

## CALCULATION AND DESIGN OF VERTICAL REINFORCING ELEMENTS (VAE) IN SOILS

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Article history:	Abstract:
<p><b>Received:</b> April 10<sup>th</sup> 2021</p> <p><b>Accepted:</b> April 22<sup>th</sup> 2021</p> <p><b>Published:</b> May 19<sup>th</sup> 2021</p>	<p>The paper discusses the issues of comparing bases made of compacted soil pads, pile foundations and bases reinforced with vertical reinforcing elements (VAE). The analysis of methods for determining the main geometric indicators of VAE and their bearing capacity is given. A mathematical computational model is presented that makes it possible to determine changes in axial normal strengths along the length of the VAE. The resulting solution allows you to optimize the cross-section and length of VAE depending on external loads.</p>
<p><b>Keywords:</b> Vertical reinforcement element (VAE), foundation, base, soil, loess, settlement, stress and strength, deflection.</p>	

### INTRODUCTION

Recently, in geotechnical practice, methods of soil strengthening using injection, jet and drilling-mixing technologies become widespread. These technologies are used both for preparing the foundation of newly raised buildings and structures, and for strengthening the bases and foundations of emergency buildings. VAE materials can be plastic cement-sand, cement-grouted mortars and concrete. Depending on the longitudinal stiffness and stability, VAE can be conditionally divided into rigid, pliable and flexible. Concrete and transformed as cement-ground VAE with aspect ratio  $D/L \geq 0,075$  belong to the category of stiff,  $0,075 \leq D/L \leq 0,05$  final stiffness and at less  $D/L \leq 0,05$ -flexible. Soil piles are flexible. Such a gradation in VAE stiffness is necessary for the correct acceptance of the base calculated scheme. VAE with 1 and 2 types of stiffness can be conventionally taken as rigid structural bar elements embedded in the soil massif, type 3 VAE can be conventionally taken as a fortified massif. In accordance with such a gradation, when calculating deflections and forces in strip and slab foundations, two types of models are adopted: Zhemochkin's model [1] - a support in the form of a pliable elastic rod  $k = \frac{P}{s} \left( \frac{kN}{m} \right)$  and bed coefficient according to Winkler's model  $k = \frac{P}{s} \left( \frac{kN}{m^3} \right)$ . Reinforced VAE foundations should also be calculated for 1 and 2 ultimate states. In this case, the task is complicated by the fact that the calculation of such bases is taken as a procedure for pile foundations or the base is taken as a conditionally homogeneous massif with a deformation modulus E. In this regard, we consider the main distinctive features between piles and VAE.

**The fundamental difference between VAE and pile foundations.** Vertical reinforcement elements made from compacted or hardened soils are fundamentally different from rigid reinforced concrete piles. In our opinion, there are the following differences between them.

Reinforced concrete piles together with the raft foundations make up a single foundation for a building or structure. When calculating pile foundations, almost all external loads are distributed to the piles. Soil, cement-ground and concrete VAE are not a structure, and refer to the elements of strengthening the subgrade, which perform the function of strengthening it using reinforcement methods. VAE, in contrast to reinforced concrete piles, do not work for bending loads, and allow the redistribution of stresses in a large volume of soil mass (Fig.1). VAEs

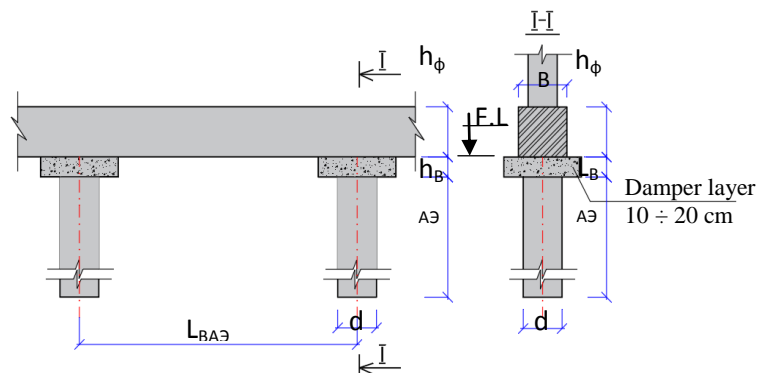


Fig. 1. Structural diagram of strip foundations

allow regulating contact stresses, reducing deflections and forces in the foundation structure, and increasing the rigidity (flexibility) of the subgrade under the foundation. In contrast to conventional piles, VAEs are not subdivided into rack piles and hanging piles in terms of working conditions in the ground. It is explained by the fact that VAEs are relatively weakly strong and, in accordance with this, are much more pliable than reinforced concrete piles (the strength of the VAE material significantly exceeds the strength of the soil and is an order of magnitude less than the strength of reinforced concrete). In addition, for this reason, under the action of external loads in the base, a more intense dissipation of strengths occurs, which allows you to connect a larger volume of soil to work.

In [2, 4], a detailed analysis of the calculation of the VAE bearing capacity is given, where the condition of cohesion of the solution to the soil on the lateral surface of the VAE is taken into account.

$$F_u = R_s A + \gamma_{sf} f h_u \tag{1}$$

In the expression (1)  $R_s$  and  $f$  -in contrast to pile foundations, they are determined based on the results of static sounding in the in-situ tests (SP24.13330.2011). The VAE draft is determined from the condition of penetration (puncture) into the medium of a rigid rod without taking into account the drag. In accordance with this model, the vertical movement of VAE with a radius  $r_0$  in the surroundings is determined by the expression

$$w = \frac{\tau_0 r_0}{G} \int_{r_0}^{r_m} \frac{dr}{r} = \frac{\tau_0 r_0}{G} \ln \left( \frac{r_m}{r_0} \right), \tag{2}$$

where  $\tau_0$ - shear strengths on the lateral surface of the VAE;  $G$  is the modulus of elastic shear. From expression (2) it follows that with an increase in the ratio  $\left(\frac{r_m}{r_0}\right)$  up to 7, all other things being equal, the displacement increases up to 2 times. Such a condition, from the point of view of a soil massif without VAE, is fair, but for a centrally loaded vertical rigid element, it will obviously have the opposite character. Otherwise, for a centrally loaded VAE, the dimple of maximum displacements will coincide with its axis.

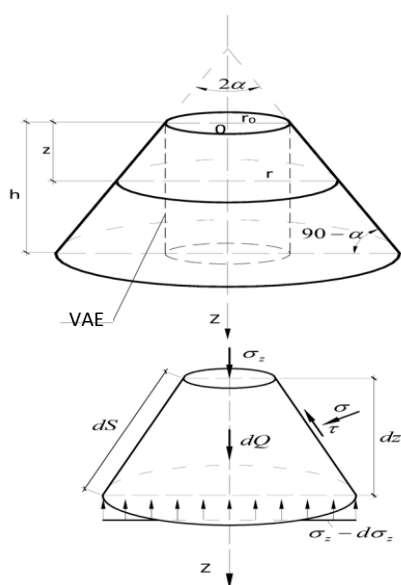
Numerous experiments carried out on concrete and complex concrete-cement-soil VAE have shown that, with the calculated bearing capacity, its settling does not exceed 2-3 mm (Fig). Based on the analysis of such experiments on the same type of soil conditions, it was found that the bearing capacity of the VAE and the distance between them can be determined by the expressions

$$F_d = \frac{A \cdot Lk}{m}, \tag{3}$$

$$L_{VAE} = \frac{F_d - A \cdot P_{sl}}{q - P_{sl} \cdot B} \tag{4}$$

where-  $k, m$ -respectively, the coefficients of the equation, depending on the technology and the type of soil. Determined for specific soil conditions;  $A \cdot L$  – respectively, the transverse area and length of the VAE,  $P_{sl}$ - initial subsidence pressure (kPa) or design resistance of a weak subgrade –  $R$ .  $q$ - external distributed load on the raft foundation and  $B$ -width of the raft foundation. For example, for the same type of loess soils in Uzbekistan and on the basis of numerous experiments, it was found that the coefficients  $k = 0,5$  and  $m = 0,003 \text{ m}^3/\text{kN}$ ;

**Calculation model for determining normal stresses along the VAE axis.** Taking into account the absence of a



**Fig. 2. Calculation model for determining the bearing capacity and normal**

computational model in relation to VAE, the authors made an attempt to develop a computational scheme that allows determining the stress state of the soil massif along the VAE. Below we consider a computational model characterizing the operation of VAE in a soil environment. In accordance with this model, it is assumed that due to the strong cohesion along the lateral surface of the VAE, the working volume of the soil connected to the work is represented along the length in the form of a truncated cone. When a critical load is applied to the VAE, a shear along its lateral surface is assumed. The top base of the frustum is equal to the radius  $r_0$  (Fig 2). To compose the equilibrium equation, we select an elementary layer of thickness  $dz$  at a depth  $z$ . Under the conditions of the limiting state on the outer surface of the cone, a shear is possible according to the Coulomb law.

The analysis of the results of field studies carried out both at the Samarkand State Institute of Architecture and Civil Engineering and in other organizations showed that the strength propagation in the base is somewhat different from those determined by the theory of elasticity for homogeneous continuous media [3]. In fact, along the axis of the foundations, stresses are highly concentrated and therefore rapidly decrease in the horizontal direction. Obviously, the intensity of strength dissipation at the base essentially depends on the type of soil and its strength characteristics.

The working volume of the soil under a round the plate is represented as a truncated cone with an apex angle " $\alpha$ " where the shift is expected. The design diagram of VAE and subsoil is shown in Figure 2. To solve the task and

compose the equilibrium equation in the body of a truncated cone, we select an elementary layer with a height  $dz$ . Let us define the function of changing the radius along the depth  $z$ .

$$r = r_0 + ztg\alpha \quad ds = \frac{dz}{\cos\alpha} \quad (5)$$

Let us compose the equilibrium equation for all forces on the vertical axis:

$$dQ + \pi r^2 \sigma_z - \pi(r + dr)^2 (\sigma_z + d\sigma_z) + (\sigma \sin\alpha) 2\pi r ds - \tau(2\pi r) \cos\alpha ds = 0 \quad (6)$$

where  $dQ$  - self-weight of a layer  $dQ = \pi r^2 \gamma dz$ .

Determine the projection of normal forces on the horizontal axis

$$\sigma_x = \sigma \cos\alpha$$

Using the well-known regularity arising from the condition of soil strength

$$\xi = \frac{\sigma_x}{\sigma_z} = \frac{\sigma \cos\alpha}{\sigma_z} = tg^2 \left( \frac{\pi}{4} - \frac{\varphi}{2} \right)$$

and substituting these expressions into (6), we obtain

$$\begin{aligned} &\pi \gamma (r_0 + ztg\alpha)^2 dz - 2\pi (r_0 + ztg\alpha) \sigma_z tg\alpha dz - \pi (r_0 + ztg\alpha)^2 dz + \\ &+ 2\pi (r_0 + ztg\alpha) (\sigma \sin\alpha) \frac{dz}{\cos\alpha} - 2\pi \tau (r_0 + ztg\alpha) dz = 0 \end{aligned} \quad (7)$$

the solution of the homogeneous differential equation is represented in the form

$$\frac{d\sigma_z}{dz} + \frac{2tg\alpha \left( 1 - \frac{\xi}{\cos\alpha} + \frac{\xi tg\varphi}{\cos\alpha} \right)}{r_0 \left( 1 + \frac{z}{r_0} tg\alpha \right)} \sigma_z = \gamma - \frac{\frac{2C}{r_0}}{1 + \frac{z}{r_0} tg\alpha} \quad (8)$$

introduce the notation

$$A = \frac{2tg\alpha \left( 1 - \frac{\xi}{\cos\alpha} + \frac{\xi tg\varphi}{\cos\alpha} \right)}{r_0} = \frac{2tg\alpha}{r_0} \lambda \quad \lambda = 1 - \frac{\xi}{\cos\alpha} + \frac{\xi tg\varphi}{\cos\alpha}$$

or

$$\frac{d\sigma_z}{dz} = -A \frac{dz}{1 + \frac{z}{r_0} tg\alpha} \quad (9)$$

Taking into account the boundary conditions  $z=0, \sigma_z = q$  and integrating expression (8) we finally obtain.

$$\sigma_z = \frac{1}{tg\alpha} \left[ \frac{\gamma r_0}{2\lambda+1} \left( 1 + \frac{z}{r_0} tg\alpha \right) - \frac{c}{\lambda} \right] + \left[ q - \left( \frac{\gamma r_0}{2\lambda+1} - \frac{c}{\lambda} \right) \frac{1}{tg\alpha} \right] \left( 1 + \frac{z}{r_0} tg\alpha \right)^{-2\lambda} \quad (10)$$

Expression (10) allows you to analytically determine the magnitude of normal strengths for an arbitrary depth and accepted contour conditions according to the truncated cone model.

**Example.** Determine the changes in normal strengths for a weightless foundation along the VAE depth using expression (8). Radius  $r_0 = 0,25$  m. length  $z=l=6$  and  $3$  m. lateral stress coefficient  $\xi = 0,25$ , strength characteristics of soil surrounding VAE  $\varphi = 25^\circ$   $c = 20$  kPa. Load on the surface of VAE  $P = 400$  kN,  $q = 2050$  kPa.  $\alpha = \frac{\varphi}{4} \cong 6^\circ$ . The calculation results in the form of a graph are shown in Fig. 3. The average strength across the VAE tip is 210 kPa. This amounts to approximately 41 kN, i.e. 1/10 of the load. With a decrease in the VAE length to 3 m, respectively, the frontal strength and force increase, respectively, to 480 kPa and 95 kN.

Thus, the presented calculation model allows, depending on the strength characteristics of soils, to determine the length and section of the VAE. When calculating the VAE length  $L$  is selected in such a way that under its tip the reactive strengths do not exceed the permissible value of the design resistance  $R$  taken for pile foundations.

The vertical displacement of the "VAE-base" system with a linear relationship between relative deformations and strengths in the case of a linear statement of deformation and strength are in the following relationship:

$$s_z = s_{BAЭ} + s_0 \tag{11}$$

Where  $s_{VAE}$ ,  $s_0$  - accordingly, the displacements and settlements of the VAE itself and the base soils located below the bottom of the VAE. For concrete VAE when the condition  $D/L \geq 0.075$  can be taken  $s_{VAE} \cong 0$ . In other cases, vertical displacements and subsidence of the base are determined by the traditional method by the expression:

$$s_z = \sum_{i=0}^{i=L} \frac{\sigma_z}{E_{0i}} \Delta h + \sum_{i=L}^{i=H_s} \frac{\sigma_z}{E_{0i}} \Delta h \tag{11^1}$$

In this case, the settlement of the soil layer is determined by summing the relative deformations of the

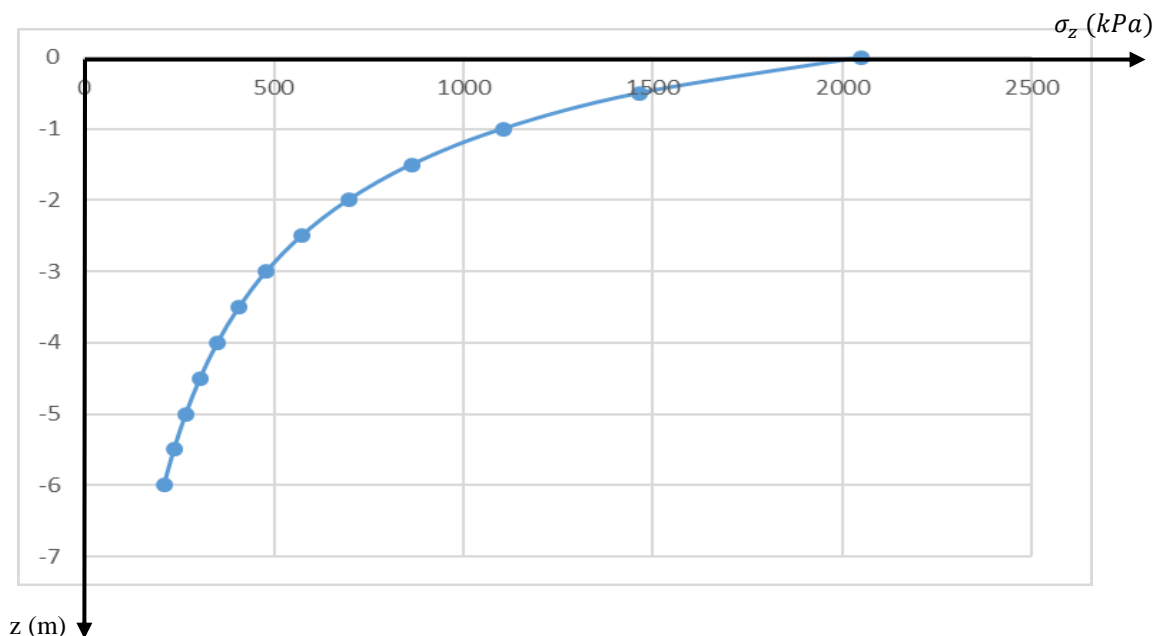


Fig. 3. Graph of changes in axial normal stresses along the VAE axis with depth

elementary layers of the VAE and the soil.

**CONCLUSIONS**

1. Depending on the longitudinal stiffness and stability, VAE can be conditionally divided into rigid, pliable and flexible. Concrete and transformed in the form of cement-soil VAE with aspect ratio  $D / L \geq 0.075$  are categorized as rigid,  $0.075 \leq D / L \leq 0.05$  of final stiffness and, if less than  $D / L \leq 0.05$ , flexible. Ground piles are flexible.
2. Determination of the design bearing capacity with specific VAE dimensions according to expression (3) is possible only with control testing of it for compression. Any design changes to the VAE geometry do not allow reuse of the initial test results. For this reason, it is recommended to determine the determination of the bearing capacity and permissible loads on the VAE on the basis of the accumulated test examples carried out in specific engineering and geological conditions of the area. The proposed expressions (10, 11) make it possible to more accurately determine the carrying capacity of VAE in separately identified geological conditions of the area.
3. The proposed design model makes it possible to determine the load-carrying capacity of VAE for multilayer bases with different strength parameters and its geometric dimensions. In this case, the VAE length is limited with the condition that  $\sigma_z \leq R_s$

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