Ensuring the Stability of Geocomposite Systems While Protecting Against Erosion of Slopes of Soil Structures

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Abstract. The problem of erosion processes constantly arises during the development of coastal territories. Previously considered uncomfortable territories are now subject to development. The investment attractiveness of such territories is very high, therefore, it is necessary to carry out engineering preparation measures, including to protect it from erosion processes. As studies show, the most environmentally friendly structures for the prevention of erosion processes are geocomposition systems based on anti-erosion geosynthetics. But before applying any measures to stabilize erosion processes, it is necessary to understand the process of interaction of applied methods with protected surfaces. The article considers the division of coastal slopes into three zones: not flooded, partially flooded and constantly flooded. Accordingly, this separation was carried out in order to determine the possible effects on the design of geocomposition systems. Each impact (hydraulic, snow, ice) is described using mathematical modeling, indicating methods for calculating the stability of the geocomposition system for the zones defined in the study. It is established that the strength of a geocomposite system also affects its stability, therefore, the concept of tensile strength is introduced into the formulas for determining the overall stability of a geocomposite system. The materials presented are important in practical application. This is due to a reduction in material and labor costs for the implementation of erosion protection measures when applying the results of this study. Further studies are aimed at optimizing the design of anti-erosion protection based on geocomposition systems in order to organize their in-line production and the creation of typical industrial designs.

1. Introduction
The problem of erosion protection is not new. For the urban environment, this problem, like other exogenous geological processes, creates inconvenience in the development of territories[1,2,3,4]. Currently, cities are developing through the use of previously uncomfortable territories that were difficult to develop. Territories prone to gully formation were not previously considered as potentially suitable for development. Most of these territories were devoted to beautification, parks, recreational areas, i.e. those territories that did not require significant capital investments for their development and did not have a special impact on security, due to the lack of capital facilities. Territories subject to erosion processes have a very high investment attractiveness, as located, as a rule, on the banks of water bodies.
In this article, geocomposite systems developed on the basis of geosynthetic anti-erosion mats are considered as anti-erosion protection, which, as the studies show, being environmentally friendly, create reliable protection of soil surfaces from erosion processes.

2. Relevance
Considering that erosion is a slope process, in addition to the main task, erosion protection, it is necessary to ensure stability on the slope of the materials used, since in the case of local or complete destruction of the methods used, the efficiency is reduced to a minimum. Accordingly, ensuring the stability of erosion protection on the slope is a prerequisite for its reliable operation.

This problem in their works was considered by Goncharov N.A., Alekseev A.A., Makkaveev N.I., Chalov R.S., Mirtskhulava Ts.E., Scherbina E.V. and other authors\cite{1,6,8,9,11,15,17}.

3. Scientific significance of the issue
Considering the process of development of erosion processes on the slopes and shores of the city’s water bodies, three main zones can be distinguished, where erosion has various sources of occurrence: a non-flooded zone, a zone of variable water level, and a zone constantly under water.

In the first zone, erosion is caused only by surface runoff, in the second zone, erosion is a process occurring under the influence of both surface runoff and wave action, and in the third zone, erosion is already a channel process.

4. Formulation of the problem
Given that each zone of the protected coastal slope has a different effect, therefore, the design schemes for ensuring the stability of the protective screen in each zone will be different.

For the first zone, where the presence of water is caused only by surface runoff, which is formed as a result of precipitation, it is possible to adopt the design scheme developed by A. Alekseev \cite{5}:

5. Theoretical part
The stability of the system, the design scheme of which is presented in Fig. 1\cite{1,3}, will be provided, if the following conditions are met:

\[
\sum F_h = \sum F_s \cdot K_{st},
\]

\[
\begin{align*}
\sum F_h & \quad \text{holding force (kN)}; \\
\sum F_s & \quad \text{shear forces (kN)}; \\
K_{st} & \quad \text{safety factor}.
\end{align*}
\]

Figure 1. Design diagram of the stability of the geocomposite system on the slopes of zone 1 (1-soil-plant layer; 2-base soil; 3 - anti-erosion geomat).
In this case, the main shear force will be the pressure of the dead weight of the filler of the geocomposition system:

\[ F_s = F_{sw}, \]

\[ F_{sw} = G_i \cdot \sin \alpha, \] (2) (3)

\[ G_i \] - geocomposition system section weight;
\[ \alpha \] - slope angle;

Be sure to take into account the load from the snow cover, respectively, the dead weight of the geocomposition system section, taking into account the snow load, can be calculated by the following dependence:

\[ G_i = (\gamma_n \cdot h_n + \gamma_s h_s) \cdot L_i, \] (4)

\[ \gamma_n \] - the specific gravity of the filler of the geocomposite system (kN / m³) in this case, the specific gravity of the erosion control mat can be neglected, since it is not significant compared to the specific gravity of the filler
\[ \gamma_s \] - specific gravity of snow cover (kN / m³);
\[ h_n \] - thickness of the geocomposition system (m);
\[ h_s \] - thickness of snow cover (m).

When using anti-erosion mats as engineering protection, when calculating the holding forces, it is necessary to take into account the tensile strength of the geosynthetic material, \( P \), (kN / m):

\[ \sum F_h = F_t + F_a + \frac{P}{K_z}, \] (5)

\[ K_z \] - safety factor for tensile strength for geosynthetic material.
\[ F_t = G_i \cdot \cos \alpha \cdot \tan \varphi \]
\[ G_i, \alpha \] - same as in formula 3;
\[ \varphi \] - angle of internal friction at the contact of the base soil and the geocomposite system (determined experimentally).

\[ F_{ad} = a \cdot L_i, \] (6)

\[ a \] - adhesion between the geocomposite system and the base soil (kN / m²).

As a rule, in the initial period after laying, the value of adhesion is minimal; accordingly, it can be ignored in the calculations. Over time, the value of adhesion may increase. And since adhesion belongs to the holding forces, accordingly, its value will go to the stability margin [12].

These calculations are valid for elementary (\( \Delta x \)) lengths of the slope \( L_i \). To determine the stability of the geocomposite system along the entire length of the slope, it is necessary to calculate the step of fixing it with anchors \( L_z \). To do this, you must accept \( L_i = L_z \). Then from the condition (5):

\[ L_z = \frac{P}{K_z (F_s \cdot K_{st} - F_h)}, \] (7)

As experiments show, the value \( L_z \), as a rule, almost always exceeds the technological step of fixing the geocomposite system, which is designed to ensure its tight fit to the surface of the slope. The experience of application on real objects shows that the optimal step of technological fastening of the geocomposite system is 1 m. The use of anchors significantly reduces the load on the geosynthetic material and makes it possible to use anchors of smaller thickness and length, which reduces resource consumption.

The calculation of the stability of the geocomposition system for the second zone, where the effect of water is temporary, should include additional loads: in the warm period - from the roll of waves, in winter - with the temperature expansion of ice.

In general, the calculation is similar to the above, with the exception of the values of shear and holding forces. In the summer, the shear force will be equal to:

\[ \sum F_s = F_{sw} + F_w, \] (8)

\[ F_{sw} \] - same as the formula (2);
$F_w$ – force from hydraulic action;

The hydraulic action of the run-up of waves is defined as:

$$F_w = 0.5 \cdot \gamma_w \cdot \gamma_{sk} \cdot i \cdot h_w \cdot l \quad (9)$$

- $\gamma_w$ – specific gravity of water;
- $\gamma_{sk}$ – safety factor;
- $i$ – hydraulic gradient, for slopes with a laying angle $\alpha = i = \sin \alpha$;
- $h_w$ – water depth, m.
- $l$ – drain path length, m.

The holding force in this case will remain unchanged and will be the same as in (5)(fig. 2).

**Figure 2.** Calculation scheme of the stability of the geocomposite system on the slopes of zone 2 in the summer (1-soil and plant layer; 2-base soil; 3 - anti-erosion geomat).

In winter, the structure is affected by a linear load $F_l$, from a continuous ice cover with its temperature expansion [1,4,7,10], increasing the holding force (Fig. 3) is determined by the formula (10)

$$F_l = h_{max} k_l p_t, \quad (10)$$

- $h_{max}$ – maximum thickness of ice cover, m;
- $k_l$ - the coefficient adopted according to table 1;

**Figure 3.** Design diagram of the stability of the geocomposite system on the slopes of zone 2 in the winter (1-soil-plant layer; 2-base soil; 3 - anti-erosion geomat).
Table 1. Coefficient value $k_l$.

| The length of the ice cover $L$, м | 50 и менее | 70 | 90 | 120 | 150 and more |
|-----------------------------------|------------|----|----|-----|--------------|
| Coefficient $k_l$                | 1          | 0.9 | 0.8 | 0.7  | 0.6          |

$p_t$ - pressure due to elastic and plastic deformations, MPa, with temperature expansion of ice, determined by the formula

$$p_t = 0.05 + 11 \cdot 10^{-5} \nu_{ta} \cdot \mu_i \cdot \varphi,$$

$v_{ta}$ - maximum rate of increase in air temperature, °C/h, during $t$, h;

$\mu_i$ - coefficient of viscosity of ice, MPa/h, determined by the formulas:

at $t_i \geq -20$°C

$$\mu_i = (3,3 - 0,28t_i + 0,083t_i^2) \cdot 10^2,$$

at $t_i < -20$ °C

$$\mu_i = (3,3 - 1,85t_i) \cdot 10^2,$$

$t_i$ - ice temperature, °C, determined by the formula

$$t_i = t_b \cdot h_{rel} + \frac{\nu_{ta}}{2}\Psi.$$

$t_b$ - initial air temperature, ° C, from which its increase begins;

$h_{rel}$ - relative thickness of the ice cover, taking into account the influence of snow, determined by the formula

$$h_{rel} = \frac{h_{max}}{h_{red}},$$

$h_{red}$ - reduced ice cover thickness, m, determined by the formula

$$h_{red} = h_{max} + 1.43 \cdot h_{s, min} + \frac{2.3}{\alpha},$$

$h_{s, min}$ - the smallest snow cover for the billing period, m, determined from field observations, and in their absence, it is necessary to take $h_{s, min} = 0$;

$\alpha$ - heat transfer coefficient from air and snow surface, W / m², taken equal in the presence of snow

$$\alpha = 23^{\frac{1}{3}}\nu_{w,m} + 0.3,$$

in the presence of snow

$$\alpha = \frac{t}{\nu_{w,m}} + 0.3,$$

$\nu_{w,m}$ - average wind speed, m / s;

$\Psi, \varphi$ - dimensionless coefficients taken from the graphs of fig. 4, 5 at given values of the relative thickness of the ice sheet $h_{rel}$ and dimensionless quantity

$$F_0 = \frac{4 \cdot 10^{-3} \cdot t}{h_{2red}}.$$

$t$ - time interval, h, between two measurements of air temperature.
In the summer period of time, an increase in the value of the shear force is exerted by the action of water from the wave runoff, which accordingly leads to a decrease in the safety factor of the geocomposite system as a whole, and in the winter period the holding force increases, while, accordingly, this coefficient increases [4,7,10,13]. Consequently, the worst conditions for ensuring the stability of the geocomposite system arise in the summer. Thus, when determining the stability of a geocomposite system in the second zone, it is necessary to use formulas (8) and (9).

In the third zone, the entire geocomposition system is under water, while the shear and holding forces are calculated by the formulas (1 and 2, respectively), but the weight of the section changes, which is caused by the weighing effect of water.

The weight of the elementary section of the geocomposition system located in zone 3 will be [10,14,20]:

\[ G_i = (\gamma_{nap} - \gamma_w) h_{gs} \cdot l_i, \]  

(20)

- \( G_i \) – weight of the elementary section of the geocomposition system;
- \( \gamma_{nap} \) – geocomposition system filler density (kN/m³);
- \( \gamma_w \) – density of water (kN/m³);
- \( h_{gs} \) – geocomposition system thickness (m);
Tensile strength consideration \( P \), (kN/m) and calculation of the pitch of the placement of anchors for zones 2 and 3 is performed according to formulas (5) and (7), respectively, taking into account the values of the shear and holding forces obtained for each zone. Thus, despite the fact that the slope, protected from the development of erosion processes, is continuous along the entire length, several stability calculations are necessary. The design scheme depends on the slope location zone. Each zone is characterized by various influences, on which the calculation scheme depends. For the first zone it is surface runoff and snow load, for the second - wave and ice load, for the third - the weighing effect of water.

6. Practical significance, proposals and results of implementation, the results of experimental studies

The results of long-term experimental studies at the Lower Tsaritsynsky Pond facility in Moscow confirm the reliability of the studies. Prototypes of protective structures were made taking into account the impacts for each of the zones. The materials were laid in such a way that each zone corresponded to its own sample of material. After a year of operation, the state of geocomposition systems was evaluated, which confirmed the results of mathematical modeling.

The practical significance of the research is to formulate sustainable protection of the city’s water bodies from the development of erosion processes based on the most environmentally friendly materials that do not negatively affect the flora and fauna of water bodies and coastal areas.

7. The conclusion

Protection from the erosion of the coast of urban water bodies is one of the main both in the development of uncomfortable territories and in the reconstruction of already built-up territories. To reduce the negative impact of environmental factors on the flora and fauna of urban water bodies, it is necessary to implement environmental friendly measures, one of such measures is the creation of an environmentally friendly geocomposition system that can protect coasts from erosion. Studies have shown that this method of protection is subjected to various influences depending on the location zone, therefore, the problem arises of determining these effects and developing the structure of the geocomposition system. The article addresses the above issues and presents a mathematical model confirmed by experimental studies. Further development and research will be aimed at optimizing the structure and filler of the geocomposition system and creating an industrial design.

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