The critical forces in the weak ground under the influence of technogenic relief

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Abstract. The initial critical force that the ground is exposed to from the weight of a structure is one of the main characteristics of the "structure-ground environment" system. A significant part of grounds are classified as weak, and the strain modulus value does not exceed 5 MPa. These soils have a weak load-carrying capacity and they are significantly deformed by the weight of the structures and the static load of technogenic relief. The theory and methodology of determining the initial critical force and its maximal action depth for various two-dimensional technogenic land forms, the force diagrams of which are described by trapezes and triangles of various types, are considered. The models grounds considered herein are a homogeneous elastic half-space or horizontally layered strata on the surface of a homogeneous elastic half-space. The nomograms of the relations of the initial critical force and its maximum depth of action to the ground’s physical and mechanical properties are attained. The identified relations are quasi-linear and the value of the initial critical force increases with an increase in the ground’s physical and mechanical parameters. The presented nomograms significantly simplify the calculation of the initial critical force in the ground.

1. Introduction
Artificial or technogenic positive and “negative” land (relief) forms of various geometric kinds are often formed during the construction of various buildings and structures. The ground environment is deformed by the static load conditioned by technogenic land forms. The level and kind of deformation (elastic, elastoplastic, plastic) are determined by the kind of ground and its physical mechanical properties. The minimal physical mechanical property values among all types of soils are found in the soils referred to the weak category and most pliant to deformation [1-10].

The setting of ground under the influence of vertical static load from technogenic land forms goes through several phases, including elastic deformations, compaction, sliding, and heaving. The phase of the outstanding interest to the evaluation of the ground’s carrying capacity or design ground resistance $R$ is the sliding phase when limit equilibrium zones form in the ground. In this case, the ground does not become compact and is considered incompressible (in this phase Poisson’s ratio is close to 0.5), whereas the pressure on the ground is scalled initial critical force $P_{cr}$. According to theoretical and experimental studies [11], the value of this force depends on the ground’s physical mechanical properties and on the power characteristics of static load produced by various technogenic land forms. These properties of the ground and static load also determine maximal depth $z_{max}$ at which the initial critical force shows.
The task of finding $P_{cr}$ and $z_{max}$ is considered in the 2D version according to Hooke’s law for two models of the ground environment. The first model is a homogeneous heavy elastic half-space in hydrostatic stress state; the second model is horizontally layered strata on the elastic half-space surface; the strata do not exceed three in number, and one of them is saturated with water [11].

The geometry of positive and negative technogenic land forms is represented by various kinds of triangles and trapezes. These forms correspond to earth dams, earth fills, dirt piles, and slag heaps. The kinds of distributed load plots correspond to the geometric forms of technogenic relief.

The stress state in ground environment models was found as the sum of stresses conditioned by the weight of technogenic land forms and the ground environment. The physical mechanical properties of the ground environment corresponded to weak grounds [1-10].

The task solution procedure relied on the formulas describing main stresses $\sigma_1$ and $\sigma_2$ for various kinds of distributed load corresponding to technogenic land forms [12]. These formulas and the limit equilibrium condition are used to find the function of depth $z$, at which the force, conditioned by the weight and physical mechanical properties of the ground and technogenic land forms is generated. The analysis of this function allows finding maximal depth $z_{max}$ at which the critical load will be effective.

2. Results and discussion

Let us consider the described procedure of finding the initial critical force and the maximal depth, at which it shows, by the example of the model of a 1D half-space burdened with distributed load the plot of which is described with an equilateral triangle (Figure 1).

The half-space is found in hydrostatic stress state at which $\sigma_x = \sigma_y = \gamma z$ can be taken, where $\sigma_x$ and $\sigma_y$ are the initial values of horizontal stress components; $\gamma z$ is the load from the weight of the ground at depth $z$. The stress state in the half-space at depth $z$ is generated by the half-space’s weight and the influence of the static load conditioned by technogenic land forms. The task is about finding the value of critical load $P_{cr}$ at which the limit equilibrium area reaches $z_{max}$.

Main stresses $\sigma_1$ and $\sigma_2$ for the static load shaped as an equilateral triangle are found as follows [12]:

$$\sigma_1 = \frac{P}{\pi a} [a(\alpha_1 + \alpha_2) + x(\alpha_1 - \alpha_2) - z \ln \rho] + \frac{Pz}{\pi a} \sqrt{\ln \rho} + (\alpha_1 - \alpha_2)^2 + \gamma z; \quad (1)$$

$$\sigma_2 = \frac{P}{\pi a} [a(\alpha_1 + \alpha_2) + x(\alpha_1 - \alpha_2) - z \ln \rho] - \frac{Pz}{\pi a} \sqrt{\ln \rho} + (\alpha_1 - \alpha_2)^2 + \gamma z. \quad (2)$$

where $2a$ is the length of the action base of load $P$, and $\alpha_1$ and $\alpha_2$ are the visibility angles of the load action base from random point $M(x,z)$,

$$\rho = \frac{R_1 R_2}{R_0^2}.$$

The limit equilibrium equation is

$$\sigma_1 - \sigma_2 = 2 \sin \varphi \left( \frac{\sigma_1 + \sigma_2}{2} + C \cot \varphi \right). \quad (3)$$

Here $C \cot \varphi$ is the coherence pressure, $C$ is the specific cohesive ground adhesion, $\varphi$ is the ground’s internal friction angle.
The expression for the z coordinate derived from considering (1), (2), and (3) together and making obvious conversions is recorded as

\[ z = \frac{[a(\alpha_1 + \alpha_2) + x(\alpha_1 - \alpha_2)] + \frac{\pi aC}{P} \text{ctg } \varphi}{\frac{1}{\sin \varphi} \sqrt{\ln \rho^2 + (\alpha_1 - \alpha_2)^2} + \frac{\pi a \nu}{P} \sin \varphi + \ln \rho}. \]  

\[ (4) \]

The analysis of function (4) for extremum for variables \( \alpha_1 \) and \( \alpha_2 \) allows finding, at the calculated values of these angles, largest coordinate \( z_{\text{max}} \), at which critical effort \( P_{\text{cr}} \) is generated:

\[ z_{\text{max}} = \frac{[a(\alpha_1 + \alpha_2) + x(\alpha_1 - \alpha_2)] + \frac{\pi aC}{P} \text{ctg } \varphi}{0.96 - \sin \varphi \ln \rho + 0.4(\alpha_1 - \alpha_2) \sin \varphi} \]

\[ (5) \]

We assume that this value of \( z_{\text{max}} \) corresponds to critical load \( P_{\text{cr}} \). This load is found using the equation taken from [12] and recorded as

\[ z_{\text{max}} = \frac{0.88PB}{C_z} \]

\[ (6) \]

where \( C_z = E/(1 - \nu^2) \) is the elastic half-space coefficient, \( B = 2a \) is the length of the load action base, \( E \) is Young’s modulus, \( \nu \) is Poisson’s ratio (\( E \) and \( \nu \) are taken as constant for the half-space).

If to equate the right parts of (5) and (6), we shall have

\[ MP^2 + NP + L = 0, \]

\[ (7) \]

Where

\[ M = 1.76 \left[ 0.96 - \frac{\sin \varphi}{\sin \varphi} \ln \rho + \frac{0.4(\alpha_1 - \alpha_2)}{\sin \varphi} \right]; \]

\[ N = - \left\{ C_z \left[ (\alpha_1 + \alpha_2) + \frac{x}{a}(\alpha_1 - \alpha_2) \right] + 1.76a \nu \right\}; \]

\[ L = -\pi C_z \text{ctg } \varphi. \]
The formula for finding critical load is derived by solving quadratic equation (7) and recorded as

$$P_{cr} = \frac{N}{2M} \left\{-\left[1 + \left(1 - \frac{4ML}{N^2}\right)^{-\frac{1}{2}}\right]\right\}$$ (8)

Figure 2. Relation of critical load $P_{cr}$ to specific ground weight $\gamma$ at constant values of adhesion $C$ (a); specific ground adhesion $C$ at constant values of specific ground weight $\gamma$ (b).
Formulas (5) and (8) were used to find relations of critical load $P_{cr}$ and its maximal action depth $z_{max}$ for various values of physical and mechanical characteristics. For the calculation results see Figures 2 and 3.

**Figure 3.** Relation of coordinate $z_{max}$ to specific ground weight $\gamma$ at constant values of adhesion $C$ (a); specific ground adhesion $C$ at constant values of specific ground weight $\gamma$ (b).
3. Conclusions
It follows from the results of the calculations made for the specified model and the results of the calculations according to other models for external loads, the plots of which are described by various relations [11], that the ground’s limit state from the action of static load is generated at a certain depth and depends on the physical and mechanical characteristics of the ground:
- $P_{cr}$ and $z_{max}$ quasi-linearly increase with an increase in the ground’s physical and mechanical characteristics in all the studied cases (for all the models), which indicates that the ground’s carrying capacity improves;
- the critical effort for the $P_{cr} (\gamma)$ function increases not only with an increase in $\gamma$ but also with an increase in $C$ and $\phi$;
- the critical effort for the $P_{cr} (C)$ function increases mainly through an increase in specific adhesion $C$, whereas it does not increase much with an increase in $\phi$ and $\gamma$ (by about 8% only).

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