, in order to compare the accuracy and the reliability of the acquired data. Besides, a vibration velocity for the worksite was also derived using triaxial accelerometers, placed to complete the proposed monitoring system and with which they were evaluated for making a comparison to the reference values. Therefore, the main goal of this ecosystem is to create an interoperability framework involving these monitoring systems for data acquisition, evaluation and management, also supported by the advances provided by the Internet of Things (IoT) for the SHM solutions.

II. OVERVIEW OF THE STUDY CASE

Starting from the necessity of a comprehensive survey of a construction site, the subject of this research work is a civil building which needs to be monitored due to its proximity to a demolition area. Specifically, we have focused on monitoring the structural performance of the building's high wall adjacent to the site (Figure 1). So, starting from the demolition works, the aim is to establish an initial situation and the subsequent presence of possible problems with the area affected by a future excavation for a pile work construction.

The absence of a dividing element or seismic joint between the monitored wall and the adjacent building that has to be demolished, it made the operation particularly critical, so a great care was taken for both structures during the demolition phase, thanks also to the monitoring system installed nearby. Observations and measurements (*e.g.* acceleration values (Figures from 2 to 5), angles of inclination (Figures 6 and 7), horizontal and vertical displacements (Figures 8 and 9) and velocity time response (Figures from 10 to 13)) were also carried out during excavation phase for the construction of the piles. So, a special attention was given to also this phase. In fact, very often, during excavation works the level of the trench bottom is lower than the existing foundation level of the adjacent structures which are therefore very sensitive to any horizontal displacements and settlements resulting from the works in progress whereby very strict restrictions in this respect are imposed (Lupieżowiec, 2021).

Figure 1. The wall to be monitored adjacent to the building to be demolished.

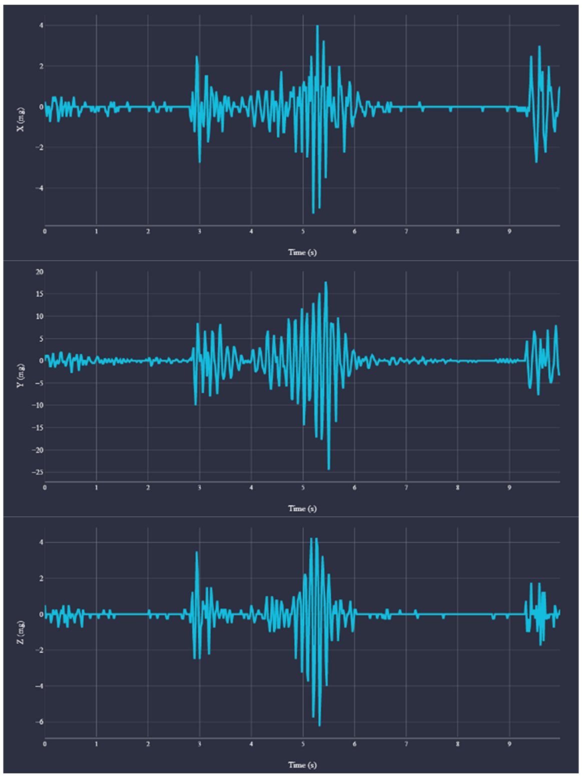

Figure 2. Acceleration Time Response during demolition phase detected by Sensor AXE-A (peak-peak 42,25 mg).

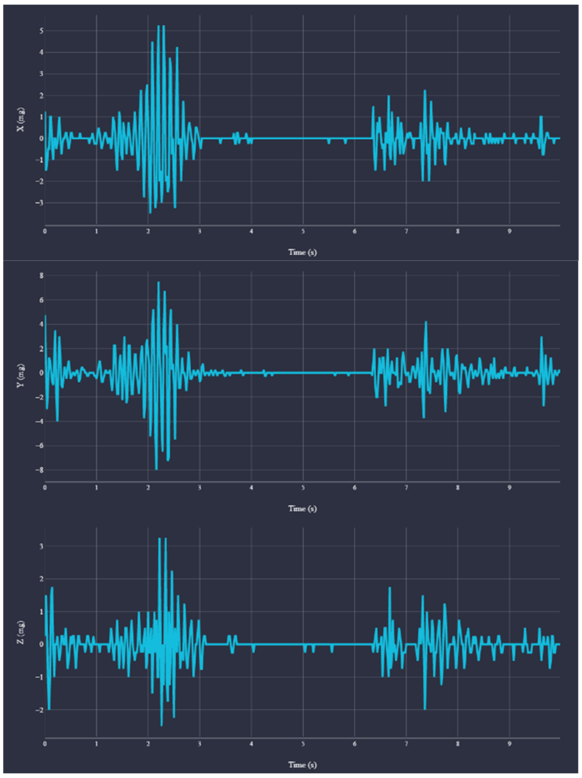

Figure 3. Acceleration Time Response during demolition phase detected by Sensor AXE-B (peak-peak 15,5 mg).

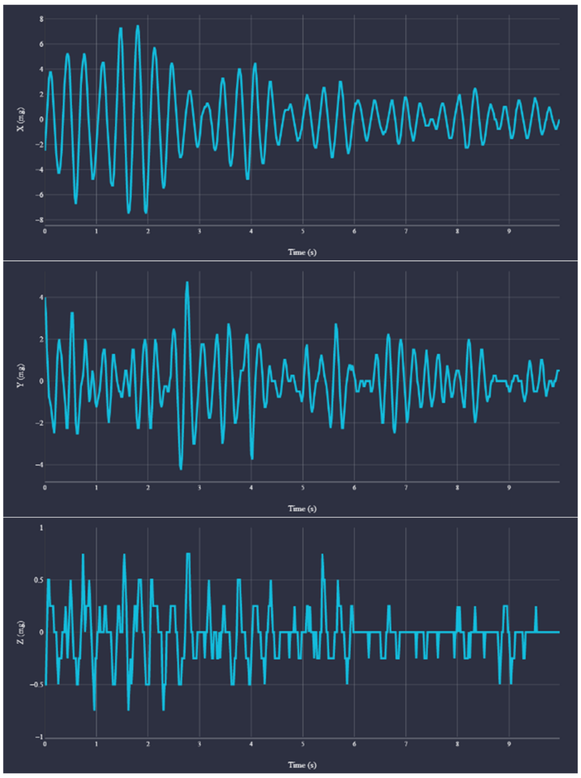

Figure 4. Acceleration Time Response during piling work construction detected by Sensor AXE-A (peak-peak 15 mg).

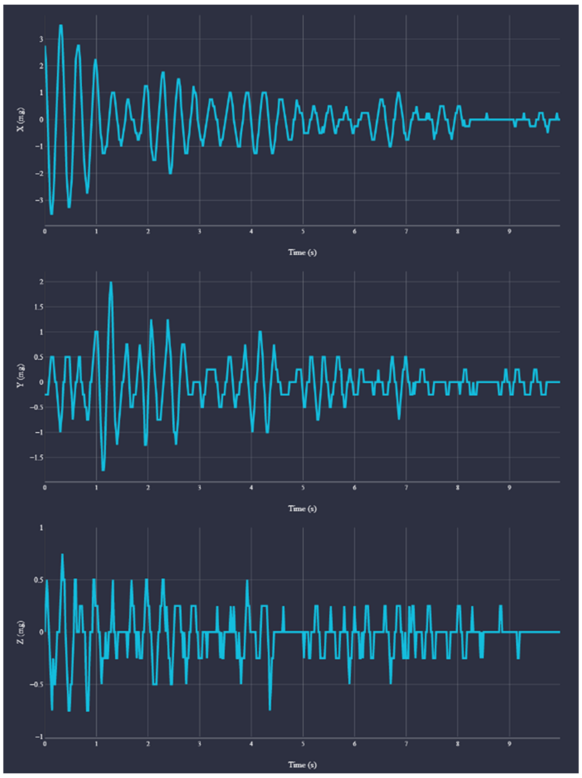

Figure 5. Acceleration Time Response during piling work construction detected by Sensor AXE-B (peak-peak 7 mg).

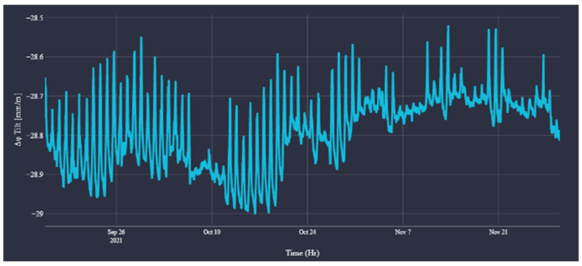

Figure 6. Trend of ϕ angle detected by TILT-B sensor.

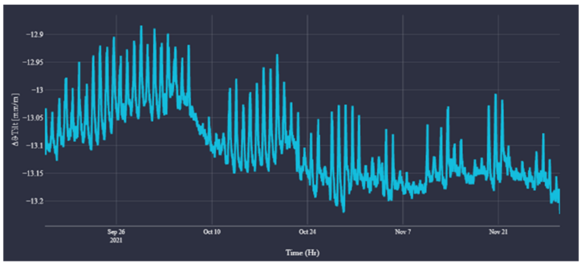

Figure 7. Trend of Θ angle detected by TILT-B sensor.

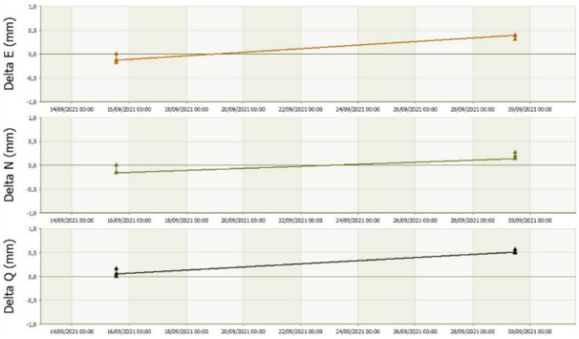

Figure 8. Prism 104A trend.

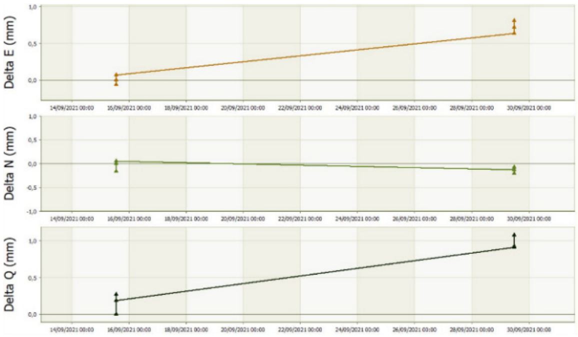

Figure 9. Prism 102B trend.

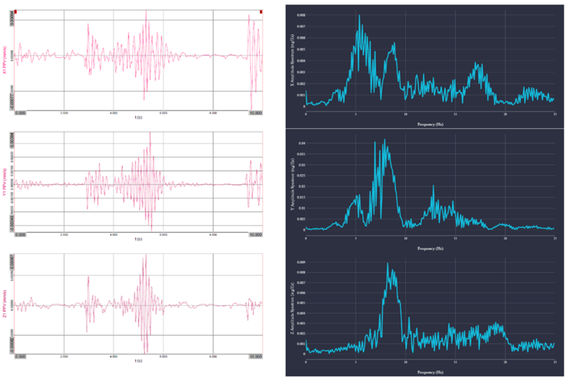

Figure 10. Velocity Time Response (left) and FFT anaysis (right) of demolition detected by sensor AXE-A.

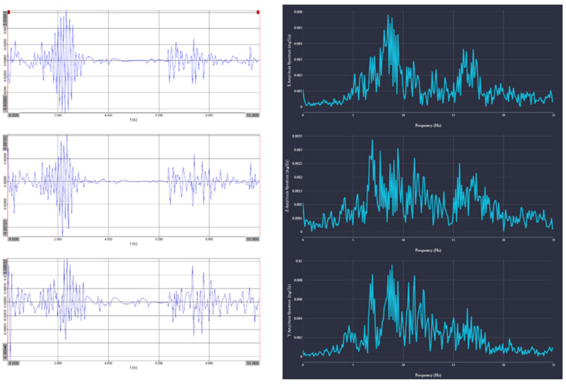

Figure 11. Velocity Time Response (left) and FFT anaysis (right) of demolition detected by sensor AXE-B.

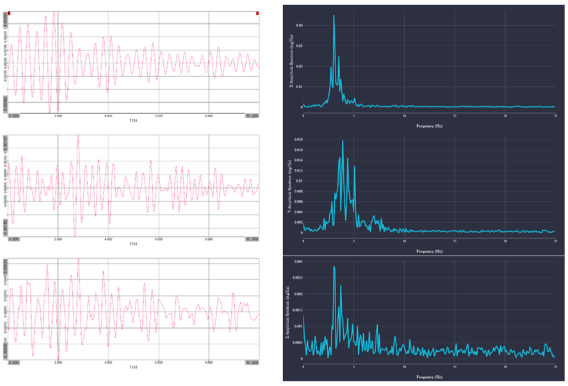

Figure 12. Velocity Time Response (left) and FFT anaysis (right) of piling work construction detected by sensor AXE-A.

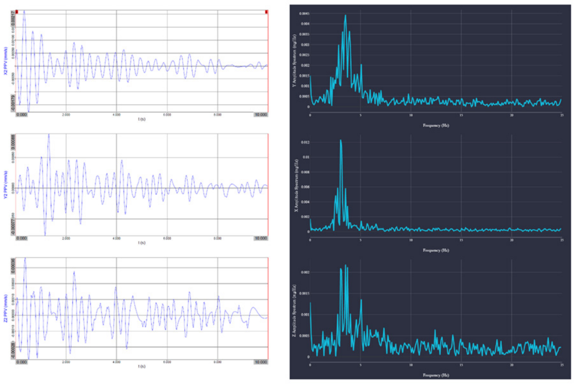

Figure 13. Velocity Time Response (left) and FFT anaysis (right) of piling work construction detected by sensor AXE-B.

III. METHODOLOGY

A. *Wireless monitoring ecosystem*

The proposed performance monitoring system (Figure 14) was installed to monitor the wall during the demolition phase of the nearby building. The sensor system is reported in the following table (Table 1).

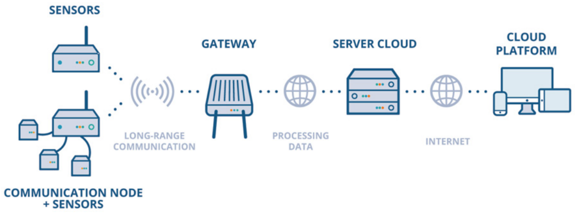

Figure 14. The wireless monitoring ecosystem.

Table 1. Sensors deployed in the monitoring system

Sensor type	Monitoring items	Nº of sensors
Accelerometer	Acceleration	2
Tiltmeter	Inclination	2
Prisms	Translations and rotations	5
Total station	Orientation and measurement	1
Total		10

All these sensors were selected to capture important information about the static and dynamic properties of the structure. The real-time data acquired from the sensors have been transmitted from the sub-stations to the Cloud Platform via gateway. This is a control unit device that is essential for receiving and sending data with which, thanks to the wide-range communication protocol LoRaWAN, it is possible to manage and communicate with all the sensors deployed.

B. *Dynamic characterization*

Performing a dynamic response characterization of the building is the typical practice to detect velocity and use its significant kinematic parameter to assess the effects of vibration on structures during construction phases (Monti *et al.*, 2013). Some velocity-based vibration criteria depends on the knowledge of the spectral energy distribution so as the frequency content. Therefore, for the purpose of calculating the velocity, the analysis can be limited to frequencies up to 100 Hz as the most building damages falls in the frequency range from 1 Hz to 100 Hz (UNI 9916). Table 2 shows, purely as an indication, the range of interest for different types of excitations.

Table 2. Characteristic frequency ranges of vibration sources

Vibration sources	Frequency range [Hz]
Road or rail traffic	From 1 to 300
End bearing piles	From 1 to 300
Demolitions	From 1 to 100
Machines outside the building	From 1 to 300
Machines inside the building	From 1 to 300
Human activities	From 0,1 to 100
Wind	From 0,1 to 2

The analysis of the measured data should lead to determinate if the vibration level causes damages to the monitored building. There are various approaches for evaluating if the vibration levels are dangerous or not. Some criteria refer to the PCPV (Peak Component Particle Velocity), defined as the maximum modulus of one of the three orthogonal velocity components obtained by integration. However, other criteria refer to PPV (Peak Particle Velocity), defined as the maximum value of the modulus of the velocity vector obtained by integration at the control points. Different thresholds are defined in DIN 4150-3, BS 7385-1, BS 5228-4, and SN 640312a.

C. *Vibration monitoring with MEMS technology*

Searching for a reliable, versatile, and yet cost-effective monitoring system design, led to the use of a system equipped with MEMS (Micro Electro-Mechanical Systems) based sensors as well as accurate but low-cost triaxial accelerometers assembled by Movesolutions (www.movesolutions.it). These sensors are ideal for a monitoring system and can act as data collectors during man-made phenomena or during earthquake events. Continuous improvements in the manufacturing processes for these types of sensors, and in their technical specifications (Table 3) make them more efficient, better performing, and available at a lower cost, making structural monitoring more affordable than other off-the-shelf solutions. The wireless accelerometers transmit accurate data from the site by the LoRaWAN wireless communication protocol with a gateway. So, it is possible to view and interact with all the acquired data on the web using a Cloud Platform.

Experimental acceleration measurements with MEMS sensors were taken at two control points on the building.

Both measurement points were set up on the side of the building close to the vibration source. Accelerometer AXE-A was placed on the top floor and accelerometer AXE-B at the base of the building (Figure 15). For both points, acceleration was measured in the vertical direction and in the other two orthogonal horizontal directions, with reference to the main axes of the building. For each event it was possible to visualize the specific vibration, analyze the trend and the amplitude of the detected peak-peak value.

Table 3. Technical specifications of the wireless sensors

	Tiltmeters	Accelerometers
Technology	MEMS	MEMS
Radio channel	LoRaWAN	LoRaWAN
Resolution	0,000015°	15bit (31,25µg)
Accuracy	0,005°	±62,5 µg
Range	±90°	±0,512g
Sample rate	-	50 Hz
Noise density	-	22,5 µg/√Hz

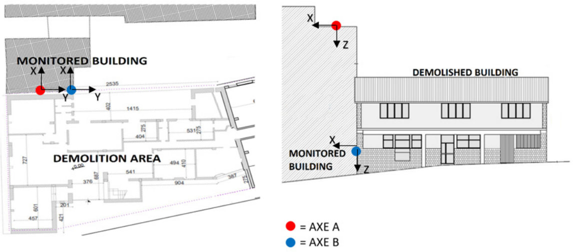

Figure 15. Accelerometers layout.

Therefore, each detected event is represented by six graphs, with reference to the three axes. Three graphs correspond to the "Time response" (Figures from 2 to 5) of each sensor then, they describe the acceleration detected by the sensors in 10 seconds of sampling.

The other three graphs correspond to the "Frequency response" (Figures from 10 to 13, on the right) of the oscillations (mg) so they are relating to the FFT (Fast Fourier Transform) algorithm which allows to highlight the spectral content of the signals coming to the sensors. So, it is possible to obtain characteristics ad information of the signal perceptible in the time domain and not. The two main events which were investigated are the demolition of the adjacent building and the piling work construction.

During the demolition phase, the maximum peak-peak was detected by the sensors on the 15th of September at 15:49 p.m. and it amounted to:

- 42,25 mg for the triaxial accelerometer AXE-A.
- 15,50 mg for the triaxial accelerometer AXE-B.

During the piling work construction, the maxim peak-peak was detected by the sensors on the 29th of October at 12:53 a.m. and it amounted to:

- 15 mg for the triaxial acceleration AXE-A
- 7 mg for the triaxial accelerometer AXE-B.

In this work, it was necessary to trace the measurements taken by the accelerometers in terms of velocity. Accelerations are traced back to this kinematic quantity by integration. For this case, the integration of the accelerometric signal was carried out in the time domain, considering the filtering on the recorded signal. A high-pass filter was used to eliminate the low-frequency noise components, after having duly verified that no significant components of the useful signal were lost with such filtering.

The aim of a vibration evaluation is to guarantee that the allowable vibration levels in the nearby building are met. So, the acceleration time series (mm/s^2) recorded by the wireless triaxial sensors has been integrated over the time in order to change it in velocity ($\Delta v = \int a\, dt$) and to evaluate the higher vibration velocity values to assess possible exceedances of the permissible limits.

D. *Inclinometer monitoring*

Displacement monitoring is an important part of the construction processes. Inclinometric control systems are designed to determine the angular displacement of structure elements. Inclinometers, tiltmeters of various designs are based on the principle of recording the deviation of a horizontal or vertical surface from the direction of the gravity vector (Glot *et al.*, 2021). Some works (Su *et al.*, 2013) show the application of inclinometric control systems equipped in high-rise structures and the key features of this monitoring system which are the simultaneous installation of all the sensors and data acquisition using the cloud platform to record initial values, and the measurement of structural settlement and displacement at different construction stages.

Wall's displacement monitoring includes horizontal and vertical displacement. For these processes we used two different technologies: a total station survey is supportive to the tiltmeter placed in two control points.

1) *Wireless tiltmeters:* tilt control devices were placed as follows. Tiltmeter TILT-A was placed on the upper end of the wall and the other tiltmeter TILT-B in the middle of the monitored wall (Figure 16).

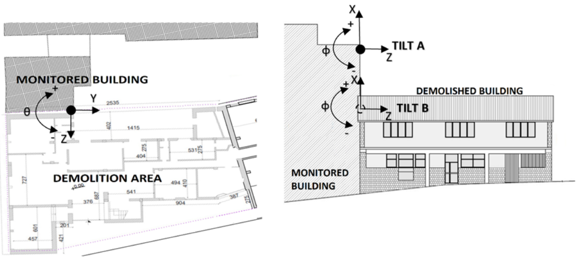

Figure 16. Tiltmeters layout.

These triaxial tiltmeters were installed to measure the variation of the static angular inclination of the monitored wall. These systems are battery powered and have a LoRaWAN wireless transmission of the MEMS previously introduced, so they too acquire data and transmit them to the Cloud platform (Figure 14).

The Tiltmeters give in output angles (Figures 6 and 7, Tables 4) that describe any variation in inclination (Table 5) of the wall on which the devices were installed. The calculation of these angles is based on the projections of the gravity vector on the three axes of the sensor, averaged over an acquisition interval of one minute (Figure 17).

Table 4. ϕ and Θ angles detected by TILT-B sensor

	ϕ [mm/m]	Θ [mm/m]
15/09/2021	-28,68778	-13,07825
29/09/2021	-28,75519	-12,96675
15/10/2021	-28,84568	-13,03855
29/10/2021	-28,69111	-13,08553
15/11/2021	-28,64456	-13,09804
29/11/2021	-28,77162	-13,17783

Table 5. Variation of tilt angles ϕ and Θ

	Δϕ [mm/m]	ΔΘ [mm/m]
Δ_1	0,06741	-0,081575
Δ_2	0,1579	-0,0397
Δ_3	0,00333	0,00728
Δ_4	-0,04322	0,01979
Δ_5	0,08384	0,09958

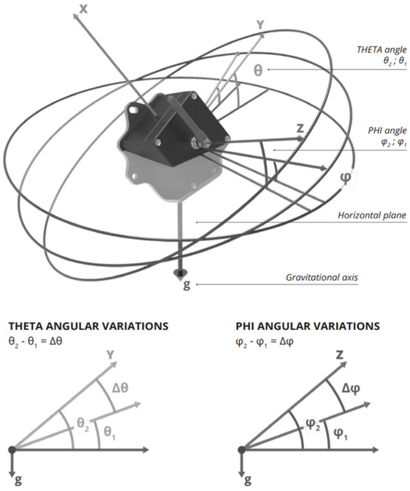

Figure 17. Phi and theta angles.

The angles provided by the device are:

- ϕ – Phi angle: it represents the angle between the Z axis, represented on the orientation label, and its projection on the horizontal plane.
- θ – Theta angle: it represents the angle between the Y axis, represented on the orientation label, and its projection on the horizontal plane.

2) *Topographical survey*: the topographic monitoring activity started using a Sokkia NET05AX robotic total station which was placed in a position where it could be repositioned for upcoming topographical measurements.

Three orientation prisms were installed and used to orientate the total station and two control prisms were installed to monitor translations and rotations (Figure 18).

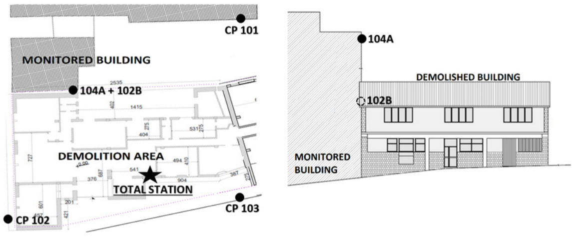

Figure 18. Topographical survey layout.

Three orientation prisms were positioned as absolute reference point to determine the coordinates of the station by inverse intersection.

The prisms were named CP101; CP102; CP103 and they were positioned facing the construction site as follows:

- CP101 on a wall of the monitored building.
- CP102 on a niche in the perimeter of the construction site area.
- CP103 on the jersey barrier enclosing the area.

Once the coordinates of the station were calculated, the measurements were carried out on two control prisms on the building's wall to be monitored, positioned below the triaxial tiltmeters.

The prisms were respectively named 104A and 102B were positioned as follows:

- 104A on the wall under the triaxial inclinometer TILT-A.
- 102B on the wall under the triaxial inclinometer TILT-B (Figure 19).

Topographical measurements started with the zero-measurement acquisition which was consisting of the average of three layers acquired in straight line mode and conjugated on the horizontal, vertical, and inclined distance angles. The measurements are aimed at verifying any elevation (ΔQ) and planimetric displacements (ΔN, ΔE). From data processing software (Polifemo, www.geopro.it) it was possible to extrapolate the raw measurements relative to the prisms measured (Figures 8 and 9).

Figure 19. Prism 102B positioned under the TILT-B sensor.

IV. DISCUSSION AND RESULTS

During both demolition operation and the pile work construction, the acceleration was measured and afterward the velocity was obtained so PPV was calculated. Accelerations and PPV are within the permissible limits according to DIN 4150. Velocity time history and the corresponding FFT analysis are shown hereafter in the following Figures (from 10 to 13).

Regarding to the monitoring of the inclination angles, the elevations and planimetric displacement measured by the two inclinometric proposed systems (total station and sensors) the measured data show that they are in the order of tenth of a millimeter. For this reason, the displacement measured are within the accuracy of the robotic total station or the positioning of the prisms which should be rotated in order to recreate a perfect perpendicularity. Since these measurements are correlated to the total station's accuracy, the comparison between the two systems don't reveal any discrepancies or particular problems. This is also due to the fact that the measurements taken over a very short observation period are not sufficient for the estimation of any trends or drifts. On the other hand, it may be interesting to pay attention to the correlation revealed between the measurements of the angle of inclination and the temperature (Figure 20). In Figure 20 it is possible to clearly see fluctuations in the tilt values consistent with daily changes in the temperature. In fact, the temperature strongly influences the changes in the measured inclination (Glot *et al.*, 2021).

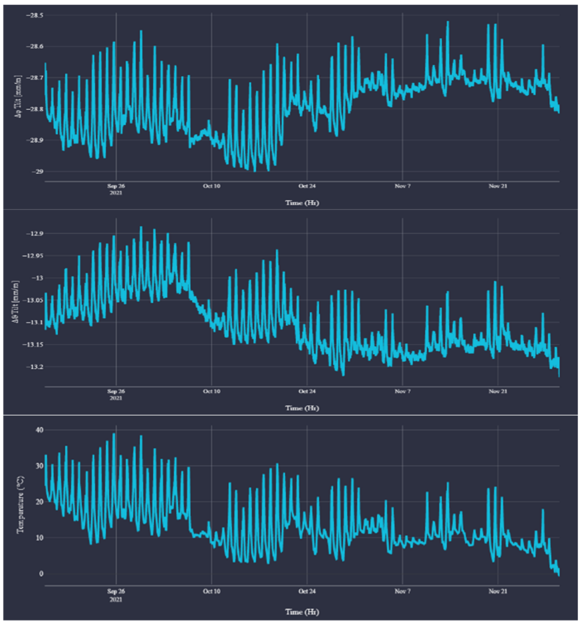

Figure 20. Correlation between the angle alteration and temperature trend.

V. CONCLUSIONS

Starting from the identification of the velocity based on the vibrations produced during the yard phases, the different approaches for evaluating the effects of vibration produced were highlighted. Specifically in this work we monitored a demolition phase and the successive excavation for pile work construction, with the installation of a wireless system network. This long-term monitoring may help the definition of any damage, fortunately absent in this case study, which were caused by different vibration levels referring to one of the mentioned criteria. The combination of the dynamic characterization with a static one, by using tiltmeters sensors and topographical measurements, provides a comprehensive overview of the site's health from the beginning of the works through the subsequence various phases. The efficiency of the system, the validity of the measured data and the widespread low-cost sensors solution, made this integrated system a valid approach to be taken into account and to support to all construction phases.

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