Soil Erosion on the Yamal Peninsula (Russian Arctic) due to Gas Field Exploitation

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Summary

Arctic cryogenic soils in the western part of the Yamal peninsula are poor and unstable because of the high ice content. The combination of high natural erosion potential and anthropogenic influence causes extremely intensive rates of erosion. The mean rate of gully length growth is 20-30 m per year on loam deposits and 150-200 m per year on sands. Intensity of sheet erosion on the bare slopes is up to 30-50 t ha^{-1} per year on sands and up to 7-8 t ha^{-1} per year on loam.

Complicated processes of thermoerosion and thermokarst, which take place under permafrost conditions, prevent the use of hydrotechnical methods for soil conservation. The main measures to prevent erosion are 1) to avoid unstable geomorphic units for construction; and 2) to improve the quality of vegetation cover in the area of gas exploitation activities.

Key words: gully erosion and thermoerosion; Yamal peninsula; gas fields exploitation; soil conservation under permafrost conditions.

Introduction

Natural processes of erosion are widespread in the arctic tundra of Russia. The main natural factors of erosion in this region are 1) high density of rivers combined with the relief amplitude of up to 40-45 meters; 2) sufficient precipitation (350-400 mm $year^{-1}$); 3) low soil permeability due to the permafrost and therefore high runoff coefficients (up to 0.9-1.0); 4) high erodibility of frozen and thawing soils due to the combined mechanical and thermal action of flowing water (the so-called process of thermoerosion).

This natural high erosion hazard has been greatly increased recently by human impact. In areas of gas production and transportation facilities the erosion potential increases due to: 1) deterioration of the vegetation cover due to industrial development; 2) increased snow storage on the slopes due to excessive snow accumulation near buildings and roads; 3) an increase of the runoff coefficient on impermeable surfaces of the urbanized territories and roads; 4) local industrial and urban sources of warm water; 5) exploitation of sand-pits, gas and oil fields, and construction of pipe lines and ditches. The combination of high natural erosion potential and human interference causes extremely intensive gully, rill and sheet erosion. The old stable drainage lines are subjected to erosion, and new gullies cut into previously gently sloping elongate depressions. This gully growth leads to the formation of badlands and failures of engineering constructions. Rill erosion causes serious damage to the bare slopes of the road embankments and within the exploitation camps.

The main methods for soil and water conservation has been designed for the Temperate Zone, and there is no experience of their application in the conditions of continuous permafrost. It is necessary to devise special methods to reduce erosion and thermoerosion within an already disturbed field and to prevent erosion in this extremely unstable landscape.

Climate of the west-central Yamal

The Yamal peninsula is situated at the northern part of the West Siberian plain and has an area of about 122,000 km^2. At the west-central part of the Yamal peninsula the mean annual air temperature is -8.3° C. In January (the coldest month of the year) the mean temperature is -21.8° C (minimum of -52° C). The mean temperature of August (the warmest month) is 6.7° C (maximum of 28° C). The air temperature is below 0° C for 223 days per year. Snow covers the territory from October till June. The thickness of snow cover at the beginning of the snow melt period does not exceed 0.3-0.4 m on gentle slopes and flat interfluves, but it can exceed 3-5 m in gullies and creek valleys and near steep river and lake banks due to wind transport. The depth of runoff for the period of snowmelt is 220-250 mm. Its main source being snow packs in erosion landforms.

Rainfall occurs generally in June – September; its total mean duration is 470 hours with a maximum up to 900 hours within this season. The mean rainfall for this period is 140 mm with a maximum of 357 mm and a minimum of 25 mm. The mean daily rainfall maximum is 12 mm (absolute maximum is 40 mm) with mean maximal 30 minutes' intensity of 0.8 mm min^{-1} and up to 12 mm min^{-1}.

Low winter temperatures cause the formation of deep permafrost layer with very low (almost zero) permeability. The summer thaw layer thickness reaches its maximum (0.6-1.2 m) in August-September, but the soil is often highly saturated with water because of melting of ground ice. Under such conditions the runoff coefficient is up to 0.9-1.0 for the period of snow melting in June. It decreases to 0.3-0.4 in August-September. Accordingly, even low precipitation produces relatively high surface water flow.

Natural destructive processes

The main natural destructive processes are 1) river channels and cryogenic lake migrations; 2) massive ground ice melting, cryoplanation; 3) thaw slumps and active layer detachment failure (skinflow); 4) gully erosion (Fig.1).

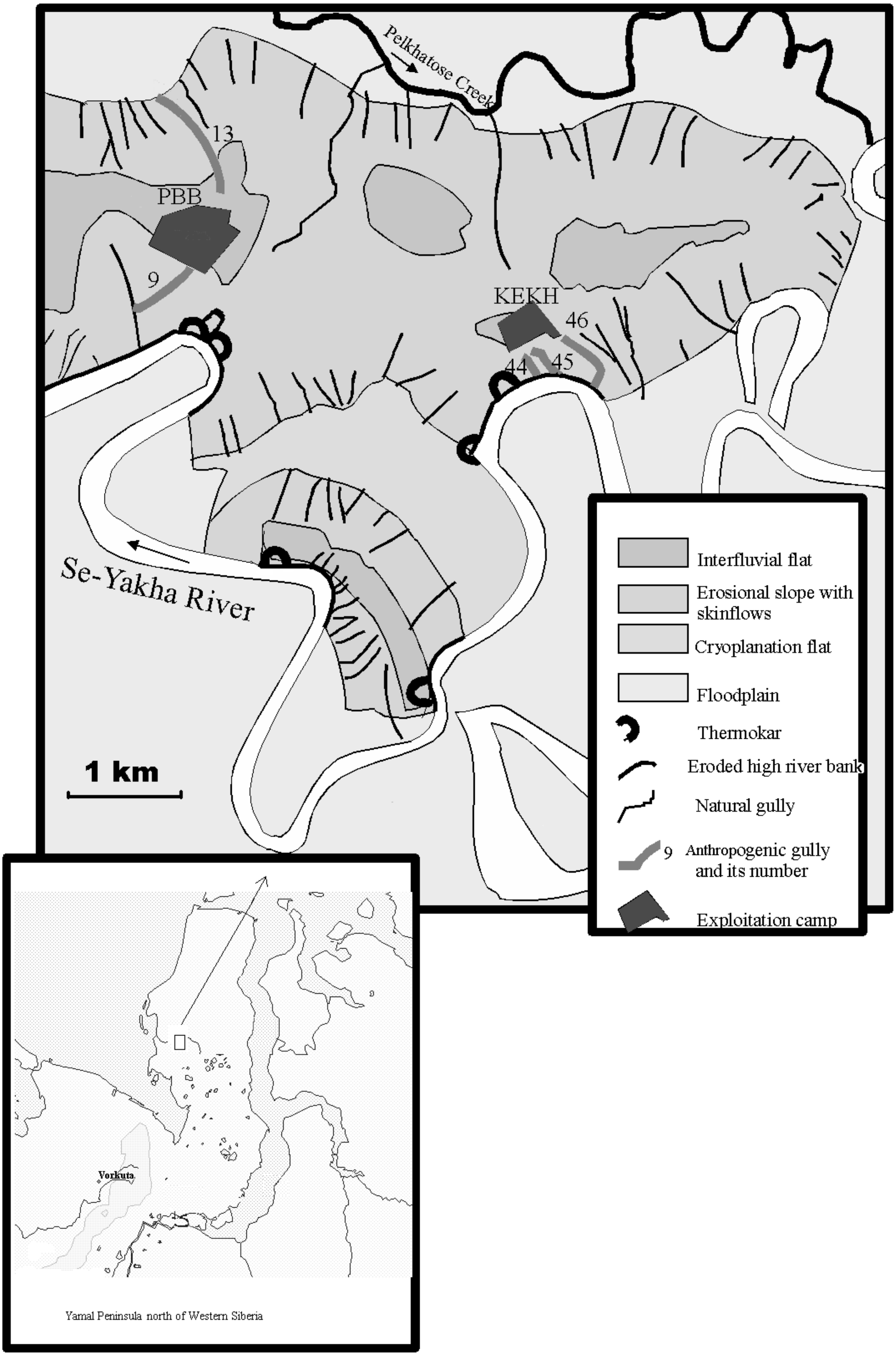

Fig.1. Erosional landscapes of the west central Yamal.

The main river channels on the Yamal peninsula have meandering patterns. The rate of bank erosion is usually 0.3-0.5 m per year and up to 2-3 m per year. River erosion causes formation of steep bare slopes at the concave sides of meanders, accompanied by various destructive processes.

Cryoplanation is the process of massive ground ice melting, mainly in the outcrops in the steep banks of the rivers. It leads to formation of thermokars up to 250 m wide and 300-500 m long. Cryoplanation is generally accompanied by gully erosion. These processes together can form extensive low terraces because the sheets of massive ground ice are about 50 m thick and have areas of several square kilometers.

Skinflows often occur during a wet summer, if it follows 2 or 3 warm summers. Numerous laminations of ice appear near the lower boundary of the thaw layer and the bulk cohesion of the loamy slope deposits decreases to 50-100 Pa. In this situation a heavy block of water-saturated thaw deposits can rapidly slide over the ice-rich surface to a distance up to several hundred meters even on slopes with an inclination of 1-2° or less. Newly exposed soil is subjected to intensive erosion, and a new gully can be formed the following year after the skinflow. The most favorable conditions for such an event took place in 1989-90. Skinflows occurred on 2.0% of the area on the slopes of loamy high terrace, and the vegetation cover was destroyed. The mean area of individual slumps was 7300 m^2, and the mean depth was 1.2 m. The numerous remnants of the old skinflows cover all the surface of these slopes.

The natural gully erosion occurs mainly on terraces with height 20-45 m above sea level. The high (30-45 m) terrace consists of loam and clays with a massive cryogenic structure. Steep riverside slopes of this terrace are dissected by numerous natural bank gullies, usually 50-70 m long. Some of these gullies are up to 1-2 km long in the areas where the ice content in eroded deposits is high. There is a net of long gentle troughs on the flat surface of the terrace. Their density is 2.3 km km^{-2}. Natural and man-induced gullies usually follow these troughs where the vegetation cover is deteriorated or the volume of runoff increases. The lower terrace (20-25 m above sea level) is composed of fine silty sand with ice wedges in the upper layer and massive ground ice in the lower layer. The natural gullies are more widespread on this surface, and the main part of the drainage network is eroded due to the high erodibility of fine sands.

Erosion in the west-central Yamal

Investigations conducted in 1990-1995 concentrated on the territories of two exploitation camps (PBB and KEKH), where the vegetation cover was significantly destroyed by heavy tractors, and the thaw water supply was increased due to snow accumulation near buildings and road embankments.

A dendritic system of rills develops rapidly on the bare slopes with irregular microrelief. The rill depth varies from 0.1 m to 0.5-0.6 m, and the width varies from 0.3 to 1.5 m. Their density is about 0.1 m m^{-2} at the upper part of the slopes and 0.05 m m^{-2} in the middle part of the slopes. At the lower part of the slopes the rills become gullies. On a slope with inclination 3.5° and area 1 ha, situated in the basin of gully 44, the depth of runoff was 171 mm and the erosion rate was 40 t ha^{-1} during the snow melt period of 6-27 June 1991. At the basin of gully 45, on the adjacent slope with an inclination of 2.5° and an area of 2.8 ha, the depth of runoff was 132 mm and the erosion rate was 6 t ha^{-1}. During the rainfall event of 8-9 August 1990, when the maximum rainfall intensity for 30 minutes reached 0.44 mm min^{-1} (20 year frequency), the depth of runoff was 11 mm for both slopes. The rate of erosion for this event at the first slope was 4.3 t ha^{-1}, and for the second slope it was 5.6 t ha^{-1}. Mainly different levels of human activity explain this variance on these slopes at different times.

The process of the water and sediment transport in the gullies is even more complicated. The water and sediments from the basin collect at the gully head, but at the beginning of the thaw period the gully is full of snow. The rate of snowmelt in gullies depends strongly on snow porosity and the quantity and temperature of melt water supplied from the upper part of the watershed. For example, at the first week of snow melt (6-10 June 1991) in gully 9, where the area of slopes above the gully head was 7-10 ha, and in gully 46, where this area was 10 ha, the inside snow packs (2-3 m thick) were completely cut by meandering channels with vertical snow banks. The flows were continuous with only several snow bridges remaining in the lower parts of the gullies. The sediments from the catchments and gully beds were delivered to the gully mouths. Gully 45, where the area of the slopes above the gully head was 3 ha, and gully 44, where this area was 1 ha, were completely filled by snow. Up to 83% of sediments, supplied to the gully head, was withheld by snow within the gully at the beginning of the snowmelt period. Only at the end of the thaw period did active erosion begin of the deposited sediments and gully bottom. The average rate of erosion and thermoerosion in the gullies during the snowmelt period of 1991 was 0.8-1.2 m for the month, and the depth of runoff was 150 mm.

Summer and autumn rains have duration of 74-171 hours per month on the west central Yamal. Only 2-4 events per month are characterized by rainfall depths more than 1 mm day^{-1}. Some of these rains cause intensive gully erosion. During 8-9 August 1990 the average rate of erosion and thermoerosion in the gullies at the KEKH camp was 0.5-0.6 mm day^{-1}. The rate of erosion in the middle section of the gully 9 during the rainfall period of August 1993 was twice that of the period of snow melt in June, despite the fact that the runoff in June was six times higher.

Narrow rectangular trenches with depths of 0.6-1.4 m (and up to 2.5 m) and width 0.4-0.6 m are usually formed by erosion and thermoerosion at the gully heads or bottoms during the snowmelt. Such trenches with vertical walls are stable only in frozen deposits. When the thaw layer reaches a depth more than 0.5-0.8 m, the sides of the gully become unstable. Shallow landslides quickly transform the gully cross-section shape to triangular or trapezoidal, and this process continues from days to weeks.

The alternating processes of quick intensive incision and rapid sidewall slumping results in gully deepening and growth in length and volume. Repeated instrumental leveling of gully longitudinal profiles showed relatively low mean rates of deepening. For the period 1991-1995 the increase of the mean depth of gullies 9 and 45 was 0.6 m, and that of gully 44 was 0.9 m. At the upper section of gully 46, the depth increase was 1.3 m, but in its lower section deposition occurred with a thickness of sediments 0.7 m. The mean rate of gully deepening is about 10 times less than the rate of incision at the periods of snow melt and rainfall runoff. Analysis of the airphotos reveals that gully length growth is also a complicated process. The main head of gully 44 was stable since 1970, but a long and deep rill was formed at the middle part of the catchment, and the second active head was developed at the convex upper part of the slope. The length of gully 45 was 165 m in 1988, 190 m in 1989, 210 m in 1990, 230 m in 1991, and 280 m in 1995. The rate of the main gully head growth decreased in time, but as in the case of gully 44, the second head was formed at a distance of 400 m from the gully mouth in 1991-95. The same trend is obvious for gully 46. The rate of gully length growth was 40 m per year between 1988-1991, and 10 m per year between 1991-1995. In 1989-1991 a gas flame was operated at the bank of the gully; that was the period of its intensive deepening. Gully 9 did not exist in 1986; only 240 m long shallow elongated depression existed. After PBB camp construction in 1986-87, erosion and thermoerosion were initiated due to the increase in water supply. In 1988 the gully length was 450 m, in 1989 it was 740 m, and in 1990 the length was 940 m. The gully head reached the buildings of PBB camp, and here its growth was stopped by continuous filling of the head by heavy loam from the banks by bulldozers. Nevertheless in 1995 the gully was 25 m longer, than in 1991.

Soil conservation under conditions of continuous permafrost.

Several methods to stop gully growth were used on the territory of Bovanenkovskoye gas field of the west central Yamal peninsula. All these methods were designed for the temperate zone, and all of them proved to be useless under conditions of permafrost. The check dam was constructed at the head of gully 9, but a new gully head had passed around the check dam in 1995. The erosion cut was filled with sediments from gully sides by bulldozer, but every year it was renewed by gully erosion. Several wall cuts in gully 9 were covered by technical textiles. Cuts with small subcatchments were stabilized, but in most of them the cover was destroyed by erosion that took place around the covers.

These cases highlight, that human developmental activities in the arctic tundra, accompanied by deterioration of the vegetation and an increase of runoff causes intensive erosion. This is due to low permafrost permeability, high runoff, high erodibility of bare soils with high ice content, and low slope stability. For existing gullied basins, it is very difficult to stop erosion and thermoerosion. To minimize it several methods can be tried: mechanical snow removal from gully catchment areas; vertical drainage of industrial and rainfall waters; covering of disturbed slopes with a peat layer; filling of the gullies with heavy loam and a peat cover. Two main general measures are recommended: 1) to remove all buildings and construction from unstable interfluvial surfaces and erosion slopes with skinflows to more stable floodplains; 2) to recultivate vegetation cover near roads and pipe lines, especially where they cross unstable areas.

The first measure has been applied on the Bovanenkovskoye gas field. The location of engineering facilities on the floodplain causes problems with riverbank erosion and flooding (Sidorchuk and Matveev, 1994). The second approach has been intensively studied for arctic soil conditions, and hydraulic thresholds of erosion stability of tundra soil with different vegetation cover qualities have to be taken into account.

The biomass in typical tundra of the Yamal peninsula varies from 500 to 2000 t m^{-2}, and 10-25% of this amount is represented by plant roots in the soil (Vasilevskaya et al., 1986). Thin (less that 1 mm in diameter) living and dead roots penetrate into the soil aggregates, gather together and increase soil cohesion. Field and laboratory experiments show that the bulk soil cohesion C_h (in Pa $10^{5)}$ increase rapidly with the content of thin roots R (kg m^{-3}):

$$C_h = C_0 \exp(0.05R) \quad (1).$$

Here C_0 is cohesion of the same soil, but without vegetation roots.

The critical shear stress and velocity of erosion initiation in cohesive soil are mainly controlled by the forces of friction and by cohesion. Critical velocity U_{cr} (m s^{-1}) can be calculated with the formula (Grigor'ev et al.,1992):

$$U_{cr} = 2.25\sqrt{d + 0.18C_h^{2.25}} \quad (2).$$

Here d - mean diameter of soil aggregates (m). Empirical coefficients include the influence of flow turbulence, soil porosity, and the variance of measured values.

When the flow velocity U is less than the critical velocity of erosion initiation, U_{cr}, both erosion and thermoerosion rates are lower than the rate of soil formation. The critical velocity for a given soil type can be increased by improving the vegetation cover quality (that is, increase of soil top layer cohesion). Formulas (1) and (2) were used with the models of sheet erosion (Grigor'ev and Sidorchuk, 1996) and gully erosion (Sidorchuk, 1996) to determine the threshold qualities of vegetation cover for recultivating the area, which will be crossed by pipe lines on the Bovanenkovskoye gas field. This critical quality varies from one basin to another due to different catchment morphology and is changed if water supply from the catchment is increased by human activity. For example (Fig.2), the basin of gully 46 in natural conditions will be stable in the case U_{cr}=0.58 m s^{-1}, and the vegetation cover quality R not less than 20 for clays, 31 for loam and 41 kg m^{-3} for loamy sands. Under conditions of snow storage increase at the KEKH camp, this basin will be stable in the case of U_{cr}=0.65 m s^{-1}, and vegetation cover quality not less than 22 for clays, 33 for loam and 43 kg m^{-3} for loamy sands.

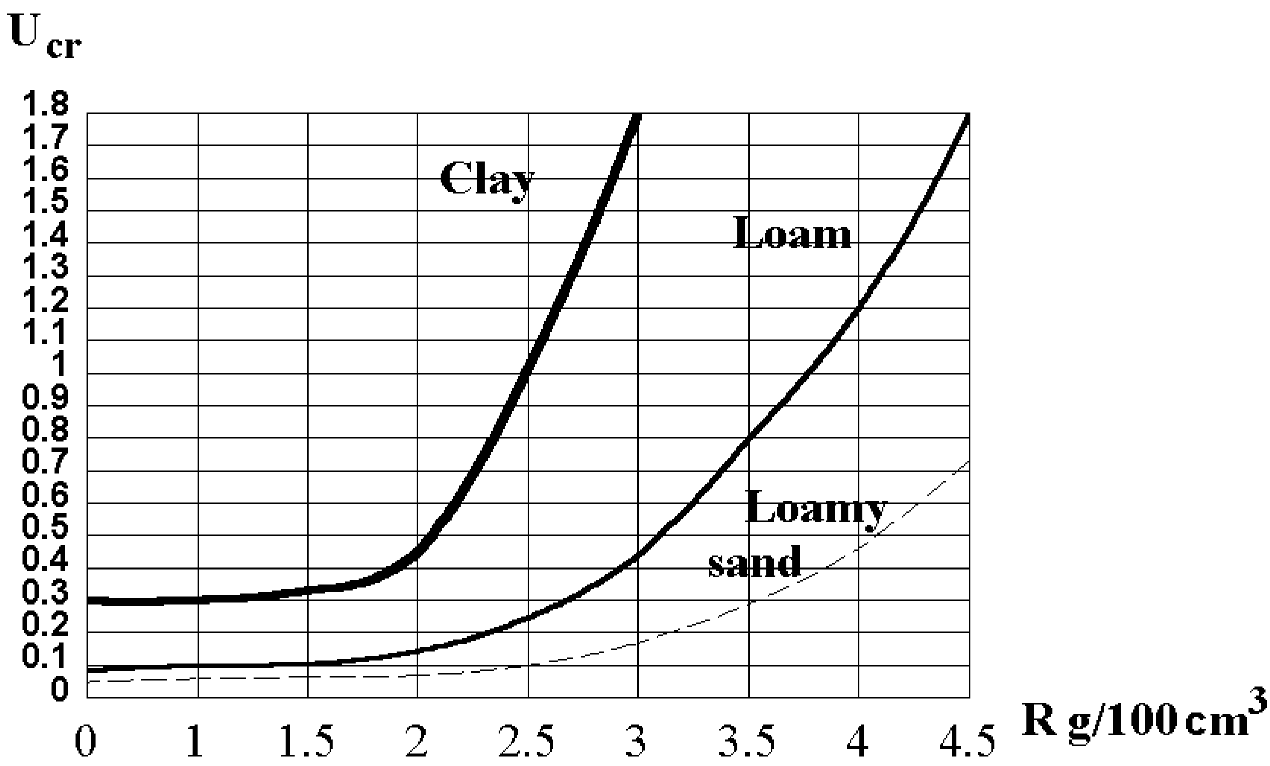

Fig.2. Diagram for evaluation of the vegetation cover quality R for a given critical velocity U_{cr} and soil type.

Conclusion

1) The heavy and local constructions are not suited for soil conservation under permafrost conditions with complicated thermoerosion and thermokarst processes. Once initiated, thermogully growth can not be stopped by methods normally used in a temperate zone.

2) The methods to reduce erosion on already disturbed fields are: mechanical snow removal from gully catchment areas; vertical drainage of industrial and rainfall waters; covering of disturbed slopes with a peat layer; filling of the gullies with heavy loam and a peat cover.

3) The main steps to prevent erosion are:

- avoiding unstable geomorphic units for construction;
- improvements of vegetation cover quality at gas exploitation sites.

4) The method was developed to evaluate the quality of vegetation cover required to protect soils of different types from erosion and thermoerosion.

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