Numerical simulation and geotechnical monitoring results of a deep excavation on a hill slope – case study

Alexandra Alisa Găină
SAIDEL Engineering SRL, Bucharest, Romania, alisa.gaina@saidel.ro

Ion Răileanu[1], Tudor Stanciu[2], Tudor Saidel[3]
SAIDEL Engineering SRL, Bucharest, Romania, ion.raileanu@saidel.ro[1], tudor.stanciu@saidel.ro[2], tudor.saidel@saidel.ro[3]

ABSTRACT: The aim of the paper is to highlight through a practical example the effective collaboration between a detailed geotechnical investigation, geotechnical site monitoring and numerical modelling in order to lead to a balance between a safe construction process and optimization of the retaining system. The paper presents the execution of a 30 m long retaining system and 10 m deep excavation on a hill slope required for the construction of a new building near the historical center of Brașov city, Romania. Flat Dilatometer Tests (DMT), Cone Penetration Tests (CPT), geotechnical boreholes and laboratory tests were carried out in order to characterize the soil stratigraphy. The behavior of the retaining structure and slope stability were evaluated through finite element numerical analysis using Plaxis 2D computer software. Throughout the entire deep excavation works, horizontal displacements of the retaining system were continuously monitored by use of in-place inclinometers.

Keywords: deep excavation, in-place inclinometers, Flat Dilatometer Test, observational method, HS small

1. Introduction

In recent years, the increased traffic, lack of parking spaces, rapid development of housing and real estate are new challenges for most of the big cities of Romania. Thus, demolition of the deteriorated or unfunctional buildings and constructions developed below the ground level are solutions adopted by architects and engineers in many cases, which lead to numerous deep excavations, most of them in crowded areas and having irregular shapes.

All these aspects mentioned above make each excavation unique, requiring detailed geotechnical investigations, geotechnical site monitoring and an adequate numerical modeling in order to avoid negative influences on the nearby buildings. Due to all of these particularities of an excavation, associated to a high geotechnical risk, the observational method (OM) is recommended to accompany the analysis and construction of the geotechnical works.

The paper presents the execution of a 30 m long retaining system and 10 m deep excavation required for the construction of a new building on a hill slope near the historical center of Brașov city, Romania. The investigated site has an area of 2544 m^2.

From topographical and morphological point of view, the site has an uneven ground, characterized by a slope of approximately 40º, decreasing from south to east with a height difference of approximately 4 m on 6 m length and continues on 26 m with 11º slope until it reaches the horizontal ground surface. On the top part, the site is bordered by a street and downstream is bordered by a near-horizontal field.

The aim of the paper is to present the behavior of the retaining system evaluated through 2D numerical simulation in comparison with recordings of in-place inclinometers (IPI). By applying the OM considerable technical and economical optimizations were gained.

2. Case study description

2.1. Geotechnical conditions

Geotechnical investigations were carried out in order to establish the parameters necessary for the design of the retaining and foundation system. In Fig. 1 are positioned the in situ ground investigations that consist in eight dynamic probing heavy tests (DPH), 13 flat dilatometer tests (DMT), three geotechnical boreholes performed down to 12 m depth, and three trial pits. Disturbed and undisturbed soil samples were taken out of the boreholes in order to perform detailed geotechnical laboratory tests. No ground water was found in any one of the boreholes.

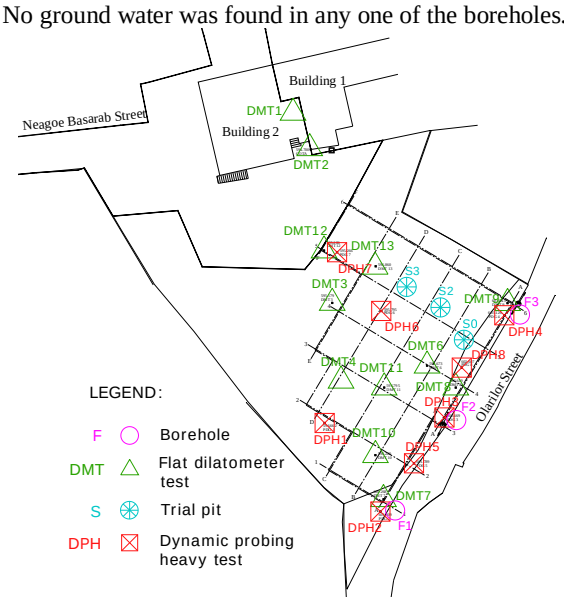

Figure 1. Ground investigations layout.

DPH tests highlight the presence of a soil layer on the first five meters deep having weak mechanical properties and underneath soils having good and very good mechanical characteristics.

The DMT is an efficient method that allows to estimate quickly and accurately the compressibility characteristics of the soils. The obtained data are used as input parameters in advanced design models in order to assess soil settlements and deformations [1 - 2].

The DMT blade has a circular steel membrane on one side having a diameter of 6 cm and a thickness of 0.25 mm. A compressed nitrogen tank supplies the gas pressure required for expanding the membrane. As the membrane expands to a limited travel, the soil is slightly compressed. Three readings are recorded, at specific moments and further the blade is pushed to the next investigation depth by a step of 25 cm.

By using flat dilatometer tests the shear strength parameters of soils were determined at depth intervals of 25 cm down to reaching the penetration refusal. The DMT were performed by advancing the DMT equipment into the ground, using a CPT truck.

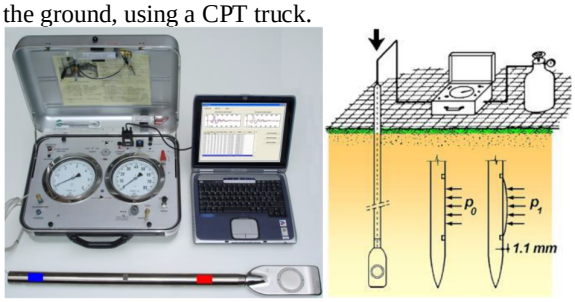

Figure 2. The dilatometer equipment (left) and schematic layout of the dilatometer test (right), equipment used by SAIDEL Engineering SRL [1 - 2]

The overlapped DMT diagrams are shown in figure 3.

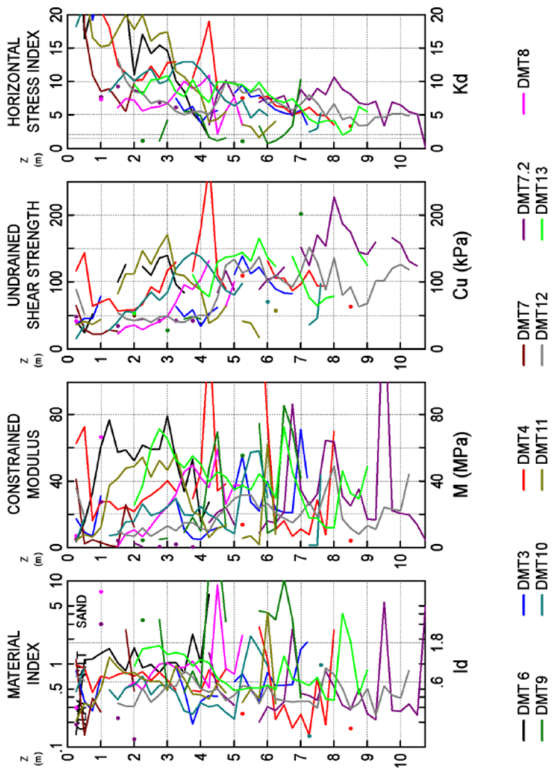

Figure 3. Interpreted geotechnical parameters obtained from DMT

In table 1 geotechnical parameters gained out of the in situ and laboratory investigations are presented.

Table 1. Characteristic values of geotechnical parameters

Soil layer	γ [kN/m^3]	$E_{50,ref}$ [MN/m^2]	$E_{ur,ref}$ [MN/m^2]	ϕ' [°]	c' [kN/m^2]	G_0 [MPa]
0. Heterogeneous fill	19	5	15	20	20	30
1. Silty clay	20.5	20	100	20	42	90
2. Clay	20.5	25	125	30	42	120
3. Limestones in matrix clay	21	45	135	30	250	-
4. Limestone	23	95	300	43	500	-

Note: γ represents the unit weight, $E_{50,ref}$ Young's modulus of elasticity corresponding to 50% of the maximum shear strength, $E_{ur,ref}$ deformation modulus for unloading/reloading, ϕ' drained angle of shearing resistance, c' the drained cohesion and G_0 initial shear modulus.

2.2. Monitoring works

Throughout the entire deep excavation works the monitoring of the neighboring buildings was ensured by geodetic measurements on settlement marks and reflective targets, while the lateral displacements of the retaining structure were recorded by means of in-place inclinometer (IPI) probes installed within three inclinometer casings, placed down to two m bellow the final excavation level and embedded into the rock layer [3].

The inclinometer casings, having 12 m length, were installed in boreholes drilled adjacent to the retaining structure, prior to its construction, with the annular space between the casings and the borehole walls being filled by bentonite-cement grout.

Figure 4. IPI inclinometer probe and extension rod

Each tilt profile comprised of 6-7 probes, each equipped with biaxial MEMS sensors shown in Fig. 4 and distributed at 1-2 m intervals along the entire depth of the inclinometer tubes [4]. The connection between the IPI probes is ensured by means of dedicated extension rods so as to maintain a physically connected string and obtain a 'truly accurate' displacement profile.

The continuous data acquisition from the IPI sensors is ensured by means of a datalogger equipped with a

GPRS modem in order to allow remote access for configuration and data download purposes. The sampling rate was set between one to four hours for all installed probes.

2.3. Temporary works and construction stages

The design solution was technologically limited due to the soil topography, existing structures and narrow access.

Thus, it was designed an optimized retaining system consisted of steel profiles type HE 120A mounted at 1.30 ÷ 1.50 meters axial distance, timber lagging between them and two horizontal support layers, consisting of steel struts mounted at 3 meters distance. The struts rested on the second basement slab and first basement slab, respectively. The excavated side of the Berliner Wall was down to 5.50 m depth in order to allow the installation of the steel struts and the excavation continue with a slope up to final excavation level (fig. 10) for constructing the underground structure (fig. 13). The execution of the soldier piles was made using Beretta T44 equipment.

Since it was difficult to predict the behavior of the slope, OM represents the most adequate method in establishing the design solution. In 1969 Rankine defined two OM approaches: "Ab Initio" approach, adopted from the conceptual design of the project, and "Best Way Out" approach, adopted when the project had begun and unexpected events have occurred [5 – 6].

In the present paper "Ad Initio" and Eurocode 7 OM approaches have been adopted together with a design adapted to the construction process as well as a close collaboration between the entire Project Team including the client [6]. The methodology for applying the OM in the design and execution process is defined based on the flowchart proposed by CIRIA (1999) [5], as it is shown in Fig. 5.

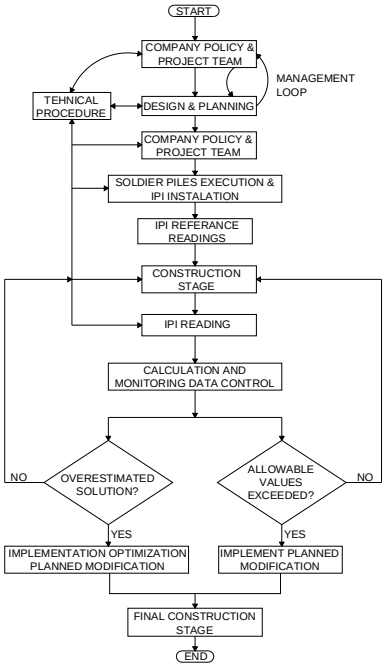

Figure 5. Flowchart of the OM implemented in design and execution process

First, the design concept is initiated based on geotechnical investigations and all the necessary procedures for the possible scenarios are prepared and everyone involved is informed. Secondly, a continuously reviewing design during the construction is followed were the monitoring data are analyzed and the optimal solution is decided and implemented. This process ends when the final construction stage is reached.

Below the first construction stage is presented through the numerical simulation (see Fig. 6) and its correspondent in the construction site (see Fig. 7).

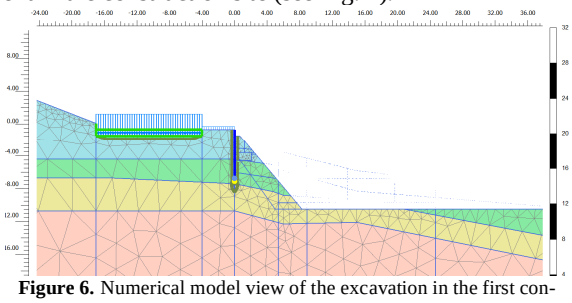

Figure 6. Numerical model view of the excavation in the first construction stage

Figure 7. First excavation stage

Analogously, an intermediated construction stage is presented in Fig. 8 and Fig. 9 and the final excavation stage is presented in Fig. 10 and Fig. 11, where two struts layers were installed.

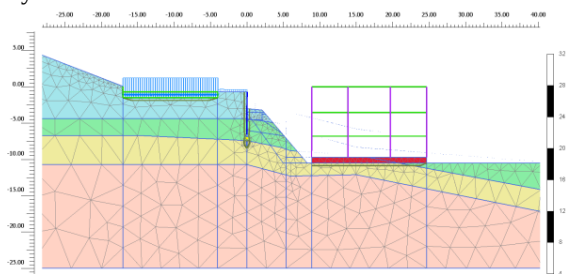

Figure 8. Numerical model view of the excavation at an intermediate construction stage

Figure 9. Execution process at an intermediate construction stage

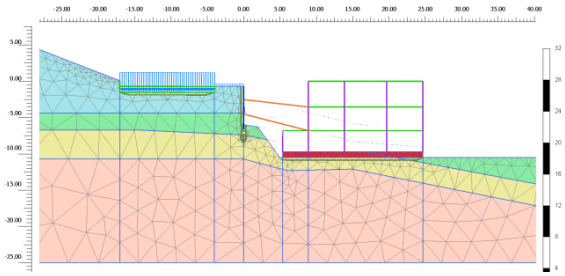

Figure 10. Numerical model view of the excavation at final excavation construction stage

Figure 11. Execution process at final excavation construction stage

3. Numerical analysis

The evaluation of the behavior of the retaining system, safety of the adjacent buildings and slope stability was conducted using Plaxis 2D computer software and based on Eurocode 7 [7-8]. The plane strain finite element numerical model had 15 construction stages which include the surrounding buildings by applying the equivalent load, six intermediate excavation steps including installation of the two struts layers and two safety analysis stages. Due to the non-horizontal soil layers, gravity loading has been used in order to determine the initial stresses of the subsoil [9].

The soil is modeled using the hardening soil model with small-strain stiffness (HSsmall). The material model used for limestones soil layers is Mohr-Coulomb. For the concrete and steel elements, the elastic behavior model is used. The advantage of using Hardening soil (HS), compared with an elastic model is the control of stiffness parameters: tangent oedometer modulus $E_{ref,\ oed}$, secant triaxial modulus $E_{50,\ ref}$, unloading-reloading modulus $E_{ur,\ ref}$ [5]. Compared with HS, HSsmall has two additional parameters needed to describe the variation of stiffness with strain: the initial shear modulus, G_0, and shear strain level $\gamma_{0,7}$ at which the secant shear modulus, G_s, is reduced to about 70 % of G_0 [9].

The influence of the excavation on the adjacent buildings has been evaluated considering a 75 kPa load at the foundation level of the nearby buildings.

In Fig. 12 the longitudinal soil profile, soldier piles depth and in-place inclinometers layout are presented, with the inclinometer columns installed in the boreholes performed during the geotechnical investigation campaign.

Three main sections were taken into account into calculation considering the layers found in the boreholes, DMT and CPT.

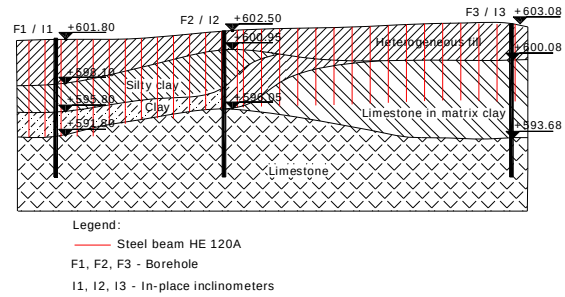

Figure 12. Longitudinal profile of the retaining system model

4. Results of numerical analysis and monitoring measurements

In Fig. 13 are presented four main construction stages that are analyzed from the displacement point of view.

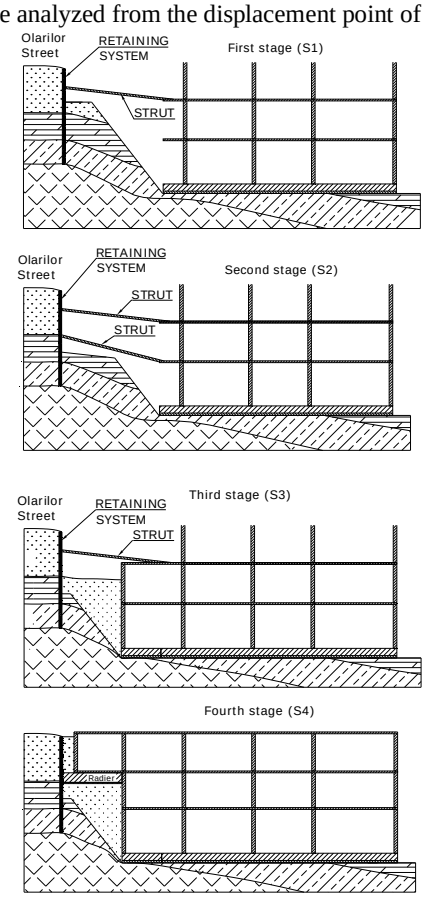

Figure 13. Four main construction stages

The correlation between the displacement of the retaining wall, evaluated by means of finite element numerical analysis and the inclinometer measurements performed at site is presented in the below graphs.

In Fig. 14 and Fig. 15 the recorded cumulative displacement is plotted against the displacement estimated by numerical simulations for critical construction stages.

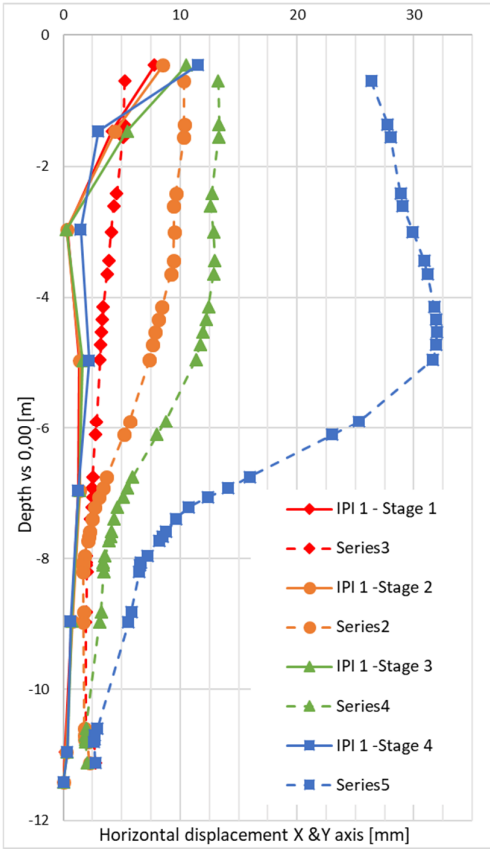

Figure 14. Displacement comparison between inclinometer I_1 readings and results of Plaxis 2D analysis

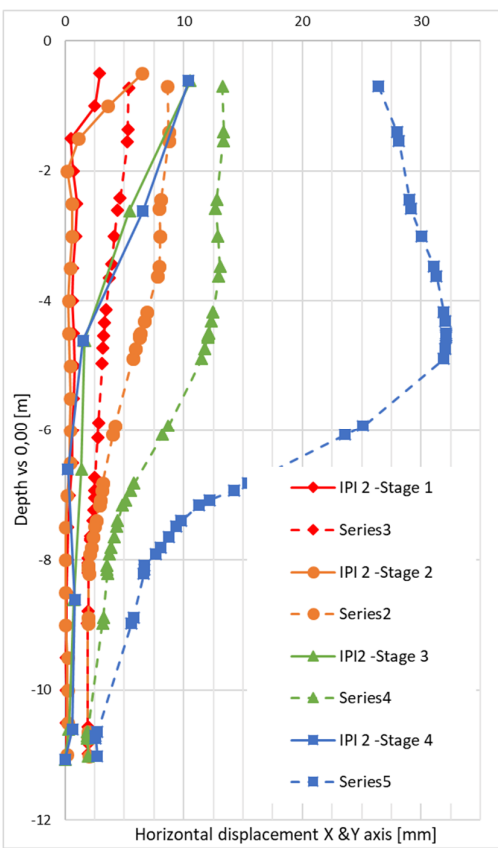

Figure 15. Displacement comparison between inclinometer I_2 readings and results of Plaxis 2D analysis

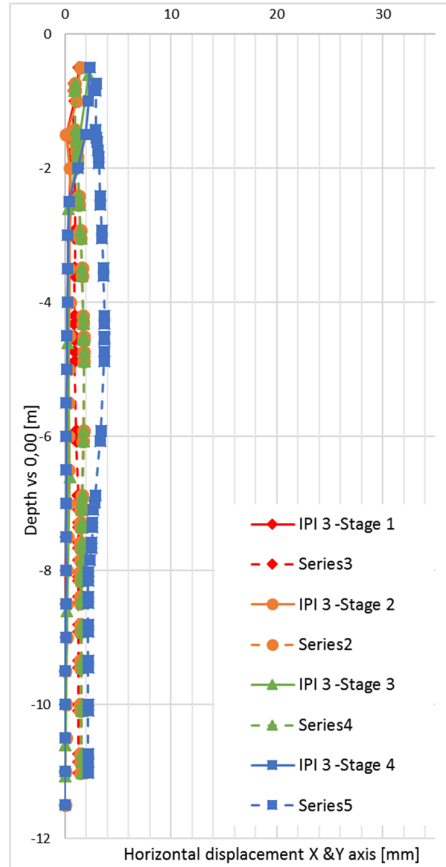

Figure 16. Comparison between inclinometer I_3 readings and Plaxis 2D analysis

As shown in the graphs, the horizontal displacement values of the retaining system obtained from IPI are lower than the estimated ones. This aspect was noticed before the excavation for the struts montage. At this stage a back-calculation analysis has been performed and it was decided to reduce the number of the struts between I_2 and I_3.

Instead, between the I_1 and I_2, supplementary measurements were taken due to the verification of the slope stability and weather conditions.

A minor unpredictable situation occurred and emergency mobilization of all parties involved in the project was imposed. The harsh weather conditions and disregard of the slope protection lead to local loss of stability at the base of the slope, as it can be seen in Fig. 17.

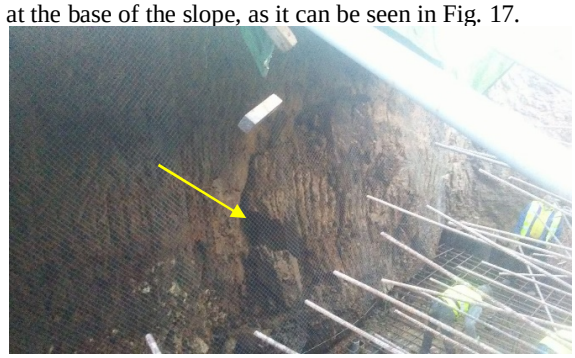

Figure 17. Local minor loss of slope stability at the base

5. CONCLUSIONS

In this paper OM applied on a particular case was presented.

A safe and economical design solution has to be based on reliable detailed geotechnical investigations, an adequate monitoring system, previous experience in similar conditions and a complete evaluation of the acceptable limits.

Unfavorable soil topography and non-horizontal soil layers including narrow work spacing led to the necessity of the implementation of the OM design approach in this particular case.

The number of struts was considered as being the main element to be further optimized. Thus, a supplemented number of struts was considered in the initial design phase between I_1 and I_2. By having real time horizontal displacement values of the retaining system, it was possible to compare them with results obtained from numerical modeling, as it is presented previously. Based on this comparison a back-calculation has been performed and the number of struts was reduced. The slope execution was also optimized by reducing the slope gradient from 1:1 to 2:1 which led to a time reduction of the entire execution process.

By following the steps described in the OM flowchart, established from the beginning, optimizations during the construction process were done without compromising safety.

References

[1] Totani G., Marchetti S., Monaco P., Calabrese M. "Use of the Flat Dilatometer Test (DMT) in geotechnical design", In: 2001 International Conferance On In situ Measurement of Soil Properties, Bali, Indonesia, May 2001

[2] Marchetti S. "In Situ Tests by Flat Dilatometer", Journal of the Geotechnical Engineering Division, pp. 299-321, 1980.

[3] European standard, "Geotechnical investigation and testing – Geotechnical monitoring by field instrumentation – Part 3: Measurement of displacements across a line: Inclinometers", 2017

[4] Geosense instruction manual, "Mems Digital Vertical In-Place Inclinometer", 2017

[5] Nicholson D., Tse C. and Penny C. "The Observational Method in ground engineering – principles and applications". Report 185, CIRIA, London, 1999

[6] Patel D., Nicholson D., Huybrechts N., Maertens J. "The Observational Method in Geotechnics". http://www.geotechnet.org/

[7] Eurocode 7 (BS EN 1997-1:2004) "Geotechnical design - Part 1: General rules

[8] SR EN 1997-1:2004 Eurocod 7: Geotechnical design - Part 1: General rules. National Annex.

[9] Brinkgreve R.B.J., Swolfs W.M., Engin E. "Plaxis 2D 2010", Plaxis bv, The Netherlands, 2019