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Earthquake–Resistant Steepness of Slope Structures

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Abstract. This report presents the results of the authors' research on the development of a method for assessing the earthquake-resistant steepness of slope structures and experimental verification of the main provisions of the method. The internal and external factors that directly affect the stability of the oscillating slope are given. As an internal factor, the strength and deformation parameters of soil in the body of the slope are considered, depending on the type of soil, its granulometric and mineralogical state, the state of density-humidity, etc. The external factors are the slope loading and the dynamic effect (amplitude, frequency, period, duration). The stability of the slope steepness is also affected by the height of the slope, the method of its construction, and the soil liquefaction that occurs under the influence of concussions. An account for all these factors allowed the authors to propose a theoretical method for assessing the earthquake-resistant steepness of slope structures. Comparisons of the data counting with the results of experimental studies showed good convergence.

INTRODUCTION

In the practice of construction and operation of soil slopes (dams of hydraulic structures, embankments of roads and railways, levees, etc.), cases of sliding, melting, subsidence, liquefaction as a result of exposure to various dynamic loads were often observed. In most cases, they occurred during strong earthquakes and caused huge damage to the national economy. Scientists from Russia [1-4], Japan [5-8], the USA [9-14], Uzbekistan [15-20], and other countries studied the seismic stability of soils as part of slope structures.

Several publications [21-28] investigate the stability of slopes and the dynamic behavior of various earth dams, and consider dynamic processes in systems working together with soil media, taking into account their design features and soil properties.

Here is a brief overview of some of the publications devoted to the problem of studying the strength and dynamic behavior of earth structures.

Specialists who studied the consequences of earthquakes noted several possible reasons that led to the damage of slope structures under vibrations. The main ones include insufficient strength of soil as part of the slope, non-compliance of the soil density with the requirements of state normative documents (GOST), additional moistening of soil during the operation of structures, failure to take into account the dynamic pressure that occurs in pore water with additional compaction of the soil in conditions of oscillation, problems associated with the height and steepness of the slope, etc.

However, to date, there is no generalizing method for assessing the stability of slope structures. Summing up the results of this review, it should be noted that the problem of assessing the stability of slopes and the dynamic behavior of earth structures, taking into account various soil properties and the features of acting loads, is far from a final solution presents an urgent task.

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RESEARCH METHOD

Following Fig. 1, the coefficient of the short-circuit stability margin of a small volume with a thickness of z^1 installed on a flat slope with a slope *a* is expressed as short-circuit.

$$\kappa_з = \frac{T}{Q}, \tag{1}$$

where *T* is the shear resistance force of the selected volume; *Q* is the force that shifts the selected volume.

In this case, a violation of the slope stability can occur in the following cases: an increase in the seismic shear stress (τ_c) or a decrease in the resistance to soil shear ($S_{\sigma,w}$).

The first case, related to the tangential impact of an earthquake (τ_c) is associated with natural conditions. In our case, it is expressed by seismic acceleration (α_c) in the form [16]:

$$\tau_c = 0,64\, \gamma_w H k_s, \tag{2}$$

where k_s is the coefficient of seismicity.

The soil resistance to shear under the influence of seismic acceleration α_c is expressed as [19]:

$$S_{\sigma,w} = \sigma_{din} tg\varphi_{w+} c_v \tag{3}$$

where σ_{din} are the dynamic stresses from the external load (*p*) and the natural weight of the soil ($\gamma_w H$).

In cases of concussion under conditions exceeding the threshold value,
i.e., $a_s > a_t$ (where a_s, a_t - are the seismic and threshold accelerations, respectively):

$$S_{\sigma,w}(t) = (\sigma_{din} - \gamma_{в.} h_{z,t})\, tg\varphi_{w+} c_{v,t} \tag{4}$$

In the absence of external loads on the soil surface, i.e., (p=0):

$$S_{\sigma,w}(t) = (\gamma_{w.} H - \gamma_{в.} h_{z,t}) tg\varphi_{w+} c_{v,t} \tag{5}$$

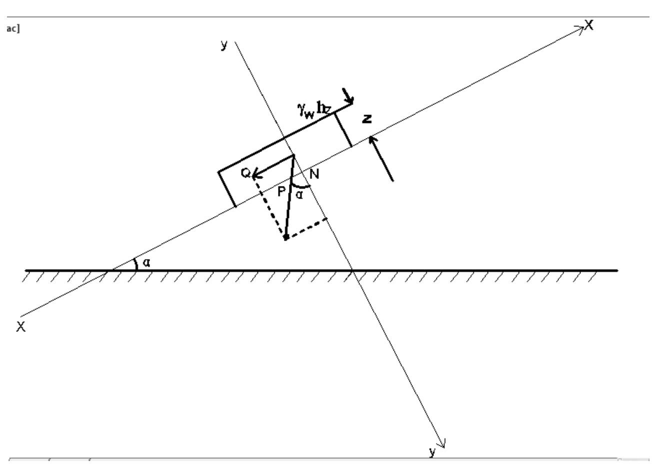

FIGURE 1. Design scheme for assessing the degree of slope stability.

Hence, earthquake-resistant steepness of the slope following the expression (1) is provided in the margin:

$$k_m = \frac{0,64\, \gamma_w H k_s}{\sigma_{din} tg\varphi_{w+} c_v} \tag{6}$$

If we denote the weight of the selected element by P, then the force Q shifting the element will be written as (Fig.
1):

$$Q = P.sin\ a \tag{7}$$

At the same time, the force T that ensures the stability of the slope will be:

$$T = P.cosa \tag{8}$$

In the conditions of the limiting equilibrium $a_s = a_t$, the resistance to soil shear in the simplest form, i.e., in the absence of cohesion (c_v= 0) according to (3) is represented as:

$$S_{\sigma,w} = T.tg\varphi_w, \tag{9}$$

where $T = \sigma_{din}$.
If to take into account that

$$P.sina = P.cosa.\ tg\varphi_w \tag{10}$$

we have

$$tga = tg\varphi_w \tag{11}$$

or

$$a = \varphi_w \tag{12}$$

Expressions (11) and (12), indicating the equality of the slope angles and shear resistance in the conditions of slope equilibrium, are important for our reasoning. This, in turn, makes it possible to express the coefficient of the stability margin in the conditions of slope equilibrium in the form:

$$k_m = \frac{tg\varphi}{tg\alpha}, \tag{13}$$

where α is the bial angle of the slope.
Based on equalities (6) and (13), the earthquake-resistant steepness a of the oscillating slope can be determined as:

$$tga = \frac{(\sigma_{din} tg\varphi_{w+} c_v) tg\varphi_w}{0{,}64\ \gamma_w H k_s}. \tag{14}$$

Expression (14) allows us to determine the earthquake-resistant slope steepness under conditions of seismic vibrations. At the same time, any steepness that is less than the value calculated by the formula (14) will withstand the effects of the corresponding seismic vibration, ensuring the stability of the slope structure itself.
Following expression (14), the earthquake-resistant slope steepness, in general, depends on the intensity of the impacting earthquake (k_s) and the strength characteristics of soils (φ_w, c_v). The second part of the dependence indicates the possibility of ensuring the stability of the structure at a given steepness by increasing the strength indicators of soil.
In addition to those noted above, the role of the normal stress (σ_{din}), consisting of an external fit (p) and the soil's own weight ($\gamma_w . H$) is also significant. By adjusting the value of σ_in, it will also be possible to ensure a stable slope steepness.
In cases when there is no loading on the slope surface, i.e., when p_0=0, the formula (14) takes the form:

$$tga = \frac{tg\varphi_w}{0{,}64\ k_s}\left(tg\varphi_w + \frac{c_v}{\gamma_w H}\right) \tag{15}$$

It is known that under conditions of seismic impact at $a_c > a_t$, the strength parameters of the soil change (decrease) due to a decrease in the connectivity $c_{w,t}$ and the weighing effect of the dynamic pressure $h_{z,t}$ [10]. Dynamic pressure, under certain conditions, can have a catastrophic effect on the stability of the slope. So, under the condition $h_{z,t} = \sigma_{din}$in, the value of $c_{v,t}$ will also be closer to zero. Such an extreme state indicates that any slope steepness in the conditions under consideration will not be able to ensure the stability of the structure. As a result of soil liquefaction, landslides are formed, under certain conditions of enormous size, with all the consequences that follow from this.

It should be noted that the formula (14) forms the basis of the proposed method of earthquake-resistant steepness of slope structures. With its help, it is possible to predict the seismic stability of any slope under the influence of earthquakes. This method is very simple and convenient in practical use.

The following are experimental studies of the factors determining the earthquake-resistant steepness of slope structures.

RESULTS AND DISCUSSION

Following the expression (14), the earthquake-resistant slope of the slope depends on the following internal and external factors, such as the strength parameters of the soil ($c_v; \varphi_w$); the vertical component of the stress from the soil's own weight and external load (σ_{din}); the density-humidity of the soil (n-w); dynamic pressure (h_z); acceleration of the oscillatory motion and its components (α_c,A, f,T).

In addition, in cases when the seismic acceleration (α_c) prevails over the threshold value inherent in the soil (a_t), i.e., in the presence of the condition $a_c > a_t$, the change in soil cohesion ($c_{v,t}$) and dynamic pressure ($h_{z,t}$) during the shaking also affects the grade of the slope.

To confirm the dependence (14), experimental studies were conducted to study these factors, which are compared below.

The density of the soil. Experiments conducted on loess and sand slopes under various dynamic influences showed a direct dependence of the grade slope on the state of the soil density (Fig.2). The expression of the soil density in terms of a relative value makes it possible to extend the data to other similar soils, as indicated in figure *tgα=f (D),* indicating a stable grade of the slope consisting of soils of different densities.

Soil moisture. The results of the experiments also showed the dependence of the slope bevel on the soil moisture (Table 1).

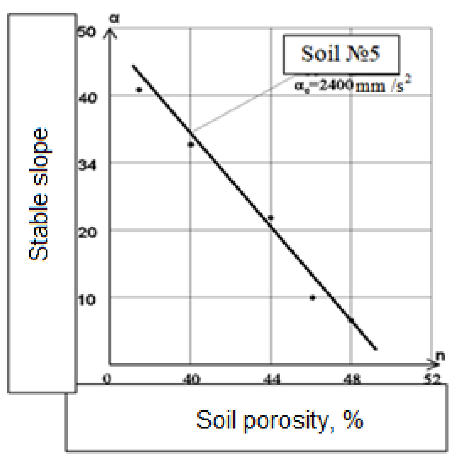

FIGURE 2. Dependence of the stable slope steepness on porosity of loess soil.

TABLE 1. The dependence of the slope bevel on the soil moisture at $a_c = 2880$ mm /s^2

Soil	External load, MPa	Vibration acceleration, mm/s^2	Soil moisture, %	Slope of a stable grade, *tga*
2	0.03	3000	11.5	0.38
2	0.03	-«-	16.0	0.26
2	0.03	-"-	24.2	0.18
8	0.03	3400	14.9	0.42
8	0.03	-"-	20.0	0.37
8	0.03	-"-	28.5	0.23

Soil cohesion. A violation of the slope stability under dynamic influences occurs only after a violation of the general cohesion of the soil and in moistened loess - plastic connectivity.

In this case, the role of internal friction manifests itself after a violation of the connectivity of the soil.

The relationship between the stable grade of the slope and the cohesion of the soil can be seen from Table 2, where the vibrations of loess soils numbered 2, 4, 5, and 7 are given when shaking with an acceleration of 3000mm/s^2.

It should be noted that any increase in the amount of soil cohesion not only contributes to the cooling of the slope but also, due to the increase in threshold acceleration, also increases the seismic stability of soils in the body of the embankment (Fig. 3)

TABLE 2. The dependence of the stable skew of the slope on the cohesion of the soil.

	Total cohesion, MPa						
Soil	0.01	0.02	0.03	0.04	0.05	0.06	0.07
№2	0.19	0.20	0.24	0.27	0.29	0.36	0.45
№4	0.25	0.30	0.35	0.41	0.48	0.58	-
№5	0.13	0.16	0.18	0.22	0.32	0.37	0.50
№7	0.09	0.14	0.21	0.31	0.40	0.47	0.60

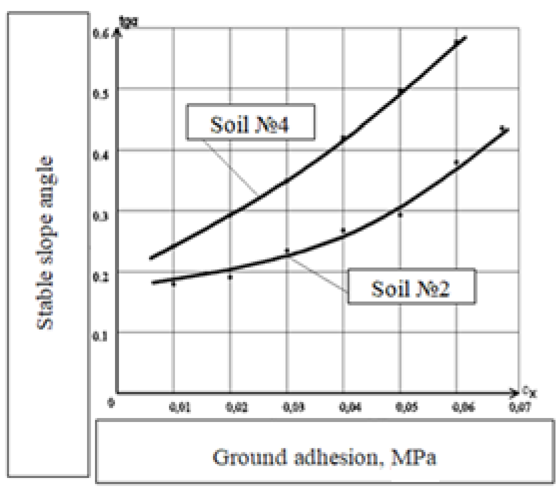

FIGURE 3. Dependence of the stable angle of inclination of the slope on the cohesion of the soil.

Dynamic impact. One of the main directions of our research was to clarify the role of dynamic impact (a_c) and its components in frequency (f) and amplitude (A) in the stable skew of the slope (*tga*).

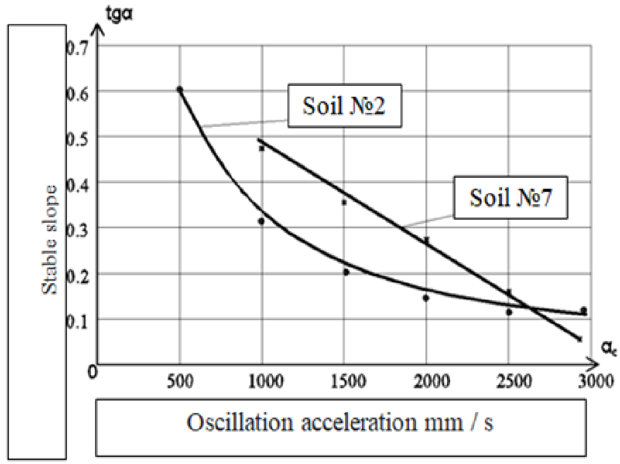

FIGURE 4. Dependence of the form $tg\alpha = f(\alpha_c)$ for soils of different homogeneity.

The relationship between the stable skew of the slope and the intensity of shocks is seen from fig.4, which illustrates the dependence of the stable bial of loess slopes on the intensity of vibrations. Following this figure, this dependence *tga =f(p)* is represented as a curve. Hence, the role of soil density in the dynamics is important.

External load. We also conducted several experiments to study the influence of external load on a stable slope, some of the results of which were reflected in table 3.

TABLE 3. Dependence of the stable grade of the slope on the external load at a_c = 2689 mm/s^2

Soil	The value of the external load, MPa					
	5.0	10.0	15.0	20.0	25.0	30.0
Soil №3	0.31	0.40	0.51	0.60	0.66	-
Soil №6	0.44	0.46	0.53	0.57	0.63	0.68
Soil №9	0.37	0.39	0.40	0.40	0.42	0.44

As follows from the data of the table, external loading on the slope surface in all cases has a positive effect on its stability during shaking.

The duration of the concussion is reflected in Fig. 5, where the change in the grade slope under prolonged impacts is illustrated.

Dynamic pressure. Many of the above data relate to the slope fluctuations under conditions of $a_c < a_t$ and characterize the stable grades of the slope structures. At the same time, we should not lose sight of the opposite case, i.e., $a_s < a_t$, when the soil composing the slope is represented by insufficient strength. Moreover, it is saturated with water and is subjected to strong fluctuations.

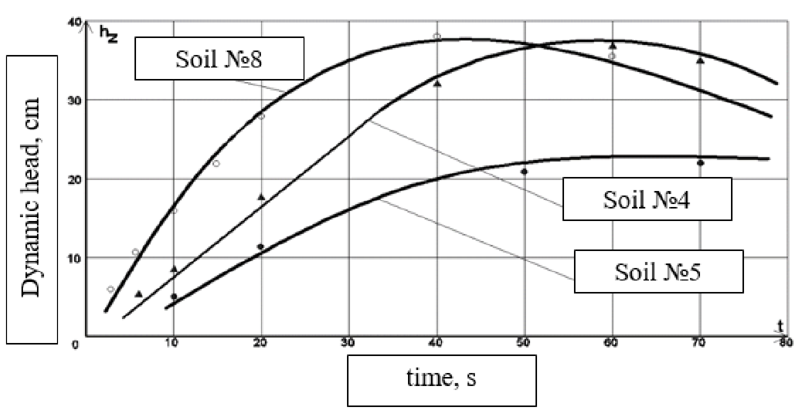

FIGURE 5. Dependence of the form *hz=f (t)* for loess-like soils. The measurement was performed at a depth of *z*=30 cm.

Landslides in natural and artificial slopes occurring during strong earthquakes are associated with the influence of dynamic pressure, which has a weighing effect on the slope under conditions of oscillation of $a_s < a_t$, which is proved by the data from table 4.

TABLE 4. The relationship between the stable grade of the slope and dynamic pressure.

Soil	Dynamic pressure, sm				
	10	20	30	40	60
№3	-	-	0.58	0.36	0.25
№5	0.43	0.30	0.19	0.10	0.06
№7	0.52	0.21	0.08	-	-
№8	-	0.50	0.30	0.21	0.19

CONCLUSION

The proposed method "Earthquake-resistant steepness of slope structures" has been confirmed by experimental studies conducted with different soils under various effects of seismic accelerations (α_s), including:

1. The earthquake-resistant steepness of the slope α primarily depends on the magnitude and components of the active seismic acceleration, α_s the slope steepness decreases.

2. The strength of soils ($\varphi, c_{v,t}$) is of significant importance in the seismic stability of the slope steepness.

3. The stress (σ_{din}) arising in the thickness from the weight of the external load (p) and the natural weight of the soil ($\gamma_w . H$) also has a positive effect on the earthquake-resistant slope steepness. As the value (σ_{din}) increases the slope becomes steeper.

4. The dynamic pressure $h_{z,t}$ negatively affects the stability of the slope. In cases when $h_{z,t} = \sigma_{din}$ the soils in the slope completely pass into a liquefied state with the occurrence of landslides.

REFERENCES

1. E.A. Voznesenskyб Soros educational journal **2**, 101-108 (1998)
2. L.A. Agaeva, in Proceedings of the International scientific conference dedicated to the 110th anniversary of academician G.A. Mavlyanov, pp. 8-11, (2020)
3. V. I. Dzhurik, A. F. Drennov, S. P. Serebrennikov, E. V. Bryzhak, A. Yu. Eskin, Volkanologiya i seismologiya **5**, pp. 1-11, (2015)
4. G. Kopylova and S. Boldina, in E3S Web of Conferences **98**, 01029 (2019), doi.org/ 10.1051/e3 sconf/2 0199801029 WRI-16
5. K. Ishihara, *Behavior of soils during earthquakes*, (Translated from English under license from Oxford University Press, St. Petersburg, 2006), p. 383
6. T. Kokusho, in Proc. of International Geotechnical Symposium, pp.17-25, (Astana, 2005)
7. M. Kazama, N. Sento, H. Omura, H. Toyota, M. Kitazume, Soils Found. **43**(3), 57-72 (2003)
8. M. Kazama, Y. Yamakawa, A. Yamaguchi, S. Yamada, A. Kamura, T. Hino and S. Moriguchi, *Disaster report on geotechnical damage of Miyagi prefecture in Japan*, (caused by Typhoon Hagibis in 2019)
9. K. Lingwei, S. Zsilang, G. Aiguo, in Proc. of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, (Japanese Geotechnical Society, SIMSG, ISSMGE Fukuoka Japan)
10. H. B. Seed, L. F. Harder, in Proceedings of the B. Seed memorial Symposium **2**, 351-376 (1990)
11. G. Wurman *Earthquake Early Warning and the Physics of Earthquake Rupture*, (University of California, Berkeley, 2010), p. 97.
12. Eduardo M. Sosa, Luis A. Godoy, Journal of Sound and Vibration **283** (1–2), 201-215 (2005)
13. H. K. Gupta, Earth Science Reviews **58**, (3–4), 279–310 (2002)
14. T.Kato, T. Honda and S. Kawato, in International Symposium on «Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries» (Johannesburg, South Africa, 2016)
15. I. U. Atabekov, J. Geodesy and Geodynamics **11**(4), 293-299 (2020), doi.org /10.1016/j.geog.2019. 12. 005
16. H.Rasulov and D. Artykbaev, in International scientific and practical conference, (Berlin, Germany, 2019), pp. 68-71

17. Kh. Rasulov and R. Rasulov, Japanese Geotechnical Society Special Publication, **2**(19), 729-732 (2015)
18. R. Kh. Rasulov, European science review, (3-4), 290-292 (2016)
19. Kh. Z. Rasulov, *Seismic resistance and seismic subsidence of loess soils*, ("Fan" of the Academy of Sciences of the Republic of Uzbekistan, Tashkent, 2020), p. 335
20. D.Zh.Artykbaev, Kh. Rasulov, K. Baibolov, International Journal of Engineering Research and Technology **12**(8), 1259-1262 (2019)
21. M.M.Mirsaidov and E. S. Toshmatov, Magazine of Civil Engineering **89**(5), 3–15, (2019) doi:1018720\mce.89.1
22. M.M.Mirsaidov, T. Z. Sultanov, A. Sadullaev, Magazine of Civil Engineering **40**(5), 59-68 (2013) doi: 10.5862/mce.40.7
23. M. M. Mirsaidov and T. Z. Sultanov, Magazine of Civil Engineering **49**(5), 73-82 (2014) doi:10.5862/mce.49.8
24. M. Mirsaidov, T. Sultanov, J. Yarashov and E. Toshmatov, in E3S Web of Conferences **97**, 05019 (2019), doi.org/10.1051/e3sconf/20199705019
25. K.S.Sultanov, B. E. Khusanov, B. B. Rikhsieva, Journal of Physics: Conference Series **1546**(1), 01214 (2020)
26. K. S. Sultanov, N. I. Vatin, Applied Sciences (Switzerland) **11**(4), 1–28, (2021) doi.org/10.3390/app11041797
27. K. S. Sultanov, J. Kh. Kumakov, P. V. Loginov, B. B. Rikhsieva, Magazine of Civil Engineering **93**(1), 97–120 (2020), doi: 10.18720/mce.93.9
28. K.S. Sultanov, Journal of Applied Mathematics and Mechanics **62**(3), 465–472 (1998) doi:10.1016/S0021-8928(98)00058-6