Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
© 2000 Balkema, Rotterdam, ISBN 90 5809 1 066

Tunnel face reinforced by longitudinal bolts: Analytical model and in situ data

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ABSTRACT: In this paper, we are interested in the displacement behaviour of the tunnel face during excavation taking in account the face reinforcement in the farm of longitudinal fibreglass. This technique is now commonly used and is at times a viable alternative to tunnelling machines in difficult ground. For design and analysis, an analytical model, based on the main hypotheses of spherical symmetry and using homogenisation approach, was developed at ENTPE by Wong *et al* (1996, 1997). Recently, in situ data have become available from a tunnel project in France, which showed, among others, the existence of a perturbed zone of roughly one diameter ahead of the tunnel face. The predictions of the analytical model concorded remarkably well with in situ data. Such good results give confidence on the validity of the model, and encourage its use in practical designs and its further development to incorporate more sophisticated soil behaviour.

1 INTRODUCTION

Tunnel excavation methods are intrinsically conditioned by the tunnel face behaviour: ground movements ahead of the face must be minimised to avoid damages to surface and nearby structures, and the stability must be maintained at acceptable levels. Where tunnelling machine is used, construction is carried out in a continuous manner, ground stability being in this case maintained by the face pressure and the continuous lining behind. However, due to its high cost, use of tunnelling machines is limited to particularly unfavourable ground conditions or long tunnels.

Hence, when use of tunnelling machines is not justified, different pre-lining or pre-confinement techniques are used (Lunardi 1993), such as jet grouting, injection or ground freezing etc. Among them, use of fibreglass bolts has become very popular, due to its cost-effectiveness, and a few technical advantages (high longitudinal strength while relatively brittle in the transverse direction hence easily broken during excavation). Note that use of bolts is often combined with prevaults to eliminate entirely unsupported spans in weak ground.

From the point of view of design, logical and reliable design tools for the dimensioning of such longitudinal bolts remained to be elaborated. To this end, an simple analytical model was recently proposed at ENTPE by Wong *et al* (1996, 1997), based on earlier work by Jassionnesse and Dubois (1996). Its results have been shown to be consistent with more sophisticated 3D numerical approaches (Dias *et al* 1998).

In order to gain confidence on the aforementioned analytical model, and to better delimit its domain of validity, its predictions are confronted with in situ monitoring data from Tartaiguille Tunnel in France. Note that this is one of the few large scale tunnelling projects in France using fibre glass bolts for face stabilisation. Owing to problems encountered at an early stage of the works, an extensive monitoring program was proposed, including, among others, radial convergence and face extrusion measurements. Moreover, the extensive site investigations performed prior to tunnel construction, make available an important quantity of information on the geotechnical characteristics of the site. This makes the comparison all the more significant.

2 SITE INVESTIGATION AND MONITORING

2.1 *Presentation of site*

The Tartaiguille Tunnel, near Montélimar (France) is part of the TGV (high speed railway) project in the south of France (EMCC and Paulus, 1998). Its length is 2338 m, and the overburden is more than 75 m over a length of 1600 m and reaches a maximum of 137 m. Excavation began simultaneously at both extremities in February 1996.

The main geological formations encountered are :
- over 360 m, the calcareous Upper Stampien formation, partially weathered,

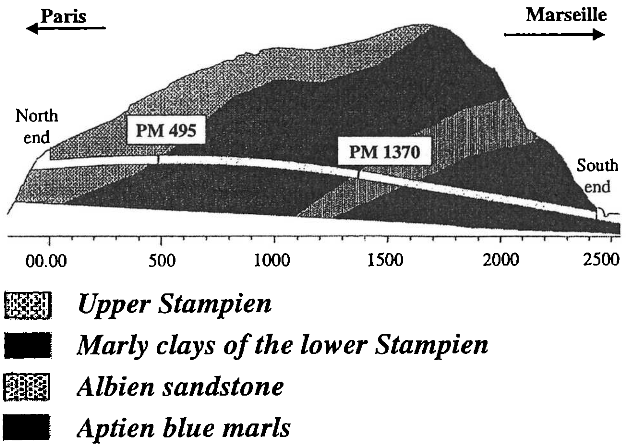

Figure 1. Longitudinal geological profile of Tartaiguille Tunnel (unlarged vertical scale).

- over 920 m, the marly clay of the Lower Stampien formation,
- over the last 1150 m, alternating layers of Aptien blue marls and Albien sandstone.

The excavated section is very large, approximately 180 m², which means a 15 m wide and high tunnel. A two phase excavation scheme (upper half followed by lower half) without face treatment was initially planned. However, during excavation in the Blue Marls, important convergences occured, and lead to local failure of the shotcrete lining. A new investigation survey was therefore performed, which showed that the large convergence was due to the underestimation of the at rest earth pressure coefficient k_0 (1.2 instead of 0.5 initially estimated).

The new calculations thus performed not only concorded with the large convergences observed, but have also showed that the initially forseen excavation method was unacceptable in the Lower Stampien clay as it would lead to convergences in the order of 30 to 40 cm. The full-section excavation method was then retained for the clayey portion with fibreglass longitudinal bolts for face reinforcement (between PM 495 and 1370).

2.2 *Additional investigation*

Several types of investigations have been carried out involving in situ as well as laboratory tests to characterise the mechanical properties of the massif. The main results can be found in a few reports (for example TERRASOL 1995). Concerning the Lower Stampien marly clay, the most significant results, in regard to the two input parameters of the model (undrained cohesion C_u and Young's modulus E), are listed in Table 1.

Table 1. Main investigation results

Young's modulus (MPa)	E_{moy}	E_{mini}	E_{maxi}
Dilatometer (SC 28)	260	150	360
Dilatometer (testing section)			
- vertical borehole	640	260	1040
- horizontal borehole	410	235	680
Ø60 plate load test	380		
autoboring pressiometer test	843	546	960
Cohesion			
Triaxial test UU	C_{uu} = 0.4 to 2 MPa		

Some discrepancies in the results among different tests can be observed, especially the Young's modulus. This is in part due to the highly heterogeneous character of the ground, and in part inherent to in situ measurements. It appears unrealistic to chose a unique value representative of the entire clayey formation. For subsequent analyses, we have retained the values recommended by the steering committee, summarised in Table 2. Such values seem more applicable though to the homogeneous clayey portions, and appear to underestimate the ground strength in the presence of calcareous bands.

Table 2. Soil parameters recommended by the steering committee.

Young's modulus	$E = 400$ MPa
Undrained cohesion	$C_u = 1.2$ MPa
Undrained friction angle	$\varphi = 0°$
Unit weight	$\gamma = 21$ kN/m³

2.3 *Monitoring*

Extrusion of the tunnel face is monitored by a multiple points extensometer called the Extrusometer (Jassionnesse 1998) at the tunnel face centre.

For the section inside the upper Stampien formation (PM626 to PM1275), where fibre glass bolts were used as face reinforcement, monitoring data were obtained from 16 extrusometers:

- Extrusometers n° 1 to 6, between PM1275 and PM1119, in the southern part,
- Extrusometers n° 7 to 16, between PM626 and PM901, in the northern part.

The monitoring reports showed that Extrusometers n° 4 to 5 at the southern end, between PM1203 and PM1119, as well as those of the northern part, are located inside highly heterogeneous ground, where the presence of resistant calcareous layers stiffens the clayey formation, deviating therefore from the hypothesis of the analytical model (homogeneity and isotropy). As a matter of fact, the measured extrusions at these locations (15 mm) are much lower than the three extrusometers n° 1 to 3 inside

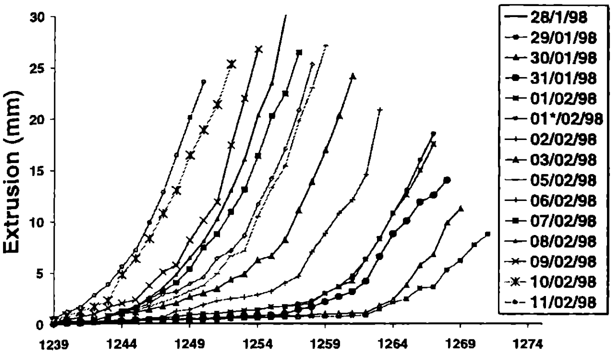

Figure 2. Extrusion profiles of Extrusometer n° 1 between PM1275 and PM1239.

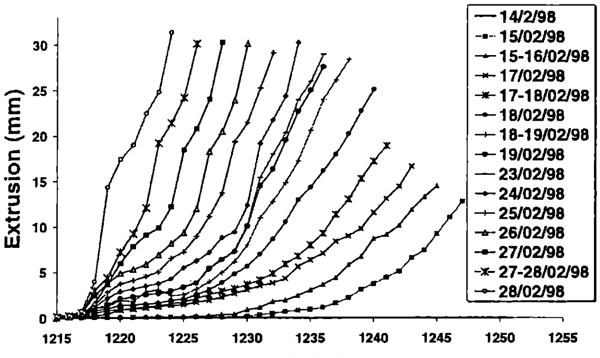

Figure 3. Extrusion profiles of Extrusometer n° 2 between PM1251 and PM1215.

homogeneous ground (30 mm). Nonetheless, for Extrusometer n° 3, only two sets of measurements have been made, and are insufficient for a proper interpretation. Hence, the comparative study will only be carried out for Extrusometers n° 1 and 2. Their detailed locations as well as the corresponding quantities of bolts are shown in figure 4. The extrusion profiles vs. PM (a fixed reference frame) for different tunnel face positions are plotted in figures 2 and 3. Note that excavation advances in the direction of decreasing PM.

2.4 *Interpretation*

When the tunnel face advances, mechanical perturbations so introduced lead to extrusion movements of the ground ahead of the face.

Take for example Extrusometer n° 2, installed when the face is at PM1251 (fig 5). Extrusions are taken as zero at this particular position, taken to be the reference. The extrusion profile at 15/02/98, when the face advanced to PM1247, corresponds to perturbations due to the 4 m excavation PM1251 and 1247.

In consequence, the extrusion measurements are underestimated as the movement before placement of extrusometer is not recorded (due to face advance from far field up to point of placement).

Notwithstanding, the extrusion at a particular point P starts to rise only when the face is within a finite critical distance to P, noted D_{crit}. By joining the points of maximal extrusion (i.e. at the current position of the face), it can be noted that the extrusion curve rises at first sharply from the installation point, but stabilises beyond a critical distance of around D_{crit}~15 m. Hence it exists a zone of influence ahead of the face beyond which the ground remains yet undisturbed by the excavation. The above observation suggests that this zone is roughly of one diameter ahead of the face in the present case.

For the comparative study, we will not take into account measurements taken inside the zone of influence with respect to the reference point (placement of extrusometer) for the above reason. The measurements within D_{crit} of the anchorage point will also be discarded since the displacements are measured with respect to this reference point supposed fixed.

In consequence, for each of the two extrusometers, only the extrusion profiles inside the central zone will be retained for analysis. These curves will later on be translated to a reference frame with a common face position (§ 4).

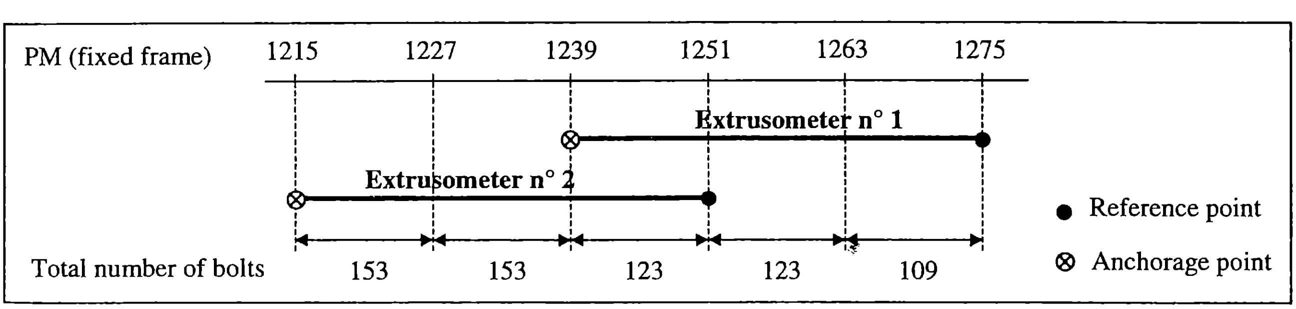

Figure 4. Locations of Extrusometers n°1 and 2 with respect to the fixed frame – definition of the reference point and the anchorage point.

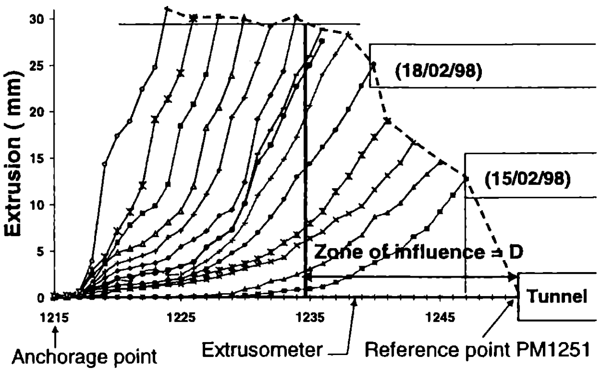

Figure 5. Interpretation of the measurements from Extrusometer n° 2.

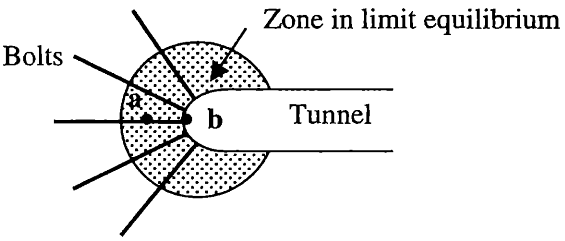

Figure 6. Schematic representation of the problem geometry.

3 ANALYTICAL MODEL

The analytical model developed in ENTPE is based on a small number of simplifying assumptions :

- the stress history at a particular point, such as point a in figure 6, when the face advances from far off up to this point, can be simulated by that of a fixed point b, situated on a stationary front and subjected to a decreasing internal pressure from overburden to zero.
- the tunnel face is assimilated to the surface of a spherical cavity, while the bolts, of infinite length, are installed in the radial direction.
- all the field quantities such as stress, strain, and displacements verify spherical symmetry ahead of the face.
- the approach of homogenisation of periodical media allows to replace the composite medium composed of soil (elastic perfectly plastic behaviour obeying Tresca's yield criterion) and bolts by an equivalent anisotropic medium due to the preferential action of bolts in the axial direction.
- the bolt-soil interface is supposed to be perfectly bonded in the original development (Wong *et al*, 1996). This assumption was later relaxed to include the case of finite bond strength (Trompille 1998).

These theoretical developments were built into a computer program (EXTRUSION® 1997) written in C^{++}, with built-in graphic utilities to facilitate quick design calculations and parametric studies.

4 COMPARISONS

4.1 *Mechanical parameters*

The soil parameters considered are those listed in Table 2. Concerning the ground, on account of an average depth of H=110 m near the extrusometers n°1 and 2, the geostatic pressure is therefore around P_∞=2.3 MPa. The tunnel section has been estimated to be around 180 m^2, giving an equivalent radius of R=7.4 m.

Regarding the bolts, they have a cross sectional area of S_b=840 mm^2, an elastic modulus of E_b=40 GPa, and a yield stress of σ_{yb}=1000 MPa. The total number of bolts at the face, and the corresponding densities are respectively N_b^1=123 (d_b^1=0.68 m^{-2}) for Extrusometer n° 1, and N_b^2=153 (d_b^2=0.85 m^{-2}) for Extrusometer n° 2.

4.2 *Results of comparison*

The extrusion profiles, plotted against the distance ahead of the face, are superposed with the theoretical predictions using the ENTPE analytical model in figures 7 and 8.

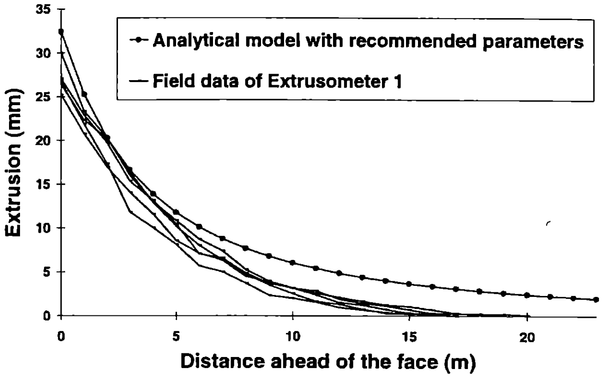

Figure 7. Results of comparison for Extrusometer n°1.

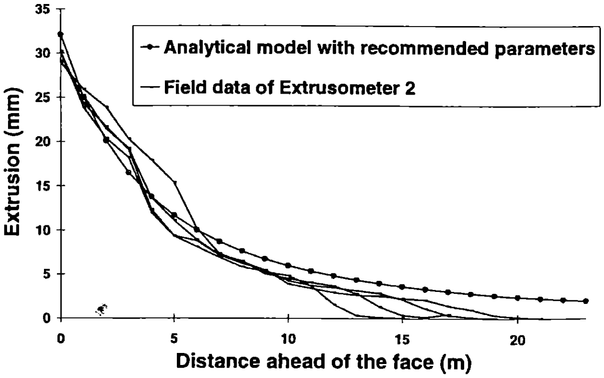

Figure 8. Results of comparison for Extrusometer n°2.

4.3 *Comments*

Independently of any comparison with the theoretical model, the in situ data deserves the following comments:

- the various extrusion profiles, plotted against the distance with respect to the current face position, all lie within a narrow gap, indicating repeatability and consistency of the measurements;
- moreover, the maximum extrusion values of both extrusometers are quite close to each other – 25 to 30 mm for Extrusometer n° 1 (20 % dispersion) and around 30 mm (5 % dispersion) for n° 2. This and the last point indicate a relative homogeneity of the ground, thus presenting ideal conditions to check the validity of the theoretical model;
- as mentioned previously, a zone of influence of around 15 m can be observed, beyond which extrusion values are negligible.

In regards to the comparative study, the results are remarkable. Notably:

- the theoretical predictions, based on the geotechnical parameters recommended by the steering committee, are in excellent agreement with in situ observations. The maximum calculated extrusion of 32 mm represents no more than 20 % error compared to the mean observed value;
- the overall trend also approximates closely to the observed values away from the face, at least within the zone of influence. The displacements theoretically tend to zero only at infinity, due to the simplifying assumptions inherent to this type of continuum models, whereas the measured value necessarily goes to zero at the anchorage point by definition. Nonetheless, no longer within the critical zone, this divergence has no practical consequence.

5 PARAMETRIC STUDY

The comparative study has considered the soil parameters recommended by the steering committee. Nonetheless, on account of the dispersions observed, it appears interesting to perform a parametric study in order to investigate their influence on the results of the theoretical predictions.

Influence of the cohesion : Taking account of all the in situ and laboratory tests performed, it appears realistic to suppose that the undrained cohesion varies within the following interval :
800 kPa $\leq C_u \leq$ 1400 kPa.

Substitution into the analytical model leads to face extrusions from 31 to 41 mm, a relatively narrow range (Fig. 9). It can equally be observed that for the recommended value C_u=1200 kPa, the soil behaviour is not far from elastic, since the face extrusion becomes independent of the cohesion when the latter is above 1500 kPa.

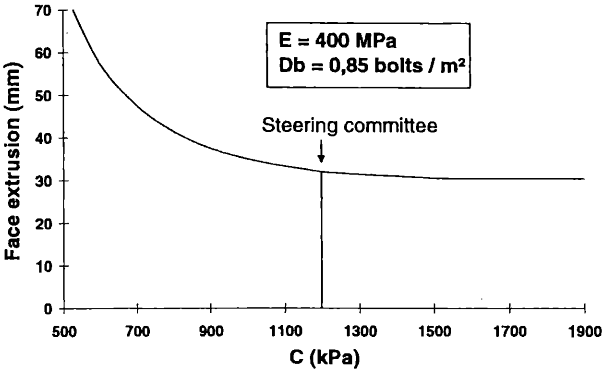

Figure 9. Analytical model – influence of cohesion on face extrusion.

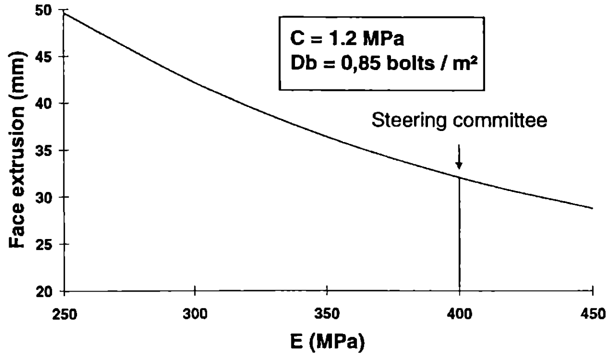

Figure 10. Analytical model - influence of Young's modulus.

Influence of Young's modulus : From the investigation results (Tab. 1), it seems reasonable to suppose that the modulus of elasticity varies within the following interval : 250 MPa $\leq$ E $\leq$ 450 MPa.

The corresponding face extrusion varies between 29 and 49 mm. Thus the larger uncertainty on Young's modulus also leads to a larger uncertainty on its consequences on the face extrusion.

Influence of the bolts density : It was also interesting to investigate the influence of the bolt density in this case. By considering a total number of bolts varying between 0 (no reinforcement) and 350, the calculations revealed that the calculated face extrusion was not much influenced, as it varied only from 34.5 mm to 30 mm.

Such result is an indication that, for the geotechnical data of the project adopted and with the hypothesis of an elastic perfectly plastic behaviour of the soil, the relative stiffness of the bolts compared to the ground was relatively low and its contribution on the face extrusion not very significant. Actually, the ground showed a strain-softening behaviour, and the effect of the reinforcement was undoubtedly more effective than calculated one. Site observations also showed that the bolts avoided local failures.

6 CONCLUSIONS

The first comparisons between the analytical model developed in ENTPE on the behaviour of a tunnel face reinforced by fibreglass bolts, and other more sophisticated numerical approaches such as 3D finite differences (Dias *et al* 1998) gave encouraging results. Comparison with in situ measurements comes as a logical continuation in order to determine its degree of precision and its domain of validity with respect to the "reality".

The quantity, diversity as well as the excellent quality of the in situ data obtained at the Tartaiguille Tunnel all contribute to the interest of this study, while the important geotechnical investigations gave sufficient information for site characterisation and determination of soil parameters for input to the theoretical calculations (we should of course bear in mind the usual dispersions of such data). Independently of the comparisons with the theoretical models, the monitoring results already showed, among others, the existence of a critical zone, in the order of one tunnel diameter ahead of the face, beyond which the massif remains undisturbed by the excavation. The excellent concordance between in situ data and the ENTPE model demonstrate the consistency of the latter, despite the (inevitable) simplifying assumptions, and give confidence on its validity as well as its utility. Currently, experimental studies under ideal laboratory conditions are being untaken (Egger *et al* 1999) to investigate the stability behaviour. Moreover it appears necessary to consider more sophisticated constitutive of the ground such as a strain-softening model. Such theorical development, already accomplished (Subrin 1997), will be incorporated into the computer program EXTRUSION®.

It remains however to enlarge the present comparative study to other construction sites with different sets of parameters in order to constitute a larger and more complete knowledge base. New techniques and more detailed monitoring programs should then cover field quantities not yet investigated here, such as the magnitude as well as the distribution of bolt tension.

REFERENCES

Dias, D., D. Subrin, H. Wong, P. Dubois & R. Kastner 1998. Behaviour of a tunnel face reinforced by bolts: comparison between analytical and numerical models. *2nd Int. Symp. Geotech. Engg. Hard Soils - Soft Rocks*, Naples, Italie.

Egger, P., D. Subrin & H. Wong 1999. Behaviour of a tunnel reinforced by bolting : experimental study and theoretical modeling. *Submitted to 8th Int. Symp. Rock Mech.*, Paris, France.

EMCC. 1998. Tartaiguille, une nouvelle méthode. *Tunnels et ouvrages souterrains n°145* : 29-31, France.

Wong, H., D. Doanh 1997, EXTRUSION® ver.1.01, Computer program and accompanying user manual, Ecole Nationale des Travaux Publics de l'Etat.

Jassionnesse C., Dubois P. 1996, Tunnel face reinforcement by bolting, soil bolts homogenisation strain approach. Proc. Symp. Geotech. Aspects Underground Constructions Soft Ground, London, U.K.

Jassionnesse, C. 1998. Contrôle du massif renforcé par boulonnage au front de taille d'un tunnel. Etude d'un cas réel en site urbain: Exploitation des mesures et modélisation par une méthode d'homogénéisation. *PhD thesis of INSA Lyon.*

Lunardi, P. 1993, La stabilité du front de taille dans les ouvrages souterrains en terrain meuble : études et expériences sur le renforcement du noyau d'avancement. *Renforcement des sols : expérimentations en vraie grandeur des années 80* : 92-131. Paris : Presses de l'ENPC.

Paulus, M., JM. Estre, D. Michel & E. Mathieu 1998. Le tunnel de Tartaiguille : méthode pleine section pour la traversée des argiles. *Travaux n°742* : 74-79, France.

Subrin, D. 1997. Etude du comportement du front de taille d'un tunnel renforcé par des inclusions en fibre de verre, voie analytique. *MSc. thesis, ENTPE.*

TERRASOL 1995. Tunnel de Tartaiguille, projet d'exécution : Note d'hypothèses géotechniques générale de dimensionnement. *Report 1995.019BB/01.*

Trompille, V. 1998. Mouvements d'extrusion du front de taille d'un tunnel renforcé par des boulons en fibre de verre : Comparaison entre des mesures in situ et un modèle analytique développé à l'ENTPE. *MSc. thesis, ENTPE.*

Wong, H. & C. Jassionnesse 1996. Stabilité du front d'un tunnel renforcé par des inclusions en fibre de verre, modèle analytique. *Symposium GEO*, Aussois, France.

Wong, H. & E. Larue 1998. Modelling of bolting support in tunnels taking into account of non-simultaneous yielding of bolts and ground. *Proc. 2nd Int. Symp. on Geotech. Engg. of Hard Soils - Soft Rocks*, Naples, Italie.

Wong, H., D. Subrin & C. Jassionnesse 1997. Comportement du front d'un tunnel renforcé par des inclusions en fibre de verre, modèle analytique. *Géomatériaux – Environnement – Ouvrages, Vol. 2* :133-147. Ed. Hermès, France.

Wong, H., D. Subrin & P. Dubois 1997. Mouvements en avant du front de taille d'un tunnel renforcé par du boulonnage - influence du comportement du sol. *Symposium GEO*, Aussois, France.