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Seismic Monitoring of a Retaining Wall in Reinforced Concrete Piles

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ABSTRACT

The trend of using numerical simulations when designing buildings is growing with the availability of increasingly higher capacity computers and the prevalence of a performance-based design philosophy requiring accurate forecasts of structural movements under seismic stress. In cases where consolidated calculation procedures do not exist, these simulations often provide the only rational approach. There are many examples of this in the field of geotechnical engineering. However, the reliability of these forecasts depends on forming correct models of the problems, having advanced knowledge of subsoil characteristics, and most importantly, having valid calculation models which are proven through comparisons with well-documented case studies of full-scale construction projects.

The need to "measure" the dynamic responses of structures has driven the scientific community to design and create different types of monitoring plans. Within this field of study, a seismic monitoring system has been installed for the construction of the "Casa dello Studente" (Student House) near the Campobasso campus of the University of Molise. The system consists of a retaining wall of reinforced concrete piles and the instrumentation consists of four inclinometer casings and eight customized accelerometer systems with two components installed inside two piles. This type of installation is one of the few examples of seismic monitoring on actual full-scale geotechnical works. Its purpose is to provide an interesting case study through which to calibrate simplified and complete calculation methodologies.

The line of reasoning used to design and install the monitoring system is described in this article.

1 INTRODUCTION

The so-called "performance-based" design approach, initially developed for buildings, was introduced to the geotechnical field a few years ago (SEAOC 1995, Iai & Ichii 1998, Steedman 1998, PIANC 2001). This new design philosophy is based on recognizing that:

- Deformations in the ground and the foundation soils and the corresponding states of tension and deformation in the structures are fundamental design parameters;
- Conventional methods based on limit equilibrium are not suitable for evaluating these parameters;
- Within certain limits, residual deformations can be acceptable.

The new design methodology attempts to surpass some of the traditional limits of conventional seismic design.

In conventional procedures, the seismic design aims to provide the structure with the capacity to resist seismic actions hypothesized in the design phase, but it gives no information about the structure's performance if the resistance limit is exceeded.

Additionally, if designers are limited to reference information from more frequent seismic events, it becomes difficult to forecast the structure's seismic performance when it is subjected to earthquakes of magnitudes higher than those envisioned during the design phase.

Requiring a structure to be in a condition such that its limit equilibrium is never exceeded during rare seismic events would make construction or retrofitting costs excessively high.

In performance-based design, the level of acceptable damage (which is one of the so-called damage criteria) must be specified in engineering terms by defining the limits of displacement, deformation, or ductility, or the stress limit states, depending on the dynamic and seismic responses of the structure.

Based on the scientific literature available on this topic, Silvestri & Simonelli (2005) summarize the main phases to follow for a modern anti-seismic design in any geotechnical system:

- Definition of the level of seismic action, usually represented by the choice of a suitable return period for the earthquake envisioned in the design phase;
- Definition of the level of acceptable damage, which corresponds to the required performance level;
- Definition of the analysis method;
- Definition of the reference seismic action;
- Geotechnical analysis of the building site;
- Design/verification of the system by checking the performance requirements.

Analysis methods can be classified as follows:

- Simplified analysis, by which the safety factor of the soil-structure system is assessed through a simple global equilibrium of the forces involved;
- Simplified dynamic analysis, by which a pre-defined collapse model for that soil-structure system provides the amount of displacement induced by the earthquake;
- Complete dynamic analysis, which assesses both the amount of displacement and the collapse mode.

By focusing on flexible retaining walls made of piles, the respective seismic performance criteria can be specified in terms of operability and structural damage, and described in terms of the state of stress, or rather, of displacement. Some damage criteria useful for determining structural typologies are available in the literature (PIANC 2001, European Committee for Standardization 2003, Callisto 2005).

It is vitally important to develop, test, and apply calculation models and methods, even simplified, which consider the deformations of geotechnical structures, mainly because the mechanisms of interaction between the soil and the structural components of the system are not completely clear, in particular during earthquakes.

In this context, the University of Molise has designed and installed a monitoring system to assess the behavior and responses to dynamic actions of a retaining wall of reinforced concrete piles.

The configuration of the system, particularly regarding the placement of sensors and the automatic data acquisition and processing procedures, makes it a model of an intelligent structure. It is also one of the few examples of full-scale geotechnical structural monitoring projects.

The first part of this article contains a brief description of the structural monitoring applications in the field of civil engineering, and the second part describes the University of Molise’s system in detail, with particular reference to the instrumentation and installation procedures. The latter aspect is particularly interesting because it was necessary to develop “embedded” modules of accelerometer sensors specifically for this retaining wall. These sensors were installed using specific procedures to ensure homogeneous behavior and characteristics (in terms of rigidity and resistance) between the instrumented piles and the rest of the piles in the retaining wall.

2 SEISMIC MONITORING

Over the last fifty years, the development of design and numerical analysis procedures has been based mainly on data obtained from laboratory experiments and post-earthquake observations.

The scarcity of data regarding observations of earthquake aftermaths, and the necessity to learn more about real response mechanisms of real structures, has made full-scale experimentation an essential component of the research procedure in the field of seismic engineering (Elgamal et al. 2007).

A typical monitoring system is made up of a series of sensors for observing the environmental conditions and structural responses to dynamic and static events. The layout is based on the use of remote sensors connected directly to a centralized data acquisition system with wiring. Recent developments in this field are, conversely, based on the use of wireless sensors.

If, on one hand, considerable progress has been made in recent years in the field of structural monitoring in terms of hardware and sensor performance, on the other hand, greater effort is now required to develop efficient, reliable data processing algorithms. Suitable strategies are also necessary to manage the results from monitoring data and to combine information that often derives from heterogeneous sensors, which refer to different physical variables.

Algorithms for identifying damage were proposed for typical civil engineering structures (bridges and buildings); these procedures are based on different physical or mechanical principles. They can be classified into two basic categories: methods based on observing variations in modal parameters, and methods based on directly processing the measured responses.

In the first case, monitoring dynamic parameters over time allows researchers to correlate the variations to possible damage phenomena that happened to the structure. In the second case, the data is processed to identify anomalies directly in the measured response (ARMAV model, wavelet decomposition, etc.). In both cases, however, people tend to develop completely automated damage identification methods to take full advantage of the recent progress in communication technology (Aktan et al. 2005).

In this context, it is very important to identify the modal parameters of the structures under operative conditions. Recently, different strategies have been developed to automate the identification process and the monitoring of modal parameters. This allows for the complete integration of dynamic identification techniques into the structural monitoring process; a detailed discussion of this topic is available in the literature (Rainieri 2008, Rainieri et al. 2009).

Monitoring systems have been applied to different types of structures, such as buildings, bridges, pipelines, and wind turbines. The monitoring system installed on the main building of the School of Engineering at the University of Naples Federico II is an interesting example of an Italian application in this sector. It attempts to integrate structural monitoring and an early seismic warning system (Rainieri et al. 2006, Rainieri et al. 2007).

In geotechnical engineering, static control of movements and pressure is a common practice, but dynamic monitoring applications prove to be relatively limited. Monitoring the propagation of seismic waves in free field conditions is a common work method in seismology and seismic engineering. Vertical seismic arrays are also quite common (Iwasaki & Tai 1996, Tang 1987, Nigbor & Steller 1996). However, full-scale dynamic monitoring systems have been limited to geotechnical structures, while data related to permanent post-earthquake deformations is readily available.

In the literature, it is possible to find a series of case studies regarding the seismic monitoring of earth dams (Sica 2003). The interaction between soil, foundation, and structure has also been the object of specific studies (Steidl & Nigbor 2004, Pitilakis et al. 2005). The authors are not aware if seismic monitoring systems are operating for actual scale flexible support works. Therefore, an integrated geotechnical and structural monitoring system has been designed and is currently being implemented by the Laboratory of Structural Dynamics and Geotechnics at the University of Molise (Italy). Different competencies, models, and knowledge from different scientific areas were successfully integrated.

The data collected by the monitoring system while in operating conditions will be processed and used to refine numerical models and to study current knowledge about the behavior of flexible supporting structures in more detail. Data recorded during seismic events could be crucial for better understanding dynamic behavior and the interaction between the ground and the structure during high magnitude earthquakes; this information could prove to be very useful for improving seismic design procedures for these types of structures.

Linear and non-linear data models and processing methods will be used to study and understand dynamic behavior and the interaction of the structure with the soil. Professionals in structural and geotechnical competencies will cooperate to achieve this goal.

3 DESIGNING THE RETAINING WALL OF PILES

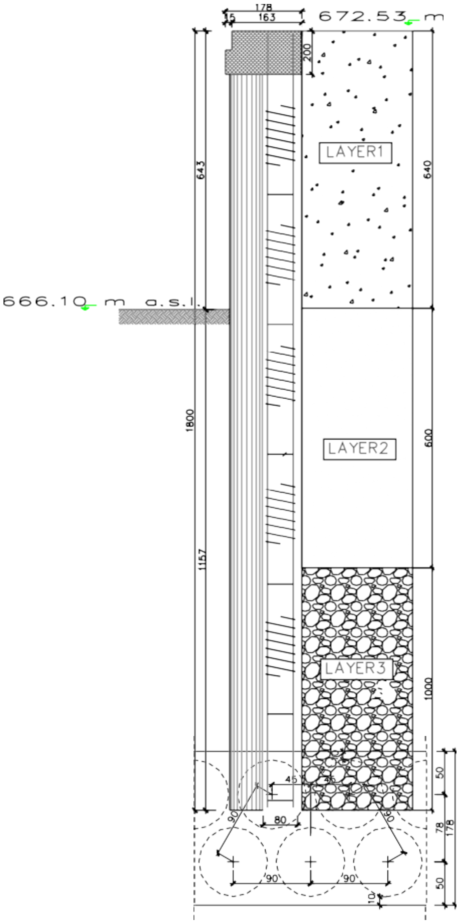
The retaining wall made of reinforced concrete piles, for which the dynamic monitoring system was designed, was built during the construction works for the Casa dello Studente (The Student House) at the University of Molise in Campobasso.

At the construction site, the main soil formations present were clays in various colors, scaly fabric, marl and marlstone, calcarenite, and fragments of flysch. The upper part of the material was slightly altered and covered with a superficial layer of debris and compact fill that measures 0.4 meters thick. The level of the water table assumed during the design phase was under the structure. Based on a conventional characterization of the subsoil, in designing the Casa dello Studente, a geotechnical model of the subsoil was adopted. Its main characteristics are summarized in Table 1.

Table 1. Main characteristics of the geotechnical subsoil model adopted for the site of the new Casa dello Studente in Campobasso.

LAYER	THICKNESS (M)	WEIGHT (KM)	FRICTION ANGLE Φ(°)	COHESION, C' (KPA)
1	6.40	18.64	25	0
2	6.00	19.62	19	19.6
3	10.00	19.62	18	58.9

A flexible retaining wall made of two rows of reinforced concrete piles was built, based on conventional design procedures, to support a free height of about 6 m, adopting a friction angle between the soil and the structure equal to zero and a pseudo-static seismic coefficient equal to 0.1875. The piles measure 800 mm in diameter and 18 m long. They were bored and made without an exterior coating. No anchoring devices were used. A crowning beam made of reinforced concrete was manufactured and placed on the summit of the support structure. A structure scheme is shown in Figure 1.



Dimension in centimeters

Figure 1. Cross section and plan view of the retaining wall of piles for the new Casa dello Studente in Campobasso.

Two piles in the retaining wall have instruments installed on them, which are the “embedded” accelerometer modules specifically developed for this application. The monitored piles were selected to avoid possible edge effects (Figure 2).

Figure 2. Global view of the retaining wall and position of the monitored piles.

The monitoring system will be completed with the installation of more sensors on the building on the valley side of the wall. The nearness of the two structures (retaining wall and building) could lead us to consider possible interactions phenomena. Therefore, being aware of structural behavior can help us understand the results of the measurements provided by the geotechnical sensors.

4 "EMBEDDED" SENSORS

Two contiguous piles, one in each row of the retaining wall, were fitted with embedded accelerometer modules and commercial inclinometer casings with a diameter of 47 mm.

The singularity of the application and a series of problems connected with inserting the sensors into the reinforced concrete piles (impact, pouring pressures, humidity, etc.) required us to ask the manufacturer to develop a specific enclosure for creating a biaxial accelerometer module that could be immersed in the poured concrete. Technicians and researchers of the Laboratorio di Dinamica Strutturale e Geotecnica at the University of Molise cooperated with technicians and engineers from PCB Piezotronics to develop a new accelerometer module as a final result.

Each module contains two highly sensitive piezoelectric seismic accelerometers arranged in two orthogonal directions and inserted into a stainless steel enclosure that is waterproof and protects them from pressure while the concrete is poured. Each module was designed and installed inside the piles to measure the vertical component of acceleration and a horizontal component as well (which is the normal reading at the base of the retaining wall).

The sensors can measure 10 V/g, and their bandwidth goes from 0.15 Hz to 1 kHz with a resolution of 8 µg rms. The full scale is 0.5 g. The characteristics of the sensors were selected in a balanced manner to respond to typical measurement needs under operating conditions and also be able to measure under conditions of extreme seismic stress. Furthermore, they have a 5000 g shock limit; therefore, even though specific procedures were adopted to protect the sensors during the concrete pouring phase (which was done with a pressurized hose that was progressively lifted to prevent the concrete from having a direct impact on the accelerometer module enclosure), the high shock limit has proven to be very important for guaranteeing full functionality of the sensors after installation. After all, these sensors cannot be repaired once they are immersed in the concrete.

Inside each enclosure, the sensors are immersed in a rigid epoxy resin that insulates them and ensures that the enclosure walls have the necessary rigidity and that they are not damaged during the pouring phase or by the pressure of the cement. The resin also waterproofs the inside of the enclosure.

The design drawings of the accelerometer module are shown in Figure 3, and the prototype of the modules is shown in Figure 4. During the installation phase, each module was connected to a pipe acting as a wiring duct. The diagram of the connection to the wiring duct pipe, with the sheathing necessary to render it waterproof, is shown in Figure 5.

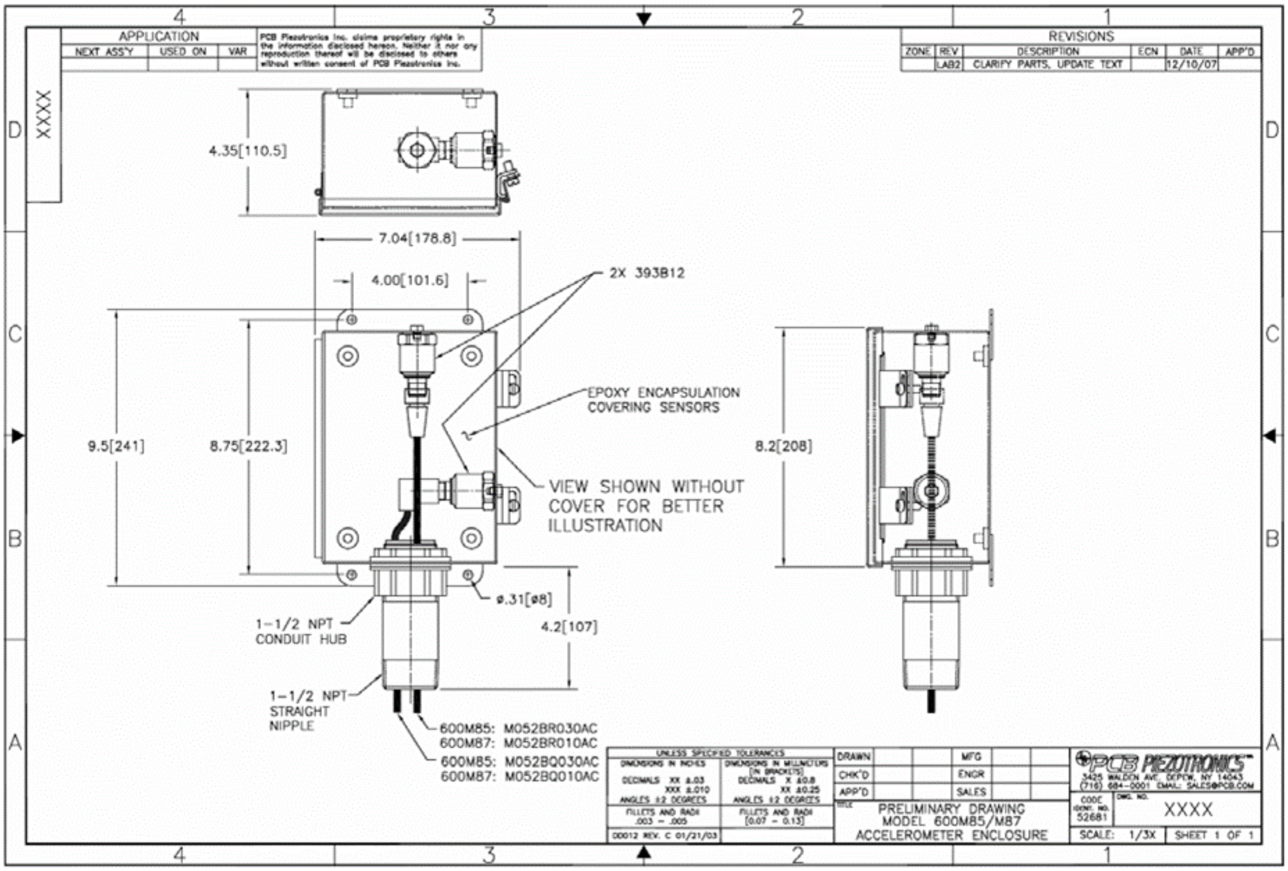


Figure 3. Diagram of the embedded accelerometer module (reproduced with permission from PCB Piezotronics Inc.).

Figure 4. Prototype of the accelerometer module.

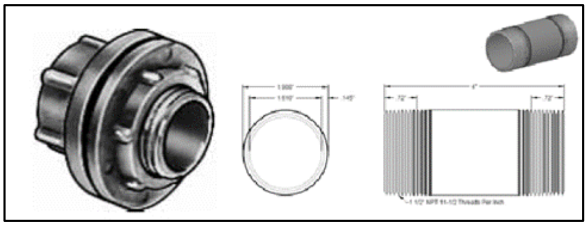


Figure 5. Details of the connection.

5 DESIGNING THE INSTRUMENTED PILES

Three accelerometer modules were inserted into each pile. To ensure significance in this study and avoid singularities in the global behavior of the structure, specific calculations were done and a suitable reinforcement was designed to guarantee that the instrumented piles had the right level of resistance and rigidity, similar to the piles next to them.

The positions were chosen to place the sensors as far as possible from the rotation centers calculated for the structure during the construction and operative phases. Two more sensors were installed at the head of each pile, in a groove in the crowning beam that connects the two rows of piles in the retaining wall. A schematic drawing of the instrumented piles is shown in Figure 6. As specified above, the dimensions of the accelerometer modules required the design of an additional reinforcement to place around them; due to their size, the part of the pile where they are positioned is no longer circular. It looks like a hollow section with an external diameter of 800 mm and an internal diameter of 300 mm, which equals the amount of space that the module occupies.

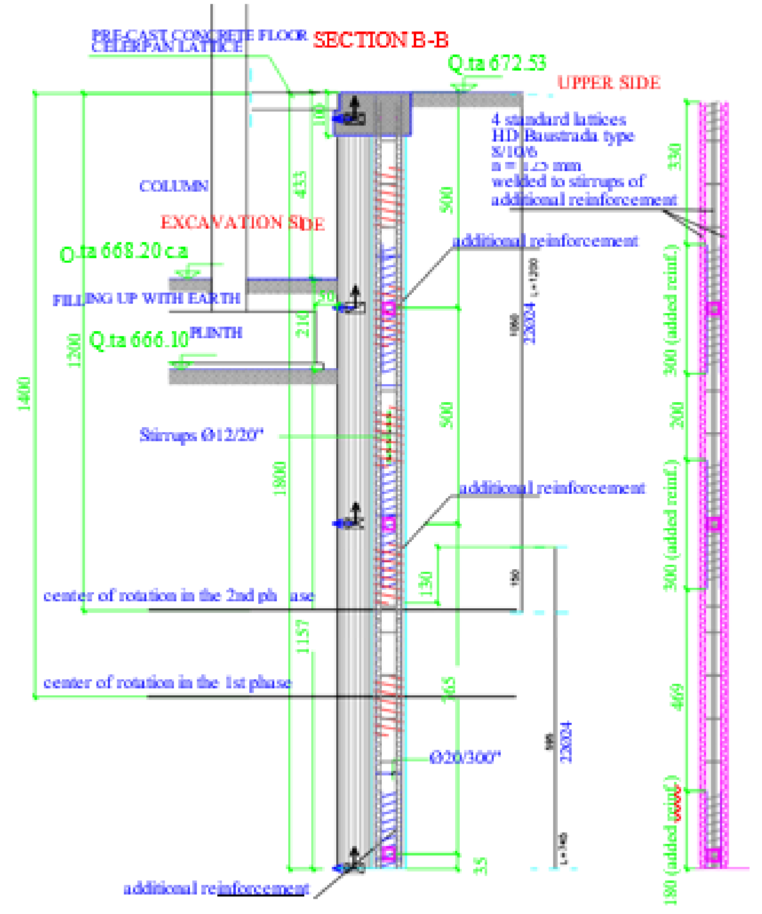


Figure 6. Diagram of monitored piles

The additional reinforcement consists of eight longitudinal bars measuring 14 mm in diameter each, and in brackets made with bars, 10 mm in diameter and placed at intervals of 200 mm. The additional reinforcement was installed in correspondence with the positions of the piles with the different accelerometer modules and then extended on both sides for a length suitable to guarantee that they were anchored to the longitudinal bars.

The additional reinforcement was connected to the other reinforcement with four standard Baustrada lattice girders, 8/10/6, h = 125 mm (Figure 6 and Figure 7).

Figure 7. Additional reinforcement for installing the sensors.

In the reinforcement design phase, pile resistance and bending stiffness were explicitly considered. The first was employed to prevent changes in the pile's plastic mechanisms; the second was carefully assessed to prevent interferences with the dynamic response caused by shocks of moderate intensity. The calculations show how the variations in resistance and stiffness of the instrumented piles, compared with that of the other piles, are not important. In particular, a maximum increment of resistance of 5% and an increment in inertia moment of 0.5% were estimated for the sections of pile around the sensors compared with the current section of the same pile. More details can be found in other sources (Fabbrocino et al. 2008).

Studies on the reduction in axial and torsional rigidity have also been conducted, which revealed a variable difference between 11% and 13%. This confirms that the methods used to install the "embedded" sensors are valid for an accurate assessment of the dynamic response of the piles that also reflects the behavior of adjacent piles; in fact, the primary bending response of the piles was preserved with minimal effects on the axial and torsional properties as a whole. From a structural point of view, these are not fundamental aspects of the local dynamic response of the flexible retaining wall.

The presence of the additional reinforcement, the sensors, and the pipes for wiring, as well as the installation of two inclinometer casings inside each instrumented pile, has made the pouring process very complex. A pressurized hose 120 mm in diameter was used to pour the concrete. It was progressively lifted during the pouring process while taking care that its end was always positioned under the surface of the concrete.

The large quantity of reinforcement near the accelerometer modules and the use of a pressurized hose with a smaller diameter to pour the concrete have required specific studies to define the properties of the concrete. Its workability and fluidity were fundamental characteristics for this specific application. Self-compacting concrete was therefore designed to obtain the rock cube strength characteristic equal to 30 MPa. This value is also the value adopted for the concrete resistance in the adjacent piles. Using a self-compacting concrete also facilitates the pouring phase in particularly difficult conditions, like those described here, without producing segregation phenomena (Fabbrocino et al. 2009).

6 SENSOR INSTALLATION

The accelerometer module enclosure was connected to the additional reinforcement with a steel plate that was then welded to the longitudinal bars. Four bolts were used to fasten the enclosure onto the plate, as shown in Figure 8.

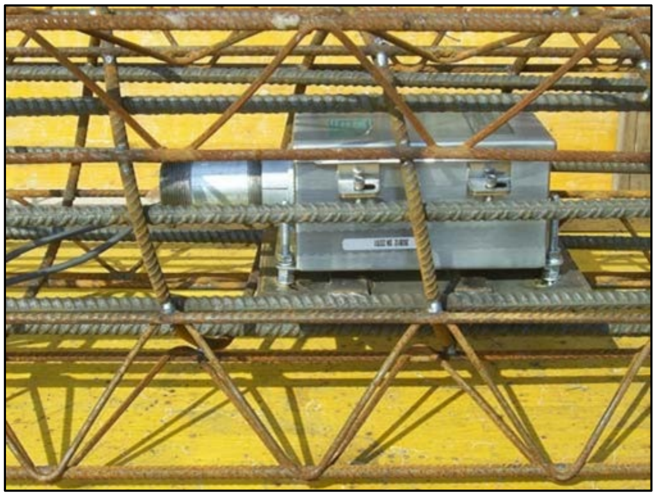


Figure 8. Connection between the accelerometer module and the reinforcement.

The main problem during the assembly phase was aligning the sensors properly. To ensure correct alignment with extremely small tolerances, the accelerometer module and the plate were connected with four slots created in the enclosure. Fasteners with nuts and lock nuts were used to fasten the enclosure in four points and then the position inside the post was regulated. The slots permitted rotations of the enclosure in the measuring plane, and the bolts allowed three different actions: the enclosure rotating around the pile axis, shifts in the measuring plane, and rotations with respect to the orthogonal plane of the measuring plane and the pile axis.

The sensors were then aligned using three parallel reference lines. Parallelism of the enclosure walls was verified with respect to the planes identified by the reference lines. The correct orientation of the sensors inside the retaining wall was obtained by tracing reference lines to the heads of the adjacent piles and checking parallelism, or the orthogonality between those straight lines, and the measuring directions reproduced on the heads of the reinforcements on the instrumented piles before they were inserted into the hole.

The image in Figure 9 shows the additional reinforcement of the instrumented piles along with the accelerometer module on the lower end, the wiring compartment pipe, and the two inclinometer casings, assembled at the building site and ready to be installed.

Inclinometer measurements were done to verify the verticality of the additional reinforcement on the piles and the girders after they were inserted into the hole and before the concrete was poured.

Figure 9. Accelerometer module, wiring compartment and inclinometer casings assembled at the building site before installation.

The lack of a perfect initial vertical position combined with the physiological rotation of the retaining wall due to static loads caused the positions of the sensors to change with respect to the design values. Nevertheless, corrections can be made if necessary during the data processing phase when the system becomes fully operative.

The inclinometer measurements carried out before the concrete was poured have also allowed researchers to verify the correct installation of the sensors, ensuring that the pile axis line and the normal retaining wall line were maintained as measurement directions. Moreover, the calculation of the expected deflection of the system consisting of the four girders and the additional reinforcement around the accelerometer modules during the lifting and installation phases showed that the expected deflection was within the elastic limit for steel; therefore, no permanent deformations were expected after lifting.

Inclinometer measurements will be taken periodically during the entire lifespan of the structure to monitor its static position. During the excavation phase, the movements of the pile heads will also be monitored with topographic instruments. A test record made after the concrete pouring phase showed that the sensors installed inside the piles were functioning correctly (Figure 10).

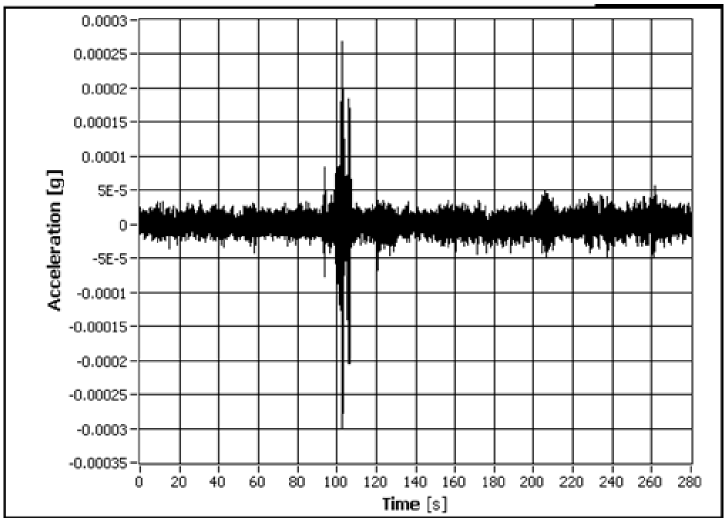


Figure 10. Examples of accelerometer records during testing.

7 CONCLUSIONS

The need to broaden our knowledge about the seismic behaviors of geotechnical structures, such as flexible support works, was the main reason behind the design and installation of a full-scale monitoring system on a retaining wall made of reinforced concrete piles built within the scope of the construction project for the new Casa dello Studente at the Campobasso campus of the University of Molise.

The monitoring system in the retaining wall consists of six embedded accelerometer modules developed specifically for this project and inserted inside two contiguous piles. The insertion of the sensors inside the piles and the implementation of suitable automatic data processing procedures have allowed researchers to create an example of an intelligent structure at the University of Molise.

Each accelerometer module can measure acceleration in the vertical direction (along the pile axis) and the horizontal direction at a right angle with the plane of the retaining wall.

Specific assessments were conducted to verify that the presence of the accelerometer modules inside the piles would not modify their resistance and rigidity properties significantly; for this reason, a specific additional reinforcement was designed to facilitate the installation of the sensors inside the piles, and connected to the original reinforcement.

Researchers feel that studies on the interaction between the ground, the geotechnical structure, and the building will provide a fundamental contribution to learning how retaining walls made of piles behave in the context of performance-based design methods.

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