Bearing resistance of foundations abutting berms from TERZAGHI's Formula up to an evaluation of centrifuge tests

Charge de rupture des fondations proches des bermes des formules TERZAGHI à l'évaluation des tests centrifuges

L. Martak – *Hon. Prof. Dipl.-Ing. Dr.techn. Government of the City of Vienna, Municipal Dept. 29 – Bridge Construction and Foundation Engineering*
O.Pregl – *o. Univ.-Prof. Dipl.-Ing. Dr.nat.techn. Chair of Geotechnical Engineering, University of Agricultural Sciences, Vienna*

ABSTRACT: Within the scope of harmonising the Austrian standards with EUROCODE 7, Part 1, it was necessary to revise and update ÖNORM B 4432 "Erd- und Grundbau, Zulässige Belastungen des Baugrundes, Grundbruchberechnungen", a more than 20 year old soil and foundation engineering standard that covers calculations for the load-bearing capacity and soil failure. The new ÖNORM B 4435-2 "Geotechnical engineering – Flat Foundation – EUROCODE-orientated analysis of the bearing capacity" was completed on 19 May 1999 and presented at a workshop in February 2000. It fully replaces the old ÖNORM B 4432, adding chapters on tilt, slide and hydraulic uplift. In addition to introducing calculation parameters defined as nominal values or characteristic values, the new standard includes proposals for calculating the bearing capacity for sloping surfaces exposed to true vertical or inclined loads, inclined foundation areas, and the bearing resistance of foundations adjacent to berms. This paper shows the development of equations based on TERZAGHI to state-of-the-art solutions based on EUROCODE 7, Part 1, Annex D and ÖNORM B 4435-2. Tests carried out in the laboratory centrifuge of the Institute of Geotechnical Engineering at the Vienna University of Agricultural Sciences confirm the proposed values for the bearing capacity factors.

RESUME: Dans le cadre de l'harmonisation des normes de calcul autrichiennes avec l'EUROCODE 7, 1ère partie, il s'est avéré nécessaire de réviser et adapter aux règles de l'art la norme autrichienne ÖNORM B 4432 portant sur le terrassement et les fondations, la charge s'exerçant sur le sol de fondation et le calcul de la charge de rupture du sol, texte datant du 1er juillet 1980. La nouvelle norme ÖNORM B 4435-2 « Terrassement et fondations, fondations à semelle continue, calcul de la charge de rupture sur la base de l'EUROCODE », achevée en 1999 et présentée lors d'un séminaire le 29 février 2000, ne vient pas seulement remplacer l'ancienne norme sur la charge de rupture du sol de fondation, elle la complète en incluant des chapitres sur la stabilité à l'inclinaison, au glissement et à la poussée verticale hydraulique. Elle introduit des paramètres de calcul définis comme « valeurs nominales » ou « valeurs caractéristiques » et propose une méthode de calcul pour une surface inclinée, exposée à une charge de rupture des fondations s'exerçant verticalement ou obliquement par rapport à la base. Par ailleurs, elle fournit pour la première fois des indications pour le calcul les fondations proches d'une berme. L'exposé montre l'évolution du calcul des ruptures de fondation, des formules de TERZAGHI à la méthode de calcul normalement utilisée aujourd'hui basée sur ÖNORM B 4435-2 et EUROCODE 7, 1ère partie, annexe D. Des essais effectués sur l'installation centrifuge de l'Institut de Géotechnique de l'Université d'Agronomie de Vienne complètent et confirment les valeurs proposées pour les coefficients de portance.

1 BEARING CAPACITY BASED ON TERZAGHI

For soil mechanics engineers, calculating the bearing capacity of a foundation is basically a stability problem, which involves equilibrium equations for ideal soil conditions and the assumption of failure at plastic flow. Deformation is ignored for as long as it does not exceed given limits, such as restrictions on lateral strain under bulk tank conditions. PRANTL (1920), REISSNER (1924) and TERZAGHI (1943) developed their models of bearing capacity for loads acting on a homogeneous isotropic hemisphere of soil without weight, based on COULOMB's equation of ideal elastic and ideal plastic soil. Soil deformation is assumed to act only in parallel to a vertical plane rectangular to the compressed area, and in the event of failure must be sufficiently large to achieve a full plastic state for the soil adjacent to the failure. These assumptions are not compatible with actual practice, but adequate safety factors are applied to compensate for the error. The foundation plane is assumed to have a coarse face, flattening the active RANKINE's wedge below the foundation. Fig. 1, copied from TERZAGHI/JELINEK (1954), shows the trend of failure lines when adapted to real soil conditions.

The commonly used failure model consists of an active RANKINE wedge (I) in its elastic state, a plastic transition zone (II) based on a logarithmic spiral by OHDE (1938), and a passive lateral RANKINE shearing wedge (III). The embedded length of the strip footing is simulated by an adequate lateral surcharge, which does not affect shearing. If no embedment is available and therefore no lateral surcharge applies, this simplification means that the foundation load will be calculated as a triangularly shaped load rising from the lower edge of the foundation strip rather than a uniformly acting load, in line with RANKINE's main stresses which are still used in all soil failure standards. The bearing resistance of the strip footing is given by a linear equation including the sum of all vertical loads. This equation consists of three terms with dimensionless bearing capacity factors for cohesion c, surcharge q and width 2b of the strip footing.

$$Pg = 2b\,(c\,\kappa_c + \gamma\, t_g\, \kappa_p + \gamma\, b\, \kappa_\gamma) \quad \text{TERZAGHI 1943;} \tag{1}$$

based on PRANTL/REISSNER,

$$\kappa_c = \cot\varphi \left[\frac{a_\vartheta^2}{2\cos^2(45° + \varphi/2)} - 1 \right] \tag{2a}$$

and

$$\kappa_p = \frac{a_\vartheta^2}{2\cos^2(45° + \varphi/2)} \tag{2b}$$

are $\qquad a_\vartheta = e^{(3/4\pi - \varphi/2)tg\varphi}$

If $\gamma > 0$, $c = 0$ and $p = 0$:

$$\kappa_\gamma = tg\,\varphi\,(\lambda_p / \cos^2\varphi - 1) \tag{3}$$

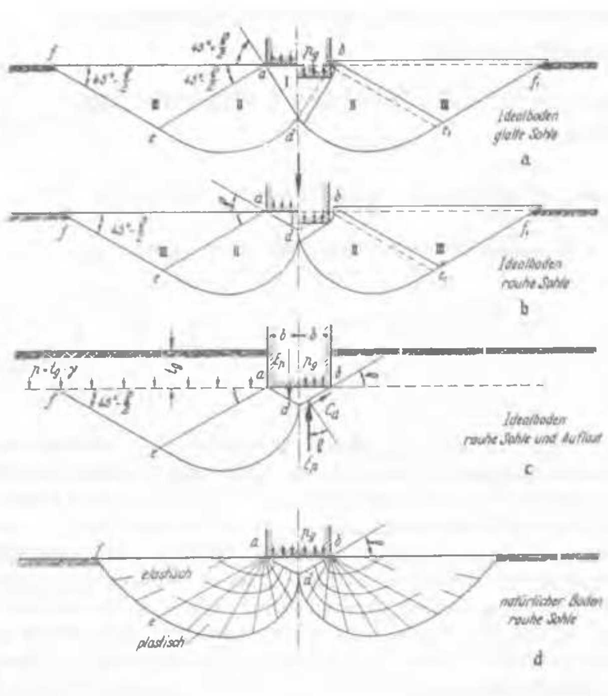


Fig 1: TERZAGHI/JELINEK 1954, limits of plastic flow due to strip footing yielding into the ground, a.) ideal soil, smooth face, b.) coarse face, c.) coarse face and surcharge, d.) real soil, coarse face of the foundation strip

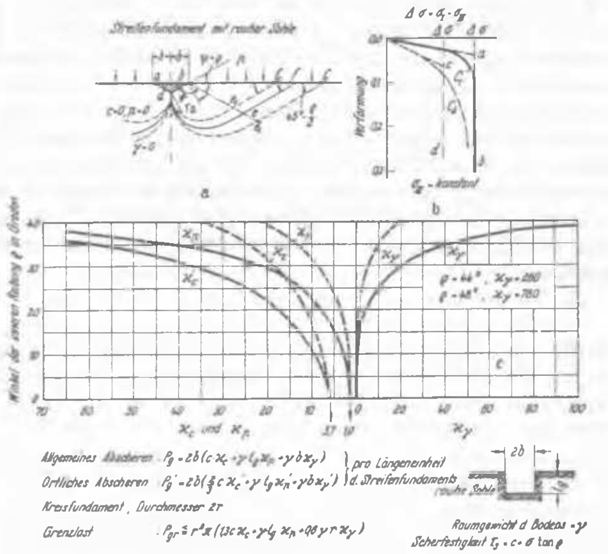


Fig. 2: TERZAGHI/JELINEK 1954, Evaluation of the bearing resistance, a.) threshold conditions of the method, b.) simplification for dense and loose soil, c.) relation of φ to the dimensionless factors κ_c, κ_q and κ_φ

The diagram of the dimensionless bearing factors κ_c, κ_q and κ_φ in Fig. 2, taken from TERZAGHI/JELINEK (1954), clearly shows the smaller size of the sliding mass when the soil weight is taken into account. Moreover, the TERZAGHI equation applies to the final bearing resistance of cohesion c′ and $\varphi > 0$. Modern equations also account for bearing capacities for an initial state $c = c_u$ with $\varphi = 0$. TERZAGHI solved this problem by providing for "local shear" at a cohesion reduced to two-thirds, and a friction angle tgφ similarly reduced to two-thirds. The respective bearing capacity factors, given in dotted lines, are obviously lower than those obtained from "general shear" and more in line with the final state. If the (coarse) bed friction is neglected, the complete active RANKINE's wedge is developed at $\varphi = 45° + \varphi/2$ and the bearing capacity factors are similarly reduced. Furthermore, TERZAGHI was aware of the problem of pressure distribution underneath the footing base with and without friction and its impact on the bearing capacity. BOROWICKA (1996) studied the problem, proving with his soil mechanics of discontinuity that the absence of a lateral surcharge reduces bearing resistance under structural conditions valid for all kinds of soil (BOROWICKA/ MARTAK 1998; Fig. 3).

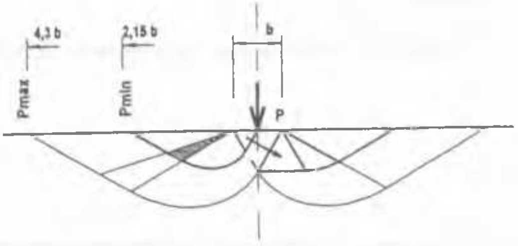


Fig. 3: BOROWICKA (1996), symmetrical yielding of a strip footing due to loss of surcharge

2 CALCULATION ACCORDING TO ÖNORM B 4435-2 AND EUROCODE 7, PART 1

The equations by TERZAGHI et al. (1 to 3) have since been extended to cover foundations, retaining structures supported by surcharges and slopes (equations 4a and 4b). The former ÖNORM B 4432 used the same thresholds as TERZAGHI's equation, so that substantially higher bearing capacities were obtained than accepted by most other European standards (SIEFFERT 1998). The new ÖNORM B 4435-2 uses the bearing capacity factors $N_{\gamma 0}$, N_{q0} and N_{c0} taken from TERZAGHI, as well as – to some extent – those from MEYERHOF (1963). They are identical to the bearing capacity factors N_γ, N_q and N_c of the last version of the final draft of EUROCODE 7, Part 1.

$$Q_{f,d} = A'(\gamma_u' b' N_\gamma + \gamma_0' t N_q + c_d N_c) \tag{4 a}$$

for the final state

and

$$Q_{f,d} = A'(\gamma_0 t N_q + c_{u,d} N_c) \tag{4 b}$$

for the initial state.

$Q_{f,d}$	total bearing capacity resistance
γ_0', γ_0	effective weight of the soil above the base
γ_u'	effective weight below the base
φ	angle of friction below the base
c	cohesion below the base
t	embedding of the strip footing
b' (≤ l')	foundation width
l' (≥ b')	foundation length
A' = b'l'	design effective foundation area

In contrast to EUROCODE 7, however, ÖNORM B 4435-2 includes a large number of geometrical thresholds for the foundation and ground which can be taken into consideration (Equations 5 to 7).

If φ> 0:
$$N_\gamma = N_{\gamma,0} i_\gamma g_\gamma t_\gamma s_\gamma \tag{5}$$

$$N_q = N_{q,0} i_q g_q t_q s_q d_q \tag{6}$$

$$N_c = \cot\varphi.(N_{q,0}.i_c.g_c.t_c - \frac{1}{\cos\alpha.\cos\delta_s}).s_c \tag{7}$$

i_γ, i_q, i_c inclination factors of the load with subscripts c,q,γ

g_γ, g_q, g_c inclination factors of the surface of the vicinity

t_γ, t_q, t_c inclination factor of the base

s_γ, s_q, s_q shape factor of the foundation base

The bearing capacity factors N_γ, N_q and N_c in the general case with $\alpha \neq 0$, $\beta \neq 0$, $\delta \neq 0$ and $\varphi > 0$ can be calculated from the bearing capacity factors $N_{\gamma 0}$, N_{q0} and N_{c0} for the principal case α=0, β=0, δ=0 and a foundation width of $b = B'$ in accordance with EUROCODE 7, Part 1, Annex D:

$$N_{\gamma 0} = (N_{q,o} - 1) \tan \varphi$$

$$N_{q,0} = \frac{1+\sin\varphi}{1-\sin\varphi} e^{\pi \cdot \tan\varphi}$$

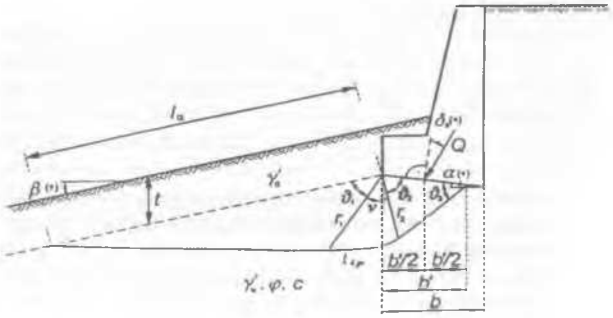
Accordingly, from equation (7) the following applies for the general case:

$$N_{c,o} = (N_{q,o} - 1) \cot \varphi$$

The bearing resistance thus can be calculated in accordance with the assumptions of DIN 4017-100 (1996):–

- for coarse soil if compactness coefficient $D > 0.2$ (uniformity coefficient $U \leq 3$) or $D \geq 0.3$ ($U > 3$) respectively;
- for cohesive soil with a consistency coefficient $I_C > 0.5$

In order to get an idea of the size of the potential sliding mass, especially when abutting a berm or slope, it is necessary to determine the course of the slip surface at least approximately and for specific thresholds (($c = 0$, $\gamma_{u'} = 0$). ÖNORM B 4435-2 provides equations for the general case and some special cases. All angles are given as radian measures (Fig. 4).



$$\vartheta_1 = \frac{\pi}{4} - \frac{\varphi_k}{2} - \frac{\varepsilon_1 - \beta}{2}$$

$$\vartheta_2 = \frac{\pi}{4} + \frac{\varphi_k}{2} - \frac{\varepsilon_2 - \delta_s}{2}$$

$$\vartheta_3 = \frac{\pi}{4} + \frac{\varphi_k}{2} + \frac{\varepsilon_2 - \delta_s}{2}$$

$$\sin \varepsilon_1 = -\frac{\sin\beta}{\sin\varphi_k}$$

$$\sin \varepsilon_2 = -\frac{\sin\delta_s}{\sin\varphi_k}$$

$$v = \pi - \alpha - \beta - \vartheta_1 - \vartheta_2$$

$$r_1 = r_2 \cdot e^{v \cdot \tan\varphi_k}$$

$$r_2 = b' . \frac{\sin\vartheta_3}{\text{cas}\alpha . \sin(\vartheta_2 + \vartheta_3)}$$

$$l_G = r_1 \frac{\cos\varphi_k}{\cos(\varphi_k + \vartheta_1)}$$ (length of the slip surface)

$$l_{Sp} = \frac{r_1 - r_2}{\sin\varphi_k}$$ (length of the logarithmic spiral)

Fig. 4: Course of the mechanical failure below a strip footing, according to ÖNORM B 4435-2, equations for the slip surface, general case $\varphi_k > 0$, $\beta < \varphi_k$, $\delta_s < \varphi_k$.

EUROCODE 7, Part 1, Section 6; Spread Foundation, Annex D (informative) gives a very similar equation on bearing capacity:

for drained conditions

$$R/A' = c'N_c\, b_c\, s_c\, i_c + q'N_q\, b_q\, s_q\, i_q + 0.5\, \gamma\, B\, N_\gamma\, b_\gamma\, s_\gamma\, i_\gamma \qquad (8a)$$

for undrained conditions

$$R/A' = (\pi + 2)\, c_u\, b_c\, s_c\, i_c + q. \qquad (8b)$$

The bearing capacity factors N_c, N_q, N_γ and the geometrical condition factors $b_c\, s_c\, i_c$, $b_q\, s_q\, i_q$, $b_\gamma\, s_\gamma\, i_\gamma$ of the footing load and the ground in the vicinity are almost identical. With this, a consensus for the equations to calculate bearing resistance appears to have been achieved for the scope of EUROCODE 7.

3 CALCULATIONS OF BEARING RESISTANCE CONSIDERING BERMS

Analogously to the proposal of DIN 4017-100, the influence of a berm on bearing resistance is calculated in accordance with equations (4a) and (4b). The berm of width l_B is simulated by a greater surcharge t' (Fig. 5) with $t' = t + 0.8\, l_B \text{ tg } \beta$, with limits of $l_B \leq l_{G,h}/3$. For the bearing capacity factor N_q the embedment t is changed to t′.

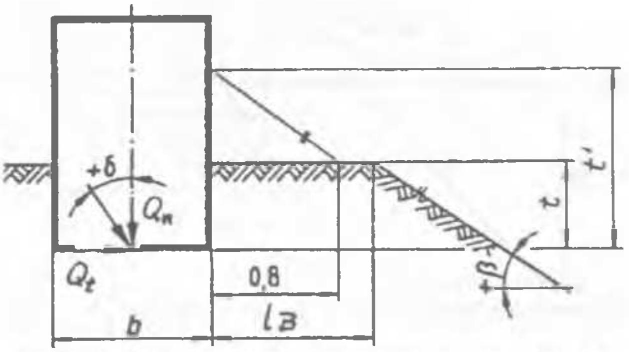
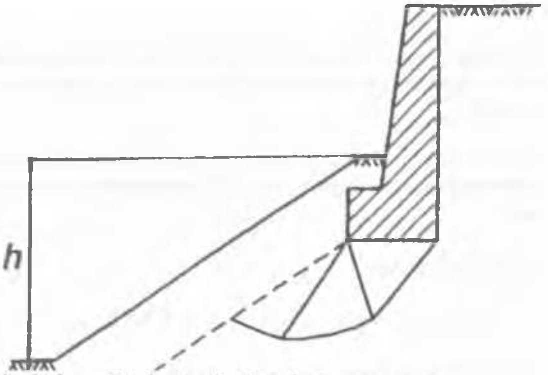


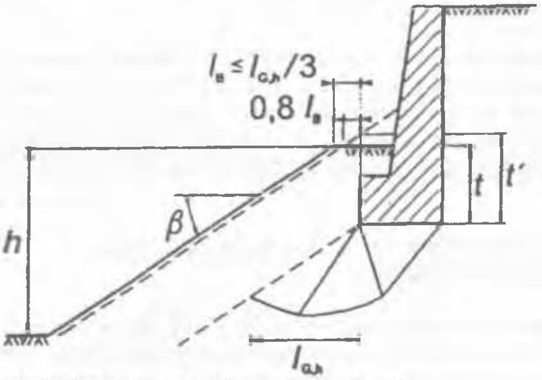
Fig. 5: Calculation method for small berms pursuant to DIN 4017-100

Retaining structures in the vicinity of slopes with berms frequently cause problems for soil engineers, which are rarely reviewed by way of a detailed geotechnical stress analysis. One reason is that, while the ground sloping factors g_γ, g_q, g_c were already included in the previous ÖNORM B 4432, although with slightly different equations, it is only in the new ÖNORM B 4435-2 that the impact of the berm width, with due regard to the embedding depth, is given consideration. Fig. 6, copied from ÖNORM B 4435-2, provides a plausible proposal for four simple cases. The proposal has not yet been sufficiently tested in its validity and safety margin for all possible cases (broad foundations and small loads, pore pressure on the berm). Nevertheless the mirror group FNA 023C of the Austrian Standard Committee decided to adopt the model based on tests

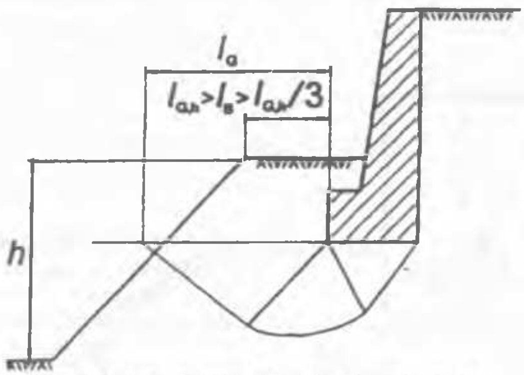
University of Agricultural Sciences carried out on their centrifuge in 1999 (BELLINA, 1999), and on the basis of additional calculations (SCHWARZ, 2000) which are currently in their final stage and which apply the sliding circle method and local shear factors (SHAIGANI/PREGL, 1997, and PREGL, 1999). The requisite software is known as BOSCH.



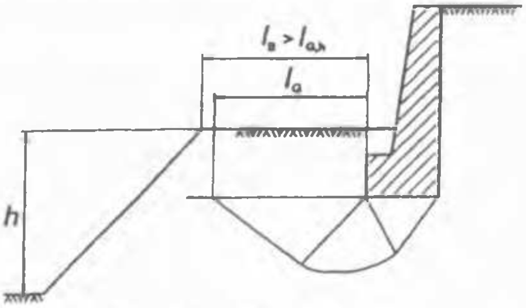
a) Calculation with the inclination factors g_γ, g_q, g_c,



b) Calculation by approximation $l_B \leq l_{G,h}/3$



c) Calculation of slope stability based on berm factor b_γ



d) Calculation of conventional bearing resistance

Fig. 6: Calculation methods for slopes with berms of different widths according to ÖNORM B 4435-2

4 RESULTS OF CENTRIFUGE TEST RUNS

The centrifuge operated by the Institute of Geotechnical Engineering at the Vienna University of Agricultural Science since 1989 accelerates model boxes of a volume of up to 18 dm³ to 200 g, and transmits up to 50 measuring signals on load and deformation to a computer and monitor. The bearing resistance tests were performed with well-compacted coarse sand ($\varphi \cong 47.5°$). The bearing load was simulated by a steel strip b of a width of 30 mm fitted at the slope crown to act as a line load. In front of the strip of width l_B, berms of sand were modelled at ratios $l_B/b = 0.0$, 0.5 and 1.0. The tests were run at berm slopes $\beta = 10°$, 20° and 30°, and a reference test was performed for a fully horizontal surface ($\beta = 0°$), accelerated to 5 g. After its failure, the sand surface was scanned at a resolution of 1 mm on both sides of the steel strip and shown as deformation zones. Fig. 7 shows an example of a failure at a surface inclination of $\beta = 30°$ and $l_B = 0$ (no berm). As expected, deformations at the inclined side of the steel strip extended much further than on the horizontal side. Evaluating the sliding mass grew the more difficult the steeper the slope surface was inclined (sand overlapping from the passive RANKINE wedge).

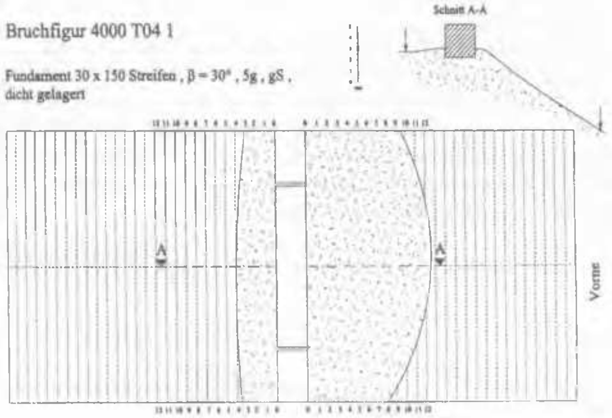


Fig. 7: Centrifuge tests; slope rupture in coarse sand $\varphi \cong 47.5°$, width without a berm ($l_B = 0$), inclination of the slip surface $\beta = 30°$, deformations given in cm

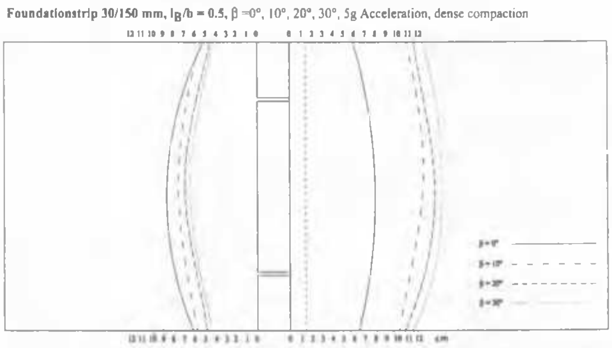


Fig. 8: Centrifuge tests; slope rupture in coarse sand $\varphi \cong 47.5°$, width with a berm ($l_B = 0.5.b$), inclination of the slip surface $\beta = 0°$, 10°, 20°, 30°, deformations of the sliding areas given in cm

Fig. 8 sums up the results of all failure tests. It is noticeable that the slope deformation is greatest between $\beta = 0°$ (level ground) and $\beta = 10°$. Fig. 9 gives the inclination factors g_γ for a berm width $l_B = 0$ from the centrifuge tests in terms of ÖNORM B 4435-2 and the BOSCH program, based on the local shear factors method as a function of slope inclinations $\beta = 0°$, $\beta = 10°$, $\beta = 20°$, and $\beta = 30°$. Additional evaluations were performed for the results obtained by the Union of Swiss Road Experts (VSS, 1978) where the stress characteristics method was applied to calculate berm problems. The linear regression functions for the inclination factors g_γ from the centrifuge tests and the ÖNORM B 4435-2, as shown in Fig. 9, indicate that the factors used in the Austrian standard are on the safe side.

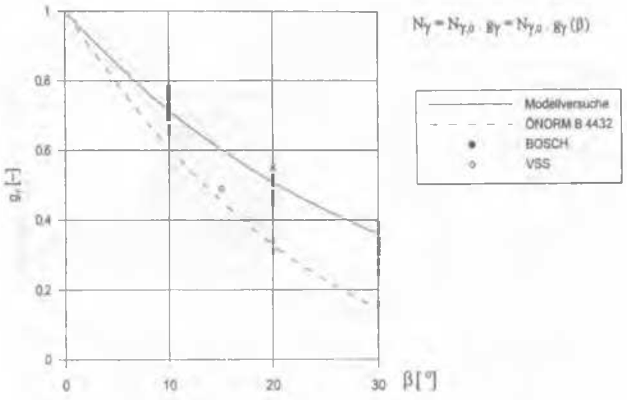


Fig. 9: Factor of surface inclination g_γ derived from 30 centrifuge tests in relation to the factors of ÖNORM B 4435-2

In order to check the proposed calculation methods as per Fig. 6, the sizes of the sliding mass including berms and slopes were compared with the shapes of the sliding circles of the stability analysis for slopes. This was rather difficult because the sliding masses of the slope analysis and the sliding circles of the bearing resistance calculation are actually taken from two different calculation methods. They greatly depend on the size and shape of the sliding masses φ, c or c_u respectively, and on the width of the foundation base b (assuming a coarse base) even under equal threshold conditions like embedding depth, inclination of foundation load, surface inclination and base inclination, shape of foundation and weight of soil. To simplify the problem, cohesion and pore pressure were neglected. In Fig. 10, the sliding masses and resistance capacities were compared according to the stress characteristics method (a), the BOSCH local shear factor program (b), using the failure shape obtained from method (a) and a circular shape (c), and to the shape of the sliding mass obtained from applying the equation of ÖNORM B 4434-2. The comparison was performed for a horizontal surface (general case) in Fig. 10 and for an inclined surface with β = 30° in Fig. 11, in both cases without a berm but with a lateral surcharge of 10 kN/m2.

5 CALCULATION MODELS FOR THE BERMS

In order to take into account the effect of a berm on the bearing capacity of a footing strip without any embedding (t = 0 and a triangular distribution of the pressure on the base), the following method is proposed. For different widths of berms, the stress of the backside of a strip foundation q_R is varied sufficiently so that the volume of the soil inside the sliding circles results in a safety factor of 1.00 (by varying the central point of the rectangle in Fig. 12). The examples of berms given in Fig. 11 show the limit of effect on a berm of width l_B = 1.50.b. The small berm results from the circular line of the sliding surface based on the local shear factor method of the BOSCH program.

To obtain a calculation model, berm factor b_γ is incorporated as a ratio of the foundation strip bearing capacity depending on the parameters φ, β and l_B/b (berm width/base width) to the bearing capacity of the same foundation strip with a horizontal surface on both sides (general case).

$$b_\gamma = \frac{Q_f(\varphi,\beta,l_B/b)}{Q_f(\varphi,\beta)} = \frac{N_\gamma(\varphi,\beta,l_B/b)}{N_{\gamma,0}(\gamma)\cdot g_\gamma(\beta)}$$

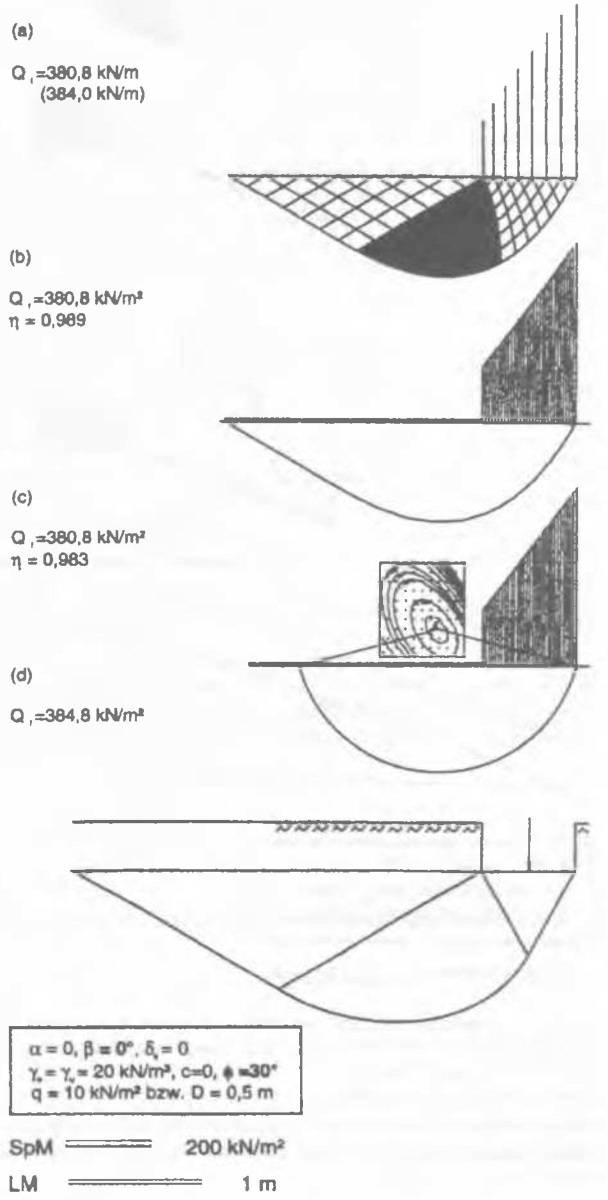


Fig. 10: Comparison of four different calculation methods for a horizontally adjoining surface and a lateral surcharge of 10 kN/m2 (γ_0 . t = 20 kN/m3 . 0.50 m = 10 kN/m2)
a) stress characteristics method
b) slope analysis by the local shear factor method for the failure shape a),
c) slope analysis by the local shear factor method for a circular failure shape,
d) bearing resistance calculation method and size of the sliding mass as per ÖNORM B 4435-2.

As of the critical value $(l_B/b)_{cr}$, the reciprocal value of berm factor bγ/1 meets the factor of surface inclination g_γ; i.e. at this berm width, the result of b_γ. g_γ = 1.00.

In order to account for the effect of a berm, we propose incorporating berm factor b_γ which was developed from the centrifuge results as a function of berm width/base width l_B/b in relation to the angle of surface inclination β (Fig. 13). For the 30 model tests the bearing capacity factors N_γ were recalculated starting from the measured maximum bearing resistance $Q_{f,d}$,

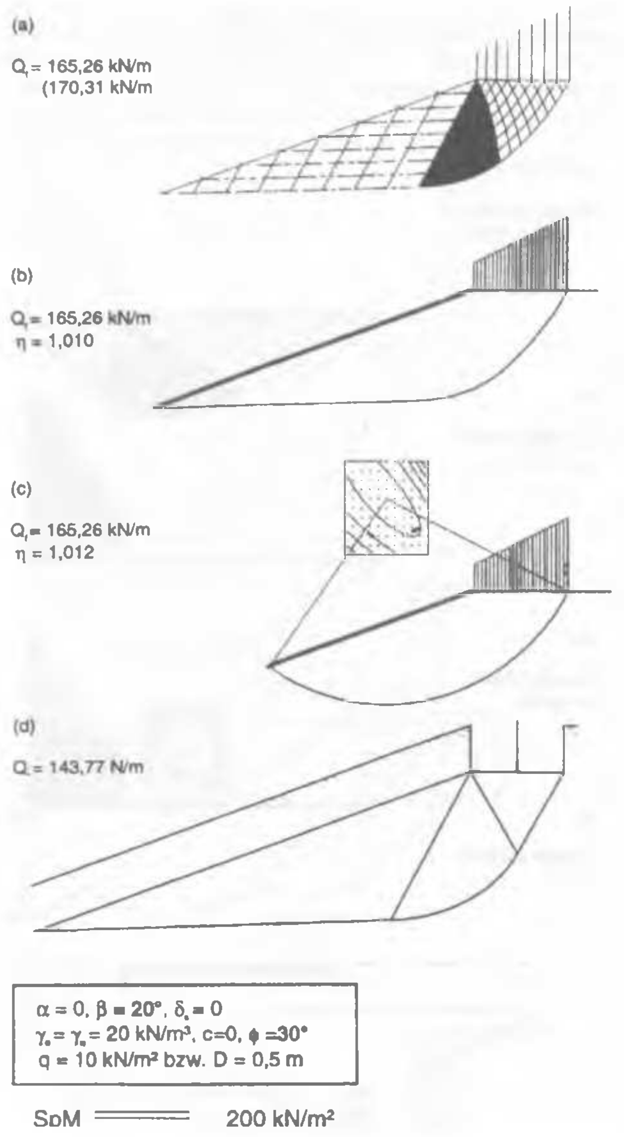


Fig. 11: Comparison of four calculation methods for an adjoining inclined surface ($\beta = 30°$) and a lateral surcharge of 10 kN/m2 ($\gamma_0 \cdot t = 20$ kN/m3 . 0.50 m = 10 kN/m2)
a) stress characteristics method,
b) slope analysis by the local shear factor method for failure shape a)
c) slope analysis by the local shear factor method for a circular failure shape
d) bearing resistance calculation method and size of the sliding mass as per ÖNORM B 4435-2.

according to ÖNORM B 4435-2. Considering the factor of surface inclination g_γ for $l_B/b = 0$ of Fig. 9, the berm factor b_γ for $l_B/b = 0.5$ and for $l_B/b = 1.0$ was determined. The reciprocal value $1/b_\gamma$ is drawn in Fig. 13. Moreover, the results from recalculation of the BOSCH program and the results from the VSS tables were marked with different symbols. The regression curves for $\beta = 10°$, 20° and 30° are calibrated for the berm factors so that $l_B/b \cong 5$ will be equal to the factor of surface inclination g_γ in $l_B/b = 0$ (inclined surface without berm).

The surface inclination factor g_γ of ÖNORM B 4435-2 is lower than the results of the centrifuge tests and therefore on the safe side. By multiplying g_γ with berm factor b_γ we obtain 1.0 for $l_B/b \cong 5$. This result is identical with the initial state of $l_B/b = \infty$ (horizontal surface of the foundation base).

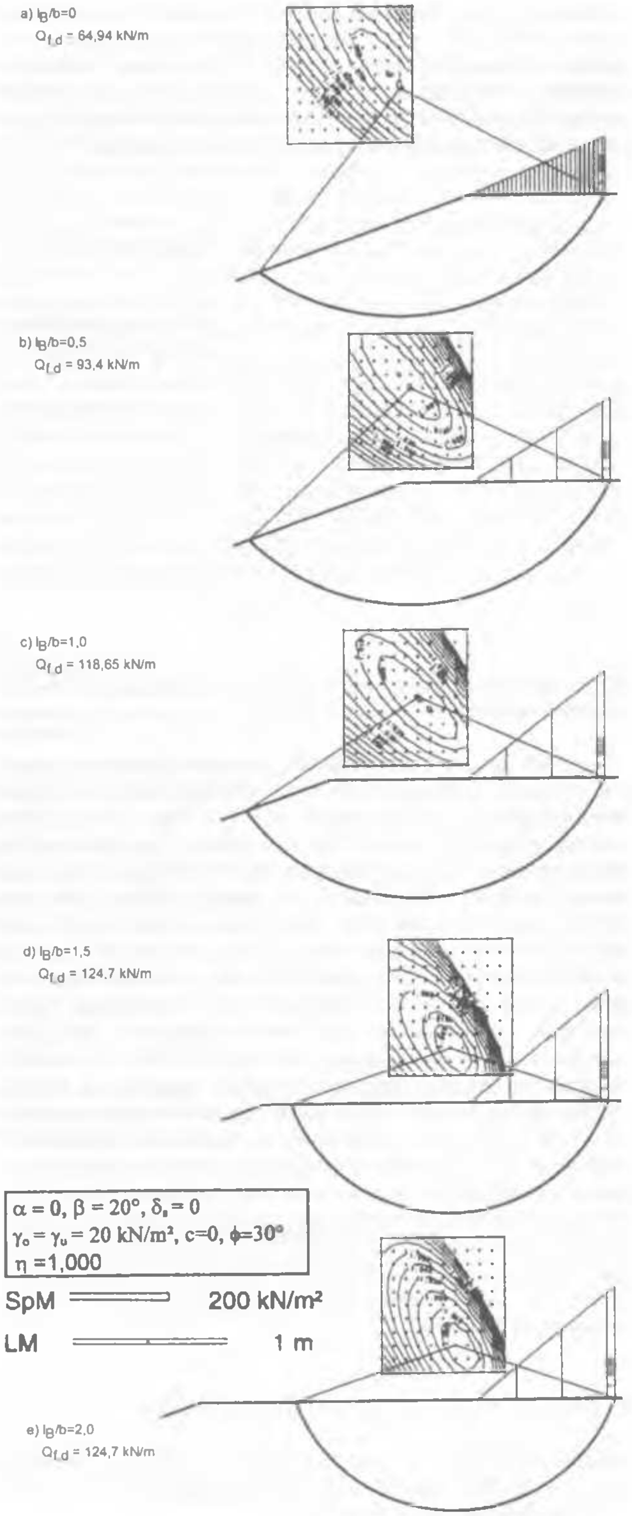


Fig. 12: Calculation of the bearing resistance capacity by the local shear factor method, varying $l_B/b = 0$ up to $l_B/b = 2.0$; the threshold is obtained at $l_B/b = 1.5$ (general case with horizontal surface)

$$N_\gamma = N_{\gamma,0} \cdot g_\gamma \cdot b_\gamma = N_{\gamma,0} \cdot g_\gamma(\beta) . b_\gamma(l_B/b, \beta)$$

$$g_\gamma(\beta) = (1 - \beta)^{1.67} \quad , \quad b_\gamma(l_B/b, \beta) = (1 + l_B/b)^{0.04+0.72\beta}$$

The value of b_γ given by the exponential function was found sufficient

for the limits $0 < l_B/b < 5.0$,

for the limit $l_B/b = 0$, b_γ is 1.0, which results in $N_\gamma = N_{\gamma,0} \cdot g_\gamma \cdot 1.0$ (inclined surface), for the limit $l_B/b \approx 5$, $N_\gamma = N_{\gamma,0} \cdot g_\gamma \cdot 1.0/g_\gamma = N_{\gamma,0}$ (horizontal surface) applies with sufficient accuracy,

for horizontal surface $\beta = 0°$ and $g_\gamma = 1/b_\gamma = 1.0$, following $N_\gamma = N_{\gamma,0}$.

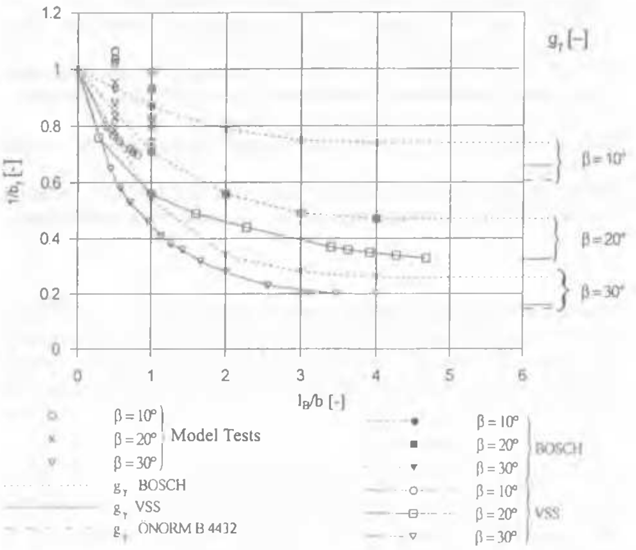


Fig. 13: Evaluation of the centrifuge tests from compacted coarse sand φ ≅ 47.5°, compared with calculations as per ÖNORM B 4435-2, BOSCH program (sliding circle method with local shear factor as per SHAGANI/ PREGL) and the stress characteristics method used by VSS, with limits $0 < l_B/b < 5.0$

According to Fig. 13, if $\beta = 0°$, g_γ will be 1.0. The values of g_γ for $\beta = 0°, 10°, 20°, 30°$ are given at the right-hand ordinate. The Institute of Geotechnical Engineering at the University of Agricultural Science performed similar evaluations for berms using the BOSCH program for different angles of friction $\varphi = 45°, 40°, 30°, 20°$. Fig. 14 demonstrates the correlation of $1/b_\gamma$ to l_B/b. Accordingly, at a ratio of $l_B/b > 4$, the berm width no longer affects the bearing resistance of the noncohesive ground, so that the general case (horizontal surface) applies. It is interesting to note that the impact of the berm decreases with a decreasing angle of friction φ at the same surface inclination β, i.e., the ratio of $1/b_\gamma$ will go to a constant level the earlier the smaller the angle of friction of the ground will be.

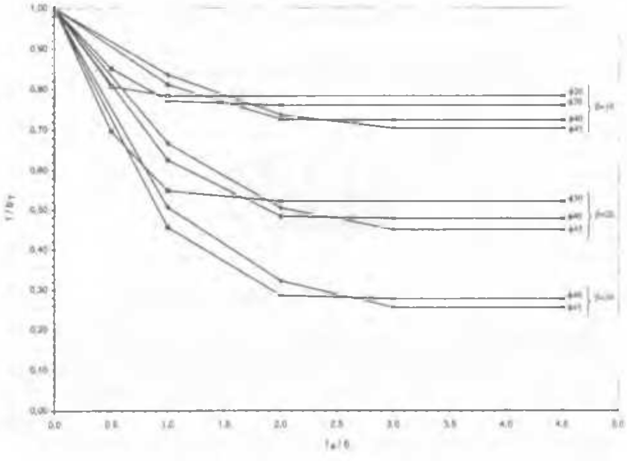


Fig. 14: Berm factor $1/b_\gamma$ is given in relation to l_B/b (berm width/base width) with and without surcharge on the berm

6 BERMS WITH SURCHARGE

If the foundation strip is embedded at a depth $t > 0$, the stress at the front corner of the base $q_R > 0$. This stress can be calculated in the special case of $l_B = 0$ and $\beta = 0$ (no berm and horizontal surface). The equation of bearing capacity will be

$$q_R = b\, \gamma_0\, t\, N_q\, (\gamma,\beta).$$

For the calculation, the stress at the back corner is varied so that the factor of safety is 1.00. If we suppose the critical ratio $(l_B/\,b)_{cr} = 3.0$, we can calculate the front stress q_{Rl} by linear interpolation between the valid values for $l_B = 0$ with $\beta > 0$ and $\beta = 0$ respectively at the limits of $l_B = 0$ and $l_B = l_{B,cr}$. Note the linear interpolation of the front stress at the corner of the base (Fig. 15).

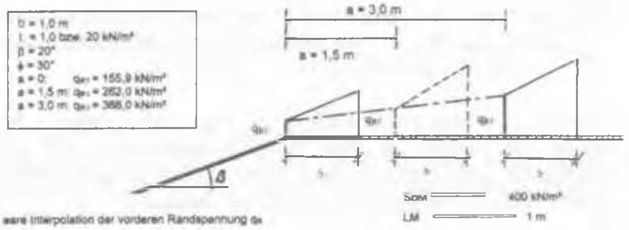


Fig. 15: Proposed method of linear interpolation of the front stress at the foundation base

The reciprocal values of the berm factors are shown in Fig. 16. It is noticeable that the embedding depth t has little impact on the berm factor b_γ. The embedding factor t_γ may be defined as follows:

$$t_\gamma = \frac{Q_f(t, l_B / b)}{Q_f(l_B, b)}$$

The results of this calculation are given in Fig. 16.

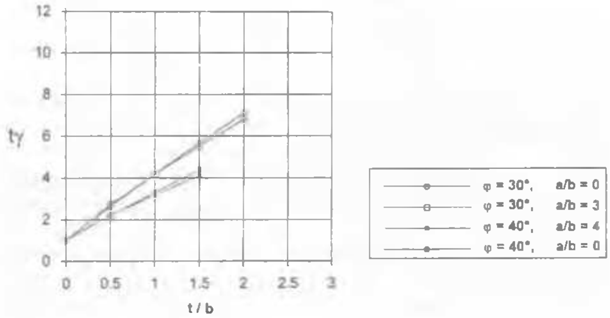


Fig. 16: Embedding factor t_γ calculated with the BOSCH program (sliding circle method with local shear factor)

For both angles of friction ($\varphi = 30°$, $\varphi = 40°$) the embedding factor t_γ depends on the embedding depth t at limits $l_B/b = 0$ and $l_B/b = 3.0$ or 4.0 respectively (general case). The results obtained are nearly identical values of t_γ with $\varphi = 30°$and $\varphi = 40°$ for $l_B/b = 0$ and $l_B/b = 3.0$ or 4.0 respectively, which demonstrates that the embedding factor t_γ does not much depend on the surface inclination β.

7 CONCLUSIONS FROM THE CENTRIFUGE TESTS AND CALCULATION MODELS

The soil mechanical problem posed by berms abutting foundations and their bearing resistance is governed, in addition to the influence of cohesion and pore-water pressure, by:

- angle of friction for ground φ below and above the berm and the inclined surface,
- angle of inclination β for the slope of the berm,
- ratio between berm width and width of the foundation base l_B/b,
- berm surcharge $\gamma_0 .t$.

From ongoing research, several basic findings have so far been obtained:

- the bearing resistance capacity and the critical ratio of l_B/b will increase with a higher angle of friction φ of the incorporated soil;
- the ratio of l_B/b will decrease with an increase of the angle of friction (φ, due to equal foundation load;
- the surface inclination factor increases with a higher angle of inclination β of the slope of the berm,
- the bearing capacity of the foundation strip increases with an increase in the surcharge $\gamma_0 .t$, due to an equal ratio l_B/b.

The four calculation proposals of Fig. 6 still need to be checked for validity in each practical application, and the mathematical solutions still need some modifications. Further research and standardisation work will be necessary.

TERZAGHI furnished a practicable solution in his book "Theoretical Soil Mechanics" (1943; German edition TERZAGHI/JELINEK 1954), using the theory of plane slip surfaces based on RANKINE and updating the bearing resistance calculations of PRANTL and REISSNER, adapting them for realistic working conditions on site. Since then numerous scientific publications on bearing resistance capacity have been written, and have been incorporated into standards in Austria and elsewhere. The new Austrian Standard ÖNORM B 4435-2 guides soil engineers away from the current concept of global safety factors to a partial safety factor system. This system took three years to develop and was published in 2000. It is designed as a step towards more realistic and safe calculation of the bearing resistance capacity of flat foundations, and as a useful tool for practitioners.

8 REFERENCES

BELLINA; Ch.(2000): Modellversuche zum Setzungsverhalten von Flachgründungen, Dissertation, Universität für Bodenkultur, Vienna

BOROWICKA, H., MARTAK, L. : (1998) Principles of Grain Mechanics, Vienna

DIN V 4017, Beiblatt 1 zu DIN V 4017-100 (Dezember 1996): Baugrund, Berechnung des Grundbruchwiderstandes von Flachgründungen, Teil 100: Berechnung nach dem Konzept mit Teilsicherheitsbeiwerten, NA Bau im DIN

EUROCODE 7, Geotechnical Design, PART 1 General Rules, Draft EN 1997-1 CEN/SC 7, Paper N 339 (02.02.2001), Section 6 Spread Foundation, Annex D

MARTAK, L.: (2000) Seminar Einführung in die neue ÖNORM B 4435-2 Erd- und Grundbau, Flächengründungen, schriftliche Fassung des Vortrages, Österreichisches Normeninstitut

ÖNORM B 4432 (1.7.1980): Erd- und Grundbau, Zulässige Belastungen des Baugrundes, Grundbruchberechnung, Österreichisches Normungsinstitut, Vienna

ÖNORM B 4435-2 (1.10.1999): Erd- und Grundbau, Flächengründungen, EUROCODE-nahe Berechnung der Tragfähigkeit, Österreichisches Normungsinstitut, Vienna

PREGL, O. (1999): Böschungen; Handbuch der Geotechnik Band 10, Institut für Geotechnik der Universität für Bodenkultur, Vienna

SCHWARZ, H.: (2000): Untersuchungen zur Tragfähigkeit von Flachgründungen, Diplomarbeit an der Universität für Bodenkultur, Vienna

SIEFFERT, J.G.(1998): Bearing Capacity of shallow foundations – Comparison of the method used by thirteen European countries, International Conference on Soil Structure Interaction in Urban Civil Engineering, 8/9 October 1998; Proceedings of Darmstadt Geotechnics, Institute and Laboratory on Geotechnics

SHAIGANI, S.H., PREGL, O. (1997): Berechnung der Standsicherheit von Böschungen mit der "Methode mit lokalen Ausnutzungsgraden". 1. Österreichisch Geotechniktagung, Vienna, pp. 125–144

TERZAGHI/JELINEK, (1963): Theoretische Bodenmechanik, Verlag Springer

VEREINIGUNG SCHWEIZERISCHER STRASSENFACHMÄNNER (VSS), (1978): Stützmauertabellen, vol. II., unpublished manuscript