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Impact of retaining walls' structural solution on their stability increase in seismic regions

Impact de la solution structurelle des murs de soutènement sur leur augmentation de stabilité dans les régions sismiques

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ABSTRACT: The paper develops ideas about formation nature of a stressed and deformed state during loading of cantilever retaining walls and walls formed from separate blocks and reinforced with geomaterials. Traditional concept of linear sliding surfaces is being replaced by nonlinear sliding areas, recorded by the results of laboratory tests of retaining wall models. Surfaces of destruction in static and seismic conditions for cantilever retaining walls were obtained with various variants of structural solution. Obtained results make it possible to select a variant of the wall design and perform calculations on stability and serviceability of cantilever retaining walls.

RÉSUMÉ : L'article développe des idées sur la nature de la formation d'un état contraint et déformé pendant le chargement de murs de soutènement en porte-à-faux et de murs formés de blocs séparés et renforcés avec des géomatériaux. Le concept traditionnel de surfaces de glissement linéaires est remplacé par des zones de glissement non linéaires, enregistrées par les résultats des tests en laboratoire des modèles de murs de soutènement. Des surfaces de destruction en conditions statiques et sismiques pour les murs de soutènement en porte-à-faux ont été obtenues avec différentes variantes de solution structurelle. Les résultats obtenus permettent de sélectionner une variante de la conception du mur et d'effectuer des calculs sur la stabilité et l'aptitude au service des murs de soutènement en porte-à-faux.

KEYWORDS: base, soil, strength, deformation, sensor, sliding surface, geosynthetic material.

1 INTRODUCTION

Population well-being of the Republic of Kazakhstan largely depends on living conditions and quality of their own housing. An important indicator of the country's economic development is affordability of housing and possibility of purchasing it. The pace of construction industry development is clearly visible in large cities such as Nur-Sultan, Almaty, etc. Construction industry in Kazakhstan faces many problems. But one of the most important is the variety of engineering geological and climatic conditions. Geological conditions of the South of Kazakhstan are characterized by distribution of different types of soils. There are strong gravel deposits, loess macroporous subsidence soils are widespread. Soft soils are especially common in mountainous and foothill areas, forming surface sediments. To create the required infrastructure of cities in such places, there are arranged retaining walls of a monolithic and prefabricated structural solution of different heights and complexity. Such structures increase the cost of construction, so customers are trying to save money and simplify their structural designs at the price of quality and reliability. Such an approach is unacceptable when people's lives depend on the reliability of retaining structure. That is why this work compares various structural solutions of retaining walls by modeling them and checking the models on a special test-tank.

1.1 Method for retaining walls calculation

The current practice of performing calculations is based on the use of classical concepts of the mechanics of a deformable body, which are well described by Rankine's expressions and received experimental confirmation in the works of K.Terzaghi and others [1,2]. It is generally accepted that in homogeneous soils, the stressed and deformed state of the wall and adjacent soil are determined by the values of the active and passive pressures. Active pressure on the wall is formed when the wall moves away from the soil at the moment the soil moves towards the wall. Passive pressure on the wall is formed when the wall is pushed onto the soil at the moment the soil bulges. In design practice, it

is accepted that active and passive pressures are determined by the limit equilibrium method using linear sliding surfaces. Distribution of active pressure along the back face of the retaining wall is taken according to the linear law in Fig. 1. In this case, two schemes are considered: a symmetrical collapse prism with the length of the base plate, Fig. 1 (a); asymmetric collapse prism with a short slab, Fig. 1 (b). In both cases, the weight of the soil enclosed between the surface and the back surface of the wall is added to the weight of the wall in the stability calculation [3]. The angle of formation of the prism is determined:

$$\theta = 45 - \varphi/2 . \quad (1)$$

The value of active pressure is determined through the coefficient of active soil pressure λ_a . For the simplest scheme of a retaining wall with a vertical back face, a horizontal surface of the backfill soil, the coefficient will be:

$$\lambda_a = \operatorname{tg}^2 \mu , \quad (2)$$

$$\text{where } \mu = \frac{\pi}{4} - \frac{\varphi}{2}.$$

In case when an arbitrary vertical load is present on the backfill surface, the calculation is performed by the iterative method, while, as shown in Fig. 2. From the ends of the loading section, lines are drawn at an angle Θ to the vertical, again parallel to the sliding surface. Within the selected area A'B' of the contact face, the active pressure takes into account the value of the surcharge $\sigma_{ag} = g\lambda_{ag}$. At other areas AA' and B'B, the influence of external surcharge is not taken into account.

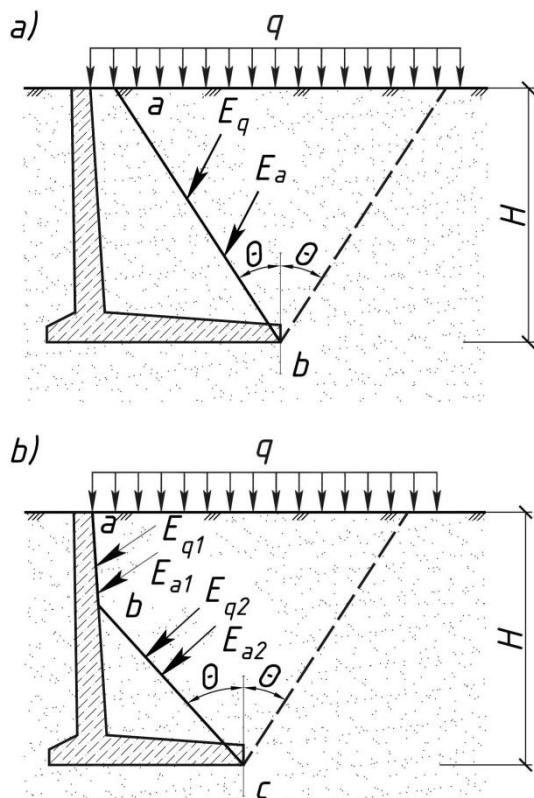


Figure 1. Scheme of sliding surfaces for determining active pressure for long (a) and short (b) base plates.

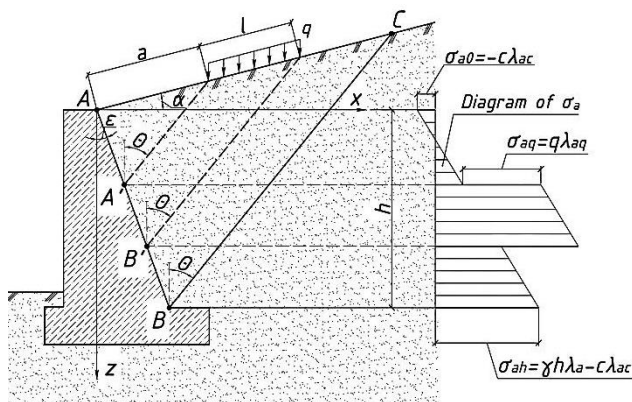


Figure 2. Scheme for constructing a diagram of active pressure under the action of the filling surface of a load of limited width.

Simplicity of the decisions made with the adoption of straight surfaces is undoubtedly captivating. However, it has long been pointed out [4] that during construction process and walls serviceability, there are displacements and deformations, which have a strong effect on the distribution of lateral pressure along the height of the retaining wall. As a result of the walls displacement, the stress-strain state of the soil near the wall change takes place, and the positions of the sliding areas of the limiting stresses change, respectively. This paper presents the results on limiting state area fixing during the operation of cantilever retaining walls.

The existing variety of structural design of retaining walls and the use of reinforcing materials makes it necessary to clarify the stressed and deformed state of backfill soils and the base of the

wall. This is especially important in conditions of seismic loading action [5,6].

To achieve this task, at the laboratory "Geotechnics in Construction" of KazGASA (Almaty city) carried out model studies of cantilever retaining walls loaded with a constant load that simulates the load from a low-rise building. The study of cantilever walls was carried out in a special test-tank with a transparent outer wall, which allows visual observation of soil deformation. The deformations were monitored using powder sensors located behind the transparent wall of the test-tank. Powder sensors are vertical strips made of talcum powder that deforms with the soil.

This allows to observe the development of shear deformations after the application of static and dynamic loads. The volume of the test-tank is 0.2m³. Length – 120cm, height – 80cm, width – 21cm.

1.1.1 Description of the soil model

To simulate a loess-like loam soil, a mixture with the following ratio of components was used: silty sand 83%, rubber chips 7%, spindle oil for the formation of particle cohesion 10%. The mass of the test soil is 100kg. The density of the soil was set approximately equal to 1.72-1.75t/cm³. The moisture content of the soil was approximately W = 20%. The dimensions of the cantilever wall are as follows: base slab (footing) – 200x200mm, wall (stem) height – 200mm, thickness – 15mm. Material – high strength plywood.

The impact from the structure was simulated by a flat stamp. Dimensions of the stamp in plan – 200x200mm. During tests in a static loading mode, the vertical load was created by a screw jack mounted on a stamp. The magnitude of the vertical load was recorded with a dynamometer DIN-1. The load was applied in steps of 0.5-1.0kN. The maximum pressure on the base of the stamp created over 100kPa. Deformations of the retaining wall's wall were recorded by deflectometers of PSK-MG4 type.

Seismic load was applied horizontally by harmonic vibrational movements of the test-tank. Intensity of the motions was varied by way of changing the frequency due to the change the rotation frequency of the seismic machine (generator). Intensity of the applied seismic action in the experiments varied from 5 to 8 magnitudes on the Richter scale. In all experiments, the deformed state of the backfill soil and the base of the wall was recorded using special powder sensors and methods of photo and film fixation. Contours (isoline) were recorded from the beginning of loading until the destruction of the wall. As a result, contours of the change in the deformed state of the backfill soil during loading and with a different number of reinforcing elements along the height of the soil backfill were obtained.

The paper presents the test results of six types of retaining wall models: three types of monolithic walls with different base slab (footing) configurations (models M1a, M1 and M2) and three models of prefabricated elements of 7-row blocks – models M1P, M2P and M3P – without geogrid, with 3 and 6 layers of reinforcing geotechnical grids, respectively, see Tables 1, 2.

The results of seismic load testing of retaining cantilever walls are shown in Fig. 3. Model M1a is different in that there is no soil that forms passive pressure. Models M1 and M2 differ by the length of embedment into the backfill soil. It is clearly seen that model M1a resists almost no external action and the shear deformation increases almost monotonically until collapse. Models M1 and M2 have approximately the same resistance to external dynamic influences, but model M2 has high stability. With an increase in seismic load, the nature of the resistance remains, but sharply increases in values.

Table 1. Test models of cantilever retaining walls

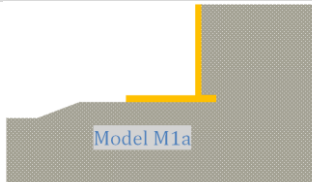
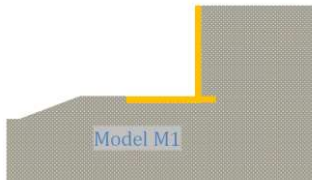
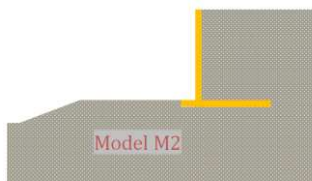
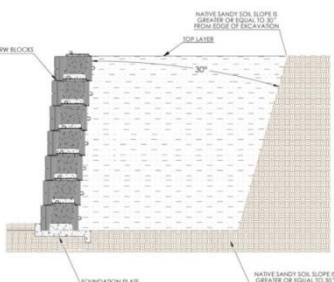
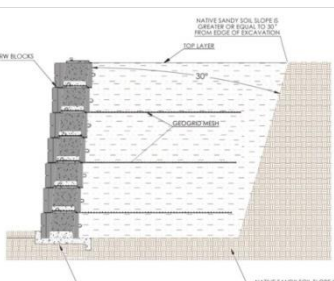
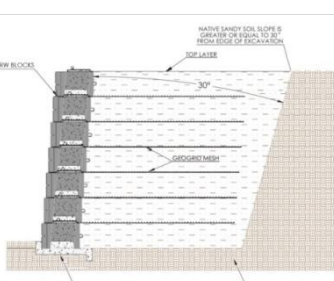
Cantilever retaining Wall Models		
Model 1aC		
Model 1C		
Model 2C		

Table 2. Test models of prefabricated retaining walls

Prefabricated Wall Models	
Model 1P. 7-row retaining walls without geogrid	
Model 2P. 7-row retaining walls with 3 layers of geogrid	
Model 3P. 7-row retaining walls with 6 layers of geogrid	

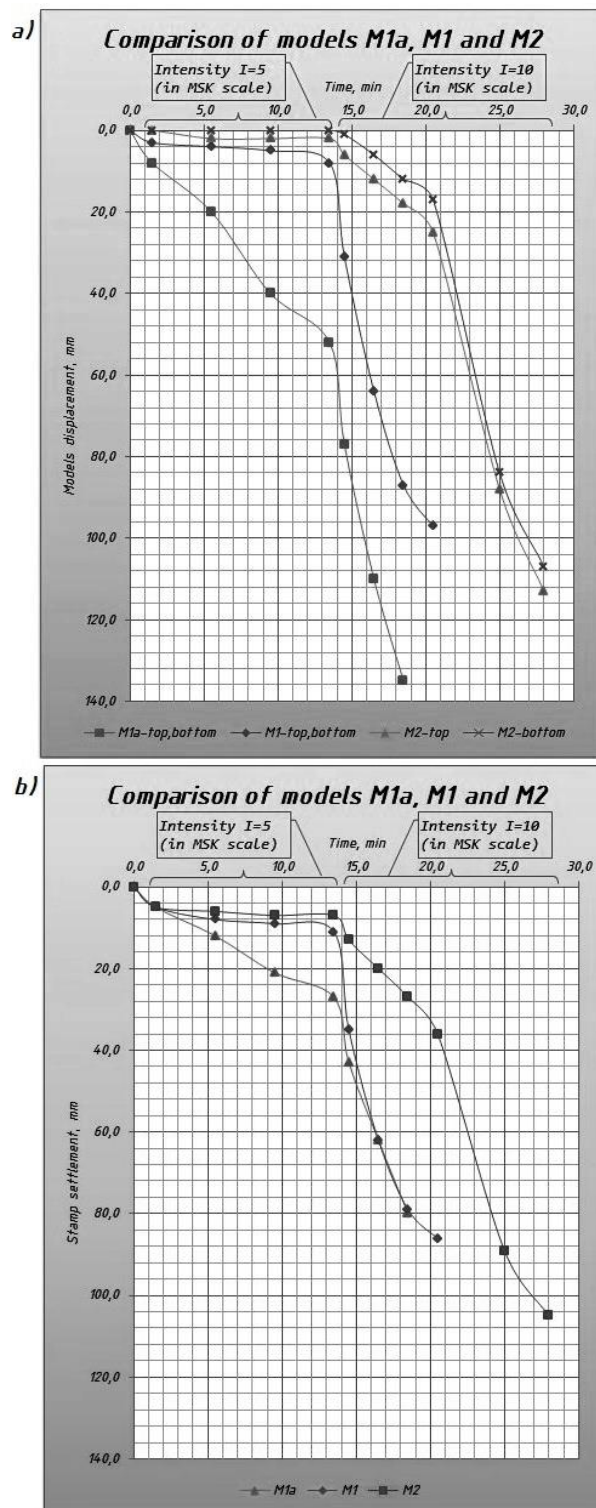


Figure 3. Test results of cantilever retaining wall models M1a, M1 and M2 by seismic load: a) models displacement; b) stamp displacement

An important role is played by the fact that it is loaded with backfill soil and there are large stresses from external loading, displacement deformations along the footing are less and the shape of the fixed sliding surfaces differs from traditional linear ones. When testing monolithic walls, specific differences were obtained in the formation of areas of destruction for different variants of the location of the footing of the wall. So the deformed state of the backfill soil causes the formation of areas

inside the backfill mass. And description of positions that requires more careful processing of the experimental material. There is also visible the influence of stability loss areas under the footing of the surcharge. Unfortunately, due to the volume limitation, the picture of the formation of areas of the limiting state at the stage of destruction is not presented. The main results and the formation of destruction areas are shown in Table 3.

Table 3. Test results for cantilever retaining walls

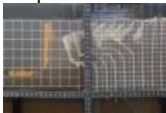
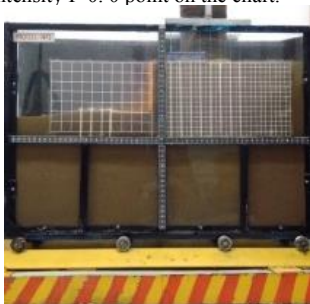
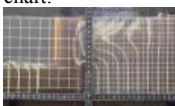
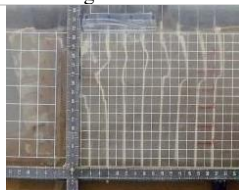
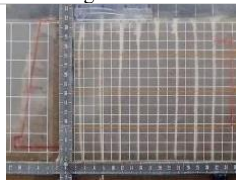
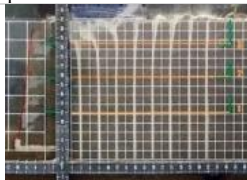
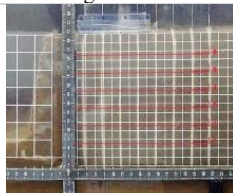
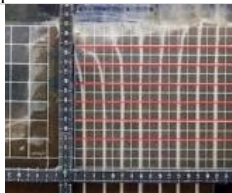
Seismic Impact on Model 1aC		
No dynamics. Intensity I=0. 0 point on the chart.		
		
Intensity I=5. 4th point on the chart.	Intensity I=10. 5th point on the chart.	Intensity I=10. 7th point on the chart.
		
Seismic Impact on Model 1C		
No dynamics. Intensity I=0. 0 point on the chart.		
		
Intensity I=5. 4th point on the chart.	Intensity I=10. 5th point on the chart.	Intensity I=10. 7th point on the chart.
		
Seismic Impact on Model 2C		
No dynamics. Intensity I=0. 0 point on the chart.		
		
Intensity I=5. 4th point on the chart.	Intensity I=10. 5th point on the chart.	Intensity I=10. 7th point on the chart.
		

Table 4. Test results of retaining walls from prefabricated blocks

Static and seismic impact on model M1P			
No statics and dynamics.			
			
Deformed state under increasing static load		Deformed state under seismic impact	
			
Static and seismic impact on model M2P			
No statics and dynamics.			
			
Deformed state under increasing static load		Deformed state under seismic impact	
			
Static and seismic impact on model M3P			
No statics and dynamics.			
			
Deformed state under increasing static load		Deformed state under seismic impact	
			

When testing retaining walls made of prefabricated blocks, it was found that without seismicity, only prefabricated walls with a height of up to 2.5 meters have sufficient stability. Stability of the walls with a height of more than 2.5 meters is ensured only with additional reinforcement of the mass with the layers of geogrids, which are firmly connected with prefabricated blocks that form the wall. At the same time, the nature of destruction under static loading and seismicity is different. Under static loading without geogrid strengthening of the area, stability losses are seen quite well. With 3 and 6 layers of reinforcing the backfilling soil of the typical destruction areas are not observed. Use of geomaterial in the backfilling soil forms a certain anisotropy of mechanical properties of the soil. In this case, processes of the formation of a deformed state are observed that are different in appearance from the isotropic composition. Minor horizontal deformations of the soil mass adjacent to the wall are visible. This testifies to the significant influence of geotechnical grids on the process of destruction areas formation.

Under seismic action without reinforcing soil backfill, the walls collapse almost immediately. Powder sensors clearly show the destruction areas of the mass (see Table 2, model M1P). Strengthening the mass with 3 or more layers of geogrids significantly increases the bearing capacity and stability of retaining walls. Destruction zone is formed only within the upper strengthened layer within one or two geogrids.

2 CONCLUSIONS

1. In the Republic of Kazakhstan, with the development of the infrastructure of cities located in mountainous and foothill areas, a large number of retaining walls of various designs are made. Usually these are cantilever or anchored walls, which serve to ensure the overall stability of slopes and are made of monolithic reinforced concrete or prefabricated, made of separate blocks and provide local stability of the slopes and mass.

2. When choosing a design solution and assessing the stress and strain state of the soil supported by the wall, linear sliding surfaces are taken into account, corresponding to the traditional concepts of linear soil mechanics, the position of which in the space of principal stresses is determined using the angle of internal friction. To increase their stability, material with a large value of the angle of internal friction is used for backfilling.

3. Special studies in the soil test-tank showed that with specific deformations and displacements, a visual fixation of the actual position of destruction areas of backfill soils was obtained and as a consequence, changes in the magnitude of active pressure along the height of the retaining wall. Positions of sliding areas were obtained for conditions of static and seismic loading, for cantilever walls with different design solutions and for retaining walls made of prefabricated blocks of different heights, reinforced with geogrids.

4. The stability of retaining walls with a height of 4.0m or more from prefabricated blocks can be increased by strengthening the backfill soil by laying three or more layers of geogrid. This leads to a certain anisotropy and changes the process of limiting state areas formation. The material of geogrid must have sufficient strength and deformation properties to ensure uniaxial strengthening of the soil in the direction of active pressure.

3 ACKNOWLEDGEMENTS

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