THE BEARING BEHAVIOUR OF GEOGRID REINFORCED CRUSHED STONE COLUMNS IN COMPARISON TO NON-REINFORCED CONCRETE PILE FOUNDATIONS

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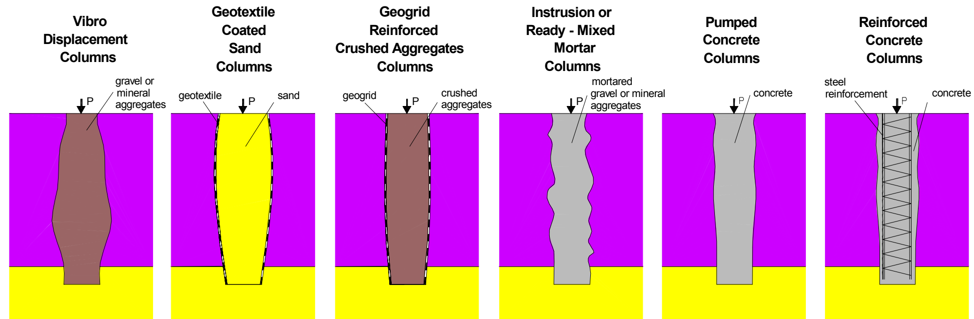
ABSTRACT: In the last years there has been developed new methods in improving the bearing capacity of soft soils by producing a raster of high compacted mineral aggregate columns or of mortar and concrete stabilized columns in this soils. A very new development is the fabrication of geotextile coated sand columns and geogrid reinforced gravel columns. The offered paper will present a attribute the theoretical foundations of the bearing behaviour of columns. Further for the geogrid-reinforced columns it will be presented back calculations of several loading tests in the laboratory and in the field by analytical methods. The included speciality is the different viewpoint in this common evolution, which combines Russian and German experiences, especially in the construction of non-reinforced columns and concrete piles

1 INTRODUCTION

The improving of the properties of soft soils by columns of draining sand, gravel or crushed aggregates is a already well known method. In the soft and saturated ground massif there will be produced cylindrical openings by drilling or by vibro displacement, which after that will filled up by the draining material (s. figure 1). The such improved ground shows a higher bearing capacity as well as a reduction of the settlements and also an acceleration of the soil consolidation by the increase of the seeping processes by the groundwater. The disadvantage of such foundation systems is the inconstancy of the geometric measures of the columns as well in fabrication as in using. That is the reason, such columns are not so suitable in very soft and organic soils with an undrained shear strength of less than c_u = 15 kPa, because already during the fabrication the soil will not be compacted, but only displaced sideward. A further disadvantage is the possible process by filtering fine soil particles in the columns and the following disturbances of the seepage function in the draining material.

To remove this disadvantages there has been developed the method of the foundation system "Geotextile Coated Sand Columns (GCC)" (s. figure 1b). The bearing behaviour of the geotextile coated sand columns is more elastically. So the axial stiffness of the column and the constancy of the geometric measures increases. As against conventional column foundations geotextil coated sand columns can be used as ground improvement in very soft or organic soils (E < 5 MPa; cu < 15 kPa) [RAITHEL, 1999; KEMPFERT et al., 1997]. Further the drain effect will be preserved.

On the other side mortar improved columns (s. figure 1d) or concrete columns with or without steel reinforcement (s. figures 1e and 1f) have no or very few draining properties. In principle they are the well known piles, which bearing capacity is high enough, to take up excentric vertical forces or bending moments.



Vertical Bearing Capacity

+	++	+++	++++	+++++	+++++

Bending Strength

o	o	++	+	+	+++

Drain Effectiveness

+++	++	++	+	o	o

Figure 1: Examples for Vibro-Column-Foundations

An advantageous alternative to the geotextile coated sand columns is a further development of the company "NAUE Fasertechnik GmbH", Germany, who proposed "Geogrid Reinforced Crushed Aggregate Columns" (s. figure 1c), using a geogrid coat and crushed stones inside. The aim of this construction is the development of columns in direction to higher strength and elasticity. The use of a mixture of crushed stones and stone chips effects a decrease of axial strain under load, because the shear strength of crushed stones is higher than that of sand. Further the radial support is higher, because the ring tension forces in the geogrid coat is relatively high in reference to the small tension strain. This results in a higher bearing capacity respectively in a reduction of the axial and the lateral strain, which finally improves the constancy of the geometric measures.

The carried out large scale loading tests (s. figure 2) have proven to be of good quality [PAUL et al., 2003]. Particularly the taken up vertical stresses have been astonishing high, for example much higher than the allowable soil pressure of the most of underlying natural soils. Further other large scale tests [SMOLTCZYK, 1999; PAUL et al. 2003] have shown, that geogrid reinforced stone or gravel columns are able, to bear excentric vertical stresses and even to a limit amount bending moments. The problem of the filter stability between the very soft soil and the coarse grained stones has been solved by an enclosure of fleece inside the geogrid coat.

Figure 2: Geogrid reinforced stone column in one dimension compression test

The results of the large scale tests encouraged the authors to investigate methods for the calculation of geogrid reinforced stone columns. This investigations have been carried out in the frame of a cooperation project of the Technical State University Perm, Russia, and the Anhalt Uni-versity, Germany. In the following there will be presented some fundamentals to the calculation of such constructions, which also point out the communities in the Russian and German calculation methods.

2 PILE CALCULATION BY RUSSIAN METHOD

According to Construction Rules and Regulations for pile foundations in Russia [SNiP 2.02.03-85, 1985], the calculation of pile foundations must be done by following limit states:

First group:

- strength of pile material
- bearing capacity of the pile foundation ground

Second group:

- settlement of the pile base and the pile foundation, due to vertical loads
- pile displacements (horizontal, up, angular turn of pile head, ψp) together with the base ground, caused by horizontal loads or bending moments.

The bearing capacity of pile foundations, reacting a vertical compressive load, is determined by the resistance of the pile material, F_{dm}, and the resistance of the ground, F_d, un-der the pile shoe and on the side surfaces of the pile. It will be accepted the lesser of the two values.

The bearing capacity of the pile material, made from crushed stones without a geosynthetic coat, under central load can be determined by analogy with known formulae for drilled and non-reinforced concrete piles:

$$F_{dm}=m \cdot \varphi \cdot R_{cs} \cdot A, \qquad (1)$$

There is:

m : security coefficient of the pile working conditions

φ : buckling coefficient

R_{cs} : calculated compression resistance of crushed stones

A : area of pile cross-section.

The form of the formula (1) is general for all known pile constructions (concrete, metal, timber) under the effect of central compressive load and differs only by material characteristics and also by the geometry of the pile section. In our case we introduced a special value, that characterizes the material of the pile construction, namely Rcs, the calculated compression resistance of crushed stones. Knowing that value and also A, we can easily determine the limiting value of the compressive force N, that can be taken up by the pile's free section without its fracture. The coefficient of working conditions of the pile section is equal to m = 0.85 for pile cross-sections with areas less than 0.1 m2 and equal to m = 1.0 in other cases.

The buckling coefficient is equal to □ = 1.0 for low pile foundations and firm ground. Sinking a pile into soft ground and having a high pile platform the buckling coefficient □ is taken within the limits of its free length, l0. In this case, the value of □ depends on the relation free length/diameter of the pile, l0/d, and changes within the limits from 0.5 to 1.0. Such approach is connected with the fact, that according to Construction Rules and Regulations [SNiP 2.02.03-85, 1985] at designing piles of all types, we must consider a pile with respect to the material strength as a bar, firmly fastened in the ground and in the pile platform. That can be defined by the formula

$$l_1 = l_0 + \frac{2}{a_\varepsilon}, \qquad (2)$$

where is:

l_1 : calculated length of pile

l_0 : length of pile part from the base of the pile platform to the ground planning level

a_ε : coefficient of deformation

The bearing ground capacity of the pile foundation ground, F_d, must be calculated by the condition

$$N \le \frac{F_d}{\gamma_k}. \qquad (3)$$

There is:

N : calculated load on the pile (longitudinal force in the pile, caused by loads, having an effect on the foundation, in the most disadvantageous combination)

F_d : ground bearing capacity of a single pile

γ_k : security coefficient, depending on the way of defining the bearing capacity (theoretical method, static tests, ground sounding, etc).

The calculated load on the pile, N, must be determined by considering the pile foundation construction as a frame construction, reacting vertical and horizontal loads and bending moments. For foundations with vertical piles the calculated load on the pile must be determined by the formula

$$N = \frac{N_d}{n} \pm \frac{M_x y}{\sum y_i^2} \pm \frac{M_y x}{\sum x_i^2}, \qquad (4)$$

where is:

N : calculated compressive force

M_x, M_y: calculated bending moments with respect to the major central *x* and *y* axes on the base of the pile foundation construction

n : number of piles in the foundation;

x_i, y_i : distances from the major axes to the axis of every pile

x, y : distances from the major axes to the axis of every pile, for which the calculated load is determined.

3 SUGGESTIONS FOR THE CALCULATION OF GEOGRID REINFORCED CRUSHED STONE COLUMNS

In the case of crushed stone columns inside a geogrid encasement it is advantageous, to use the model of a column in a regular, infinited column raster. Then the calculation of the bearing capacity and the deformations extends to the analysis of a improved ground. Usually it starts with the "unit cell concept" with a rotary symmetric sphere of influence (s. figure 3).

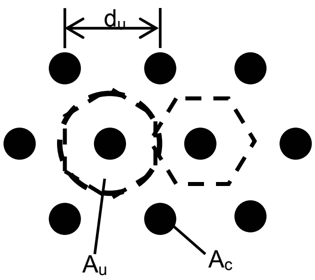


Figure 3: Raster of columns with unit cells

There is:

A_c = area of one column

A_u = area of the unit cell

d_u = diameter of the unit cell

To determine the resistance of the column inside of a unit cell, F_{dm}, first it must be calculated the maximum possible vertical stress on the top of the column. This stress causes horizontal stresses in the column, which must be lower than the maximum radial support, caused by the ring tension forces in the geogrid coat and the support effect by the surrounding soft soil (s. figure 4).

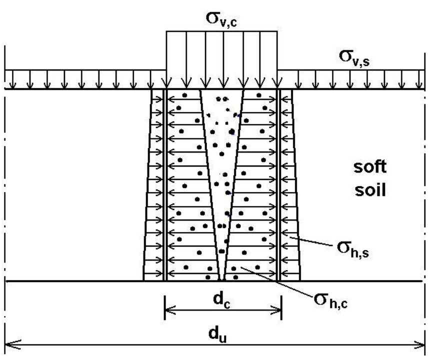


Figure 4: Stress distribution in a unit cell of a geogrid surrounded column of crushed stones

There is:

$\sigma_{v,c}$: vertical stress on the top of the column

$\sigma_{v,s}$: vertical stress on the top of the soft soil

$\sigma_{h,c}$: horizontal stress in the column

$\sigma_{h,s}$: horizontal stress in the soft soil

d_c : diameter of the column

d_u : diameter of the unit cell

In the column effects the active lateral earth pressure and in the soft soil the passive lateral earth pressure:

$$\sigma_{h,c} = \sigma_{v,c} \cdot K_{ac} + \sigma_{c,c} \cdot K_{ac} \qquad (5)$$

$$\sigma_{h,s} = \sigma_{v,s} \cdot K_{ps} + \sigma_{s,s} \cdot K_{ps} \qquad (6)$$

There is:

$\sigma_{c,c}$: vertical stress in the column, due to overburden of the crushed stones

$\sigma_{s,s}$: vertical stress in the soft soil, due to overburden of the soil

K_{ac} : active earth pressure factor in the column

K_{ps} : passive earth pressure factor in the soft soil

The possible horizontal stress in the soft soil is very low; therefore a part of the horizontal stresses in the column must be taken up by the horizontal ring tension stresses in the geogrid, $\sigma_{h,geo}$. This stress can be determined in analogy to the well known Kessel-formula (s. figure 5) by

$$\sigma_t = \sigma_{h,geo} = F_R / A_L \qquad (7)$$

There is:

F_R : ring tension force

A_L : area of all geogrid strips in the length cross section of the column ($A_L = 2 \cdot \Sigma A_{geo}$)

A_{geo}: cross section area of one geogrid strip

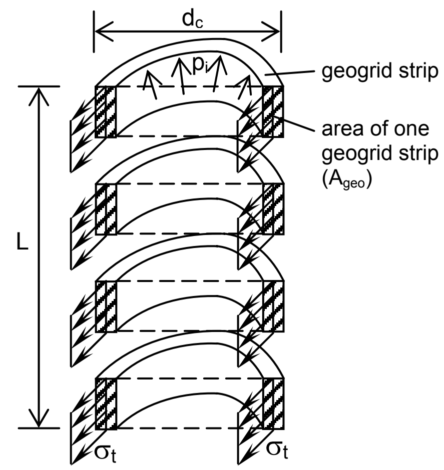


Figure 5: Determination of the ring tension stresses

Assuming, that geogrid has a linear-elastic behaviour, there is

$$F_R = J \cdot \varepsilon_{geo} = J \cdot \Delta r_{geo} / r_{geo} \qquad (8)$$

and by setting into formula (7) there is

$$\sigma_{h,geo} = J / A_L \cdot \Delta r_{geo} / r_{geo} \qquad (9)$$

with

ε_{geo} : strain of geogrid

J : modulus of elasticity

Δr_{geo}: increase of the radius of the geogrid encasement

r_{geo} : nominal radius of the geogrid encasement

All the horizontal stresses must be in equilibrium [RAITHEL, 1999]; so there is:

$$\sigma_{h,c} = \sigma_{h,geo} + \sigma_{h,c} \qquad (10)$$

Setting formulae (5), (6) and (9) in formula (10) there is:

$$\sigma_{v,c} \cdot K_{ac} + \sigma_{c,c} \cdot K_{ac} = J/A_L \cdot \Delta r_{geo}/r_{geo} + \sigma_{v,s} \cdot K_{ps} + \sigma_{s,s} \cdot K_{ps} \qquad (11)$$

By changing this formula there is received the formula (12), which can used to calculate the maximum possible vertical stress on the top of the column:

$$\sigma_{v,c} = 1/K_{ac} \cdot [J/A_L \cdot \Delta r_{geo}/r_{geo} + K_{ps} \cdot (\sigma_{v,s} + \sigma_{s,s}) - \sigma_{c,c} \cdot K_{ac}] \qquad (12)$$

In this formula all dates are known without Δr_{geo}. But this value can be estimated from the limit strain or be determined by a cylindrical widening test, similar like a borehole pressiometer test.

In the extreme case of a very soft soil there the radial support by the soil can be neglected. Then the formula (12) simplifies to

$$\sigma_{v,c} = J/(A_L \cdot K_{ac}) \cdot \Delta r_{geo}/r_{geo} - \sigma_{c,c}$$

and with

$$\sigma_{c,c} = \gamma_c \cdot L$$

to

$$\sigma_{v,c} = J/(A_L \cdot K_{ac}) \cdot \Delta r_{geo}/r_{geo} - \gamma_c \cdot L. \qquad (13)$$

To determine the bearing capacity of the whole geogrid reinforced crushed stone column, F_d, it is near, by developing the above described pile calculation method further, using the known formula for a cast-in-place concrete pile:

$$F_d = \gamma_c \cdot (R \cdot A + u \cdot \Sigma \gamma_{cf} \cdot f_i \cdot h_i), \qquad (14)$$

where is

γ_c : coefficient of working conditions of the column (in the case of dust-clayey grounds γ_c = equal to 0,8; in other cases γ_c = 1,0)

R : calculated ground resistance under the low end of the Pile (kPa)

A : area of the column on the ground basement, taken equal to the area of column pile cross-section (m^2)

u : circumference of the column touching the ground (m)

γ_{cf} : coefficient of ground working conditions on the side surface of the column, depending on the method of column fabrication and conditions of crushed stone laying. Because the lack of experimental data the coefficient γ_{cf} should be taken equal to 0.8

f_i : calculated resistance of the ground layer I on the side surface of the column (kPa)

h_i : thickness of ground layer i being in contact with the side surface of the column (m)

The strength proof of the column cross-section in respect to the construction material, made from crushed stones inside a geogrid encasement, by the first limited state of bending, can be done by the help of the well-known condition used for different pile constructions

$$M_{max} \leq M, \qquad (15)$$

where is

M_{max} : maximal bending moment in the column section, that can appear due to calculated loads (kN·m)

M : calculated bending moment, taken by the column cross-section (kN·m)

According to the construction rules and standards (for example SniP 2.02.03-85 and DIN 1054) the deformation analysis of columns of crushed stones inside a geogrid encasement must be done by the condition

$$s \leq s_u, \qquad (16)$$

where is

s : combined deformation of the column foundation and the column structure

s_u : limiting value of the combined deformation of the column foundation and the column structure, for example set by instructions of construction rules or standards.

4 CONCLUSIONS

The approaches to the design of geogrid reinforced crushed stone columns piles given above are general and base on the generally known approaches to the design of pile foundations, stated in normative documents. But taking into account the peculiarities of such constructions and the technology of their setting into different grounds the authors of the presented paper think, that the calculation procedure of constructions has some substantial differences to the classical pile elements (precast and drilled piles). In the authors' opinion the development of the calculating procedure of crushed stone columns encased in geogrid must be a synthesis of analytical solutions of column design, set into ground with low compaction, with the theory of column design, set with the help of ground displacement.

Moreover, a important fact in the calculation of crushed stone columns encased in geogrid is their design as a holding construction in sliding slopes, embankments and deep pits. To solve such problems it is possible to use the well-known theory of the arching effect. After this, when happens a displacement in any part of the underground, there happens also a re-distribution of the pressure from the displacing ground to the adjoining resting parts of the ground. Hereby the surrounding ground forms a load-bearing body. But at setting constructions under study into soft grounds the arching theory won't reflect its real effects in full measure. In that case the well-known solutions of the plasticity theory must be used. That's why their further investigations of the work of crushed stone columns, encased in geogrid, the authors are planning to devote their common studies on these scientific problems.

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