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Assessment of Slope Stability in Coastal Water Protection Zones

Radik Mustafin, Igor Ryzhkov, Rida Sultanova, Ilgiz Khabirov, Luisa Khasanova,
Larisa Zagitova, Ilgiz Asylbaev, Damir Kutliyarov, Ruslan Zubairov and Anzhelika Rajanova
Bashkir State Agrarian University, 50-Letia Octyabrya Str., 34, City of Ufa, Russia

Abstract: Landslide processes on the slopes are a common phenomenon. The purpose of this study is to determine the quantitative criteria for assessing the influence of tree vegetation on the stability of slopes. The authors developed and tested the methodology for calculating the stability of landslide-prone slopes, taking into account the erosion of the sole and the "Reinforcing" action of the root systems of trees by mathematical modeling method using the results of laboratory studies of the mechanical properties of the woody plant roots. In order to better determine the stability functions in laboratory conditions and in stationary areas, tensile tests were carried out along and across the fibers using aspen, pine and oak roots, preliminary calculations were performed, the results of which substantiated the effectiveness of the additional holding force of tree and shrub vegetation on the terrain along the river banks and spatial distribution of productive coniferous forests along such relief elements as steepness, exposure, slope shape. The regulatory provisions on the formation of forests have been developed, the water protection and soil protection functions of which are implemented with the maximum impact on the environment. The results obtained by the authors broaden the knowledge of the methods for calculating the strength of root systems and the stability of the slope banks, the role of forests actively performing anti-landslide functions on mountain slopes and banks of water bodies. The results of the research permit to solve the problem of perspective assessment of the slopes condition with the subsequent correction of forestry, silvicultural and environmental actions and also, can be used in the construction of facilities with the interpretation of landslide processes and the type of plantation.

Key words: Stability of slope, root system, test of roots, calculation of landslide, woody plants, plantation

INTRODUCTION

Protective afforestation has long been used as a resistance to the development of slope processes. At the regional level, practitioners argue that forest reclamation protects slopes by stopping the displacement of the snow cover, its accumulation (snow retention) (Isangulov and Gabdrakhimov, 2011; 2012). Research shows that tree plantations reduce the harmful effects of winds. Many authors believe that protective forests become a barrier to the erosive action of surface waters which in the presence of tree-shrub and grassy vegetation, pass into the subsoil (ground) runoff, preventing erosion. The opinion on the fixing action of the root system of trees and shrubs on the slopes dangerous to landslides deserves close attention (Catani *et al.*, 2013). Forests of coastal water protection zones perform a very important protective and accumulative function, they protect low-level banks from destruction, accumulate sandy alluvium in floodplains, protect steep slopes of valleys from erosion and landslides, thus preventing the erosion and silting of reservoirs, river beds and reservoirs (Nandi and Shakoor, 2010). The species composition of vegetation that can increase the stability of the slopes of coastal water protection zoneswhichmakes it necessary to evaluate the mechanical properties of the roots of woody plants is of most interest (Ryizhkov *et al.*, 2015; Zhang *et al.*, 2014). The stability of the coast depends on many factors that are difficult to quantify. The influence of coastal vegetation deserves special attention. Banks, covered with trees and shrubs such as pine (*Pinus sylvestris* L.), silver birch (*Betula verrucosa* Ehrh) and Cilia (*Caragana arborescens*), ceteris paribus are more resistant to erosion than without such vegetation. However, experts in environmental management are forced to solve such problems, relying only on personal experience and "Engineering intuition". In the world practice, no calculations have been proposed yet to quantify the protective properties of coastal tree and shrub vegetation. From this point of view, the principles of calculation set out in one of the works (Arkun *et al.*, 2014) in which the stability of slopes is proposed to be evaluated by the finite element modeling with a retaining wall taking into account the reinforcing action of the root system of the woody vegetation growing on this slope, deserve attention. This study proposes a method for taking plantations into account when calculating slope stability. The initial data are the results of standard engineering

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Corresponding Author: Radik Mustafin, Bashkir State Agrarian University, 50-Letia Octyabrya Str., 34, City of Ufa, Russia

surveys and additional visual evaluation of vegetation. In this study, we propose a technique for taking plantations into account when calculating slope stability when the initial data are the results of standard engineering surveys and additional visual assessments of vegetation.

MATERIALS AND METHODS

For laboratory tests on strength (for stretching along and across fibers), the roots of several species of woody forest-forming plants typical of the forests of the Republic of Bashkortostan were used, performing water protection and soil protection functions in accordance with GOST 12071-2000, aspen (*Populus tremula* L.), common pine *Pinus sylvestris* L.) and English oak (*Quercus robur* L.). The characteristics obtained as a result of the experiment make it possible to judge the strength of materials under static loading. The tests were performed on an MP-200 tensile machinewhichautomatically plotted the stretching diagram. All results of the measurement were recorded for further calculations.

RESULTS AND DISCUSSION

The test results after processing were: The tensile strength σW of the sample with the moisture content W at the time of the test was calculated to within 1 MPa by the Eq. 1:

$$\sigma_W = \frac{P_{max}}{a.b} \tag{1}$$

Where:

P_{max} = A maximum load (MN)
a.b = Dimensions of the cross section of the working part of the sample (mm)

The tensile strength of the sample with a moisture content that differs from 12% by more than±1% (within the range of 8-20%) was converted to a moisture content of 12% to an accuracy of 1 MPa by the Eq. 2:

$$\sigma 12 = \sigma W\left[1+\alpha\left(W-12\right)\right] \tag{2}$$

Where:

σW = The ultimate strength of the sample with moisture W at the moment of testing (MPa)
α = A correction factor equal to 0.01 for all species

The strength of the sample with a moisture equal to or greater than the saturation limit of the cell walls wasrecalculated to a moisture content of 12% with an accuracy of 1 MPa according to the Eq. 3:

$$\sigma_{12} = \sigma_W \cdot K_{30} \tag{3}$$

where, K_{30} is the conversion coefficient equal to 1.30 for coniferous species and 1.33 for hardwoods. The results of measurements and calculations are recorded in the test report (Table 1).

The test conditions are: air temperature is 24°C; degree of saturation with air moisture (φ) is 68%; loading speed is 20 kg/sec; duration of loading is 31-37 secs; speed of moving of the testing machine heads is 4 mm/min. The strength limit was established as 16.86 MPa for aspen , 13.3 MPa for pine and 15.85 MPa for oak. Thus, the tensile strength of the aspen root sample established by laboratory tests is higher than the strength of the samples of the roots of Scots pine and English Oak.

Experts working on the assessment of the stability of slopes in our country and abroad know that the presence of woody and shrubby vegetation on the slopes is a comfortable factor that reduces the risk of landslides. In the code of rules SP 116.13330.2012 and GOST 12536-79 (Anonymous, 1988) (as in the previous rules on engineering protection of territories SNiP 22-02-2003) agricultural afforestation is considered as one of the main anti-landslide measures. The corresponding attitude to vegetation on the slopes is typical for European standards (Guzzetti *et al*., 1999; Hemmati *et al*., 2009; Nandi and Shakoor, 2010).

The use of local woody and shrubby vegetation as one of the acceptable simple ways to protect against landslides deserves close attention. Despite this, neither in our country nor abroad, any quantitative criteria for assessing the impact of woody and shrubby vegetation is not defined. When assessing the "Stability stocks" of slopes, the presence or absence of tree plantations is not usually present in the calculations. Numerous studies are given in scientific papers and publications of Vakkuri, Kalinin, Katzenbach, Hemmati but they are usually theoretical in nature, any accurate methods of calculation are not traced in them (Vakkuri, 1960; Katzenbach and Werner, 2007; Hemmati *et al*., 2009).

Table 1: Tensile tests of the roots for tension along and across the fibers

	Cross-sectional dimensions (mm)					
Sample marking	a	b	Cross-sectional area (cm^2)	Max load P_{max} (MN)	Humidity W (%)	Strength limit (MPa σ_W)
			Wood species: aspen			
1	200	100	289	17.14	82	16.86
			Wood species: pine			
2	200	100	289	15.55	33	13.30
			Wood species: oak			
3	200	100	289	18.92	66	15.85

The consequences of landslides are often catastrophic, leading not only to great environmental and economic damage but also to numerous human casualties. As a rule, changes in the hydrogeological conditions of the slope or additional man-caused loads in the form of buildings and structures, roads, slope development in the landslide danger zone and so on cause landslides. In the central zone of Russia, landslides occur most often in the second quarter during the rise of the groundwater level.

The roots of trees on the slope, capable of performing “Reinforcement” of the soil masses, contribute to the emergence of additional restraining forces in landslide situations. The configuration of the root distribution zone, the density of their distribution in the soil NAD their strength affect the magnitude of these forces.

First of all, this refers to the experimentally established fact that the root system of trees develops mainly in the horizontal (radial) direction. The area of the roots distribution in the horizontal direction along the surface area is several times larger than the area of the horizontal projection of the tree crown and in many cases it can reach 10-18 m across. It should be noted that neighboring trees, even a few meters apart are intertwined with their roots and these roots can even be joined. But the depth of penetration of the roots of trees down (in the ground) is small and often it lies within 1.5-2.5 m. In special cases (for example in fractured rocks) it can reach 10-15 m but such cases are not typical, so, they can be ignored.

The depth of penetration of roots in the ground has the ability to vary in fairly wide ranges, depending on the age of a tree and the ground conditions. Many tree species reach the maximum penetration depth of roots at the age of 25-40 years, after which it practically does not change. At the age of 10-15 years, the depth of the roots is up to 50-75% of the maximum.

In forest podzolic soils, the penetration depth of roots is less than in chernozems (black soils) and is no more than 1.5-2 m. Wetlands reduce the penetration depth of roots to 0.6 m.

Taking into account that each region has its own forest-forming vegetation, it is necessary to know the depth of penetration of the roots of those tree species that are characteristic of a particular region.

There are practically no wetlands on the slope. Considering that woody vegetation on the slopes, as a rule is represented by various tree species, it is advisable to take the depth of penetration of the roots in calculations equal to 2 m, if necessary, subjecting it to clarification during a direct field survey. The configuration of the root branches is very complex and on the whole it is strictly individual in each tree. It is impossible to identify any single spatial pattern. It is more realistic to consider the upper layer of soil containing the “Soil-root layer” roots, as a certain area of the soil, entirely permeated with plant roots in a wide variety of directions and different diameters. Such an area should be identified as an independent Engineering-Geological Element (EGE) or a calculated ground element in accordance with GOST 20522-12 and GOST 22733-2016 (Anonymous, 2000, 2012).

With an average distance between trees not exceeding 5-8 m, the soil-root layer can be considered completely covering the slope and ridge surface which forms a protective coating with a thickness of 1.5-2.5 m and ensures the stability of this slope (Fig. 1). This “Soil-root layer” covers the slope from the base to the ridge and the creeping soil massif must overcome not only the “Internal resistance” of the soil inside the slope but also the additional resistance of this layer which must

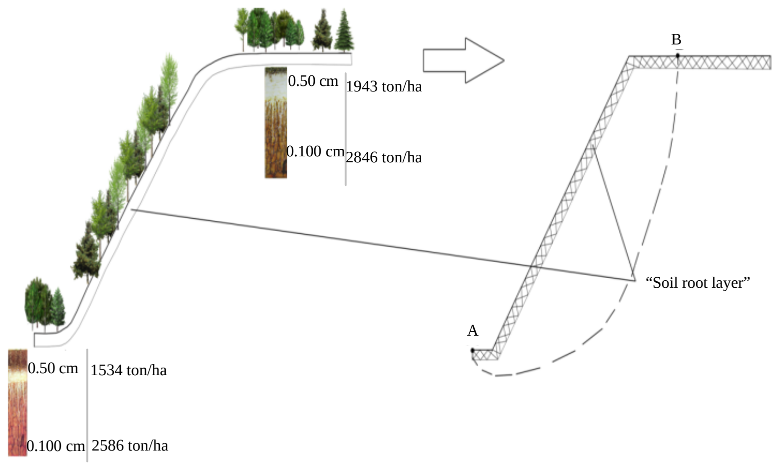

Fig. 1: Layout of the “Soil-root layer”

be “Cut off” in two places: the upper part on the ridge of the slope (point B in Fig. 1) and the lower part at the sole (point A). It is clear that if there is no vegetation in one of these places (on the ridge or at the foot of the slope), the crossing of the protective layer can be observed only in one place.

The additional holding force of the soil-root layer should be taken into account by artificially increasing the strength index of the soil specific adhesion in the upper zone of the soil (to a depth of 2-2.5 m).

The growth of woody and shrubby vegetation of such areas performs the main function “reinforcement” of the slopes. With the help of powerful root systems, trees keep the slopes from destruction.

Nowadays the calculation of slope stability is one of the most important sections of soil mechanics. Its foundations were laid 250 years ago by Ch. Coulomb and in modern environmental management the play a role no less than the calculations of the bases and foundations in industrial and civil construction. The methods of such calculations based on various theoretical assumptions have been developed, there are normative and recommendatory documents on this subject practically in all countries, the corresponding computer programs are widely used. The essence of these methods is to select the location and boundaries of the creeping soil mass and consider the static equilibrium of such an array. The selected array is usually mentally divided into blocks, the balance of which is considered by various methods of statics. The initial data for such calculations are information about the engineering-geological structure of the considered slope (the “Texture” of the soils) and the physical and mechanical properties of each type of soil. This requires mandatory engineering surveys with well drilling, soil sampling and laboratory processing.

Prospectors usually divide the soils of the slope into separate layers or lenses of various types and origin (Engineering-Geological Elements EGE) and for each of them set the calculated values of soil characteristics. Such values of characteristics are used later in the calculation of slope stability. This is the specific gravity of the soil (γ) and its strength characteristics such as the angle of internal friction (φ) and the specific cohesion (c). Naturally, all types of external loads that can affect the slope (the weight of buildings and structures, if any are on the ridge of the slope, roads and transport moving along them, hydrodynamic pressure of underground waters, etc.) are taken into account.

The calculation of the stability of slopes covered with trees and shrubs can be done by the same methods, using the same computer programs that are used in the general case in the absence of vegetation. The only difference is that in the presence of woody vegetation, the initial data for the calculation are adjusted.

The layer of soil, located at the top (2 m) is separated into an independent engineering-geological element with artificially increased strength properties. This increase is expressed in an increase in the specific adhesion of the soilwhichis taken on special tables depending on the average diameter of tree trunks and the average distance between them (Catani *et al*., 2013; Zhang *et al*., 2014; Ryizhkov *et al*., 2015).

It is advisable to conduct the calculation in the following order. At the first stage, the degree of saturation of the soil-root layer with the roots of K is established. To do this in the course of engineering surveysbyreconnaissance of the surveyed slope section (usually a site of 1-3 thousand m^2 is considered), two indicators are visually assessed: the average (avg.) diameter of tree trunks davg; the average distance between trees lavg. When estimating the distances lavg, it concerns the distance not between any pairs of trees but only between neighboring trees, i.e., this roughly corresponds to Eq. 4:

$$\text{lavg} = \sqrt{A}/n \tag{4}$$

Where:

A = The area of the site

n = The number of tree trunks

Table 2 shows the values of ($K_{l\ (\text{landslide})}$). K_l is the degree of saturation of the soil with roots, corresponding

Table 2: Degree of saturation with roots of soil-root layer k_l (percentage of root volume in percent in the total volume of the layer)

The average diameter of tree trunks, davg (m)	The degree of root saturation of the k_l soil-root layer (%) with an average distance between trees (lavg m)				
	2	3	4	5	6
0.1	0.3	0.13	0.07	0.05	0.03
0.2	1.2	0.42	0.24	0.15	0.10
0.3	-	0.87	0.48	0.31	0.22
0.4	-	1.25	0.70	0.45	0.31
0.5	-	-	0.85	0.55	0.38

The dashes “-” correspond to unlikely combinations to visual estimates of davg and lavg. The calculated value of the root saturation degree of the soil-root layer K should be determined by the Eq. 5:

$$K = K_1/\gamma_t \tag{5}$$

where, γ_t is coefficient of reliability, taking into account the unevenness of tree distributionwhichis determined by the average age of woody vegetation: at the age of 30 years = 1.0, at 60 years old γ_t = 1,2, more than 60 years old γ_t = 1.4.

The next step is to increase the strength of the soil-root layerwhichshould be equivalent to the influence of the root system. It is assumed that the angle of internal friction remains unchanged and the specific cohesion increases, reaching a certain equivalent value:

$$C_{s\text{-}r} = c_{stand} + c_{ad} \tag{6}$$

Where:

c_{stand} = Specific cohesion, determined by the standard (stand) method for engineering-geological surveys (without taking into account the roots)

c_{ad} = An additional (ad) part of the specific cohesion, determined in accordance with the established degree of saturation with roots

The last stage of the calculation is the assessment of the slope stability with woody vegetation. The calculation can be carried out by any method accepted in the practice of design, according to any computer program. As noted above, the inclusion of the root system does not affect the principles of calculation and is carried out only by inputting the "Corrected" initial data. The configuration of the slope, its geological and lithological structure with the exception of the top layer of soil with a capacity of 2 m in which the strength characteristic-specific adhesion "C" is artificially increased, remain unchanged during the adjustment. The layer itself with such strength is considered an additional Engineering-Geological Element (EGE).

As practice shows, taking into account the reinforcing action of the root system is of particular importance for small slopes (up to 15-20 m high). The increase in the coefficient of stability can reach 25-30% in these cases. At the same time, for large slopes when hundreds of thousands of cubic meters of soil are displaced, the role of the soil-root layer is less.

Studies by hydrologists show that the erosion of the shores depends on the structure of these banks, the morphology of river valleys, the water content of rivers, the peculiarities of the course of channel processes and so, on. The average speed of erosion can be in the half rock soils of 0.2-0.5 m/year in the clays of 0.5-1.0 m/year in the loamy soil of 1.0-2.0 m/year, loams and sands of 2.0-5.0 m/year (Isangulov and Gabdrakhimov, 2011). Table 3 shows the calculated slope stability coefficients (kst), reflecting the "margin" of its stability (normalized, i.e., acceptable, values are usually in the range [kst] = 1.05-1.25 (Smirnov, 2013).

Table 3: Coefficients of stability of the coastal slope for a different sub-wash (for example, calculation)

Size of undercutting (washing) of the coastal slope (m)	The coefficient of slope stability, k_{st}, calculated by the method		
	G. Kreia	K. Terzaghi	"Weight pressure"
Without washing	1.07	1.17	1.18
1 m	1.00	1.12	1.18
2 m	0.93	1.06	1.12
3 m	0.86	1.01	1.07

The calculations were carried out by the three most common methods in our country, based on the application of the hypothesis of "circular-cylindrical sliding surfaces" (the programme "SLOPE" was used).

As shown in the Table 3, the results of the calculation by different methods differ somewhat and in this case it is advisable to focus on the most "Cautious" method (G. Kreia) indicating a small "Stability margin" of the slope even in the absence of undermining (kst = 1.07). When cutting a slope at 1 m (Fig. 1), the state of limiting equilibrium of this slope (kst = 1,0) occurs when cutting by 2 m the slope in any case should collapse (kst = 0.93) with a 3 m cut, the caving becomes even more likely (kst = 0.86).

The presence of trees and shrubs slows down the washout of the coastal slope and increases the resistance to landslide processes. The theoretical calculation of the duration of the washout is not possible, yet, due to insufficient study of this issue and the presence of a large number of influencing factors of a random nature. However, the role of vegetation in this process is not in doubt. Firstly, the washout of the coastal slope includes not only the separation and entrainment of water flow of small particles of soil but also the formation of cracks of erosion, separation and removal of entire blocks of soil. The presence of roots will prevent the formation and separation of such blocks. Secondly, the "Stickiness" of the soil, i.e., its ability to stick to the tree roots, should be of significant importance. It has been experimentally established that clay soils adhere most strongly to wooden objects. The amount of such stickiness can reach 50-55 kPa. The stickiness of sand and sandy loam is one or two orders of magnitude less than the stickiness of clay soils but it can also have an effect. Washing out of clayey soil from the zone, penetrated by roots, should (with other equal conditions) be slower, than washing away of sand.

Table 4: The intensity of root growth of Scots pine in relation to soil conditions

Age (years)	Type of soil	Average annual increase				The ratio of the growth rate of the taproot to the growth rate of the average horizontal root
		Total length of skeletal roots (m)	Middle root of the first order	The longest root of the first order	Taproot	
12	Srednogorovo-weakly podzolic, sandy loam	4.2	16.3	27.1	14.6	0.9
14	Strongly-moderately weakly podzolic, sandy loamy	11.6	36.3	54.7	35.1	1.0
23	Slabodernovo-weakly podzolic, sandy loamy	6.0	17.1	36.1	11.4	0.7
24	Srednodernovo-weakly podzolic, sandy loamy	8.8	32.5	41.8	16.9	0.5

Table 5: Average annual increase in the length of horizontal roots of the first order in Scots pine (cm)

Age (years)	Length of the largest root in a group of trees (m)			Over the entire age period, a group of trees			Over the last 12 years, a group of trees		
	The best	Medium	Lagging	The best	Medium	Lagging	The best	Medium	Lagging
12	3.25	2.75	2.00	27	23	17	27	23	17
24	10.24	7.00	5.75	42	29	24	56	35	31
36	12.00	10.25	7.25	33	28	20	25	27	12

In general, the intensity of erosion of the "Foothills" of the coastal slopes (the formation of "trimming"), both in clayey soils and in the sands, should be slower in the presence of tree and shrub vegetation on such slopes.

The processes considered need additional study both from the point of view of forestry and construction (geotechnical). Many factors that could have a significant impact on slope processes remain unaccounted for.

Many types of trees at joint growth grow together under a common root system. They are common pine, fir, common ash, birch pendant, maple, common oak ordinary hornbeam, small-leaved linden, spruce, walnut, etc. (Beyer *et al*., 2013).

Growth of root systems is a widespread phenomenon, as the age increases, the share of fused roots also, increases. In many cases, after the felling, "live" stumps are formed in the trees. Most stumps die within 1-2 years after cutting. But if you cut down all the trees except one, the remaining root systems of the cut trees can survive due to the intake of carbohydrates and growth regulators from the crown of a single tree. "Live" stumps are found in larch, pine, fir, beech and other coniferous, hardwood species including fruit trees. As M.I. Kalinin noted, stumps of coniferous species can remain alive up to 35-87 years after felling. The presence of root coagulation in biogroups has a certain ecological significance, as it extends the adaptive capacity of the species under the harsh conditions of growth. The accretion of the root system increases the stability of the slopes. Differences in soil fertility significantly affect the growth intensity of both horizontal and taproots (Table 4).

Under the influence of soil conditions, the ratio of the growth intensity of Scots pine horizontal and tap roots varies within 0.5-1.0 m of soil depth. With the deterioration of soil conditions, the growth of horizontal and tap roots changes, the growth intensity of horizontal roots decreases more than the tap roots.

Table 5 shows the average periodic increase in the length of horizontal roots of the first order. It has the highest value at 12-24 years of age.

The average increase in length reaches a maximum at the age of 24 years. In 41 year old plantations, the average increment of the most developed horizontal root of the first order is only 24, 21 and 20 cm for the trees of the best, medium and lagging growth groups, respectively.

These indicators show that in the period of 31-40 years of age the current growth ceases. The same changes are typical for other tree species.

CONCLUSION

Based on the results of the mechanical properties evaluation of the woody plant roots, the ultimate strength is 16.86 Pa for aspen, 13.3 Pa for pine, 15.85 Pa for oak. Thus, the tensile strength of the aspen root sample established by the laboratory tests is higher than the strength of the samples of the Scots pine and English oak roots. The root system of trees on the slope is able to perform a "Reinforcing" function, causing additional holding forces during landslide processes. The configuration of the zone of distribution of roots, their size, the density of their distribution in the soil, their strength affects the magnitude of these forces. In the process of joint growth, the trees on the slopes are fused with root system which provides an additional increase in the stability of the slopes. The method of calculation of stability of slopes taking into account presence of wood vegetation is developed. A method for calculating slope stability taking into account the presence of woody vegetation has been developed. Under the influence of soil conditions, the ratio of the intensity of growth of horizontal and tap roots of Scots pine in the range of 0.5-1.0 m of soil depth changes. Under the influence of soil conditions, the ratio of the growth intensity of horizontal and tap roots of Scots pine varies within 0.5-1.0 m of soil depth. With the deterioration of soil conditions, the ratio of the growth intensity of horizontal and tap roots varies, the growth intensity of horizontal roots decreases more than the tap roots.

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