Operational Modal Analysis for identification of geotechnical systems

Carlo Rainieri[1], Giovanni Fabbrocino[1], Filippo Santucci de Magistris[1], Carmine Laorenza[1], Luca Deseri[2]

[1]*Structural and Geotechnical Dynamic Lab "StreGa", University of Molise, Italy*
E-mail: carlo.rainieri@unimol.it, giovanni.fabbrocino@unimol.it, filippo.santucci@unimol.it, carmine.laorenza@unimol.it

[2]*Department of Mechanical and Structural Engineering, University of Trento, Italy*
E-mail: deseril@ing.unitn.it

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SUMMARY. Over the last 50 years, earthquake engineers have relied on data from laboratory experiments and from post-earthquake reconnaissance efforts to gain knowledge and confidence in numerical analyses and design procedures. Recognizing the scarcity of reconnaissance data and the need for elucidating the response mechanism associated with actual structures, full-scale and near full-scale experimentation is becoming an essential component of research procedure in earthquake engineering.
SHM systems have been applied to a variety of structures, such as building, bridges, pipelines, wind turbine blades. In geotechnical engineering, while static control of displacements and pressures is a quite ordinary construction practice, the applications of dynamic monitoring are relatively limited. Monitoring of seismic waves propagation in free-field condition, at different scale level, is a common working methodology in seismology and in earthquake engineering. Vertical seismic arrays are also quite widespread. However, a limited number of full-scale dynamic measurement systems are applied on geotechnical structures, while several data are available in terms of post-earthquake permanent deformations.
A triale integrated structural and geotechnical monitoring system has been designed and it is currently under implementation by the Structural and Geotechnical Dynamic Laboratory 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 but characterized by several common aspects.
Data coming from the system under operational conditions will be processed and used to enhance numerical models and improve the current knowledge about flexible retaining walls. On the other hand, data recorded during seismic events might also be crucial to have a deeper insight in the dynamic behaviour of such structures and in the soil-structure interaction during strong motion events: in fact, these data will be useful to improve seismic design procedures for this kind of constructions. Linear and non-linear models and data processing techniques will be used to correctly understand the dynamic behaviour of the structure and its interaction with soil. Geotechnical and structural skills will act together to this aim.
In the present paper, after a description of the above cited integrated SHM system and of the sensors specifically developed for such application in cooperation with PCB Piezotronics Inc., some relevant issues concerning the applicability of experimental modal analysis techniques to geotechnical systems are discussed, pointing out opportunities and drawbacks related to some consolidated techniques of data processing.

1 INTRODUCTION

Over the last 50 years, earthquake engineers have relied on data from laboratory experiments and from post-earthquake reconnaissance efforts to gain knowledge and confidence in numerical analyses and design procedures. Recognizing the scarcity of reconnaissance data and the need for elucidating the response mechanism associated with actual structures, full-scale and near full-scale experimentation is becoming an essential component of research procedure in earthquake engineering [1].

SHM systems have been applied to a variety of structures, such as building, bridges, pipelines, wind turbine blades. The School of Engineering Tower SHM system in Naples is an example of Italian application in this field, where structural monitoring and seismic early warning are combined [2]. In geotechnical engineering, while static control of displacements and pressures is a quite ordinary construction practice, the applications of dynamic monitoring are relatively limited. Monitoring of seismic waves propagation in free-field condition, at different scale level, is a common working methodology in seismology and in earthquake engineering. Vertical seismic arrays are also quite widespread (see for instance the case histories of Port Island, Kobe, Japan [3]). However, a limited number of full-scale dynamic measurement systems are applied on geotechnical structures, while several data are available in terms of post-earthquake permanent deformations.

Seismic monitoring devices are not commonly used in full scale flexible retaining wall. Thus, a trial integrated structural and geotechnical monitoring system has been designed and it is currently under implementation by the Structural and Geotechnical Dynamic Laboratory 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 but characterized by several common aspects.

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In the present paper, after a description of the above cited integrated SHM system and of the sensors specifically developed for such application in cooperation with PCB Piezotronics Inc., some relevant issues concerning the applicability of experimental modal analysis techniques to geotechnical systems are discussed, pointing out opportunities and drawbacks related to some consolidated techniques of data processing.

2 DYNAMIC RESPONSE ASSESSMENT OF GEOTECHNICAL STRUCTURES: THE APPLICATION TO NEW STUDENT HOUSE IN CAMPOBASSO

2.1 *Research motivations*

A monitoring system consists of a variety of sensors to monitor the environment and the structural response to loads. SHM systems have been applied to several types of structures, such as buildings [4], bridges [5, 6], pipelines [7], wind turbine blades [8]. A synthesis is reported in [2]. However, a few applications of embedded sensors in piles are reported in the literature. Song and Zhou [9] have monitored steel reinforcement and soil stresses for static purposes.

Szyniszewski et al. [10], instead, installed wireless sensors during casting of prestressed concrete piles in order to monitor stresses and accelerations during driving: however, their interest was focused only on preventing microcracking of piles during driving, thus extending life of such elements in a marine environment. Moreover, in geotechnical engineering, while static control of displacements and pressures is a quite ordinary construction practice, applications of dynamic monitoring are limited. Monitoring of seismic waves propagation in free-field condition, at different scale level, is a common working methodology in seismology and in earthquake engineering. Vertical seismic arrays are also quite widespread [3, 11, 12].

However, a limited number of full-scale dynamic measurement systems are applied to geotechnical structures, while several data are available in terms of post-earthquake permanent deformations. Some case-histories on seismically monitored earth dam are reported in [13]; soil-foundation-structure interaction under seismic loading is also studied [14, 15].

Rarely seismic monitoring devices are adopted in full scale flexible retaining wall. Thus, an integrated structural and geotechnical monitoring system has been designed and it is currently under implementation at the StreGa Laboratory of the University of Molise. It takes advantage of different skills and it is a good chance to mix knowledge and models from different scientific areas.

Data coming from the system under operational conditions will be processed and used to enhance numerical models and improve the current knowledge about flexible retaining walls. On the other hand, data recorded during seismic events might also be crucial to have a deeper insight in the dynamic behaviour of such structures and in the soil-structure interaction during strong motion events: in fact, these data will be useful to improve seismic design procedures for this kind of constructions.

2.2 *Implementation of the dynamic response monitoring system*

Currently, two piles belonging to the flexible retaining wall of the New Student House at University of Molise have been instrumented with embedded piezoelectric accelerometers and some ABS plastic commercial inclinometer casing (Φ= 47 mm). Monitored piles have been chosen in order to avoid as much as possible boundary effects (Figure 1).

The SHM system will be completed by installing a number of sensors on the building which will be constructed on the excavated side of the wall. Closeness between the two structures suggests that a kinds of interaction can exist. Thus, knowledge about structural behaviour can help in understanding measurement results obtained from the geotechnical sensors.

The singularity of 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 technicians and scientists of University of Molise and engineers of sensor manufactory company.

Each sensor module consists of two seismic, high sensitivity (10 V/g) ceramic shears integrated circuit-piezoelectric, ICP, accelerometers model 393B12 by PCB Piezotronics Inc., placed in two orthogonal directions and encapsulated in a stainless steel enclosure which assures impermeability and protection against concrete pressure.

Each module is designed to detect one horizontal component (normal to the wall plane) and the vertical component of the accelerations. Sensor bandwidth goes from 0.15 Hz to 1 kHz. Measurement range is 0.5g pk.

Figure 1: View of the flexible retaining wall and of monitored pile location.

Moreover, they have an overload limit (shock) of 5000 g: therefore, even if specific procedures for concrete casting have been adopted, through a pipe progressively raised in order to avoid direct impact of concrete against sensor enclosure, the high shock limit has been fundamental in order to assure effectiveness of sensors, which are buried in concrete and, therefore, not repairable. Sensors in each enclosure have been encapsulated through a hard non-conductive epoxy resin to assure rigidity to the walls of the enclosure, which has not to suffer any damage during casting operation or for concrete pressure. It assures also waterproofing of the inside of the enclosure (Figure 2).

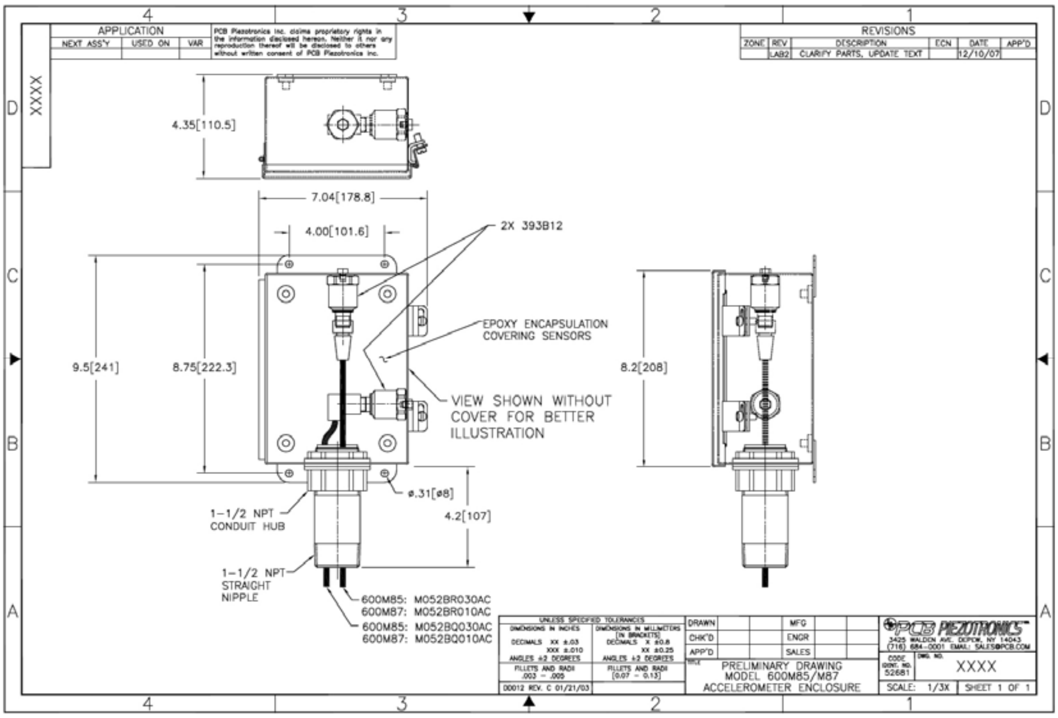
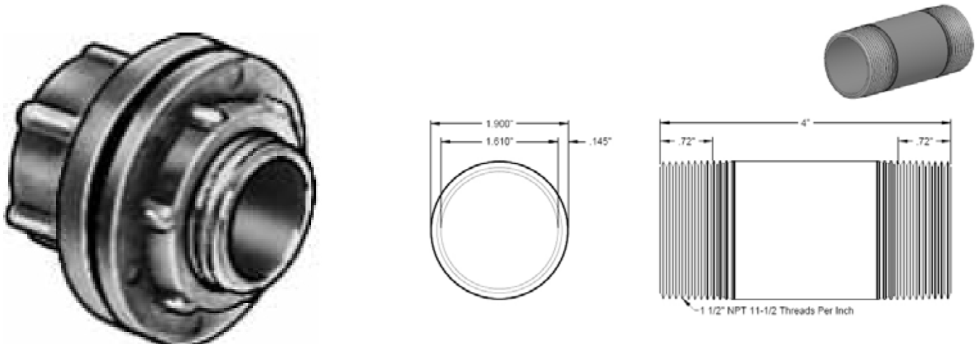


Figure 2: Scheme of developed sensor module (courtesy of PCB Piezotronics Inc.).

A picture of the prototype of the sensor module is shown in Figure 3.

Figure 3: Scheme of developed sensor module (courtesy of PCB Piezotronics Inc.).

A 1-1/2 NPT conduit hub, which has a gasket that seals against the outside of the enclosure, and a 1-1/2 NPT x 4” straight nipple have been used to connect pipes, for cable routing, to the enclosure (Figure 4). Each enclosure has been then equipped with a pipe for cable routing during installation.



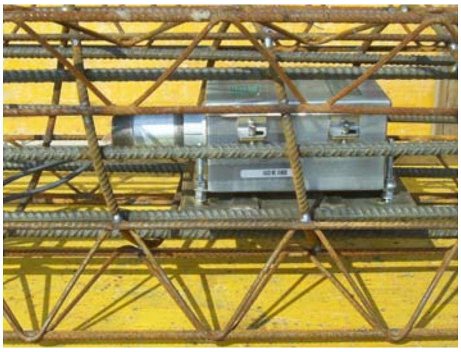
(b)

(a)

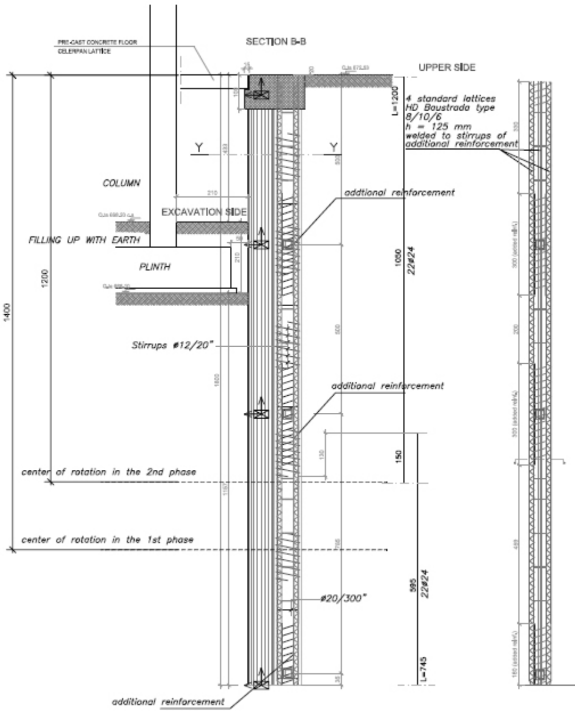
Figure 4: Conduit hub (a) and straight nipple (b) for pipe connection to module.

Three sensor modules have been placed in each pile. Additional two sensors have been placed on top of each pile, into a box over the top beams which connects all piles. A schematic view of instrumented piles is shown in Figure 5b.

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 in order to assure that the instrumented piles had similar strength and stiffness with respect to the nominal characteristics of the adjacent piles. Thus, an additional reinforcement has been designed in order to obtain piles characterized by similar strength and flexural stiffness to those ones of the adjacent piles. Strength has been considered in order to ensure that no changes in the plastic mechanisms of the pile occurred; flexural stiffness has been, instead, carefully analyzed in order to avoid changes in the dynamic response under moderate excitations. Computations have proved that, as a result of the additional reinforcement, instrumented piles are characterized by a slightly higher strength (maximum difference of 5%) and basically by the same flexural stiffness (scatter equal to 0.5% in terms of moment of inertia) with respect to the typical section of the piles. Details are reported in [16]. Checks on torsional and axial stiffness reductions have been also carried out and a scatter ranging between 11% and 13% has been found. This circumstance confirmed that the selected layout was certainly reliable, since the flexural (primary) response of the piles was preserved without relevant effects on axial and torsional global properties, that, from the structural viewpoint, are not key aspects of the flexible retaining wall local dynamic response.



(a)

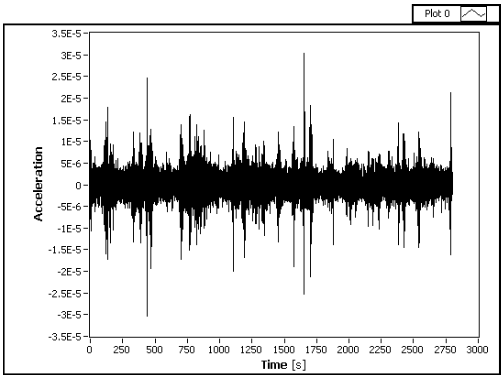


(b)

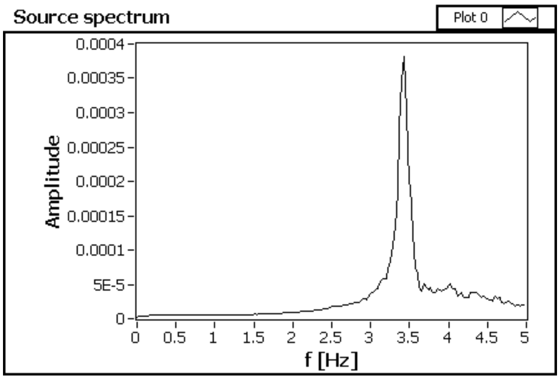
Figure 5: Prototype of embedded sensor module (a) and embedded sensor layout (b).

The additional reinforcement, the presence of sensors and of pipes for cable routing, and, finally, installation of three inclinometer casts made concrete casting more difficult. A pipe with a diameter of 120 mm has been used for casting: it has been raised during the operations but being careful that its end was always under the surface of concrete. The large amount of reinforcement near sensors positions and the use of a pipe for concrete casting characterized by a reduced diameter required adequate studies about concrete properties. Concrete workability and fluidity were crucial for this application: thus, a Self-Compacting Concrete (SCC) and has been designed in order to obtain R_{ck} = 30 MPa, which was the design value of concrete strength of the adjacent piles. Adoption of a self-compacting concrete made casting possible even in these particular conditions, without segregation phenomena.

Sensor enclosures have been connected to the additional reinforcement by mean of a steel plate welded to the longitudinal bars. Four bolts have been used to fix the enclosure over the plate (Figure 5a). The main issue in the mounting phase was related to sensor alignment. In order to assure it with very low tolerances, connection between sensor module and plate has been obtained by mean of four slots on the enclosure and by using three stud nut and a bolt in order to fix the enclosure at each point. The slots allowed rotations in the measurement plane of sensor module while the bolts allowed rotation along the pile axis, translations in the measurement plane and rotation with respect to the plane orthogonal to the latter and to the pile axis. By using three straight lines as references and checking parallelism of the walls of the enclosures, a precise alignment of sensors has been obtained. Proper orientation of sensors in the hole has been obtained by tracking some reference straight lines on the top of the adjacent piles and by checking parallelism between them and measurement directions, reproduced on the top of the instrumented pile reinforcement. A sample record of the dynamic response of piles is shown in Figure 6a.



(a)



(b)

Figure 6: Sample record - acceleration in g - (a) and identified source spectrum (b).

3 DYNAMIC RESPONSE ANALYSIS: PRELIMINARY ASSESSMENT

Operational Modal Analysis (OMA) is a valuable tool for investigation and identification of properties of dynamic systems [2]. Identified properties are also useful for modal-based health assessment [17] and for refinement of numerical models [2]. Thus, it provides several opportunities to study in depth the behaviour of different typologies of dynamic systems, provided that they behave linearly and that the response is stationary.

Data coming from sensors embedded in the piles will give the opportunity to have a deeper knowledge about the dynamic behaviour of flexible retaining walls under earthquake excitation. However, in the present paper the possibility to carry out modal analysis in operational conditions is assessed, since the results could be useful for numerical model refinement and health assessment. Thus, some OMA techniques have been applied to records of the dynamic response of the wall due to ambient vibrations in order to evaluate their applicability to the present case study. Due to the low level of ambient vibration, a linear elastic behaviour of the system is expected. However, due to its huge mass and stiffness, very low amplitude of vibrations is obtained, thus pointing out the importance of the measurement chain for a proper execution of tests and data acquisition before processing.

Modal parameter estimation in output-only conditions has been carried out according to the Enhanced Frequency Domain Decomposition (EFDD) [18] and the Second Order Blind Identification [19].

The (Enhanced) Frequency Domain Decomposition technique is an extension of the Basic Frequency Domain method, often called Peak-picking [20]. It is based on the Singular Value Decomposition (SVD) of the Power Spectral Density (PSD) matrix. Near a peak corresponding to the k^{th} mode in the spectrum, this mode will be dominant and the PSD matrix approximates to a rank one matrix where the first singular vector corresponding to the peak frequency is a good estimate of the mode shape of the structure. The corresponding singular value belongs to the Auto Power Spectral Density function of the corresponding Single Degree Of Freedom (SDOF) system. The Auto Power Spectral Density function of the corresponding SDOF system is identified around the peak of the singular value plot by comparing the mode shape estimate with the singular vectors associated to the frequency lines around the peak: every line characterized by a singular vector which gives a MAC value [21] with the singular vector at the peak higher than a user-defined MAC Rejection Level belongs to the SDOF PSD function. From the equivalent SDOF PSD function natural frequency and damping ratio of that mode can be estimated by analyzing the Inverse Fast Fourier Transform of the SDOF PSD function. From the free decay function of the SDOF system, the damping ratio can be calculated by the logarithmic decrement technique. A similar procedure is adopted in order to extract natural frequencies, performing a linear regression on the zero crossing times of the equivalent SDOF system correlation function and taking into account the relation between damped and undamped natural frequency.

Second Order Blind Identification (SOBI) is a Blind Source Separation (BSS) technique for signal processing and data analysis that, given a series of observed signals, aims at recover the underlying sources. In [19] it is shown that, under given assumptions, modal coordinates act as virtual sources, thus allowing application of such methodology for modal parameter identification in output-only conditions. BSS techniques can be addressed as non-parametric procedures for modal identification since the mixing model is the only assumption.

The SOBI algorithm finds components that approximately produce diagonal time-shifted covariance matrices. The main steps of the algorithm can be summarized as follows:

- observed data [x(t)] are centralized, removing the means value from each component of [x(t)], and whitened (basically through a Principal Component Analysis);
- whitened data are used to construct a number of time shifted covariance matrices;
- a numerical algorithm based on the Jacobi rotation technique [22] is then used to recover the mixing matrix;
- mode shapes are extracted directly from the mixing matrix [A], while natural frequencies and damping ratios are obtained through a Single Degree Of Freedom (SDOF) curve fitting of the sources.

The above mentioned data processing algorithms have been implemented into software packages [2, 23] developed in LabView environment (www.ni.com/labview) and applied to process records of vibration of the wall in operational conditions.

Preliminary results point out that it is possible to identify some dominant frequencies. In particular, it seems that the system is characterized by a fundamental frequency around 3.5 Hz. The spectrum of the corresponding mode provided by Second Order Blind Identification is shown in Figure 6b. Even if the signal-to-noise ratio is not high in the present application, thus resulting in a noisy identification of the source spectrum, a clear enough identification of such spectrum has been obtained. This circumstance points out that the identified frequency is likely a natural frequency of the system. Further investigations are needed for a complete characterization of the dynamic behaviour of the system; also an improvement of the signal-to-noise ratio by properly enhancing the measurement chain is desiderable. Nevertheless, these preliminary results seem to be promising and inspire confidence in the applicability of OMA techniques for investigation of the dynamic behaviour also of geotechnical structures.

4 CONCLUSIONS

SHM systems have been applied to a variety of structures, such as building, bridges, pipelines, wind turbine blades. However, a limited number of full-scale dynamic measurement systems are applied on geotechnical structures. Thus, an integrated structural and geotechnical monitoring system has been designed and it is currently under implementation at University of Molise. IN particular, such a system is characterized by the presence of embedded sensors in two piles belonging to a reinforced concrete flexible retaining wall.

In the present paper, the SHM system and sensors specifically developed for such application have been described and some relevant issues concerning installation have been discussed.

Records of the dynamic response of the wall in operational conditions have been then processed according to well-known OMA techniques in order to assess applicability of such methods to the study of the dynamic behaviour of such geotechnical system. Promising results have been obtained in such sense. However, further investigations are needed for a complete characterization of the dynamic behaviour of the system; also an improvement of the signal-to-noise ratio by properly enhancing the measurement chain is desiderable. Nevertheless, these preliminary results inspire confidence in the applicability of OMA techniques for investigation of the dynamic behaviour also of geotechnical structures. Results provided by OMA procedures can be then used to enhance numerical models and improve the current knowledge about flexible retaining walls. On the other hand, data recorded during seismic events might also be crucial to have a deeper insight in the dynamic behaviour of such structures and in the soil-structure interaction during strong motion events.

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