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Modelling the behaviour of stiff clays from continental origin in tunnel construction: back analysis of the first stage of the El Almendro Tunnel

Modelage du comportement d'argiles raides d'origine continentale dans la construction des tunnels: étude rétro-analytique des premières phases du Tunnel 'El Almendro

C. Torrero
Ayesa Ingeniería. Madrid, Spain

J. Nespereira, M. Yenes, Monterrubio, S.
University of Salamanca. Salamanca, Spain

ABSTRACT: Using data from top heading excavation, a back analysis is carried out for the Almendro Tunnel, constructed for the High-Speed Railway in the Venta de Baños-Burgos-Vitoria line (Spain). It is excavated in overconsolidated stiff clays following NATM, with a horse shoe section of 110 m^2, and an overburden that reaches 110 m. The measures from tunnel convergence monitoring diverge from the expected, and some modifications are considered for improving the model.

Tunnel top heading excavation has been modelled by means of plane strain finite element analyses in accordance with the linear displacement profile (LDP) that best fits the construction monitoring data. Hardening Soil model was used as constitutive model to capture soil stress-stiffness dependence. Undrained behavior was assumed for saturated clays and overconsolidation was computed applying and removing pre-overburden load. Numerical models were calibrated with varying soil stiffness parameters in order to match real behavior. High stiffness values resulted from the analyses, even though loading induced by tunneling was modelled following unloading/reloading path. Gompertz function is proposed as an innovative solution for defining LDP; it was used to fit the monitoring data and the resultant fitted LDP was used to validate the accuracy of current approach and simplified axisymmetric finite element models used in engineering practice.

RÉSUMÉ: Sur la base des données de la calotte du tunnel, une étude rétro- analytique a été effectuée pour le Tunnel « Almendro ». Le tunnel a été construit pour la ligne d´haute vitesse Venta de Baños-Burgos-Vitoria (AVE)(Spain). Le tunnel est creusé dans des argiles raides surconsolidées avec système NATM, une section fer à cheval de 110 m^2, et une surchargée qui atteint les 110 m. Les mesures des convergences du tunnel divergent des attendus, et nous avons considéré quelques modifications pour l´amélioration du modèle.

La calotte du tunnel a été modelé en fonction d´une simulation numérique par élément- finis conformément au profil de déplacement linéaire (LDP) qui permet d´adapter la construction aux données des contrôles. Hardening Soil model a été utilisé comme le modèle constitutif pour reproduire la dépendance de la rigidité avec l´état de tension. Le comportement non drainé a été considéré pour des argiles saturées. La surconsolidation des argiles a été obtenu avec l´application et l´enlèvement de la surcharge. Les modèles numériques ont été calibrés en base à la variation des paramètres tributaires de la rigidité du sol à fin d´établir le comportement réel.

Les hautes valeurs de rigidité obtenues des analyses, bien que le rechargement déclenché par l´exécution du tunnel ait été modelé suivant le chemin charge/décharge. La fonction « Gompertz » est proposée comme une solution innovante pour définir le LDP; la fonction a été utilisé pour adapter les données de contrôle, de façons que le LDP finalement obtenu a pu être considéré pour confirmer avec précision l´approche actuelle et les modelés d´élément- finis axisymétriques simplifient qu´ils servent comme ressources dans l´ingénierie pratique.

Keywords: modelling, stiff clays, tunnel, NATM, Gompertz.

1 INTRODUCTION

In the central-northwest area of Spain, important construction projects have been undertaken affecting, tertiary materials of continental origin on which overconsolidated clays predominate. They are not materials with especially bad mechanical properties, but their discontinuities and cementations, together with the difficulties to define realistic behavior models for them (Bilotta & Stallebras, 2009) (Adif, 2010) (Nespereira, 2013) justify the interest of back-analysis studies as a way for a better understanding their real behavior. Therefore, the construction of the Almendro tunnel was chosen as an example, as it was excavated in the clayey materials of the Duero Basin, which were deposited under lacustrine environment.

For the numerical analysis of the tunnel, a 2-D aproach has being used, as it is suitable for sections out of the portals (Hoek et al., 2009; Karakus and Fowell, 2005; Vardakos et al., 2007). The previous analysis included in ADIF (2010) was the starting point from which some modifications were later carried out in order to adapt the observations taken during the excavation of the top heading.

2 THE ALMENDRO TUNNEL

The Almendro railway tunnel is included in the High-Speed N-NE Corridor, Section Valladolid-Burgos. Subsection: Nudo de Venta de Baños-Torquemada, located in the surroundings of Reinoso del Cerrato (E of the city of Palencia) (Fig. 1). It is a 840 m long tunnel, divided in a central section 620 m long constructed as a mined tunnel, and in two 120 and 100 m long false tunnels (ADIF, 2010). This tunnel was constructed to avoid the Cotarro Lobero, a 872 m high hill, being the track at an average elevation of 780 m. The maximum overburden is located in the middle of the tunnel and reaches 110 m thick. It has a truncated circular shape, with a cross-section area of 110 m^2, a height of about 14 m and a width about 14,5 m.

Three different primary supports were settled in the project for sections according the overburden thickness –ST-I for 30 m, ST-II, for 60 m and ST-III for 110 m. They consist of reinforced concrete liner with different steel beams according to the maximum overburden thickness on each section (HEB-160, HEB-200 and HEB-220) and reinforced sprayed concrete.

Figure 1. Location of the tunnel (S Reinoso, Palencia)

The tunnel was driven by the New Austrian Tunnelling Method (NATM), starting with the excavation of the top heading in full section and with an unsupported span of 1m. The excavation of the bench was programmed in two stages. During the excavation of the top heading, no significant modifications were adopted. In accordance with data from the geotechnical survey carried out before the construction, the groundwater level was located below the area affected for the tunnel construction; nevertheless, during the excavation some hanging-water levels appeared in the contact between TC and TD.

The convergence measures used for the modelling are those from the fisrt stage of construction, and where taken between April 2010 and May 2011. These data were adquired during the top heading excavation, and refer to three directions defined by bolts located at the crown and at both lateral walls of the excavated area. Across the tunnel, sections were implemented every 25 m.

2.1 Geology

The area is located in the center of the largest continental origin Tertiary Basin in north of Spain: the Duero Basin (Alonso-Gavilán et al., 2004), where clayey levels of lacustrine origin are frequent. They appear as a sequence of siliciclastic and carbonated sediments comprising major units, called from bottom to top: Dueñas (TD), Tierra de Campos (TC), Cuestas and Páramo. The tunnel is excavated mainly in TD and TC, which are clay units that in some locations also include marls and limestone levels within TD.

2.2 Geotechnical parameters

The geotechnical information from the construction project (ADIF, 2010) defined two different geotechnical units, Tierra de Campos (TC) and Dueñas (TD)(Table 1). They consist of clay and silty clay materials, with a fine fraction above 60 %. The plasticity in the TC is defined by a WL lower than 50% and a PI lower than 20, whereas TD shows higher values. Comparing them with their moisture content, both are in the dried zone, indicating a stiff state.

Bulk density varies irregularly and a value of 20,6 kN/m^3 was adopted in the project for TD and TC. Similar low swelling pressure -49 kPa for TC, 78 kPa for TD - and uniaxial compression strength were obtained, with average values of 549 (TC) and 441 (TD) kPa, but in both cases with a large distribution on the experimental results. Considering their strength parameters, a cohesion of 49 kPa and a friction angle of 28º was adopted for the TC, whereas 39 kPa and 27º was used for the TD.

GEOTECHNICAL UNIT	**TC**	**TD**
UCS (kPa)	549	441
ϕ°	28°	27°
C (kPa)	49	39
E_M (kPa)	1000 a 15000	1500 a 2000
ν	0,4-0,4	0,3-0,4
γ (kN/m^3)	20,6	20,6
Swelling pressure (kPa)	0,8	0,8
Ko	0,5	

Table 1. Geotechnical parameters considered for the construction project (ADIF, 2010).

3 TUNNEL MODELLING

A plane-strain FEM model has been calibrated using tunnel construction monitoring data to estimate soil stiffness parameters. Numerical model has been performed by means of PLAXIS2D (Brinkgreve 2014)(Fig.2), which is a FEM software suitable for solving a wide range of geotechnical problems.

Three different cross sections have been analyzed according to three types of lining performed along tunnel alignment.

Both the TC and TD geotechnical units have been considered for calculation. The roof level has been chosen as the water table elevation as it was detected there during construction.

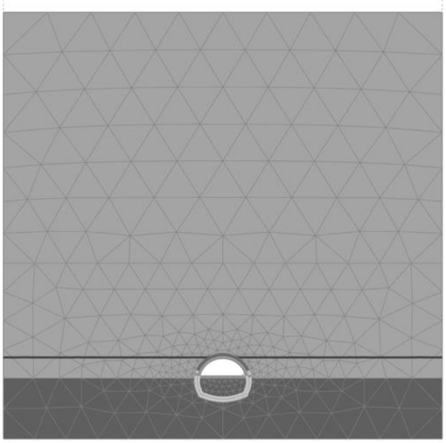


Figure 2. PLAXIS plane strain model

3.1 Ground behaviour modelling

Soil behaviour has been simulated using Hardening Soil model (HS) which is an advanced constitutive model suitable for simulating both soft soils and stiff soils (Schanz 1998). A basic characteristic of the Hardening Soil model is stress dependent stiffness superseding Duncan & Chang´s hyperbolic model, (Duncan & Chang 1970).

Undrained behaviour is assumed for saturated clays and it is implemented in calculations by means of PLAXIS Undrained A approach, which computes undrained shear strength by means of effective strength soil properties and loading conditions.

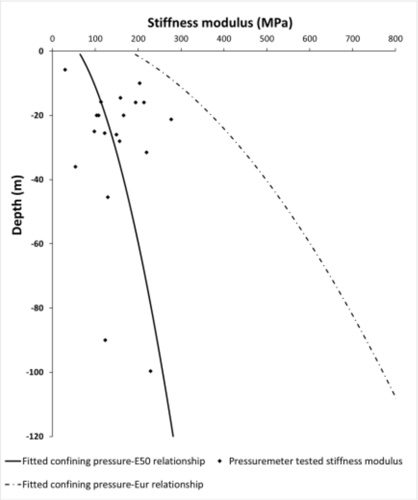


Figure 3. Stress dependent primary loading stiffness fitting. Discontinuous line represents unloading/reloading stiffness

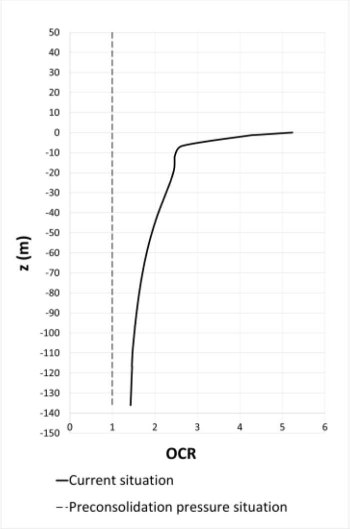


Figure 4. OCR obtained applying overload pressure in FEM model.

Overconsolidation was computed as applying and removing a pre-overburden load in a previous calculation phase. In that phase, drained behaviour was considered for the soil in order not to generate excess pore pressure.

Initial soil stiffness was obtained by fitting confining pressure-stiffness modulus equation to borehole pressuremeter tested data as shown Fig. 3 and Fig. 4.

3.2 LDP fitting

Longitudinal displacement profile (LDP) is the normalized tunnel closure along the tunnel axis. Plane strain tunnel models must be in accordance with LDP in order to relate a tunnel closure value to every construction stage. In other words, using a proper LDP to calibrate plane strain models, allows to capture tunnel construction inherent 3D effects in 2D.

Current approaches are based in sigmoid functions as LDP. Vlachopoulos and Diederichs sigmoid function (Vlachopoulos and Diederichs 2014) was firstly used for match monitoring data. This equation relates convergences with distance from face considering unsupported excavation span and tunnel radius. Nevertheless, this function does not have a proper fit to Almendro tunnel monitoring data (Fig. 5). For this reason, Gompertz function has been used in innovative way to achieve best fit. Gompertz equation is defined by:

$$\frac{\mathrm{u}}{\mathrm{u}_{\max}} = e^{-be^{-cx}} \qquad (1)$$

where $\frac{\mathrm{u}}{\mathrm{u}_{\max}}$ is the normalized closure, x is distant from tunnel face and b and c are fitting parameters which adopt the following values for the Almendro Tunnel case: $b=0.249$ and $c=0.173$.

Furthermore, a simplified axisymmetric model using PHASE2 has been carried out in order to obtain a LDP and to compare it with monitoring data and sigmoid and Gompertz functions (Fig. 6), as this type of model is commonly used in engineering practice as an alternative to 3D models. Elastic perfectly plastic model has been applied for the soil and a circular equivalent area tunnel has necessary been imputed. Isotropic stress field was also considered.

Sigmoid function overestimates tunnel closure behind face and underestimates displacement ahead to the face. Axisymmetric approach overestimates closure in excavated and supported sections but, gives a realistic movement ahead to the tunnel face.

Gompertz function has the best fit to monitoring data and provides a good displacements ahead to face.

3.3 Back Analysis

Due to soil is overconsolidated, and deviatoric stress increase due to tunnelling is lower comparing to preconsolidation stress, stress-strain behaviour follows the unloading-reloading path whose stiffness modulus is approximately three times deviatoric modulus (Brinkgreve et al. 2007). Obtained deviatoric primary loading stiffness modulus for every calculated cross section exceeds 225 MPa, higher than the initial modulus obtained by means of pressuremeter testing. This proves TC and TD are composed of highly stiff clays.

Despite the high values of stiffness modulus, roof vertical displacements obtained in numerical analysis are higher than those obtained in LDP fitting. Nevertheless, due to the highest vertical displacement measured during the supported stage along tunnel axis is only 3.6 mm, numerical analyses can be considered accurate enough.

Table 2. Stiffness modulus obtained in back analysis calculations

Unit	**Project primary loading stiffness (MPa)**	**Back Analysis stiffness modulus (MPa)**	
		Primary loading	Unloading/re loading
TC	110 z<30m 150 z>30m	225; z=30m	675; z=30m
TD	115 z<30m 200 z>30m	300; z=30m	900; z=30m

Table 3. Tunnel roof vertical displacements. Stress relaxation coefficients in numerical models. B is the convergence confinement method coefficient (Schikora & Fink, 1982).

Cross section	**Tunnel roof vertical displacement (mm)**				**PLAXIS Mstage (1-B)**	
	LDP fitting		FEM analyses			
	Unsupported stage	Supported stage	Unsupported stage	Supported stage	Unsupported stage	Supported stage
STI	9.2	10.5	9.2	16.6	0.69	1
STII	10.9	12.4	10.9	14.7	0.73	1
STIII	11.8	13.4	11.8	19.1	0.64	1

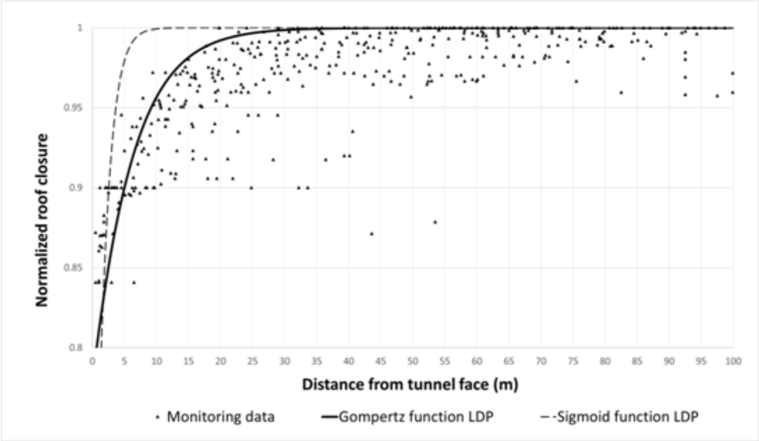
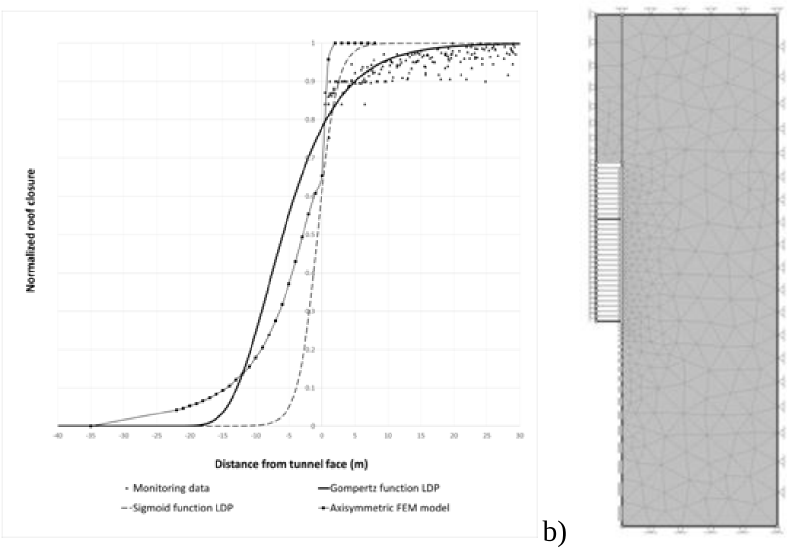


Figure 5 LDP fitting monitoring data. Gompertz function has the best fit to monitoring data whereas sigmoid function overestimates tunnel closure.



a) b)

Figure 6 a) LDP approaches comparison: Gompertz function is compared with sigmoid function and axisymmetric simplified model roof displacements profile, b) axisymmetric FEM simplified model

4 CONCLUSIONS

The monitoring data from the El Almendro tunnel, excavated on overconsolidate clays from lacustrine continental origin, has been used to improve the numerical modelling of its behavior.

LDP current approaches based in sigmoid functions have not a proper fit to Almendro tunnel monitoring data and for this reason, Gompertz function has been used in innovative way to achieve best fit. Gompertz LDP has the best fit to monitoring data and moreover, provides a realistic displacement profile ahead to face.

Numerical modelling reveals high stiffness of TD and TC clays, higher than initial modulus obtained by means of pressuremeter testing.

TC and TD clay soils are overconsolidated and shows reloading behaviour when tunnelling due to deviatoric stress does not overcome preconsolidation pressure.

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