# Sensor embedment, dynamic monitoring and model refinement for smart geotechnical structures

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ABSTRACT: Over the last 50 years data from laboratory tests and post-earthquake reconnaissance have been used to gain knowledge about the dynamic and seismic behavior of geotechnical structures and to improve analysis and design procedures. The scarcity of reconnaissance data has pointed out the need for full-scale and near full-scale tests in earthquake engineering for research purposes. Structural Health Monitoring (SHM) systems have been applied to different kinds of structures but, in geotechnical engineering, while static control of displacements and pressures is quite common, dynamic monitoring is relatively limited. In order to fill the gap of knowledge about the dynamic behavior of geotechnical structures a research project has been started for the implementation of integrated structural and geotechnical monitoring systems. In particular, attention has been focused on the possibility to combine sensors, numerical analyses and data processing procedures to turn a flexible retaining wall into a smart geotechnical structure. A multidisciplinary workgroup has been therefore congregated and different skills mixed together. Implementation of the prototype is still in progress, but some preliminary, promising results can be already outlined.

The present paper describes the relevant aspects of design and implementation of a smart flexible retaining wall. Moreover, preliminary results of experimental investigations are reported and correlated with those provided by numerical models, in view of identification of the main sources of uncertainties and of the main challenges in the field of vibration-based SHM of geotechnical structures.

## 1 INTRODUCTION

Construction management and maintenance are becoming critical issues in urban areas. The possibility to observe the structural response and assess conditions of incipient damage and follow its evolution is the main reason for the large development and spread of Structural Health Monitoring (SHM) systems for civil structures in the last 20 years. In fact, reduction of inspection costs, seismic protection, possibility to develop post-earthquake scenarios and support rescue operations are some of the main advantages related to implementation of effective SHM systems. SHM is a multidisciplinary field, where a number of different skills (seismology, electronic and civil engineering, computer science) and institutions can work together in order to increase performance and reliability of such systems, whose promising perspectives seem to be almost clearly stated. SHM systems have been applied to different kinds of structures, Doebling et al. (1996). However, a limited number of full-scale dynamic measurement systems are currently applied to geotechnical systems. Several data are available in terms of post-earthquake permanent deformations and some case-histories are reported in Sica & Pagano (2009), Steidl & Nigbor (2004), Pitilakis et al. (2005). The SHM system described in this paper, instead, focuses on static, dynamic and seismic monitoring of a full scale flexible retaining wall. An integrated structural and geotechnical monitoring system has been designed and it is currently under development at University of Molise. It takes advantage of different skills and it is a good chance to mix knowledge and models from different scientific areas. In particular, specific attention has been paid to the possibility of combining sensors and data processing procedures to turn a flexible retaining wall into a smart geotechnical structure. Implementation of the prototype is still in progress, but the primary role played by integration into the system of knowledge and models from different scientific areas can be already outlined.

The analysis of the dynamic response of the wall under operational and earthquake conditions plays a fundamental role for the enhancement of numerical models and the improvement of the current knowledge about the dynamic and seismic behaviour of flexible retaining walls. Moreover, dynamic measurements can be used to build an effective vibration-based SHM system which can be data-driven, Doebling et al. (1996), or take advantage also of results of numerical analyses, Link & Weiland (2009). On the other hand, data recorded during seismic events may give a deeper insight in the soil-structure interaction, in particular during strong motion events. Collection of such data will be useful also to improve seismic design procedures. Soil parameters obtained from in-situ geotechnical investigations have been therefore used for implementation of a preliminary Finite Element (FE) model of the wall. Results of dynamic monitoring are then used to assess the quality of the model and improve it.

In the present paper, after a description of the most relevant aspects of design and implementation of the SHM system, the main results of system identification from records of the structural response in operational conditions are illustrated. They are also used to validate the numerical model of the wall through the evaluation of correlations between experimental and numerical results. The main sources of uncertainties and the main challenges in the field of vibration-based SHM of geotechnical structures are finally identified.

## 2 SHM OF A RETAINING WALL: DESIGN AND IMPLEMENTATION

### *2.1 Site characterization*

The monitored reinforced concrete (r.c.) flexible retaining wall is a part of the new Student House at University of Molise in Campobasso (Italy). The research activities started after the preliminary design of the wall made by some consultants. Varicoloured scaly clays, limestones, calcareous marls, calcarenites and fragments of the flysch are the main soil formations in the area. Soil is slightly weathered in the upper part and is overtopped by a shallow remoulded man-made and debris cover with a thickness of 4 ÷ 10 m. Two boreholes were executed before the wall construction and a number of tests were carried out including: stratigraphic column, standard penetration test, down-hole test, laboratory tests on undisturbed samples (evaluation of physical and chemical properties, triaxial tests, shear tests). According to the results of investigations a geotechnical profile of the soil has been defined. The soil properties for each layer are reported in Table 1. Water table level is considered below the depth of interaction with the geotechnical structures. Based on conventional design procedures, a flexible retaining wall made by two rows of r.c. piles with a diameter of 800 mm and a length of 18 m has been built to sustain a free height of about 6 m. Piles have been built using drilling buckets; no casing has been employed during construction. No anchorages have been provided. A reinforced concrete top-beam has been built on top of the retaining structure.

Table 1. Characteristics of the geotechnical model

| Layer | Unit weight $\gamma$ ($kN/m^3$) | Friction angle $\Phi$ (°) | Cohesion c' (kPa) | $E_{50}$ ($kPa \cdot 10^3$) |
|---|---|---|---|---|
| 1 | 19.2 | 22 | 22.0 | 4.7 |
| 2 | 19.5 | 18 | 28.0 | 15.9 |
| 3 | 19.8 | 23 | 20.5 | 28.9 |
| 4 | 20.1 | 24 | 19.0 | 35.2 |

### 2.2 *Design and installation of the SHM system*

Two piles of the above mentioned wall have been instrumented with embedded piezoelectric accelerometers and some ABS plastic commercial inclinometer casings ($\Phi$= 47 mm). They have been chosen in order to avoid as much as possible boundary effects. The SHM system is going to be completed by installing a number of sensors on the building under construction on the excavated side of the wall. Closeness between the two structures suggests that interaction phenomena may happen. Thus, monitoring of the structural and dynamic behavior throughout its life from the construction can help to better understand the obtained measurement results. Attention is herein focused on continuous monitoring of the dynamic response of the wall. The interested reader can refer to Dey et al. (2011) for the results of static monitoring and their use for back-analysis of the behavior of the wall. In order to increase the level of knowledge about the behavior and the mechanisms of interaction between structure and soil for flexible retaining walls, a continuous SHM system has been developed based on accelerometers embedded in two piles of the wall. The singularity of the application and a number of issues directly related to sensor embedment required design of a specific enclosure for the manufacturer. As a result, a new sensor module for embedded applications was born from the cooperation among academicians on one hand and engineers of the manufactory company on the other. Each sensor module consists of two seismic, high sensitivity (10 V/g) integrated circuit piezoelectric (ICP®) accelerometers placed in two orthogonal directions. Encapsulation in a stainless steel enclosure ensures waterproofing protection against concrete pressure. More details can be found in Fabbrocino et al. (2008). Each module has been designed and installed in order to detect one horizontal component (normal to the wall plane) and the vertical component of acceleration. A schematic view of instrumented piles is shown in Figure 1.

The instrumented piles had to show similar characteristics with respect to the adjacent ones, in order to assure significance to the present study and avoid singularity in the overall behaviour of the structure. For this reason, due to the not negligible dimensions of sensor modules which caused some changes in pile geometry, specific computations and additional reinforcement have been provided so that the instrumented piles had similar strength and stiffness with respect to the nominal characteristics of the adjacent piles. In particular, the additional reinforcement has been designed in order to obtain piles basically characterized by the same strength and flexural stiffness of the adjacent ones. More details can be found in Fabbrocino et al. (2008). Sensor enclosures have been connected to the additional reinforcement by means of a steel plate welded to the longitudinal bars. A system of four bolts has been designed to fix the enclosures over the plates and to align sensors along the pile axis, Fabbrocino et al. (2008).

The additional reinforcement, the presence of sensors, pipes for cable routing and three inclinometer casts made concrete casting difficult. Concrete workability and fluidity represented crucial issues for this application. Thus, a Self-Compacting Concrete (SCC) has been designed in order to obtain the same concrete strength of the adjacent piles, namely $R_{ck}$ = 30 MPa, Fabbrocino et al. (2009). Its adoption made casting possible without segregation phenomena.

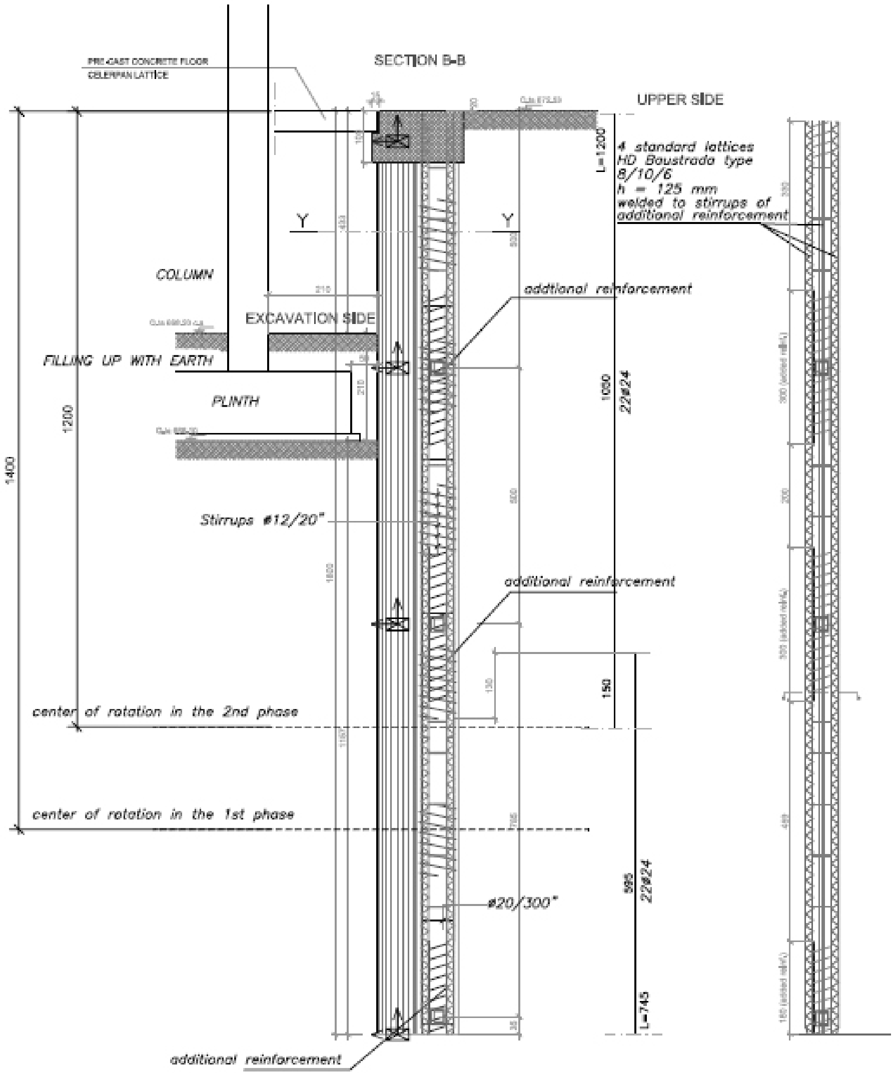


Figure 1. Embedded sensor layout.

In the following, the application of Operational Modal Analysis (OMA) techniques, Zhang et al. (2005), for the identification of the main dynamic parameters of the wall from vibration measurements in operational conditions is described. The correlation between experimental and numerical results is also evaluated to check the quality of the model. Specific procedures for continuous monitoring of the dynamic properties of the wall and structural health assessment are also under development. However, they are out of the scope of the present paper.

## 3 ANALYSIS OF THE DYNAMIC BEHAVIOUR OF THE WALL

### *3.1 Experimental analysis*

The acceleration response of the wall is continuously monitored through a customized measurement system specifically developed for the present application. It is based on a National

Instruments CompactDAQ system made by NI9233 DAQ modules. Such modules, ensuring in-built antialiasing filter, 24 bit resolution, 102 dB dynamic range and 56 dB CMRR, are originally designed for vibration measurements. The measurement hardware is controlled by a software developed in LabView environment by the Authors. It is able to continuously record the dynamic response of the monitored piles to ambient vibrations and save it into files of a desired length. This is currently set to 1 hour.

The response is sampled at 2 kHz but it is possible to apply a decimation factor before saving. The final sampling frequency is currently set equal to 100 Hz. Power spectra are continuously computed and shown on screen during the measurement process, together with the measured acceleration response in time domain. Thus, it is possible to check in real-time the quality of the acquired signal and its frequency content. The output power spectra represent also a basic tool for a quick identification of the fundamental frequency of the wall in operational conditions, Bendat & Piersol (1986). A comprehensive analysis according to the Basic Frequency Domain approach, Bendat & Piersol (1993), can be carried out off-line by stopping acquisition for a while and by recalling the analysis module directly from the data acquisition one. Since the seismic response of the structure is also of interest, a trigger level of 0.001 g has been set. When it is overcome, the dynamic response of the pile is acquired and stored in parallel also in a second file, denoted by “T”. The length of the record in this case depends on the level of acceleration with respect to the chosen trigger level. Since the system is completely homemade, in the near future more refined strategies for identification of ground motions can be implemented. For instance, a link with the national seismic network can help the discrimination between actual earthquakes and false alarms.

Records of the dynamic response of the wall to ambient vibrations have been analyzed in order to identify its fundamental dynamic properties. Widely used, powerful and robust OMA techniques, such as the Frequency Domain Decomposition, Brincker et al. (2000), the Stochastic Subspace Identification, Van Overschee & De Moor (1996), Peeters (2000), and the Second Order Blind Identification, Poncelet et al. (2007), have been used. The main issue of the dynamic identification is represented by the low amplitude of ambient vibrations and the consequent low signal-to-noise ratio. Nevertheless, a robust identification of the first two fundamental modes has been carried out. Results are summarized in Table 2. Their reliability has been confirmed by cross checks in terms of both natural frequencies and mode shape estimates. Highly coherent results, characterized by negligible scatter, have been provided by the different methods, thus ensuring the success of the identification process.

Table 2. Modal identification results and correlation with the refined model

| Mode | $f_{exp}$ (Hz) | $\xi_{exp}$ (%) | $f_{FEM}$ (Hz) | Scatter (%) | MAC |
|---|---|---|---|---|---|
| I | 3.68 | 1.4 | 3.68 | -- | 0.99 |
| II | 7.23 | 1.2 | 6.40 | -11.5 | 0.94 |

### *3.2 Numerical analysis and correlation*

The dynamic module of Plaxis 2D v.8.4, Brienkgreve (2002), has been used to develop a FE model of the retaining wall for the dynamic analysis. The basic configuration of the static model, Dey et al. (2011), has been retained; however, many subtle changes had to be incorporated in order to enable proper functionality of the model. Such modifications can be stated as the calibration of the model and they are briefly outlined in the following.

The soil is modeled as a linear elastic material. Such a choice is justified by the very low amplitude of motion due to ambient vibrations, so that the soil does not experience the development of plastic zones in the region of interest. As a consequence, the elastic modulus of the soil has been chosen in agreement with the initial tangent modulus $E_0$ obtained from the Down-Hole tests. The soil properties are shown in Table 3. The wall has been modeled as a plate.

Table 3. Soil properties for the dynamic analyses

| Layer | $E_0$ (kPa $\cdot 10^5$) | $E_{oed}$ (kPa $\cdot 10^6$) | ν | $G_0$ (kPa $\cdot 10^5$) | $V_s$ (m/s) | $V_p$ (m/s) |
|---|---|---|---|---|---|---|
| 1 | 5.344 | 1.522 | 0.43 | 1.869 | 308.8 | 881.3 |
| 2 | 19.67 | 6.375 | 0.44 | 6.83 | 585.9 | 1790.0 |
| 3 | 28.80 | 8.200 | 0.43 | 10.07 | 706.0 | 2015.0 |
| 4 | 32.95 | 9.381 | 0.43 | 11.52 | 749.5 | 2139.0 |

Since dynamic models involving the study of shear waves are largely affected by the waves transmitted and reflecting from the boundaries of the model itself, it is imperative to keep the region of interest (the region which will be under observation to study and interpret the results) as far as possible from the vertical boundaries. Hence, in order to gain experience in this regard, the effect of domain width on the frequency response of the system has been investigated. As the domain width increases, the quality of the spectra also improves. This can be interpreted as a reduction in the interference of the domain boundary on the response of the medium owing to the reflection of the waves at the boundary. Results of analyses seem to state that a domain width greater than 10 times the height of the model is adequate to simulate in a reliable way the infiniteness of the situation in reality. However, it is worthy to mention that the domain definition is customary to change with each problem, and hence, a unique study of this issue should be carried out for initial calibration of the dynamic model.

Meshing also plays a key role in obtaining reasonable results, especially in a dynamic analysis. A too coarse meshing fails to capture the subtle changes in the stresses generated in different parts of the medium, especially at the points where stress concentrations are expected. On the other hand, a too fine mesh makes the computational time very long. Hence, a trade-off is required to obtain a nearly accurate solution in reasonable time. In this study, the global meshing is achieved with a medium mesh, the central part of the model is refined twice, and the embedded wall is provided with two stages of refinement. This was done in order to take care of the stresses and acceleration generated in the important region of concern in the study.

Rayleigh damping has been used in the dynamic analysis in order to simulate the material damping of the soil for plane strain conditions.

Time integration has been carried out according to the implicit Newmark scheme. Newmark α and β parameters determine the numerical time-integration. In order to obtain an unconditionally stable solution, the parameters have to satisfy the following conditions: $N_\beta \geq 0.5$, and $N_\alpha \geq 0.25(0.5+N_\beta)^2$. For the present study, Newmark damping parameters are selected according to the *Damped Newmark Scheme* ($N_\alpha$=0.3025, $N_\beta$=0.6).

An absorbent boundary is aimed to absorb the increments of stresses on the boundaries caused by dynamic loading, which would otherwise be reflected inside the soil body. $C_1$ and $C_2$ are relaxation coefficients used to improve the wave absorption on the absorbent boundaries. $C_1$ rectifies the dissipation in the direction normal to the boundary and $C_2$ does the same in the tangential direction. For the present study, $C_1=C_2=2$ is chosen for the relaxation coefficients in order to obtain the highest wave absorption and minimize the possible reflection of the waves in the boundary.

With the above settings, a dynamic analysis has been carried out by applying a Gaussian white noise sampled at 100 Hz as input. Then, the dynamic properties of the system have been extracted by applying OMA techniques to the response simulated in positions corresponding to those of experimental measurements. A preliminary analysis has been carried out by considering a model characterized by the same properties of the soil layers obtained from the in-situ investigations before construction. In this case, the first two fundamental frequencies are at 4.4 Hz and 6.3 Hz. Thus, even if a reasonable agreement with the experimental values can be observed, further refinements of the model are needed in order to improve the match between experimental and numerical results. It is worth taking into account that the main uncertainties are associated to the top layer. In fact, it has been disturbed during the construction and the evaluation of its properties is made even more difficult by the presence of a shallow remoulded man-made and debris cover. Thus, a basic sensitivity analysis has been carried out with respect to the stiffness properties of the upper layer, obtaining a more refined model, able to better reproduce the experimental results, as shown in Table 2.

## 4 CONCLUSIONS

Recent seismic events in urban areas have stimulated the research about the dynamic behavior of embedded structures in soil. The availability of FE codes, advanced constitutive models for soil and suitable laboratory and in situ testing techniques allows more reliable evaluations of the safety conditions and an assessment of the structural performance. Based on the input given by recent large Italian research projects on this topic, a study is in progress at the University of Molise to deepen the knowledge in the design procedures for embedded retaining walls under seismic loading. In this context, a monitoring system for a full scale retaining wall has been developed in order to investigate its static and dynamic behavior.

In this paper, after a brief description of the monitoring system, the first results obtained from vibration records in operational conditions have been illustrated. Operational Modal Analysis techniques have been successfully applied to evaluate the fundamental dynamic properties of the wall. Moreover, a numerical model of the structure has been set. The comparison between the experimental and numerical results has given the opportunity to identify the main sources of uncertainties associated to the FE modeling of the system. Correlation analyses provided a refinement of the model, so that it is now able to better reproduce the experimental results with respect to its original setting. The obtained results are certainly promising and further investigations and sensitivity analyses are in progress in order to better understand the influence of the model parameters on the dynamic response. This represents the first step also towards the analysis of the issues related to soil structure interaction under strong motion loadings and the automated assessment of the performance and health state of the wall.

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