Monitoring of Full Scale Diaphragm Wall for a Deep Excavation

Francesco Castelli[1], Valentina Lentini[2]

[1] *Faculty of Engineering and Architecture, University of Enna Kore, francesco.castelli@unikore.it,*
[2] *Faculty of Engineering and Architecture, University of Enna Kore, valentina.lentini@unikore.it*

Abstract **- The paper reports the results of an experimental study carried on a full scale anchored pile diaphragm wall that is a part of the new Library of the University of Enna "Kore", Enna (Italy).**
The retaining wall has a free height of about 10 meters with an overall length of 22 meters, and it is composed of two rows of reinforced concrete (r.c.) piles 1000 mm in diameter. An r.c. top-beam was constructed on the top of the structure. Two piles, located in the central part of the wall, have been instrumented with conventional inclinometer cases and embedded piezoelectric accelerometers.
The experimental measurements recorded during the construction and in operation are reported and discussed in detail. Based on the interpretation of the geotechnical soil data, derived from conventional boreholes, down-hole and laboratory tests, a FEM model of the system was developed and implemented using the code PLAXIS. It has been observed that this model allows for a satisfactory simulation of the displacement of the wall during the construction phases i.e., under a static loading scenario.

I. INTRODUCTION

In recent decades, the demand for underground space has been increased. Deep excavations are required to meet this demand, and, in many cases, excavation sites are in closing proximity to existing structures. Advanced techniques are needed in the excavations to mitigate the large amount of lateral wall deflections and surface settlements for the purpose of avoiding damage of the adjacent structures.

Large-scale excavations requires retaining structures, such as diaphragm walls, to be installed before the soil excavation. Although the influence of excavation work on the surrounding ground and on existing structures has been commonly evaluated through numerical simulation, the main interest focuses on the influence of the excavation process on these areas after retaining structures are installed in the soil.

Monitoring of the static response of the wall (in terms of displacements) plays a relevant role for a quality assessment of the design and construction process. It is usually based on comparisons between the predicted and the observed behavior.

To construct the new Library of the University of Enna "Kore" at Enna (Italy), an anchored diaphragm wall has been realized. The paper provides a description of the monitoring system used to monitor the diaphragm wall, the interpretation of the obtained data and a discussion about assumptions and results of the numerical analyses carried out using the FEM code PLAXIS.

II. METROLOGY

Measurements of displacements and pressures during and after the construction of geotechnical structures are commonly used to check design assumptions and they are even prescribed by some codes [1], [2] and [3].

The diaphragm wall (Figure 1), located at Enna, in the Sicily Region, consists of two rows of reinforced concrete (r.c.) piles 1000 mm in diameter and has a free height of about 10 meters with an overall length of 22 meters. An r.c. top-beam has been constructed on the top of the structure and one row of anchorage has been realized at depth of 4,50 m (Figure 2).
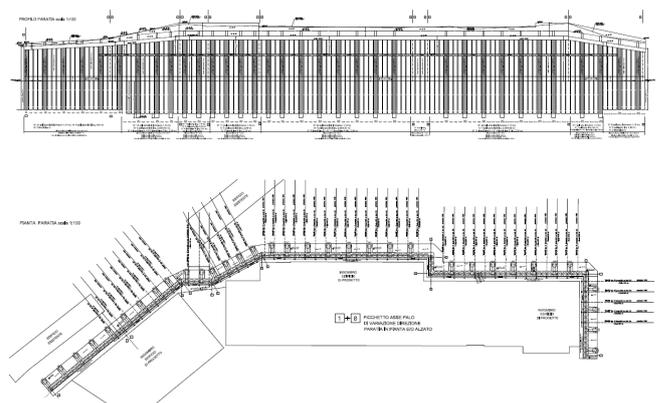

Fig. 1. Executive design of the diaphragm wall.

An integrated structural and geotechnical monitoring system for the diaphragm wall has been used. Two piles (Figure 3), located in the central part of the wall, have been instrumented with conventional inclinometer cases (Figure 4) and embedded piezoelectric accelerometers. The response of the two piles, chosen in order to avoid as much as possible boundary effects was monitored. Static displacements were monitored during the construction of the library.

Fig. 2. View of the building and anchored embedded wall.

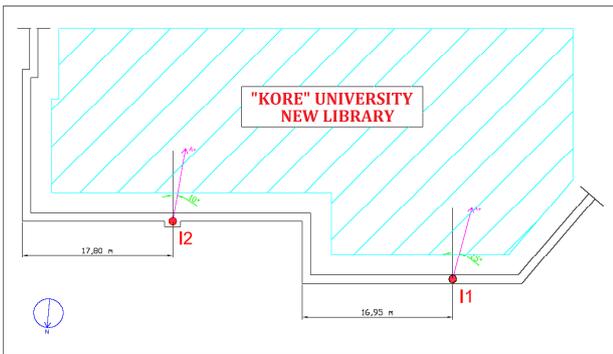Fig. 4. View of the diaphragm wall and instrumented pile.

Fig. 3. Plan view of the diaphragm wall and the monitored piles.

More frequent measurements have been carried out during the construction phase and after excavation. The need to monitor deflections and accelerations along the pile axis has driven the choice of embedding sensors in the piles. They have been equipped with two inclinometer casings and embedded piezoelectric accelerometers.

The short distance between building and wall (Figure 2) suggests that should exist an interaction between the two structures. Thus, the knowledge about the building behavior can help in better understanding measurement results obtained from the sensors in the piles. Sensor characteristics and installation phases are going to be described in detail in the following sections.

A. The embedded piezoelectric accelerometers

Over the last 50 years engineers have used traditional, manual inclinometers to monitor the soil displacements. However, the frequency and accuracy of this labor-intensive monitoring depend on a trained engineer in manually collecting and managing the data.

Recent advances in miniaturizing sensors and electronics have enabled a paradigm shift in the monitoring of soil and structures. In order to observe soil displacements, highly sensitive sensors are necessary. These sensors are typically expensive due to their high sensitivity and precision.
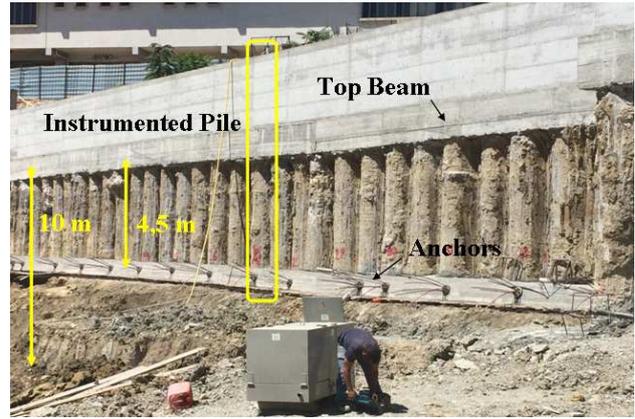
Abdoun et al. [4] developed a microelectro-mechanical system (MEMS) accelerometer that is designed to monitor soil displacements and soil accelerations. The recent MEMS technology may offer some distinct advantages over other types of tilt sensors, and in fact many manufacturers are now offering MEMS-based inclinometer probes. The wireless system can remotely collect both deformation and acceleration readings anywhere there is cell-phone coverage. The sensor array is capable of measuring soil acceleration and permanent ground deformation to a depth of 100 m. Each sensor array is connected to a wireless earth station to enable real-time monitoring of a wide range of soil and soil-structure systems as well as remote sensor configuration.

In this study MEMS accelerometers and traditional inclinometers have been used to monitor diaphragm wall behavior. Two piles have been instrumented with no.5 embedded piezoelectric accelerometers placed at different depth (Figure 5) and conventional inclinometer casings.
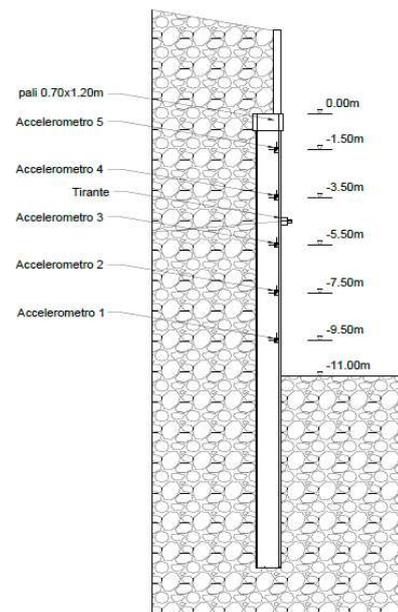

Fig. 5. Scheme of the position of accelerometers.

Sensor module consists of two seismic accelerometers, placed in two orthogonal directions and encapsulated in a stainless steel enclosure (Figure 6) to avoid any damage during the casting operations and assure waterproofing. Specific procedures for concrete casting have been adopted to ensure the effectiveness of sensors after installation, which are buried in concrete and, therefore, not repairable. Furthermore, the instrumented piles had to show similar characteristics with respect to the adjacent ones, to assure reliability of measurement.

Fig. 6. Stainless steel enclosure.

The dynamic response of the retaining wall was, also, monitored by a measurement system able to continuously record the dynamic response of the monitored piles. The measured acceleration in time domain is continuously shown on screen of the software, so as to check in real-time the quality of the acquired signals.

B. The inclinometers

Measurements of horizontal displacements of the diaphragm wall were carried out using inclinometer casings and were performed with steps of 1,0 m, starting from the bottom of the inclinometer hole. In Figure 7 is shown the installation of the inclinometer.

Experimental data have been acquired over a four month period (from July 29th, 2014 to November 4th, 2014) during the construction and excavation phases of the embedded diaphragm wall. Measurements recorded on September 15th and November 4th, 2014 are reported in Figure 8 for the monitored piles in terms of lateral displacement.

Displacements of the two piles are not very similar. A continuous increase in the horizontal displacements of the wall has been observed, until it has reached a final value of about 49 mm for inclinometer I_1 and of about 23 mm for inclinometer I_2.

III. GEOLOGICAL AND GEOTECHNICAL CHARACTERIZATION

The anchored diaphragm wall is part of the new Library of the University of Enna "Kore" (Italy). A soil investigation of the site has been performed: no.3 boreholes were carried out up to a depth of 30 m.
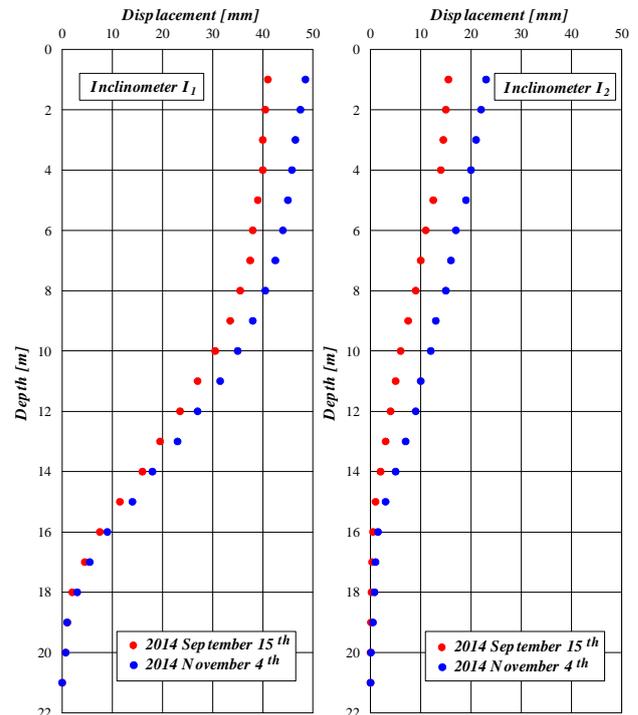

Fig. 7. Installation of the inclinometer.

Fig. 8. Lateral pile displacements versus depth.

The soil investigation included stratigraphic columns, Down-Hole tests to evaluate compression (V_P) and shear (V_S) wave velocities (Figure 9), and laboratory tests on undisturbed samples. The results of this soil investigation (Table 1) are reported in detail by Castelli et al. [5], [6].

Table 1. Geotechnical parameters.

Camp.	Prof.	γ	w_n	I_p	e_o
	(m)	(kN/m³)	(%)	(%)	
S1/C2	8,0	19,27	24,74	14,80	-
S1/C3	18,0	19,88	31,86	36,39	-
S2/C1	3,0	20,02	21,97	19,97	-
S2/C3	13,2	20,52	22,50	47,44	0,495
S3/C2	5,7	19,25	28,18	22,79	-

Camp.	Prof.	A	L	S
	(m)	(%)	(%)	(%)
S1/C2	8,0	10,15	30,01	46,11
S1/C3	18,0	25,13	53,54	21,27
S2/C1	3,0	23,35	43,79	25,63
S2/C3	13,2	37,45	51,80	10,72
S3/C2	5,7	26,24	34,80	36,44

Camp.	Prof.	e_o	c_u	c'	ϕ'	OCR
	(m)		(kPa)	(kPa)	(°)	
S1/C2	8,0	-	-	0	31	-
S1/C3	18,0	-	-	0	38	-
S2/C1	3,0	-	-	10	24	-
S2/C3	13,2	0,495	-	-	-	2,7
S3/C2	5,7	-	-	-	-	-

Based on the laboratory and in situ investigations, a simplified geotechnical model was adopted and used to set a numerical model of the diaphragm wall for PLAXIS code [7].

IV. NUMERICAL MODELING

The modeling of the behavior of the pile diaphragm wall has been performed using the FEM code PLAXIS 2D. The numerical analysis was carried out in plane strain conditions. The soil behavior has been modeled in drained conditions by the Mohr-Coulomb model.

The geometry of the model, the material properties and the boundary conditions were specified. To analyze the full scale diaphragm wall, the model extends about 100 m horizontally and 30 m vertically (Figure 10) to be sufficient to avoid border disturbances. At the base, the boundary conditions were assumed to be pinned in both vertical and horizontal directions and laterally the model is free to move vertically.

The numerical analysis includes the use of 15 node triangular elements to model the soil. The retaining wall structure was simulated with one dimensional linear beam element that can resist axial load and bending moments. The stiffness for the wall element is represented by means of the flexural rigidity (*EI*) and the normal stiffness (*EA*).
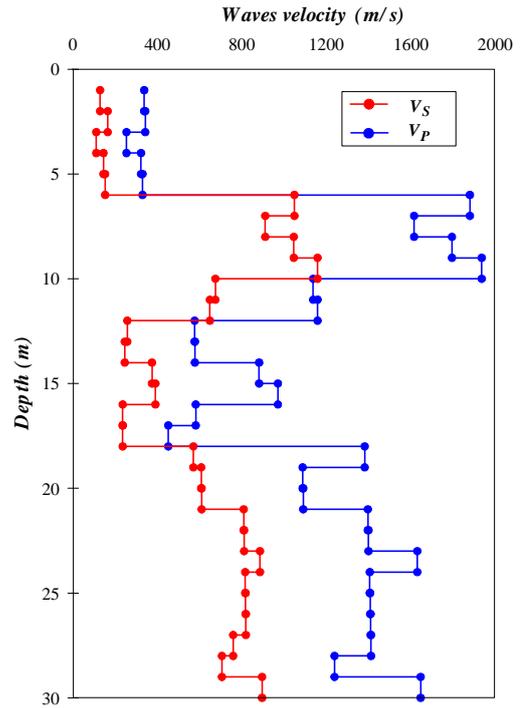

Fig. 9. Waves velocity versus depth.

Figure 10 shows the various soil clusters used to define regions with same properties within the finite element mesh. The soil model was run with a medium mesh of triangular elements, leading to 1729 elements and 13983 nodes. The reticule average dimension is strongly refined near the structure (Figure 11), for a better evaluation of the gradient of stress and strain.
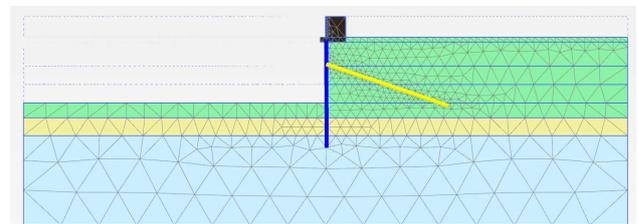

Fig. 10. Geometry of basic FE model.

Fig. 11. Finite element mesh.

Many phases have been used in the numerical analysis to establish the initial effective stress state condition existing prior to the construction of the diaphragm wall, the excavation to remove filling material, the excavation for positioning the diaphragm wall, the excavation for

anchor placement, the stage of pre-stressing and locking of the anchors. Based on the stratigraphic columns obtained by boreholes performed in the site, four different soil types have been considered. In particular, from ground level to bottom filling material (1), silts with sand clay (2), clays with chalk (3) and chalk (4).

Table 2 reports the geotechnical properties adopted in the numerical modeling for the four categories of soil considered. Strength and deformability parameters have been obtained by laboratory testing performed on the soil and by a literature database [8], [9] and [10] of model parameters used in PLAXIS for similar soil type [11].

When the initial conditions are defined, the calculation process starts and provides results in terms of stresses and displacements.

Table 2. Geotechnical parameters for numerical analyses.

Soil	γ	c'	ϕ'	E	E_{ed}
	(kN/m³)	(kPa)	(°)	(kPa)	(kPa)
1	19,6	0	24	$6,0 \cdot 10^4$	$8,9 \cdot 10^4$
2	19,6	21,6	24	$2,9 \cdot 10^5$	$3,8 \cdot 10^5$
3	18,6	50,0	22	$1,8 \cdot 10^6$	$2,4 \cdot 10^6$
4	19,6	114,0	29	$7,5 \cdot 10^6$	$10,1 \cdot 10^6$

V. NUMERICAL RESULTS

The results of the numerical analysis are presented in terms of anchored diaphragm wall and soil displacements computation. In particular, Figure 12 shows the deformed mesh of the numerical simulation corresponding to the state of end construction, while the Figure 13 gives an indication of the soil displacements predicted at the final stage.
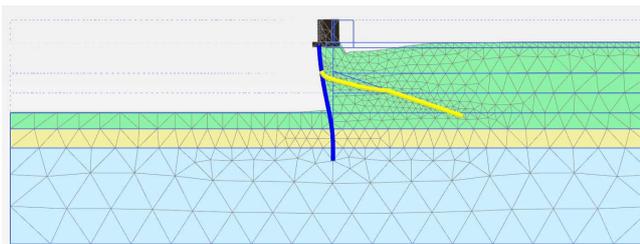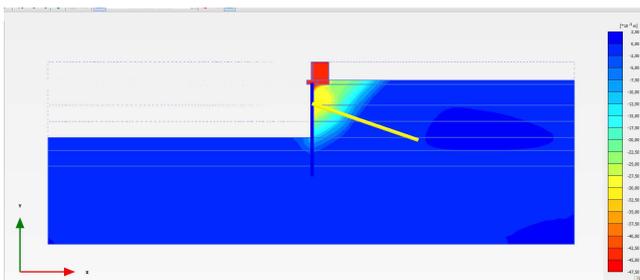

Fig. 12. Deformed mesh.

Fig. 13. Soil displacements.

Finally, the lateral displacements and bending moment along the diaphragm wall are reported in Figure 14 and 15 respectively. The maximum bending moment is approximately 650 kN·m/m.

Prediction of vertical/lateral displacements and forces are amongst the key objectives for performing reliable soil-structure interaction analysis.
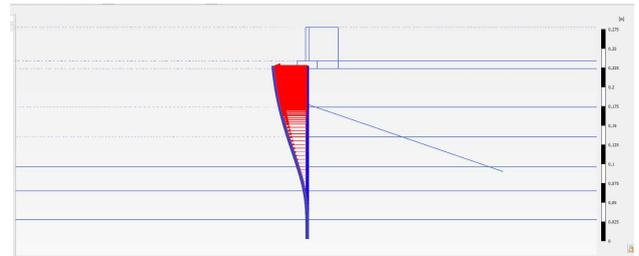

Fig. 14. Total displacements of the diaphragm wall.
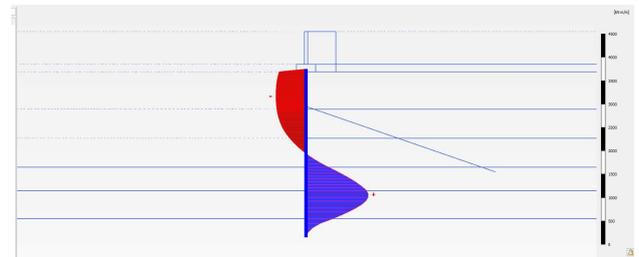

Fig. 15. Bending moment along the diaphragm wall.

VI. COMPARISON OF RESULTS

Today numerical techniques are available for integrated structural-geotechnical interaction analysis. Nevertheless, these procedures to practical problems often reveals discrepancies between experimental evidences and numerical predictions. Modification of the associated parameters and modeling assumptions can definitely be carried out in order to minimize such differences.

With this aim, the proposed numerical model intended to predict the behavior of the anchored diaphragm wall and to check the validity of the modeling concept used. This represents a phase of the well known "observational method" [12], in which observed performance can be used to verify design assumptions and formulate construction control.

Taking into account the geometry and dimensions of the embedded retaining wall, the loading conditions and the soil model, it was found that the predicted pattern and magnitude of the pile lateral displacements were close to the experimentally observed results. In this case a good agreement between the measured and the computed horizontal displacements was obtained. As depicted in Figure 16, the experimental data have been compared to the results of the numerical analyses corresponding to last on-site measurements (November 4th, 2014). The plot shows a reasonable agreement between experimental and computed results.
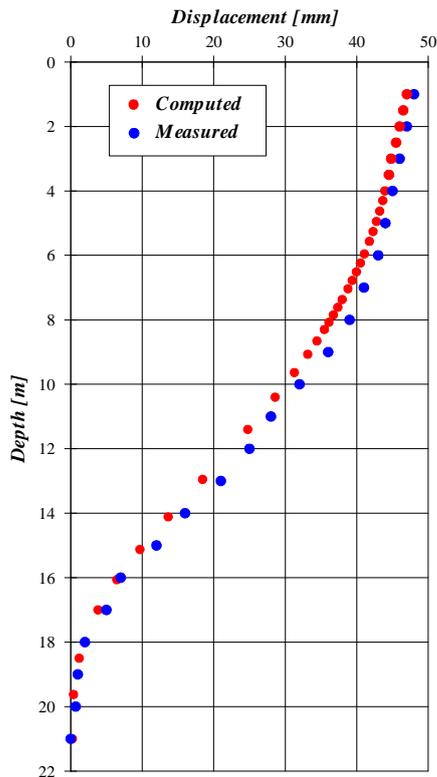
Fig. 16. Comparison between computed and measured pile lateral displacements.

VII. CONCLUDING REMARKS

In this paper, the preliminary results of a in situ static displacement measurement are presented and discussed. Static displacements were carried out starting from the excavation phase and until construction of an anchored diaphragm wall for the new Library of the University of Enna "Kore" (Italy).

Two piles of the diaphragm have been instrumented with conventional inclinometer cases and embedded piezoelectric accelerometers.

A continuous increment in the horizontal displacement of the wall has been observed, until it has reached a final and stable value of about 49 mm.

Based on careful interpretation of geotechnical data obtained by soil investigation, a numerical modeling by the Finite Element code PLAXIS 2D has been performed and calibrated. The comparison between computed results and experimental measurements in terms of horizontal displacement has been carried out, highlighting a very good agreement between experimental evidences and computed results.

Shear force and bending moment distributions have been assessed according to measured/computed lateral displacements along the embedded retaining wall.

REFERENCES

[1]   B.Simpson, W.Powrie, "Embedded retaining walls: theory, practice and understanding", Proc. 15th Int. Conference on Soil Mechanics and Geotechnical Eng., Istanbul, 2001.

[2]   A.Dey, G.Lanzano, C.Rainieri, M.Di Tullio, C. Laorenza, F.Santucci De Magistris, G.Fabbrocino, "A full scale instrumented retaining wall: interpretation of the measurements using numerical tools", Proc. of 5th Inter. Confer. on Geotechnical Engineering, Santiago, 2011.

[3]   C.Rainieri, A.Dey, G.Fabbrocino, F.S.de Magistris, "Static and dynamic monitoring of fully instrumented full scale embedded cantilever sheet pile retaining wall", Proc. of Indian Geotechnical Conf., Roorkee, 2013.

[4]   T.Abdoun, L.Danisch, D.Ha, "Advanced Sensing for Real-Time Monitoring of Geotechnical Systems", Proc. of Sessions of the Geo-Frontiers Congress, 2005.

[5]   F.Castelli, V.Lentini, S.Rizzitano, "Caratterizzazione dinamica e risposta dei terreni nell'area di Enna"; Atti Incontro Annuale Ricercatori di Geotecnica IARG, 2013.

[6]   F.Castelli, E.Castellano, F.Contino, V.Lentini, S.Rizzitano , "Valutazione della pericolosità sismica locale per la città di Enna mediante l'utilizzo di un sistema GIS", Proc. XV ANIDIS L'Ingegneria Sismica in Italia, L'Aquila, 2015.

[7]   R.B.J.Brinkgreve, P.A.Vermeer, "PLAXIS: Finite Element Code for Soil and Rock Analyses", Balkema, Rotterdam / Brookfield, 2002.

[8]   Y.C.Tan, S.S.Liew, S.S.Gue, M.R.Taha, "A numerical analysis of anchored diaphragm walls for a deep basement in Kuala Lumpur, Malaysia", Proc. of 14th South East Asia Geotechnical Conference, Hong Kong, 2002.

[9]   A.Rouili, Y.Djerbib, M. Touahmia, "Numerical modeling of an L-shaped very stiff concrete retaining wall" Sciences & Technologie, no.24, December 2005, pp. 69-74.

[10]   A.Yasushi, O.Kusakabe, O.Murata, S.Konishi, "A numerical study on ground displacement and stress during and after the installation of deep circular diaphragm walls and soil excavation", Computers and Geotechnics, vol.35, 2008, pp. 791-807.

[11]   R.B.J.Brinkgreve, "Selection of soil models and parameters for geotechnical engineering application" ASCE, Geotechnical Special Publication no.128, Evaluation, Selection, and Calibration, 2005.

[12]   T.H.Wu, "2008 Peck Lecture: The Observational Method: Case History and Models", J. Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 137, no.10, 2011, pp. 862-873.