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Soil-nailing – Theoretical basis and practical design

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ABSTRACT: A failure mode for steep nailed walls and slopes is given. It is based on the kinematic failure mechanism of rigid bodies. Four possible failure modes are investigated. By means of variation of the slip planes the unsafest mechanisms, depending on soil properties and boundary conditions, are found. Partial safety factors for the relevant variables are presented. Two examples are given using graphic solutions and design charts.

1 INTRODUCTION

The method of soil nailing is based on the principle of reinforcing natural soils by means of tension carrying bars (so-called "nails"). Soil-nailing is being used at present to stabilize natural slopes, cuts or excavation walls in granular soils (with some capillary cohesion), stiff clays and soft rocks. In general, nailed walls or cuts are carried out in a sequence of three steps (Fig.1):

1 Excavation in layers of 1m – 2m depth
2 Covering the new surface by shotcrete
3 Nailing with steel bars and grouting

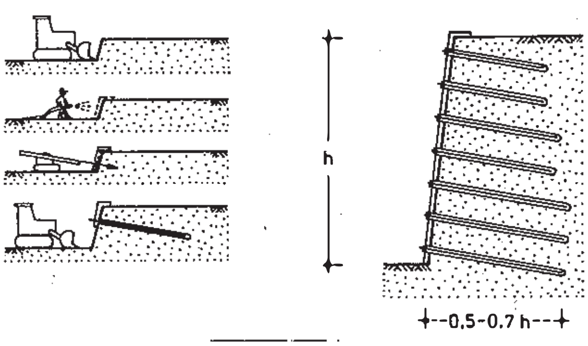

Fig.1. Construction method of nailed walls

The thickness of the wall face should be 8cm up to 20cm, depending on the soil properties, the height of the wall and the expected service life (temporary or permanent nailing). In the most cases the nails consist of steel bars with diameters of 20mm up to 28mm or even 50mm. In general, the nailing density amounts 0.5 up to 1 nail per square meter. An extensive description of the construction of nailed walls is given by Gässler(1987).

The idea of stabilizing artifical cuts by means of steel bars was realized for the first time in France (Rabejac and Toudic (1974)). Within the scope of a German research and developping project that started in 1975, the new method of soil nailing (in German : "Bodenvernagelung") was theoretically studied and worked out for practical performance (Stocker(1976, Gässler(1977)). Using the literal translation from the German term "Bodenvernagelung", the method of soil nailing was then presented to the technical world (Stocker, Gässler, Gudehus(1979), Gässler and Gudehus(1981)). In the USA a simultaneous, but independent development of reinforcing natural soils took place in the years from 1976 to 1981, which was called "lateral earth support system(Shen, Bang, Romstad, Kulchin and De Natale(1981)). In France many practical projects of soil nailing (cloutage du sol) have been carried out since the end of the seventies Louis(1981). Today soil nailing is a world wide method in ground engineering. At present the best scope on its application is given by Bruce and Jewell(1986/87).

Although numerous practical projects have been carried out, it is necessary, to clear up the mechanical behaviour of walls or slopes in the limit state. In this paper a general theory on the failure model of nailed walls and steep slopes is presented. Until now, no generally accepted safety concept for designing has made its way. Hereat the paper contents a proposal.

2 REGULAR CROSS SECTION

The principle stability analyses of nailed walls were restricted to regular cross sections in homogeneous cohesive soils. Fig.2 shows a regular cross section that is determined by the nail length $0.5 \leq l/h \leq 0.7$ (l nail length at the foot of the wall, h height of the wall), the wall inclination $0 \leq \alpha \leq 20°$, the inclination of the slope above $0 \leq \beta \leq 20°$, and the nail inclination $\epsilon = 10°$. The inclination of the rear boundary of the nailed zone may amount $-10° \leq \rho \leq 20°$. The array of the nails is regular. The vertical distance a and the horizontal distance b have to be constant. Finally the ground level at the foot is horizontal.

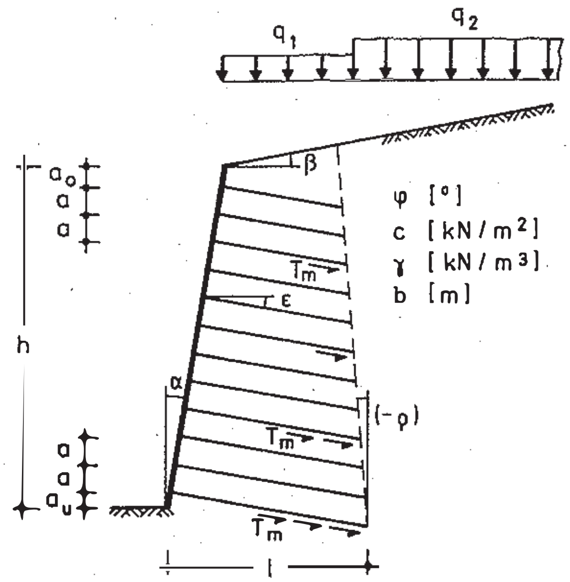

Fig. 2. Regular cross section of a nailed wall

In the regular cross section only axial nail forces are taken into account. The shear forces perpendicular to the axial forces are neglected, which is justified for granular and clayey soils by the results of several full scale tests (Gässler(1987)). The internal force of a nail at the slip surface is determined in the limit state by the mean shear force per unit nail length T_m and the section of the nail behind the slip plane. Apart from a maximum-depth of about 2.5m, the mean shear forces T_m are nearly constant and independent of the depth.

3 METHOD OF KINEMATICS OF RIGID BODIES

The kind of plastic limit state, which is attached by earth retaining structures after sufficiently large deformations, depends on the statical and kinematical boundary conditions. It was assumed for nailed walls and slopes that in the nailed zone as well as in the unnailed zone of the soil the plastic shear deformations are located in thin shear planes, whereas the greater part of the soil keeps rigid in the limit state. Thus, the failure model of nailed walls was based on the kinematics of rigid bodies that content two principles (Gudehus(1981)):

- Principle of the kinematic compatibility of the failure mechanism

This means the displacements of rigid earth bodies have to be correctly described by a hodograph.

- Principle of the minimum of safety by means of the variation of slip planes.

This means, one has to vary the inclinations (and radii) of the slip planes of a potential failure mechanism (e.g.: translation mechanism or rotation mechanism) until the most unstable configuration of the slip planes is found.

As a provisional global safety definition

$$\eta_N := \frac{Z_a}{Z_g} \qquad (1)$$

can be used. Herein Z_a denotes the available axial nail forces (determined from pull-out tests) and Z_g the axial nail forces in equilibrium or limit state. The principle of the minimum of safety now says, that failure will occur with that configuration of slip planes, which exactly fits the value 1 in the safety definition (1). This is an analogon to the principle of COULOMB's earth pressure theory (c.f. Gudehus(1981)).

Using the regular cross section of a nailed wall the safety of different potential failure mechanisms consisting of rigid bodies were investigated and compared for various boundary conditions. The procedure systematically developed in three steps :

1 Compiling of potential modes of failure mechanisms,

2 Variation of the slip planes to find the (relatively) unsafest configurations

3 Determination of the absolutely unsafest failure mechanism by means of comparing the relatively unsafest configurations of the different failure modes.

The investigated failure modes were as such as:

- translation of a rigid body (failure wedge) (TRA-I)
- translation of two rigid bodies (TRA-II)
- rotation of one rigid body (slip circle) (ROT-I)
- rotation of two rigid bodies (ROT-II).

4 PRINCIPLE STABILITY ANALYSES

4.1 Translation of one or two rigid bodies

The combined failure mechanism consisting of the rigid bodies (1) and (2), shown in Fig.3a, is determined by three slip planes. Their inclination angles $\vartheta_1 = 35°$, $\vartheta_2 = 55°$ and $\vartheta_{12} = 85°$ are assumed and do not represent the unsafest configuration. The data of the system are given in Fig.3a (horizontal nail distance b=1.25m). The soil may have an angle of internal friction $\varphi = 30°$ and a cohesion of $7.5kN/m^2$. The available ultimate mean shear force per unit length T_m may amount to 30kN/m.

The external and internal forces acting on the sliding bodies are shown in Fig.3b. Herein P_1 and P_2 denote the resultant forces of the surcharge, W_1 and W_2 the dead weight of the earth bodies, and K_1, K_2, K_{12} the cohesion forces and Q_1, Q_2, Q_{12} the friction forces for the three slip planes. The velocities v_1, v_2, and v_{12} indicate the displacements that are determined by means of a hodograph (Fig.3c). (The scale is arbitrary.) The internal force N_i of a nail in one of the lower rows i, which is intersected by the slip plane with the inclination ϑ_1, is determined by the mean shear force T_m and the section of the nail behind the slip plane l_i :

$$N_i = T_m \cdot l_i. \qquad (2)$$

The sum of the axial nail forces, referring to a unit width of the wall, can be expressed by:

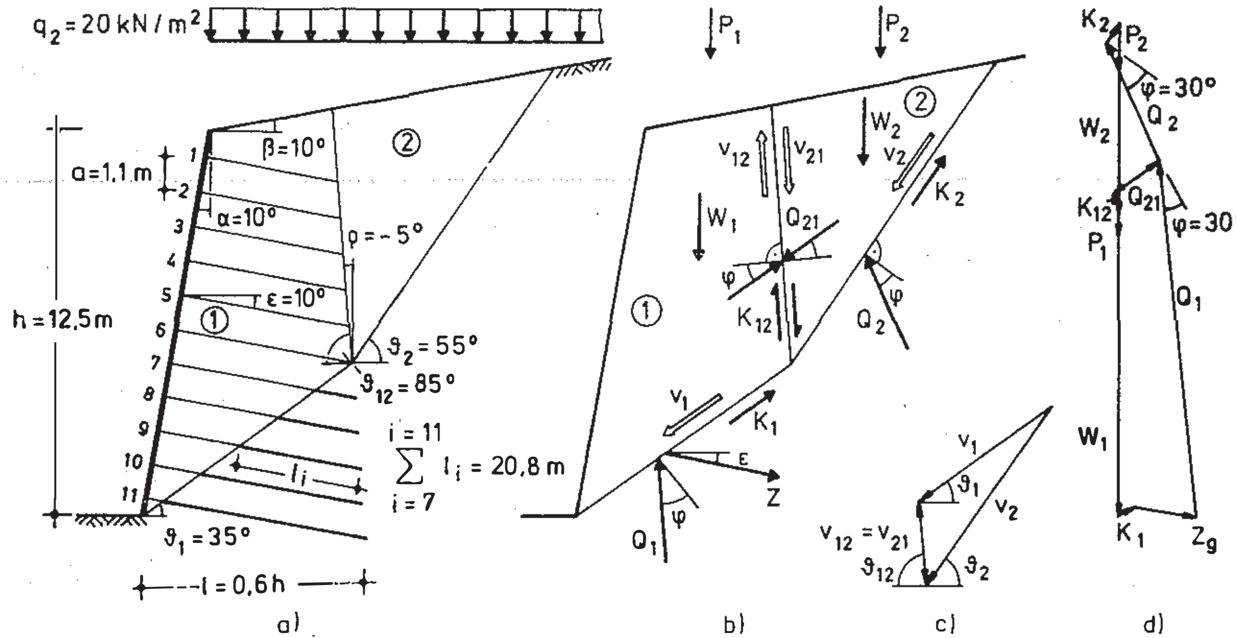

Fig.3 Stability calculation of a nailed wall: a) cross section with combined translation mechanism b) acting forces and displacements c) hodograph d) force polygon

$$Z = \frac{1}{b}\sum_{i=j}^{i=n} N_i = \frac{T_m}{b}\sum_{i=j}^{i=n} l_i \qquad (3)$$

Herein j denotes the upmost row, and n the lowest row that is intersected by the slip plane. With T_m = 30kN/m, b = 1.25m and $\sum_{i=7}^{i=11} l_i$ = 20.8m the sum of the available nail forces amounts after Equ.(3) Z_a = 500kN/m. An equilibrium system of forces can be found graphically (Fig.3d). The sum of the nail forces in the limit state totals Z_g = 260kN/m. From that the factor of safety η_N = 500/260 = 1.92 is yielded.

Following the principle of the minimum of safety, one has now to vary ϑ_1 and ϑ_2, until the minimum of $\eta_N = Z_a(\vartheta_1)/Z_e(\vartheta_1, \vartheta_2)$ is found (it is not necessary to vary ϑ_{12}). The variation of ϑ_1 and ϑ_2 using graphic methods is very cumbersome. Hence a computer program was developped that finds the minimum of η_N, starting with roughly estimated values of ϑ_1 and ϑ_2. The case of the translation of one body, where only the inclination angle ϑ has to be varied, is covered by this program. For the example of Fig.3 the minimum $\eta_{N,min}$ = 1.75 was found (Z_a = 630kN/m;Z_g = 360kN/m); $\vartheta_{1,a}$ = 43° and $\vartheta_{2,a}$ = 54°). From Z_g = 360kN/m follows $T_{m,g}$ = 17.1kN/m by means of equ.(3).
The sum of the nail forces can also be expressed by the following formula (c.f. Gässler(1987)):

$$\overline{Z} = (\frac{1}{h})^2(\tan\theta_1 + \tan\epsilon)\cdot\frac{\cos\alpha}{\cos(\alpha-\epsilon)}\cdot\frac{T_m}{\gamma ab} \qquad (4)$$

with $\overline{Z} = Z/(\gamma\cdot h)$. The last term in this equation represents the specific nailing density

$$\mu := \frac{T_m}{\gamma\cdot a\cdot b} \qquad (5)$$

which is very useful for the following theoretical considerations and also for practical design.

In the example of Fig.3 the values μ_a and μ_g can be calculated using Equ.(5). With a=1.1m, b=1.25m;γ=20kN/m^3 one yields μ_a=30/(1.1·1.25·20) = 1.09 and μ_g = 17.1/(1.1· 1.25·20) = 0.622.

Instead of the safety factor η_N (Equ.(1)) it is now proposed to use the equivalent safety definitions

$$\eta_T := \frac{T_{m,a}}{T_{m,e}} \quad \text{or} \quad \eta_\mu = \frac{\mu_a}{\mu_g}, \qquad (6)(7)$$

which can be obtained from Equ. (1),(3)and (5).

Consistently one yields the same minimal safety factors for η_N, η_T, and η_μ:

$$\eta_{T,min} = \frac{30}{17.1} = 1.75 \text{ and } \eta_{\mu,min} = \frac{1.09}{0.622} = 1.75$$

Because of the fact, that both, $T_{m,a}$ and μ_a, are constant values (not so $Z_a = Z_a(\theta_1)$ in Equ.(1)), the unsafest slip plane configuration is immediately indicated by means of the maximum value of $T_{m,g}$ or μ_g. (symbols : $T_{m,g,max}$, $\mu_{g,max}$).

4.2 Rotation of one body (slip circle)

In Fig.4a the same cross section is shown as in Fig.3a The assumed failure mechanism, however, is a slip circle, determined by the chord inclination angle ϑ = 50° and the radius r = 1.5h. This slip circle is arbitrary and not yet the unsafest configuration.
The external and internal forces acting on the sliding earth body are shown in Fig.4b. Z is located

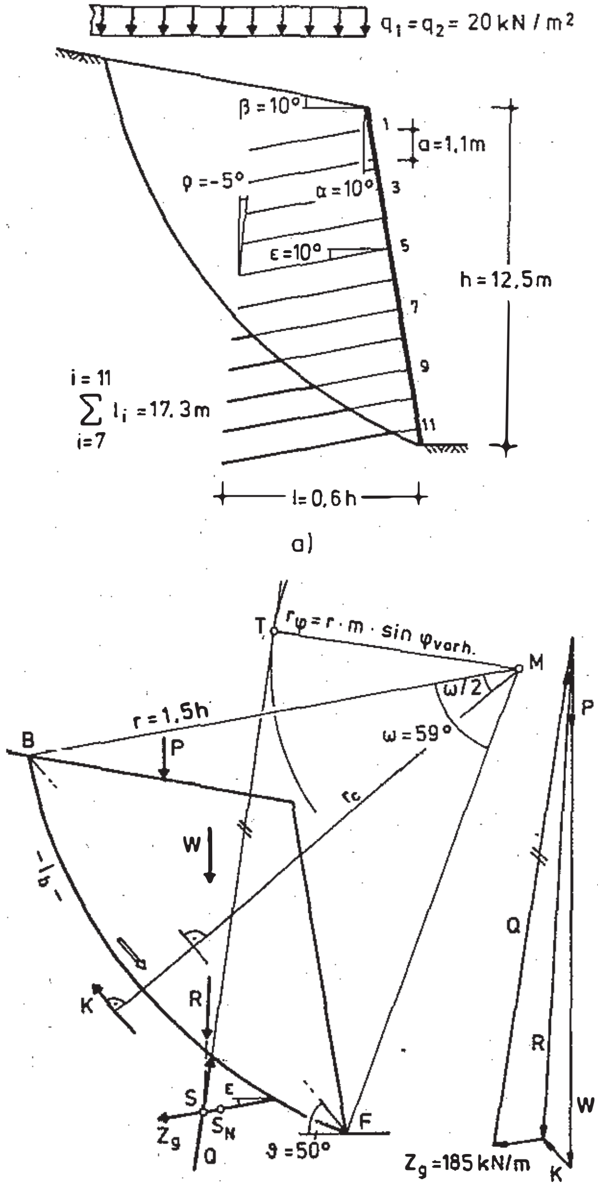

Fig.4 Stability calculation of a nailed wall: a)cross section with slip circle b) acting forces c) force polygon

in the centre of gravity S_N of the nailed zone behind the slip circle. The forces R and Z are balanced in point S by the resultant slip circle force Q, the latter determined with the friction circle assumption after Krey(1932). Closing the force polygon in Fig.4c yields the sum of the axial nail forces in the limit state $Z_g = 185$kN/m. From Equ.(3) follows $T_{m,g} = 185 \cdot 1.25/17.3 = 13.4$kN/m and finally from Equ.(5) $\mu_g = 13.4/(20 \cdot 1.1 \cdot 1.25) = 0.49$. Similar to the TRA-II-mechanism one has to vary the parameters ϑ and r of the slip circle, until the maximum of $T_{m,g}$ or μ_g is found. By means of a computer program, the solution of the arithmetic variation is found: $\mu_{g,max} = 0.636$ with $\vartheta^* = 49.6°$ and $r^* = 3.4 \cdot h$.

4.3 Rotation of two rigid bodies

The rotation of two rigid bodies may occur in the case of a extremely high surface load in the rear. This failure mode has been observed in a model test. The graphical solution as well as the numerical analysis of this failure mode are more of theoretical than of practical interest. A description of the graphical solution is given by Gässler(1987).

5 RESULTS OF STABILITY ANALYSES

The third step is made, now, to find the unsafest failure mechanism. For various soil properties and boundary conditions the maximal specific nail densities μ of the four possible failure modes, presented above, have been calculated and plotted in diagrams. The instablest mechanism is the one that leads to the absolute maximum of μ. The diagrams are restricted to an exemplary regular cross section with $l/h = 0.6$, $\alpha = \epsilon = 10°$ and $\rho = 0$ or $\rho = 5°$. The cohesion c[kN/m²] and the surcharge q are transformed to the term $\bar{c} = c/\gamma \cdot h)$ and $\bar{q} = q/(\gamma \cdot h)$.

In Fig.5 $\mu_{g,max}$ is plotted against φ for the slope inclination $\beta = \varphi/2$. The curve of the ROT-II-mechanism coincides with the one of the TRA-II-mechanism (the radii increase ad infinitum).

The result is that the TRA-II- and the ROT-I-mechanism are nearly in like manner unsafe and that both, TRA-II and ROT-I, are (slightly) unsafer than TRA-I. Fig.5b presents the case of low surface loads on a slope ($\beta = 10°$) in a soil with medium cohesion ($\bar{c} = 0.1$). The result is here, that the ROT-I-mechanism is the unsafest mechanism with a significant distance to the TRA-II- and TRA-I-mechanism.

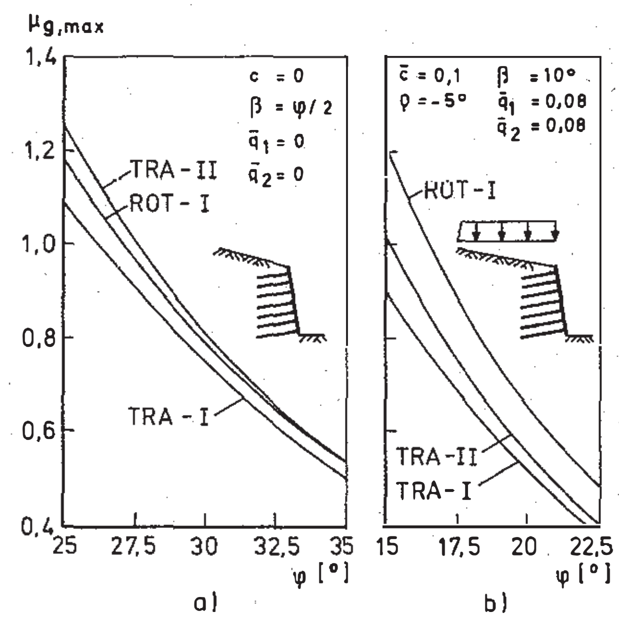

Fig.5 Maximal nailing densities in a) non cohesive soil b) cohesive soil

The results of numerous calculations performed by Gässler (1987) can be summarized as follows:

– In cohesionless soils the TRA-II-mechanism is the most critical mechanism for nearly vertical nailed walls ($\alpha \leq 10°$) with nails of constant length (or shorter nails in the upper rows), especially for high surface loads at the rear. For less steep walls ($\alpha > 10°$) and/or longer nails in the upper rows the ROT-I-mechanism (slip circle) is the unsafest mechanism. For $\phi > 35°$ the simple failure wedge TRA-I is nearly as unsafe as the TRA-II-mechanism.
– In soils with little cohesion, both, the TRA-II-mechanism and the slip circle are as far as safety is concerned nearly equivalent for nearly vertical walls (see examples of Fig.3 and Fig.4). In soils with medium or high cohesion (and for less steep walls) the slip circle distinctly is the unsafest mechanism.

6 PARTIAL SAFETY FACTORS

Instead of only one global factor η_μ it is proposed to take use of various partial safety factors. For the deduction of partial safety factors a limit state equation is necessary. For this the following limit state equation has been formulated based on the TRA-II-mechanism (Gässler(1987)):

$$\overline{Z}\cos(\vartheta_{1a} - \varphi + \varepsilon) - ((\overline{W} + \overline{P})\sin(\vartheta_{1a} - \varphi) + \overline{E}_a\cos(\vartheta_{1a} - 2\varphi)) = 0. \quad (8)$$

Herein $\overline{Z}$ is known from Eqn.(4). $\overline{W} = 1/h(2 - 1/h\tan\vartheta_{1a}) - \tan\alpha$ denotes the weight of body (1) (cf. Fig. 3b), $\overline{P} = 2q_1/(\gamma \cdot h)(1/h - \tan\alpha)$ the surcharge of body (1) and $\overline{E}_a = h'/h(h'/h + 2q_2/(\gamma \cdot h))K_a$ the earth pressure acting on the vertical intermediate slip surface of the length h′ (K_a pressure coefficient). (Notice: $\overline{W} = W/(\gamma \cdot h)$, $\overline{P} = P/(\gamma \cdot h)$ and $\overline{E} = E/\gamma \cdot h)$). ϑ_{1a} is the inclination of the slip plane with the minimum of safety.

In Eqn.(8) the quantities φ, μ (or T_m), and q are scattering, i.e. they are basic variables in the sense of the new statistic - probabilitic safety theory following Eurocode 7. Concerning the statistical distribution of the basic variables assumptions had to be made. Nevertheless, partial safety factors can be proposed on the basis of numerous Level II approach calculations (Hasofer and Lind (1974)). The Level II approach applied on soil nailing is described by Gässler and Gudehus(1983) and Gässler(1987). Using the following partial safety factors a sufficiently safe dimensioning (safety index $\beta \approx 4,7$) of steep nailed walls and slopes can be achieved:

$$\gamma_\varphi = \frac{\varphi_k}{\varphi_d} = 1.1 \quad (9)$$

with φ_k: characteristic value of φ (10% - fractile of a log normal distribution, truncated at 20°),

$$\gamma_\mu = \frac{\mu_k}{\mu_d} = 1.3 \quad \text{or} \quad \gamma_T = \frac{T_{m,k}}{T_{m,d}} = 1.3 \quad (10)(11)$$

with μ_k, $T_{m,k}$: characteristic value of m_μ, m_T (10 % -fractile of a log normal distribution),

$$\gamma_q = \frac{q_d}{m_q} = 1.3$$

with m_g: mean value of q. The index d of the symbols φ_d, μ_d, q_d denotes the so-called design point, i.e. the assumed limit state with the most unfavourable combination of all basic variables. The safety factor γ_q is fixed in according to the Eurocode 7. For the case of friction soils with cohesion the partial safety factor $\gamma_c = 1.4$ referred to a suitable characteristic value is proposed for the present. The characteristic values φ_k or μ_k can be read from Fig.6, as depending on the mean values m_φ or m_μ and the coefficients of variation V_φ or V_μ.

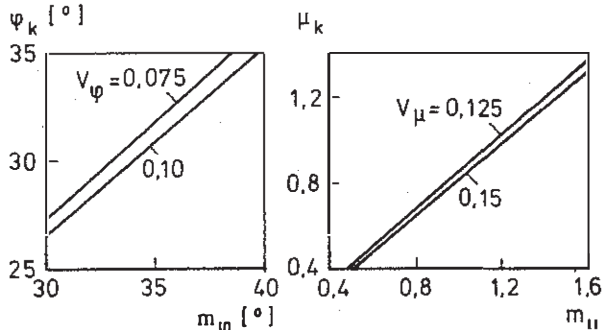

Fig.6 Charts for characteristic values φ_k(a) and μ_k(b)

7 DESIGN EXAMPLES

Nailed wall in cohesionless soil (cf. Fig.2):
geometry: h=10m, l=6m, $\alpha=\varepsilon=10°$, $\rho=0$
soil: $m_\varphi=36°$, $V_\varphi=0.075$, $\gamma=18kN/m^3$
surcharge: $m_q=20kN/m^2$
nails: a=1.1m; $T_m=30kN/m$, $V_T=0.15$
The horizontal nail distance, b, is to be determined so that $\beta = 4,7$ is kept.
One obtains the characteristic values $\varphi_k=32.7$ from Fig. 6a and $T_{m,k}=24kN/m$ via μ from Fig. 6b, and the design values $\varphi_d=32.7/1.1\approx$ 30° and $T_{m,d} = 24/1.3 = 18.5$ kN/m. The design value of the surcharge amounts to $q_d = 1.320 = 26kN/m^2$. Referring to chapter 5, the TRA-II-mechanism is the unsafest failure mode. The graphic solution may start with $\vartheta_1 = 40°$. The force Q_{12} interacting between body (1) and (2) (cf. Fig. 3b) can be substituted by the design earth pressure $E_{ad} = E_{ad}(\varphi_d, q_d) = 90kN/m$ (cf. Eqn.(8)). With $P_{1d} = 4.2q_d = 110kN/m$ and $W_1 = 655kN/m$ the graphic solution, similar to Fig. 3c, yields $Z_g = 240kN/m$. By means of graphic variation of ϑ_1 one finds the minimum of η_N (Eqn.(1)) for $\vartheta_{1a} \approx 40°$ (casually coinciding with the starting value of ϑ_1). From Eqn.(3) one obtains the mean shear force per unit length of the nail, referred to the unit width of the wall, $\overline{b} = 1.0m$, $\overline{T}_{m,d} = Z_g/\sum l_i = 240/15.8 = 15.2kN/m$. Finally, the wanted horizontal nail distance is given by

$b = T_{m,d}/\overline{T}_{m,d} = 18,5/15,2 \approx 1,20m$.
By means of a design chart, based on the TRA-II-mechanism, the solution can be found very easily. With $\varphi_d = 30°$ and $\bar{q}_d = 26/(18 \cdot 10) = 0.14$ one obtains from Fig.7 $\mu_d = 0.78$. b is given immediately by $T_{m,d}/(\mu_d \cdot \gamma \cdot a) = 18,5/(0.77 \cdot 18 \cdot 1.1) \approx 1.20m$.

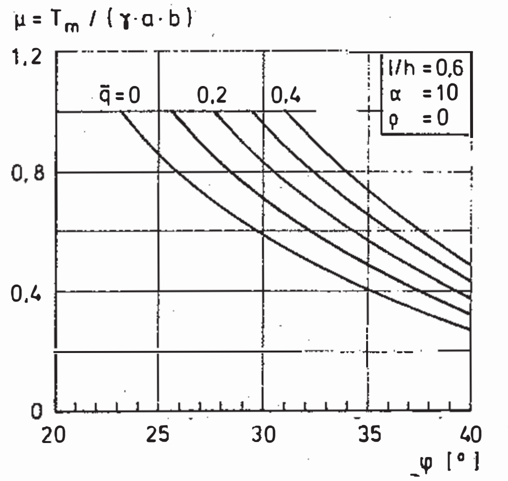

Fig.7 Design chart for cohesionless soil (β=0)

Nailed cut in cohesive soil (cf.Fig.2):
Geometry: h=11.7m, l=7m, $\alpha = 20°$, $\beta = 0$, $\varepsilon = \rho = 10°$
soil: design values: $\varphi_d = 23°$, $c_d = 11kN/m^2$, $\gamma = 19kN/m^3$. With $\varphi_d = 23°$ and $\bar{c}_d = 11/(19 \cdot 11 \cdot 7) = 0.05$ one obtains $\mu_d = 0.43$ from the design chart of Fig.8 based on the ROT-I-mechanism. For assumed distances a = 1.2m and b = 1.5m, e.g., $T_{m,d}$ gets 14.7 kN/m.

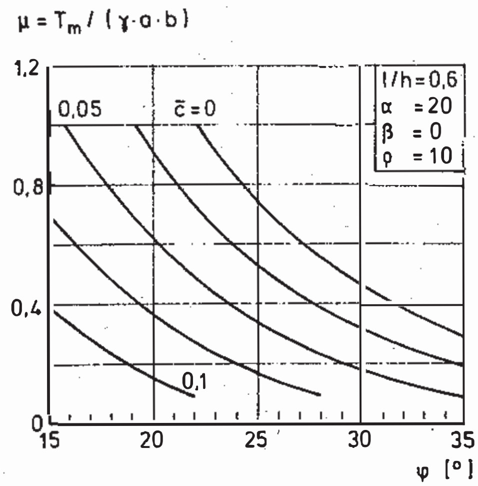

Fig.8 Design chart for cohesive soil

8 CONCLUSIONS

A comprehensiv failure model can be developed for nailed walls and slopes, based on the kinematic failure mechanism of rigid bodies. The instablest failure mode is to be found by variation of the slip planes. The results of the arithmetic variations coincide very well with model tests and field tests (Gässler, 1987).

The translation mechanism of one or two bodies and the simple rotation mechanism (slip circle) were found to be the relevant failure modes to practical design. The design procedure, especially the application of design charts, gets very practicable by means of partial safety factors, either based on the new statistic - probalistic safety theory or obtained emirically.

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