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Back-analysis of deep excavations supported by strutted retaining walls

Rétro-analyse d’excavations profondes soutenues par des murs étayés

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ABSTRACT: Design of deep excavations involves the definition of the retaining walls and struts to support earth pressures. Despite the experience and the procedures available to estimate the forces acting on the struts, their prediction is still difficult and comparison between field measurements and numerical simulations suggest that there are many factors not taken into account in the routine calculations. This paper presents a software (DAARWIN) that can be used to manage field data and to perform backanalysis in an automatic manner to predict soil parameters. It is a cloud based platform combined with the Plaxis Finite Element code, that uses genetic algorithms to solve the backanalysis. This software has been applied to the identification of soil parameters and strut loads in a real case involving a deep excavation from Toulouse Metro in France.

RÉSUMÉ: La conception d'excavations profondes implique la définition des murs de soutènement et des entretoises pour supporter les pressions des terres. Malgré l'expérience et les procédures disponibles pour estimer les forces agissant sur les entretoises, leur prédiction reste difficile et la comparaison entre les mesures sur le terrain et les simulations numériques suggère que de nombreux facteurs ne sont pas pris en compte dans les calculs de routine. Cet article présente un logiciel (DAARWIN) qui peut être utilisé pour gérer les données de terrain et effectuer une rétro-analyse de manière automatique pour prédire les paramètres du sol. Il s'agit d'une plate-forme basée sur le cloud combinée au code Plaxis Finite Element, qui utilise des algorithmes génétiques pour résoudre la rétro-analyse. Ce logiciel a été appliqué à l'identification des paramètres du sol et des charges des entretoises dans un cas réel impliquant une excavation profonde du métro de Toulouse en France.

Keywords: Backanalysis; optimization; deep excavation; retaining walls; strut loads.

1 INTRODUCION

Deep excavations using diaphragm walls usually include the installation of struts to temporarily ensure their stability. Traditional and empirical procedures to design diaphragm walls are not accurate when estimating strut forces as they oversimplify the earth-pressure distribution. Moreover, even when a “beam-on-spring“ approach is used for wall design (a popular procedure among practising engineers), the strut loads may be underpredicted , due to soil arching effects and stress redistribution (Karlsrud & Andresen, 2005). This is a classical soil-structure interaction problem in which both soil and concrete stiffness play a fundamental role. Despite the huge development of numerical codes for geotechnical design, the working load supported by the struts is difficult to predict and a conservative approach is usually proposed (Goh et al., 2017, Zhang et al., 2019). In fact, in reported cases where the loads in the struts were monitored, their values were not totally consistent with the calculated ones (Moormann, 2002; Finno et al., 2002; Houhou et al., 2019). Several factors have been described to explain the differences between measured and computed strut loads, as installation effects, stiffness of the wales, temperature changes and pre-stressing (Moorman, 2002). This is why the observational method has been a valuable methodology to control excavation works and therefore, monitoring has become an essential task. Within this context the interpretation of field instrumentation in actual excavations can be enhanced if a numerical geotechnical model is used.

In this regard, geotechnical backanalysis can be a powerful tool to compare field measurements with predictions of the model. Backanalysis in Geotechnics is useful to calibrate soil constitutive models from laboratory tests, but also to identify soil properties from field measurements. Some of the Finite Element programmes for geotechnical design developed so far include a backanalysis feature (Levasseur et al., 2008; Hashash et al., 2010; de Santos, 2015). The software DAARWIN (SAALG, 2023), coupled with Plaxis, performs backanalysis in a systematic manner and is able to manage the information provided by an initial design and by field data.

This paper presents an application of DAARWIN to a well documented case study, the Saint-Agne Metro Station, located in Line B of the Toulouse Metro, France, (Houhou et al., 2019), and focusses on the estimation of the struts loads.

Based on the information from this project, a numerical model has been built using finite elements in Plaxis 2D and Plaxis 3D, subsequently the influence of the loads produced by the struts was analyzed. The backanalysis of the measurements obtained during the excavation process improved the characterization of the soil layers and was useful to analyze the loads of the struts.

2 BACKANALYSIS USING DAARWIN

Backanalysis is also referred as “inverse problem”, that is, estimating the parameters of a soil constitutive model from field measurements. An “objective function” is defined, which depends on the differences between measurements obtained through instrumentation and values calculated through a conceptual model. The solution to the identification problem is obtained by searching for the minimum of the objective function, for which optimization algorithms are used (Levasseur et al., 2008; Hashash et al, 2010; de Santos, 2015).

Traditionally, the backanalysis methodology was carried out manually, however, numerical techniques allow to perform that task in an automatic manner. Thus, backanalysis can be used in a systematic way to continuously analyze field data from monitoring and to assess the validity of the assumptions made during the design stage (Ledesma and Romero, 1997). That fills the gap between models from the design phase and measurements during construction and helps in the interpretation of the field instrumentation, reducing uncertainty.

The software DAARWIN is in fact a cloud-based platform based on machine learning algorithms (genetic algorithms) that integrates the management of field data from monitoring with numerical analyses using Plaxis code, and is able to identify parameters of geotechnical constitutive models by comparing measurements with finite element calculations. All the analyses in DAARWIN are performed using a parallel high-performance cloud-computing architecture running 200 server instances per backanalysis. The software was developed by a start-up company from a University research work (SAALG, 2023). A complete description of the methodology can be found in de Santos (2015).

3 DESCRIPTION OF THE CASE STUDY

The Saint-Agne station is located on the new Line B of the Toulouse Metro, France. This station is a 55.2 m × 17.15 m rectangular deep excavation, described in detail in Vanoudheusden et al. (2005), Zghondi et al. (2009), and Houhou et al. (2019). The retaining structure consists of a diaphragm wall cast in situ with a thickness of 1.0 m and reaching a depth of 20.65 m. During excavation to a depth of 17.2 m, the retaining walls were supported at the top by partial slabs and diagonal beams and at depth by 2 or 3 levels of temporary steel struts. Figure 1 shows a typical section of the diaphragm wall.

The excavation area was monitored in two sections. Each section included an inclinometer on the diaphragm wall and 4 vibrating wire strain gauges installed at each strut level with an automatic data acquisition system. Maximum measured horizontal displacement was about 9.7 mm at inclinometer 1. Construction activities included staged lowering of the water table, excavation and shoring. In each stage, the water table was first lowered to 1m below the bottom of the next excavation stage, then the soil was removed and the props were installed 0.4–0.5 m above the bottom of the excavation. This procedure was carried out for each phase until reaching the end of the excavation.

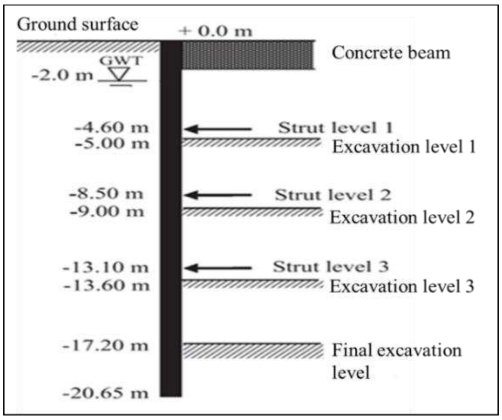

Figure 1. Typical wall cross-section (modified from Hohou, 2019).

The soil profile with the main geotechnical parameters initially provided is shown in Table 1, adapted from Houhou et al. (2019), where a 3D simulation using code FLAC and the elastic-Mohr Coulomb model was presented. Here, code Plaxis 2D and 3D was used, with the Hardening Soil model with small strains as constitutive law, and an automatic backanalysis was carried out to better match the field instrumentation.

4 BACKANALYSES PERFORMED

A sensitivity analysis was carried out first, in order to detect the parameters that have more influence on the variables measured. This is a standard first step in DAARWIN (Cordoni, 2023). Once the parameters controlling the problem were detected, it was possible to define the conditions for the backanalysis (parameters to identify and range of the values in the search space). This is the case presented in this paper.

The most significant layers, in terms of influence on the measured displacements were identified as layers 4, 7, 8 and 9 (see Table 1), and the main parameters to identify were E_{50}, E_{ur} for those layers. To simplify the analyses, the following relations were adopted: E_{oed}=E_{50} and G_o=2.6 E_{50}. The rest of the parameters were fixed and based on the information provided (Table 1). Note that in excavation problems, the unloading-reloading modulus, E_{ur}, plays an important role when predicting displacements. The values identified in the backanalysis were, for the sandy clays (layer 4), E_{50}=50 MPa, E_{ur}=200 MPa; for the fine to medium sands (layer 7), E_{50}=60 MPa, E_{ur}=220 MPa; for the sandy clays (layer 8), E_{50}=210 MPa, E_{ur}= 540 MPa; and for the clays (layer 9), E_{50}=270 MPa, E_{ur}=1010 MPa. These values obtained are consistent with the geological and geotechnical information available. In particular the high modulus of the lower clays corresponds to the type of material involved (a molasse). Figure 2 shows the comparison between the measured horizontal displacements and the computed ones using those parameters.

5 STRUT LOADS

The loads of the struts were obtained from the numerical analyses. In the papers describing the case, an efficiency factor of 0.5 was defined to account for the difference between the theoretical load obtained in the calculations and the measured value (Houhou et al., 2019). That is, the measured load was half of the theoretical load computed from the shortening of the struts obtained considering the horizontal displacement in the inclinometers at the level of the strut. This is in fact a reduction of the theoretical strut stiffness by a factor of 2, which may be due to the stiffness of the connection between the struts and the wall.

When using the backanalysis procedure, the strut loads were more consistent with the measured values and an efficiency coefficient was not required. However, it was noticed that wall dis-placements are not very sensitive to the strut stiffness beyond a minimum value. In fact, multiplying or dividing the current strut stiffness by a factor of 3 had little influence on wall displacements. That explains the difficulty in determining numerically the force at the struts. Figure 3 shows the measured and computed strut loads. Note that differences can be as high as 1000 kN, which points out the difficulty in matching strut loads.

6 CONCLUSIONS

The paper presents an application of the software DAARWIN to a real case involving a strutted deep excavation. That software is able to manage field data and to perform backanalyses in an automatic manner, which can be very useful in geotechnical design and construction and particularly when combined with the observational method.

Table 1. Main initial parameters of the soil layers: natural specific weight, permeability, earth pressure coefficient, Poisson's ratio, cohesion, friction angle, dilatancy angle, Young modulus (after Houhou et al., 2019).

Layer	Depth(m)	γ(kN/m³)	K(m/s)	K_o	ν	c'(kPa)	φ'(°)	ψ(°)	E(MPa)
1. Fill	0-1.2	20	$6 \cdot 10^{-4}$	0.5	0.3	0	25	0	66-78
2. Clays	1.2-2.8	22	$1 \cdot 10^{-9}$	1.6	0.3	80	33	0	78-94
3. Clay sands	2.8-5.2	21	$1 \cdot 10^{-7}$	1.6	0.3	52	37	3	94-117
4. Sandy clays	5.2-7.6	22	$5 \cdot 10^{-8}$	1.6	0.3	84	32	0	117-141
5. Fine to medium sands	7.6-8.6	21	$1 \cdot 10^{-6}$	1.6	0.3	0	36	5	141-151
6. Sandy clays	8.6-10.2	22	$5 \cdot 10^{-8}$	1.6	0.3	84	32	0	151-167
7. Fine to medium sands	10.2-12.7	21	$1 \cdot 10^{-6}$	1.6	0.3	0	36	5	167-191
8. Sandy clays	12.7-21	22	$5 \cdot 10^{-8}$	1.6	0.3	84	32	0	191-274
9. Clays	>21	22	$1 \cdot 10^{-9}$	1.6	0.3	80	33	0	274-360

Regarding wall displacements, they are well reproduced using backanalyzed parameters, however, measured strut loads are still difficult to simulate, because they are less sensitive to global wall displacements.

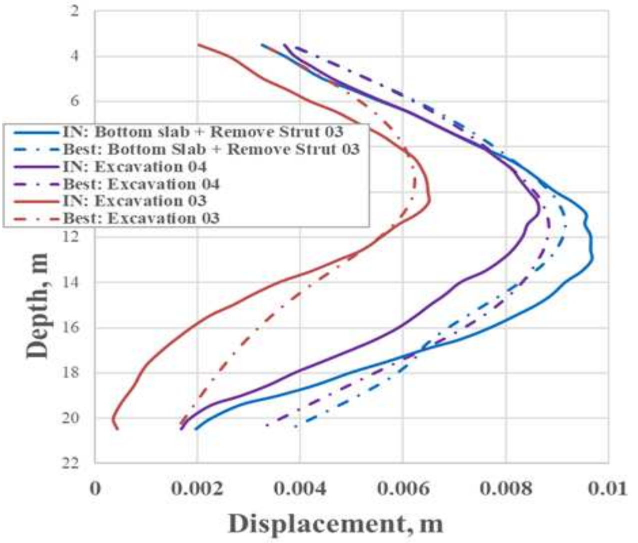

Figure 2. Measured and computed wall displacements.

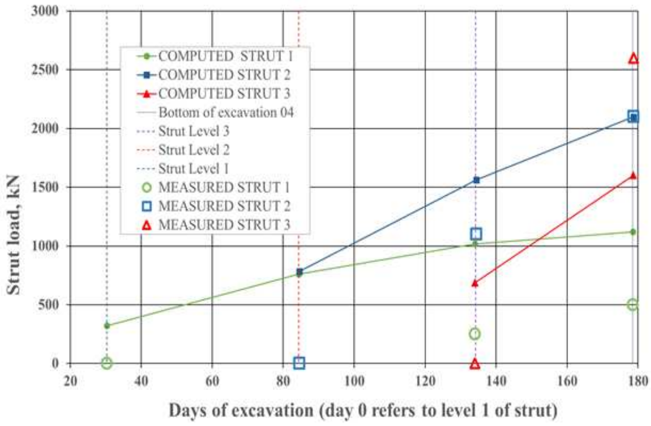

Figure 3. Measured and computed strut loads.

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