Proposals for the design optimization of nailed walls

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Abstract. The goals of this document are (1) to present the problems encountered by practitioners when making the design of soil nail walls, particularly to optimize the quantity of nail bars and to determine the efforts applied to the shotcrete wall facing, (2) to propose methods giving answers to the above mentioned problems by development of existing methods and (3) to present the practical solutions. The method is based on developments of the proposals included in the French document "Addendum to the CLOUTERRE Recommendations " published in 2002 and in the French standard NF 94 270 Geotechnical design-Retaining structures-Reinforced and soil nailing structures published in 2009. The point loads due to nail heads applied to the shotcrete face are determined from the efforts in the nail bars taking into account the mechanism of transfer.

Keywords: Nailed walls, nail bars, shotcrete wall facing, Culmann's method, active and at rest pressure.

1 Introduction

The designers of soil nail walls encounter several problems using EUROCODE 7:

(1) For the GEO design:
- the calculation of the minimal length of nails to satisfy stability criteria.

(2) For the STR design:
- the calculation of the minimal area of steel rebars,
- the calculation of the point loads applied to the shotcrete wall facing.

The determination of the minimal length of nails usually implies that the designer assess vertical and horizontal spacings, drilling diameter, lateral skin friction and their initial length. Based on these values, the factor of safety is calculated and the lengths of the nails are adjusted by trial and error to reach the required factor of safety.

This method is rather long and does not guarantee that the weight of steel is minimized.

The methods used until today calculate the force which can be mobilized behind the sliding surface (minimum of the yielding force of the rebar and of the lateral skin friction) and introduce this force in the equilibrium equations in order to calculate the factor of safety. However, these methods do not give the minimal force in each nail to reach the required factor of safety: the determination of the area of each rebar must also be determined by trial and error.

The current methods do not give the point loads applied to the shotcrete facing.

The goal of this paper is to propose a calculation method taking into account the above problems and to present the application of this method introduced in a slope stability reinforced soil software.

2 Statement of the problem and proposed methods

2.1 General

According to « French 2002 additive to the CLOUTERRE 1991 Recommendations », the point load applied to the shotcrete wall facing is:

$$T_N = \text{Max}\,[T_0\ ;\ T_1\ ;\ T_2]\cos(\theta - \eta) \qquad (1)$$

with:

θ	= angle of the nail below horizontal axis.
η	= angle of the shotcrete wall facing.
T_0	deduced from T_{MAX} to insure the overall stability.
T_1	calculated in order to insure the stability of the shotcrete wall facing by friction.
T_2	calculated in order to counteract the pressure of the soil behind the shotcrete wall facing.
T_{MAX}	upper bound or envelop of the efforts in the nails necessary to insure the overall stability in all the cases.

2.2 Determination of T_{MAX}

The method is given below:

- For each sliding surface S_i:

- Calculation of the factor of safety, FS_{oi}, without nails,

- Calculation of the factor of safety FS_{ri}, with nails, which lengths are given initially by the designer but without structural limit,

- Knowing the stabilizing force, T_{io}, induced by the nails on the sliding surface S_i and knowing that this stabilizing force induces an increase of the factor of safety from FS_{oi} to FS_{ri} ($\geq FS_{oi}$), the value of the minimal stabilizing force required to reach $FS_{ri} \geq FS$ is calculated by iterations.

with:

FS_{oi}:	Factor of safety of the specified surface without nails.
FS_{ri}:	Factor of safety of the specified surface with nails.

Such that T_{io}, $FS_{ri} = FS_{oi} + \Delta FS_{TiO}$ (2)

The problem needs

- to look for T_i such that $\Delta FS_{Ti} = FS_{visé} - FS_{oi}$ (3)
- to do once again the above mentioned calculations for each sliding surface and for each excavation step in order to get $T_{MAX} = \text{Max}\,[T_i]$.

This method can be applied considering that the nails are acting only axially or according to the multicriteria approach, as proposed by Blondeau et al.

2.3 Determination of T_o from T_{MAX}

The proposed optimization assumes that the length of the nails is always given by T_{MAX}.
It is proposed to calculate T_o, point load applied to the shotcrete facing, to insure the overall stability, from T_{MAX}, substracting the lateral skin friction mobilized along the nail between the sliding surface and the shotcrete facing.

On one side, if the nail is installed in an envelope in which it can slide freely between the sliding surface and the shotcrete face, which is the case for active anchors with a free length, then $T_o = T_{MAX}$.

On the other side, if the lateral skin friction is greater than T_{MAX} in this zone, then the force T_{MAX} is fully transferred to the soil before the shotcrete wall facing and then $T_o=0$.

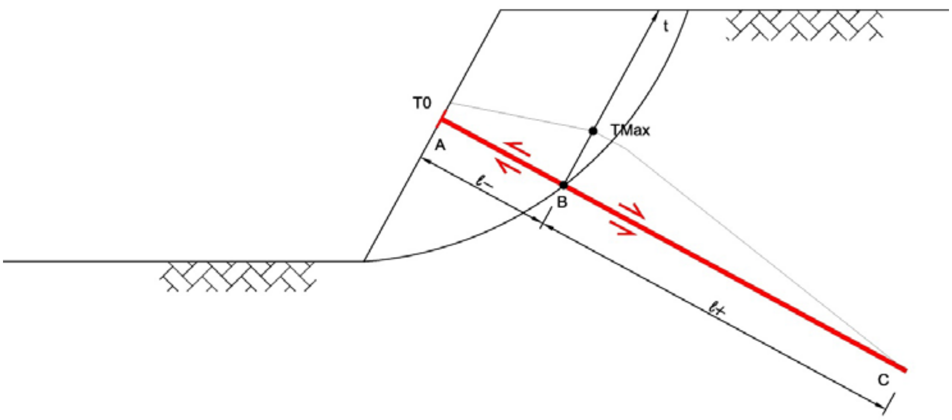


Figure.1. Variation of the forces along the nail bars

where $$T_{MAX} = Min\left[\frac{T_{barre}}{\Gamma_{acier}}; \pi\phi_f l^+ \frac{q_{s\,BC}}{\Gamma_{q_s}}\right] \quad (4)$$

and $$T_o = T_{MAX} - \pi\phi_f l^- \frac{q_{s\,AB}}{\Gamma_{q_s}} \quad (5)$$

2.4. Calculation of T_1

The calculations of T_1 are obvious and as such are not detailed in this document.

2.5. Calculation of T_2

The method to calculate T_2 is a development of the method proposed in the Appendice E3 of the French standard NF 94 270 and consists basically in a first step to calculate the active earth pressure on the shotcrete wall facing considered as a fictive face using the Culmann's method.

T_2 is the confining force necessary to counteract the active pressure on the shotcrete wall facing.

The forces acting on the earth block ADDi are given below:

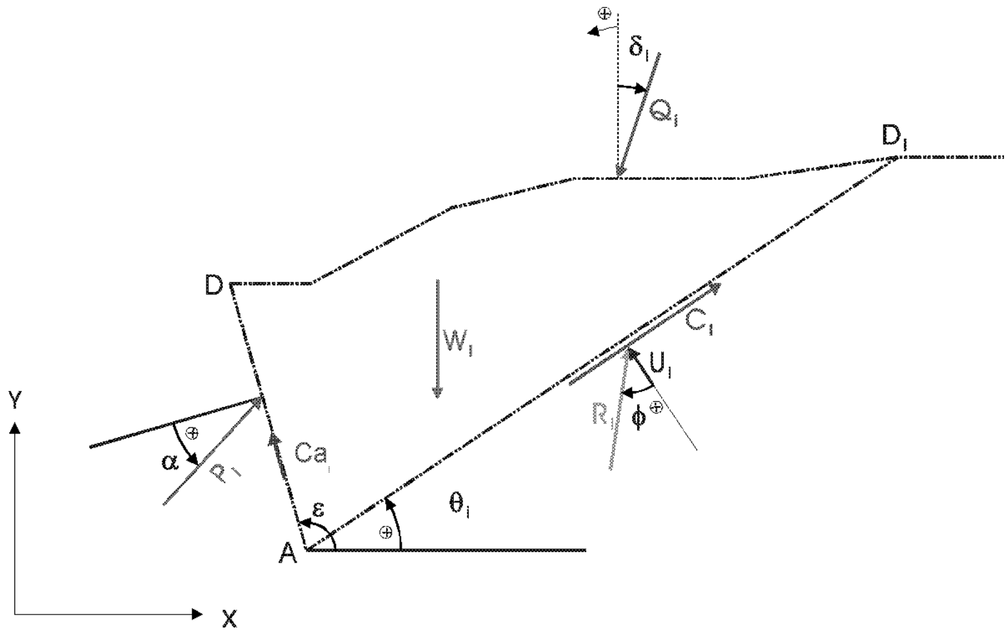


Figure.2. Forces acting on the earth block

W_i	:	weight of the earth block ADD_i
W_i	:	area $(ADD_i) \times \gamma$
Q_i	:	external loads acting on block ADD_i. $Q_i = \int q_i$
U_i	:	pore pressure acting on the plane AD_i.
C_i	:	cohesion on AD_i $C_i = C \times l(AD_i) = C \times l_i$
Ca_i	:	adhesion on the plane $Ca_i = Ca \times l(AD)$

R_i	:	reaction force on the plane $AD_{i.}$
P_i	:	resultant effort of earth pressure acting on plane AD considering sliding plane AD_i.
α	:	angle of the active earth pressure with the perpendicular to the shotcrete face fixed by the designer.

These calculations are repeated for planes AD1 to ADn, sloping from θi to θn, above horizontal axis allow to calculate the variation of the active earth pressure Pi with the inclination of the plane considered.

The Culmann’s method gives the overall force acting on the shotcrete wall facing down to point A.

In order to get the pressure diagram acting on the shotcrete face wall, the calculation must be done for a number of positions of the point A. The differences between two successive points allow determining the pressure diagram.

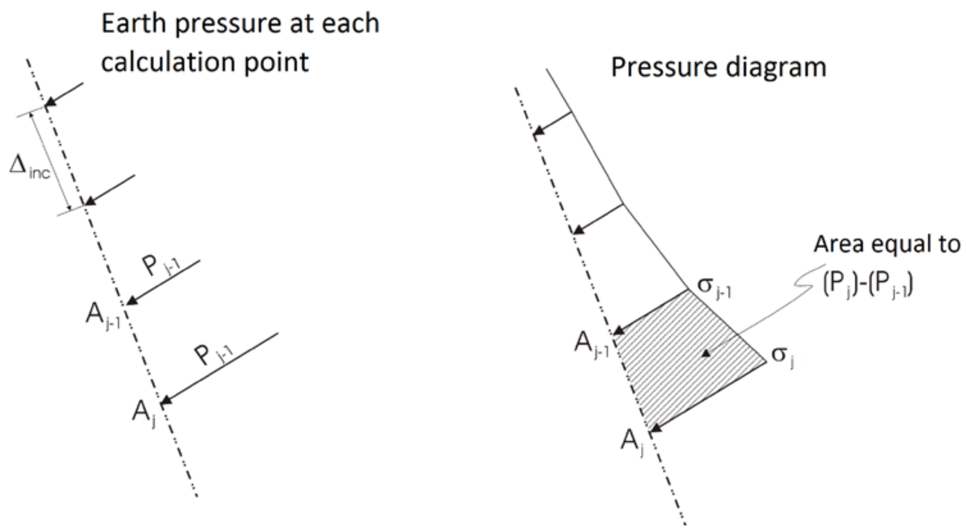


Figure.3. Determination of the pressure diagrams on a wall

Given	σ_j	:	pressure at point A_j
	σ_{j-1}	:	pressure at point A_{j-1}
	Δ_{inc}	:	distance between the two points

σ_j is given by: $$\sigma_j = \frac{P_j - P_{j-1}}{\Delta_{inc}}$$

For current values of Ø, i.e . comprised between 25° and 40°, the value of K_o / K_a, approximately equal to $\left(1-\sin\phi\right)/tg^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right)$ for an horizontal pressure, is comprised between 1.42 and 1.64, or approximately 1.5 for a current friction of 30°, average value of the extreme bounds considered.

Without any movement, the earth pressure would be the at rest pressure and in such a case:

$$T_2=1.5P_A$$

If the movement is such that the active earth pressure is reached, than the earth pressure is:

$$T_2=P_A$$

The pressure exerted against the shotcrete wall facing is:

$$T_2 = P_A\left[\frac{K_o}{K_a}\left(1-\frac{\delta}{\delta_A}\right)+\frac{\delta}{\delta_A}\right]$$

Or:

$$T_2 = P_A\left[\frac{K_o}{K_A}+\frac{\delta}{\delta_A}\left(1-\frac{K_o}{K_a}\right)\right]$$

With

- δ relative displacement measured during nail wall construction
- δ_A relative displacement necessary to reach active earth pressure

An upper bound of T_2 is given for δ minimal and δ_A maximal, that is:

$$\frac{\delta}{\delta_A}=\frac{2H/1000}{0.5H/100}=0.4$$

giving T_2 = 1.3 P_A.

It is proposed to adopt the following value for the earth pressure acting on the shotcrete face:

$$T_2 = 1.3\ P_A$$

According to the bibliographic references and to the developments proposed, the value 1.5 P_A. proposed in the French standard NF 94-270 seems to be very pessimistic and the proposed value 1.3 P_A seems to be a better estimation for most cases.

However, for soft rocks and soils, swelling, highly overconsolidated, freezing, an approach of the geotechnical behavior could justify another choice.

2.6. Calculation of the minimum bonding length

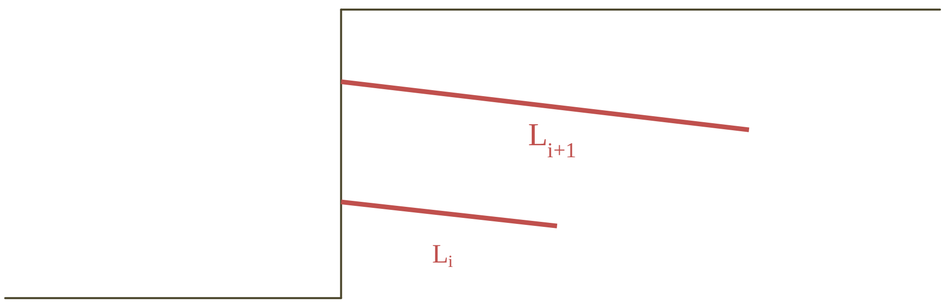
The proposed optimization assumes that the length of the nails is always given by T_{MAX}.

So, all the possible lengths must be tried respecting constructive and geometric constraints and the factor of safety must be calculated.

The optimal solution is such that the sum of the products (length of the nails multiplied by the maximal effort in the nail) is minimal. This criterion gives the minimum weight of steel.

$$Solution = \min_{nSurfaces}\left(\sum_{i=1}^{nclous} T_{\max}(i) * L(i)\right)$$

For constructive reasons, the length of the upper layers of nails must be greater than or equal to the length of the lower layers.



$$L(i) \leq L(i+1)$$

Figure.4. Constructive arrangement imposed to the length of nails

The algorithm of optimization uses the theory of graphs with the research of depth. The method allows reaching the first acceptable solution minimizing the number of iterations.

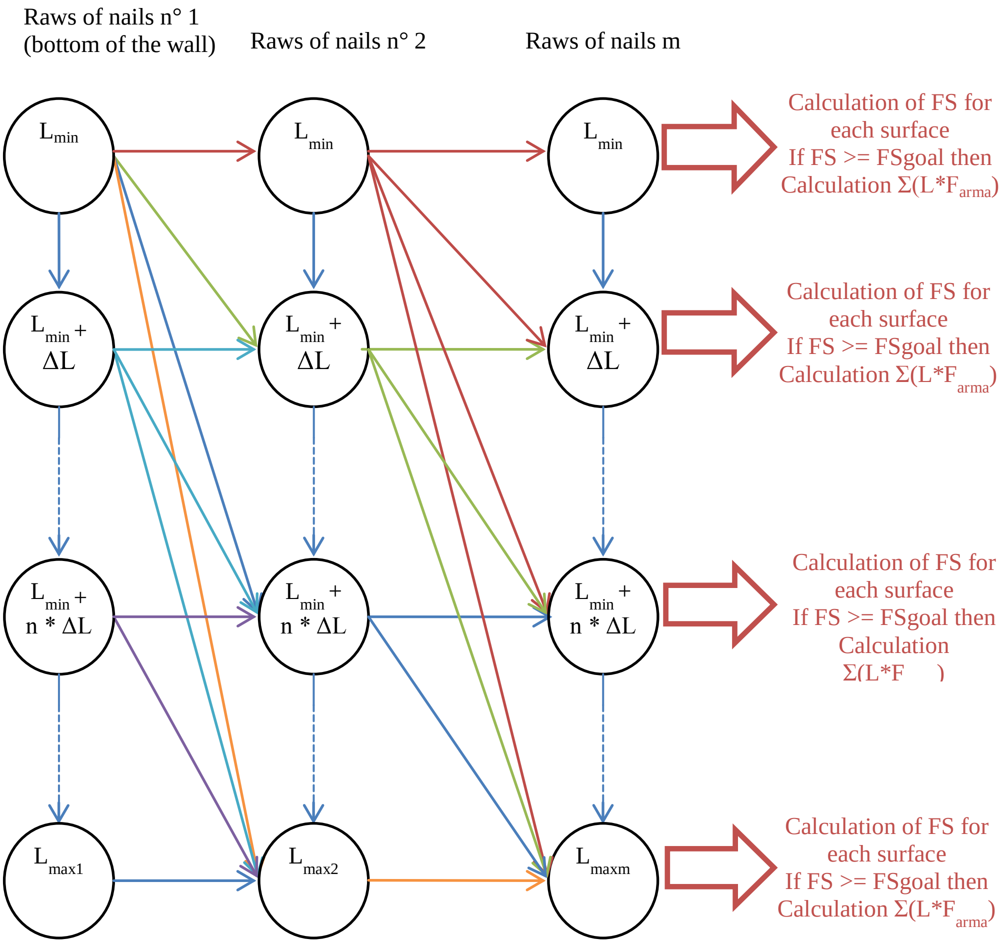


Figure.5. Algorithm to reach optimized lengths of nails

2.7 Calculation of the minimum steel area

Knowing the minimal force T_{MAX} necessary to reach the required factor of safety for a given sliding surface, the area of the steel rebar necessary for the considered sliding surface is

$$Ai = \frac{T_{MAX\,i}}{\frac{\sigma_e}{\Gamma \sigma_e}}$$

The minimum steel rebar area is the maximal steel area of all the possible sliding surfaces

$$A = MAX\left[Ai\right]$$

3 Practical applications

The above mentioned proposals have been developed in a slope stability software able to take into account nails.

The implementation of the developments allows not only to determine the factor of safety and to check that the proposed reinforcement is appropriate but also to optimize it by minimizing the quantity of steel and to determine the point load applied to the shotcrete wall facing.

An example of some steps and outputs is shown on the figures below. For simplicity reasons, the example was treated at the ULS (Ultimate Load State) without partial safety factors trying to reach a global safety factor of 1.5.

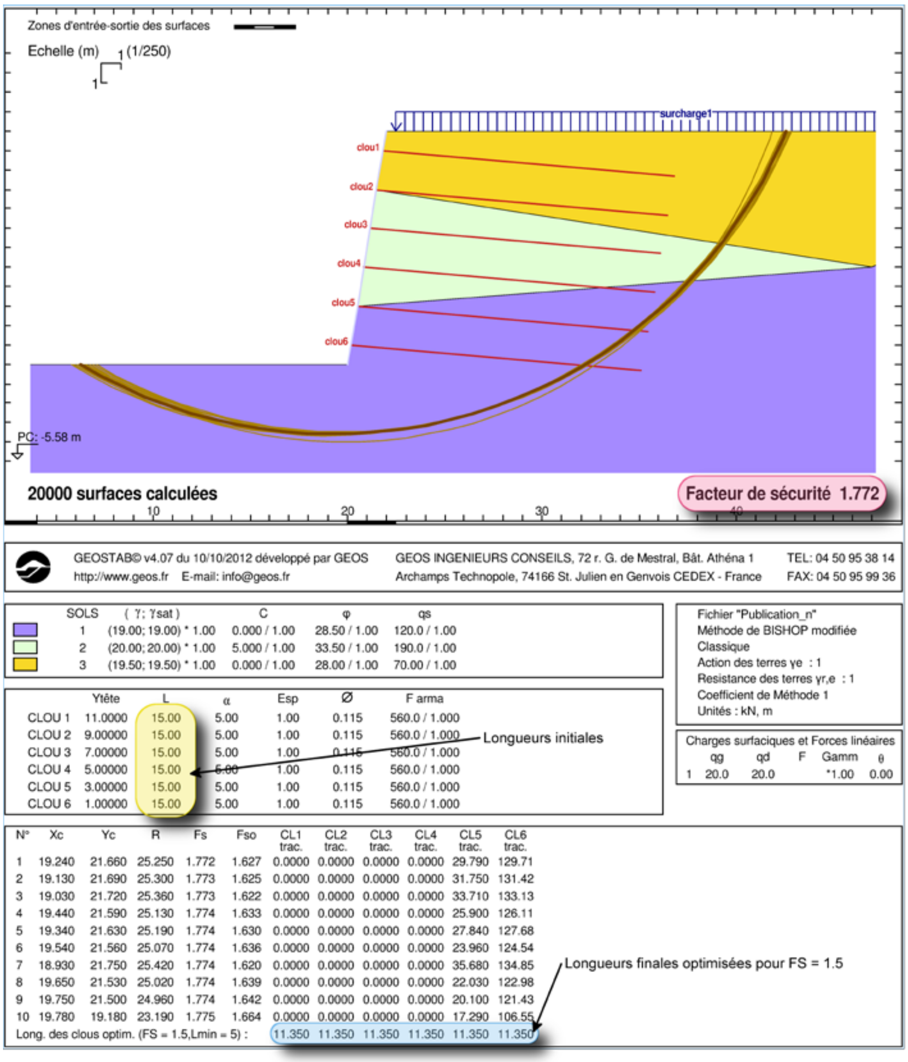


Figure.6. Determination of the optimized length of the reinforcement to reach the safety factor

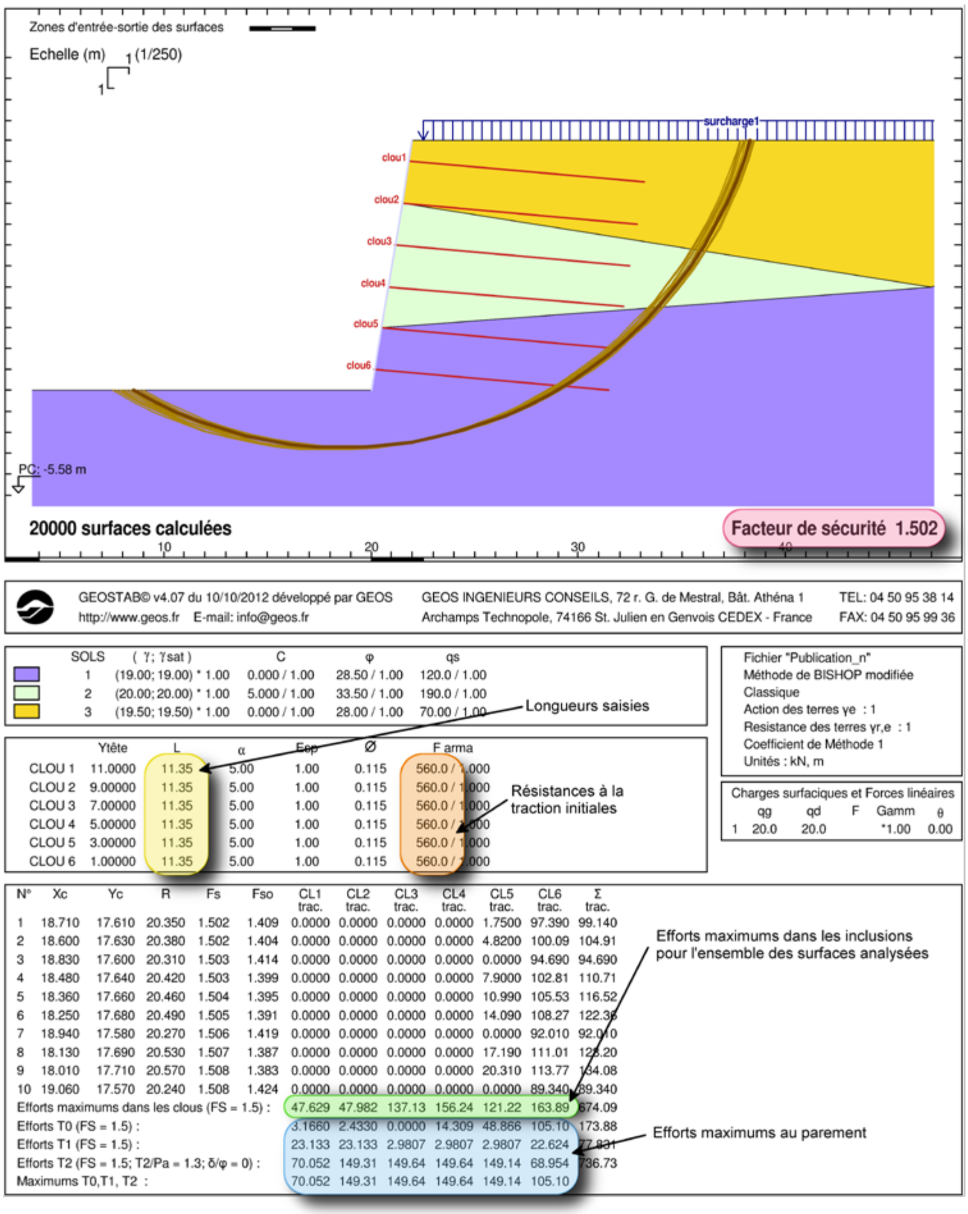


Figure.7. Determination of the maximum efforts in the nail bars T_{max}, and of the efforts applied

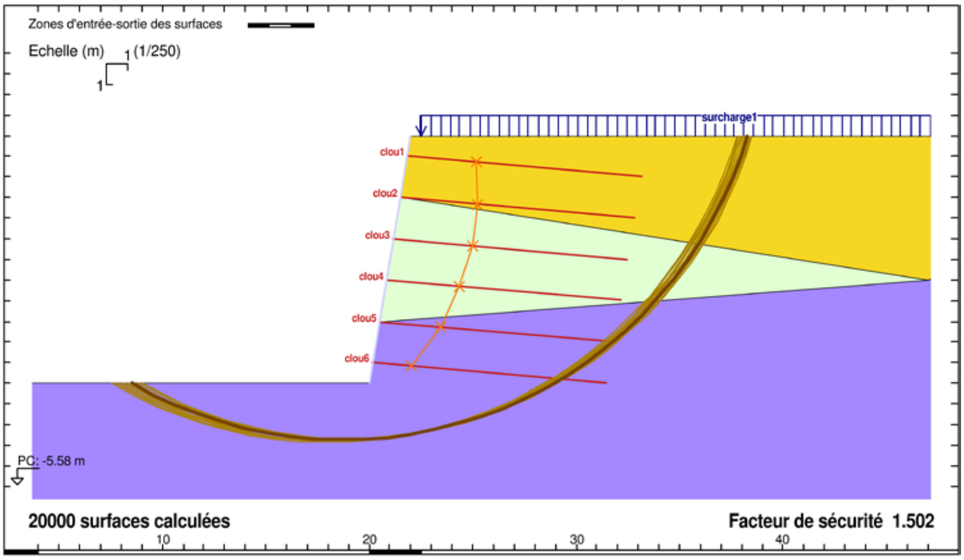


Figure.8. Location of the maximum efforts in the nails

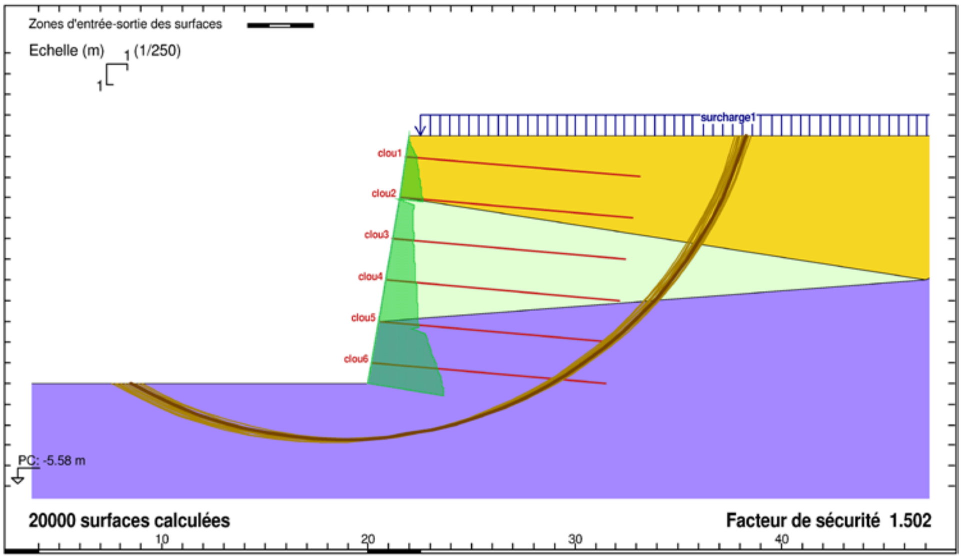


Figure.9. Diagram of pressure applied to the face according to Culmann's method

4. Concluding remarks

Considering the situation and based on a state of the art for the design of soil nail walls, methods are proposed to determine minimal lengths and steel sections to optimize nail design and calculate point loads applied by nail heads to the shotcrete wall facing.

Practical use of the above mentioned developments in a software is presented and shows that the design is economically optimized.

A cross checking of this approach should be made in order to determine the influence of paramount parameters: friction angle and lateral skin friction.

Particular soils such as soft rocks, swelling soils, highly over-consolidated soils should be dealt with a special approach to determine soil pressure applied to the shotcrete wall facing.

References

Blondeau F. et al. (9-11 October 1984) Méthode de calcul des ouvrages en terre renforcée – Renforcement en place des sols et des roches – Comptes rendus du colloque international. *Presse de l'ENPC – Paris.*

Byrne R.J. et al. (1998) Manual for design and construction monitoring of soil nail walls. *Report FHWA-SA-96-69R.*

Chapeau C. (2011 – 2012) Personnal communications.

Clouterre (1991) Recommandations Clouterre. *Presses de l'ENPC.*

Clouterre (2002) Additif aux Recommandations Clouterre 1991. *Presses de l'ENPC.*

Delattre L., Martens (2003) Un siècle de calcul d'écran de soutènement. *Bulletin des Laboratoires des Ponts et Chaussées. 244-245, pp 31-51.*

Fau Didier (1987) Le clouage des sols – Application au soutènement de fouille – Etude expérimentale et dimensionnement. *Thèse E NPC.*

Gigan J.P.(May-June 1986) Applications du clouage en soutènement – Paramètres de conception et de dimensionnement des ouvrages. *Bulletin de Liaison des Ponts et Chaussées, 143.*

Gudehus G. (1982) Clouage des sols – règles de dimensionnement et leur vérification expérimentale. *Revue Française de Géotechnique, 19, p24-37.*

Lazarte C.A. et al. (2003) Geotechnical Engineering Circular No 7 Soil Nail Walls. *Report FHWA, DTEH61-00-C-00109.*

Marche M., Favre M. (April 23, 1999) Dimensionnement et fluage à moyen terme d'un mur cloué de grande hauteur. *Conférence Société Suisse de Mécanique des Sols et des Roches, Berne.*

Menoret A. (2011-2012) Personnal communications.

Sayao A.S.F.J. et al. (September 1995) Aspects de projet et instrumentation d'un talus cloué de 40m de hauteur. *International Conference on Soil Mechanics and Geotechnical Engineering, Osaka.*

Terzaghi K., Peck E.B. (1967) Soil Mechanics in engineering practice New York. *John Wiley & Sons, Second edition.*

Tschebotarioff G. P. (1968) Ouvrages de soutènement. *Chapitre 5 dans Les Fondations G. A. Leonards, Dunod Editeur.*

Vezole P. et al. (2009) Calcul géotechnique - Ouvrages de soutènement – Remblais renforcés et massifs en sol cloué. *NF 94-270, AFNOR.*