Engineering-geological and hydrogeological features of the dzuarikau-tsikhinval gas pipeline installation and environmental aspects of its operation in high seismicity conditions

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Abstract. Despite the strategic importance and social orientation of the project to install the world's highest mountain gas pipeline to South Ossetia, the damage to the environment is great. In contrast to flat terrain, highland landscapes due to large-scale natural (landfalls, avalanches, mudflows, landslides, etc.) or anthropogenic (installation of oil and gas pipelines) negative impacts either not restored at all, due to the progressive influence of factors interventions, or the recovery takes decades. In high-mountain areas, soil destruction is accelerated due to developing sources of landslides and ravines, mudflows, creeps and collapses, active lateral infiltration of groundwater, leading to rapid dehydration of soil and biocenosis degradation. Neglecting the scientific basis for minimizing damage to the environment, the primacy of business over environmental consequences, the lack of fundamental and qualified expertise of projects relating to interference with the natural environment, the legislative vulnerability of ecological systems have become commonplace and have a very steady tendency to take root. The result of consumer attitudes towards ecosystems is estimated by the example of these works by extensive deforestation, deep cutting of extended slope intervals at high mountains and, finally, significant deviations from the original project. At the same time, there are no works on recultivation, which, however, are doomed to failure in the existing orographic and seismological conditions of the Dzuarikau-Tskhinval gas pipeline route. The route of the Dzuarikau-Tskhinval gas pipeline enters the Kassar (valley of the Ardon River) gorge near the Tamiysk resort and then it cuts through both slopes of the Ardon River to Zaramag HPP, and then passes through the picturesque valleys of the Mamikhdon and Zemegendon Rivers, where the gross impact on nature is most clearly observed.

1. Introduction
The best option for installation the Dzuarikau-Tskhinval gas pipeline was considered in the following direction: Kassar gorge (valley of the Ardon river), further along the valleys of the Mamikhdon and Zemegendon rivers, through the Kudarsky pass along the Dzhodzhora River to Kvaisa and then along the highway to the town Tsikhinval. This outline was taken as the basis for which the engineering and geological features of the site were to be studied by complex engineering and geological investigations. It was supposed to perform the strategic task of installation a gas pipeline with minimal damage to the environment, so that the environmental indifference of business goals did not replenish the other waste
of humanity by the disfigured landscape of the route, in which humanity is suffocating according to Niels Bohr [1–7].

Surveys for the preparation of a final design concept were started by the researchers of the Geophysical Institute of the VSC RAS in September 2005 and were aimed at investigation the conditions for the development of hazardous geological processes (lithological, hydrogeological, seismotectonic, anthropogenic) and the extent of their impact on the objects of the proposed construction and elements of their infrastructural planning, classification of soils composing the route, determining their physico-mechanical characteristics and predicting dangerous exogenous processes, environmental justification of project documentation for the construction of the pipeline.

According to the technical specification the soil conditions were investigated to a depth of 2.5 m along linear part of the gas pipeline over natural crossings (rivers, ravines, landslides) and artificial barriers (embankments, dumps) – up to 6 m, and, if necessary, up to 8–10 m (tectonic zones, debris cones). In some areas of the development of adverse processes, detailed engineering and geological conditions were carried out with an increase in the depth of drilling up to 15 m and the formulation of geophysical works using the vertical electrical resistance method.

Based on the survey materials, the soils along the gas pipeline route were classified into engineering-geological elements, taking into account their age, genesis, textural and structural features and nomenclature type, as well as regulatory and design characteristics were calculated. The total length of the route, within which engineering and environmental surveys are carried out, is 162 km. The layout of the gas pipeline route and the position of the geophysical profiles of geolocation sounding are shown in Figure 1.

According to the complexity of the terrain, altitude, geological and mining conditions, the route of the Dzuariikau-Tskhinval gas pipeline has no analogues in the world. The pipeline crosses a height of 3148 m, crosses 30 avalanche sections, covers 75 km of the northern and southern slopes of the Main Caucasus Range with heights exceeding 1500 m. 15 tunnels with a total length of 1848 m were driven in the rocky soils, and 29 bridges were built, the cost of the project was 15 billion rubles. Pipeline with diameter 426 mm and working pressure of 50 atm. has capacity of 252.5 million m$^3$ per year, which allows satisfying consumption with full gasification of the Republic. Typical mining-geological and landscape conditions of the route are characterized by Figures 2, 3.

2. Materials of field works
The materials of regional engineering and geological work, monitoring of exogenous geological processes in the territory of the RNO-A and specialized work carried out by the North Ossetian Geological Survey Expedition, Geophysical Institute of VSC RAS on the area of the proposed construction of the gas pipeline were used [5–12].

3. Geological research
The main geomorphological, geotectonic potential factors of negative impact on the pipeline include: geomorphology, quaternary formations, tectonics, erosion processes.

3.1 Tectonic features of the area
The tectonic features of the area is the alternation of ridges and intermontane depressions of the all-Caucasian orientation (280–295°), intersected by valleys of the submeridional direction. The main geomorphological units of the Northern Slope of the Greater Caucasus in the strip of the gas pipeline route include: Lesistyi ridge, with absolute elevations up to 1200 m, fully forested and folded with conglomerates, tuff sandstones, gravelites and ashes of Neogene; Pastbishnyi ridge with absolute elevations up to 1800 m in the majority (up to 80 %) is forested and represented by carbonate strata (limestone, marl, dolomite) chalk; Skalistyi ridge with the highest points of 3438 m (mountain Kariukhokh), composed of carbonate sediments (dolomites, limestones, dolomitic limestones) of the upper Jurassic. The northern and partially southern slopes are covered with forest up to 2500 m; Bokovoi ridge, the highest in the system of the Greater Caucasus ridges, with maximum absolute levels of
catchment areas [16], affecting the gas pipeline zone, 4404 m (mountain Adyakhkohk) and 4427 m (mountain Tepli), composed of terrigenous igneous and metamorphic rocks of the Central uplift zone. Dwarf forest (birch) is fixed at up to 2600 m on the northern slopes. The Glavnyi (Main) ridge separating the North Caucasus and Transcaucasia with absolute elevations reaching 3,938 m (mountain Khalalts), composed of Cretaceous terrigenous-carbonate deposits of flysch (limestones, marls, sandstones, shales). The gas pipeline route passes through this ridge at an altitude of 3148 m (Kudarskiy passage). Forest cover reaches the level of 2500 m.

On the southern slope (the territory of the South Ossetia) the main geomorphological units intersected by the gas pipeline route include: Rachinskiy Ridge, which is a second order structure relative to the Glavnyi (Main) ridge, has a northeast orientation, is composed of Cretaceous-age carbonate sediments, reaches absolute marks of 3500 m and it joins the Glavnyi (Main) ridge west of Zekar Pass (at an altitude of 3620 m). The gas pipeline route crosses this ridge in the vicinity of the Ertso Passage at the level of 1820 m; The Suram ridge (Likhskiy), along the northern and southern spurs of which the gas pipeline runs, connects with the Racha ridge in the vicinity of Lake Ertso. The ridge is composed of reefogenic limestones of the Upper Jurassic, porphyrite and tuff sandstones of Bayos. The absolute elevation of the ridge does not exceed 2470 m (mountain Ribisi). The ridge is completely forested to a height of 1800–1900 m.

3.2 Quaternary sediments
Quaternary sediments are represented by alluvial deposits of the floodplain and terraces. Modern alluvium consists of 65–75 % of boulders, pebbles and gravel, 20–25% of sand particles and 5–10 % of dusty and clay fractions. The thickness of modern alluvium of Ardon and Dzhodzhora rivers is 5–25 m, in the estuarine parts of its large tributaries 4–17 m, but on the rapid areas is almost absent. The thickness of the proluvial sediments of the modern – Upper Pleistocene age varies from the first meters to 30 meters. The deluvial deposits have a thickness of 0.3–0.8 meters, less often up to 9 meters (at the foot of the slopes, especially southern) and are represented by gruss-rock debris soils with sandy-clayey aggregate 20–30 %. Colluvial crust deposits on terrigenous rocks contain 77–80 % of detrital material, 10–13 % – of sandy fraction, about 10% of silty-clay. The sediment thickness is up to 10 m, less often 30–40 m. The eluvial formations along the gas pipeline route are fairly widespread and developed on the passage section (Kudarskiy passage) and the crest parts of the Dzhava and Surami ridges. The thickness of the eluvium developed, both in the rocks of the Cretaceous flysch and the terrigenous deposits of Neogene, and in the porphyrites of Bayos reaches 2.5 m in some places. Landslides formations are a type of conventional slope deluvium and differ from it by a larger fractional composition, increased natural moisture, less compaction and stability. The landslide formations can reach several tens of meters in the work area. Landslides for the most part have a seismogenic nature, localizing along zones of powerful tectonic ruptures and by the mechanism of mass movement, with rare exceptions, can be attributed to collapses.

3.3 Tectonic features of the area
The tectonic features of the area include its location at the junction of two megaplates (Scythian and Transcaucasian), which distinguishes it by its geological structure.

The main rupture structures intersected by the pipeline route, which may adversely affect it, are shown in Figure 4.

On the territory of South Ossetia, the Dzhava zone of seismic dislocations is distinguished. The most characteristic elements of this zone, regardless of 1991 events, can be considered young raptures in the Kemult region at the confluence of the Patsa and Keshelta rivers. Given the size of both individual linear forms (up to 1–10 km), and the displacement magnitude of the of the fracture wings (from 1 to 50 m), as well as the length of the system as a whole and its individual elements (3–10 km), we can talk about seismic events with intensity of 9–10 points and higher in this sector of the Greater Caucasus.

3.4 Erosion Processes
The territory is characterized by a high hazard degree for the development of exogenous geological processes. Very complex engineering-geological, hydrometeorological and seismic conditions require the implementation of ubiquitous integrated engineering protection of structures against combinations of interdependent catastrophic and hazardous processes [11,12, 17].

When analyzing the damage from the impact of exogenous geological processes using the example of a 20-year operation of Transcaucasian Highway, it turned out that in the overall balance the erosion processes account for 45 %, mudflows –30 %, avalanches – 10–15 %, rock slide-scree – 8–10 % and landslides – 1–2 %.

![Figure 1. Route of the gas pipeline Dzuarikau-Tskhinval](image)

Erosion processes include rainwash, gully erosion, lateral and bottom erosion of rivers [18]. The intensification of erosion processes on a regional scale is due to the fact that at present the orogen of the Greater Caucasus is captured by a tectonic uplift at speeds from 2 to 14 mm/year.

In high-mountain areas, the length of the erosion network is 2.5–3.4 km/km², and the depth of local erosion bases is 1000–1500 m. Under these conditions, water flows are characterized by high speed (up to 3 m/sec and more) and perform significant erosion work.

The most intense linear erosion develops in rock slide-scree, deluvial-gravity and landslide deposits, shale and mudstone of the northern and southern intermountain depressions. This is manifested in the formation of numerous ravines and gullies up to 4 m deep and a sharp increase in their growth.
The greatest negative impact on economic facilities, especially roads, has lateral river erosion. Caving in the banks as a result of lateral river erosion is most intensely manifested in the basin of the river Ardon from headwaters to the exit from the mountains to the plain.

The rate of development for lateral erosion according to long-term observations in the mountainous part of Ossetia reaches 1–5 m/day during the flood period, depending on the material composing the watercourse banks.

3.4.1 Mudflows

Mountainous of Ossetia, both South and North, is one of the most mudflow-prone regions of the Caucasus. Highly dissected relief, modern glaciation, high seismicity, huge reserves of loose detrital material, high moisture content, create favorable conditions for the mudflow formation [19, 20]. According to the volume of one-way mudflow, all the basins are divided into four groups:

- very powerful – with a single release of more than 100,000 m³ of solid material;
- average power – from 10,000 to 100,000 m³;
- weak – from 1000 to 10,000 m³;
- micro-mudflows (sloping) – less than 1000 m³.

The most common and active mudflows are in the high-altitude area in the area of the Bokovoy and Glavnyi (Main) ridges, where about 50% of all mudflow sites are concentrated.

Among the local mudflow sources there are three main types (according to geomorphological features): mudflow cuts, mudflow gulches, rocky sources.

For Mountainous Ossetia, the accumulation of the necessary amount of detrital material in the rocky mudflow source, sufficient for the formation of the mudflow, requires 8–10 years. This is especially evident in the territories of development of terrigenous sediments.

3.4.2 Rock slide-scree processes

About 90% of the entire length of the route passes through loose-debris sediments, much of which is the product of rock slide-scree processes.

The reasons for the rock slides in the conditions of sharply dissected relief and intensively stationed rocks, especially in the zone of the Central elevation of the Greater Caucasus, are: powerful geodynamic processes; phenomena of accumulated seismic effects, when the effect of collapse is manifested not from one powerful seismic impact, but from a multitude of weak ones; seismic impact – powerful seismic shocks up to 7–9 points [21], which discharge in mountain conditions occurs in the ridge and near-the-tip parts of the relief, leading to the collapse of large blocks of rock and loose rocks; the action mechanism of lateral repulse cracks, that is especially effective in the high-altitude zone with sharp daily temperature differences. In this case, the main role is played by microcracks, in which the effect of freezing moisture is especially strong.
The example of the effect of geodynamic impact can be a sudden collapse of rocks with a volume of about 5000 m$^3$ in the zone of the Nuzal thrust (1990) on the left side of the Ardon River in the area of PK 518 + 00. The road was completely blocked over 150 m.

An example of a collapse as a result of short-term powerful seismic effects can be the presence of a huge (up to 1 km$^2$) plume of large-block (up to 10 m in diameter) accumulations of granite composition on the left side of the Ardon river (region of the Buron tunnel), which was formed as a result of a
localized seismic impact about 500 years ago. The ancient road and customs buildings were littered with blocks of granite.

Along the entire pipeline route, any steep-slope (up to 50°–90°) section composed of hard-rocks can be attributed to rock slide-prone, but the most likely areas include the development of powerful tectonic disturbances (Nuzal thrust, the range of tectonic faults of north border of Central elevation – big Bad and Tsey faults, the zone of main Thrust, that limits the Central elevation from south, Tib fault zone – the right side of the Mamikhdon River).

Scree is the most common type of rock slide-scree processes, which are particularly intense on the slopes, formed by shale and thin-layer rocks of the terrigenous formation of the lower-middle Jurassic. At the foot of such slopes with a steepness of more than 30°, almost everywhere there are plumes of active fine-grained debris, ungrassed and almost devoid of aggregate. The steepness of scree plumes is 28–35°.

On slopes composed of igneous and metamorphic rocks, scree processes are less developed, scree material is coarser. The steepness of scree plumes is 37-39°. Large and active debris is developed mainly in the upper reaches of the rivers of the high-mountainous zone.

On scree deposits, passes, about 50 km of the pipeline route. The examples of scree deposits of high mobility can be scree zones of the development of carbonate flysch in the upper reaches of the Mamikhdon River.

3.4.3 Landslides
With a fairly widespread development of landslides on the territory of the proposed construction of the gas pipeline, its route was chosen so that it crosses just 6 landslide areas, only two of which can be classified as active, the rest are stabilized. A detailed description of these objects is given in the picket description of the pipeline route. The absolute majority of these formations is confined to zones of powerful regional faults and has a seismogenic nature, and can be attributed to landslide with a high degree of probability.

3.4.4 Avalanches
The area of works, and especially its high-mountain part, is characterized by a wide occurrence of avalanches. One-time snowfall with a capacity of up to 1m is an ordinary phenomenon here [22].

The most common and large ones are channelled avalanches, which are permanently tied to lower forms of relief (beams, couloirs, canyons), and the smaller ones are snow slides, which descend from slopes that have anthropogenic or natural cutting [23–25].

A special type of avalanche should include avalanches of semi-liquid consistency, which are formed after rain precipitation on the slopes overloaded with snow. Such avalanches go at low speed (about 1–2 m/s) and have low energy and reaching the traffic lane and turning around 90°, they pass directly along it, without going beyond its limits at a distance of hundreds of meters. Subsequently, the water and snow mass freezes into a single ice body.

A one-time recorded avalanche mass emission in the area of the route reached 300 thousand m³. Most avalanches belong to the high-speed category (more than 100–150 km/h) and have powerful shock waves that can heave practically any equipment (cars, bulldozers, etc.) into the air. As a rule, the shock wave capture zone exceeds the width of the area affected by snow masses in 2–3 times.

Most of the avalanches overlap the river bed with a transfer of snow mass to the opposite side. The so-called “jumping” avalanches (when the bulk of the avalanche breaks off the stream bed at the site of a sharp increase of the slope (cliff) steepness and falls into the river channel, flying several hundred meters through the air) should be referred to the most dangerous avalanches. In this case, in the affected canyon, the effect of the repeated impact of reflected shock waves is manifested, in which steel supports of power transmission lines, which have no wind resistance, acquire the most bizarre forms.

Snow density of avalanche catchment ranges from 0.06 to 0.4 g/cm³. In a discharge zone (avalanche cones) it is up to 0.5 g/cm³. As a rule, up to 70% of snow cover out of the entire area of the avalanche catchment comes down. Instrumentally measured avalanche velocities show the values of 10 to 60 m/s.
The avalanches of fresh snow at a precipitation intensity of more than 1 mm/hour, a temperature of minus 4 ° and below and a wind speed of 6 m/s and more. The daily critical amount of precipitation is about 10 mm, and for the descent of many large avalanches, it is equal to 20–44 mm/day. In general, in the Greater Caucasus, the distribution of avalanches according to genetic types is as follows: 7.5% of their total number was observed during snowfalls, 8% – during spring snowmelt, 6% – during thaws, 2% – during blizzards and 9% – during avalanches of sublimation recrystallization.

4. Geophysical study

Geophysical study was performed on individual local sections of the route, where it was necessary to determine the thickness of soils, the nature of the change in the direction of the relief uprising from the project line of the route, the presence of flooded areas in the section of a certain profile that is of interest in determining the location of the route, to differentiate the soils by material and granulometric composition, to assess a landslide activity of a certain soil massif.

The Georadar OKO-2M with the AB-150 MHz antenna unit in the sounding mode [26] (when the transmitting and receiving antenna units are rigidly interconnected) was used as a measuring complex. The scan step was set up at 300mm.

As it is known, soils as dielectrics have different values of dielectric capacity (σ). While transmitting the electromagnetic field at the boundary of two media with different values of σ, a wave reflection occurs. The reflected wave can be strengthened or weakened due to the polarization of the medium, which is superimposed or reduces the intensity of the primary wave. The isolation of such reflected waves, their correlation and interpretation form the basis of the geolocation method [27–29].

The transmitter set by the operator in the time mode sends electromagnetic pulses, during the interval between the pulses, the receiving antenna receives a reflected signal, which is amplified many times due to multiple accumulations (64,128,256 times) of single measurements over the time interval between switching on of the transmitter.

GPR works were carried out at the maximum penetration depth of an electromagnetic wave, determined by the option of 511 points, which means the detailed of registration, i.e. the equipment records 511 points at the maximum possible penetration depth, which characterizes the vertical detail. Thereat, in case of low values of σ, the depth of penetration will be greater and vice versa, but the number of measurements, in either case, will be the same (511). In order to speed up the work, this value can be reduced in 2 and 4 times.

The process of setting up the equipment, establishing the recording parameters and synchronizing with the operator’s personal computer at the initial stage of scanning the soils of the route is shown in Figure 5.

The obtained data were processed in the Geoscan-32 program, which includes various methods of filtering, amplifying, smoothing, selection of the field of spectra, taking the vertical coordinate (relief) into account, selection of layers and their coloring and filling with conventional signs (Fig. 6, 7).

Figure 6 shows a geologic-geophysical profile according to geolocation sounding along the profile located on the eastern slope of the Zemegendon River valley 300–350 m away from the thalweg. There are five different layers of soil.

The upper gravelly layer, which is underlain by a thick layer of clay and sandy-loamy sediments, located in the north on a layer of flooded coarse-grained blocky deposits, which wedge out to the south and form a landslide massif, shifted along the surface of the similar coarse-grained rocks, but not watered. The soils are potentially landslide and can shift to the valley of the Zemegendon River.

The profile of Figure 7 is passed transversely to the Zemegendon River valley to the east of its confluence with the River Kozikomdon. Here the composition of soils is similar to the cut in Figure 6, but the aquifer is not on the cutting line, has no continuation into the valley and can flow to the north. At the same time, a layer of loam can serve as slickensides for surface rubble – sandy sediments.

5. Discussion of the research results
Being based on geolocation scanning of local sections of the route allows singling out four types of Quaternary formations with a total capacity of 10 m. Under the covering rubble – sandy deposits a steeply dipping clay-loamy interlayer with a thickness of up to 2 meters is noted. It can serve as a slickenside with the activation of landslide processes by the anthropogenic or seismogenic impact. The bottom of clay-loamy formations is saturated with water, since the underlying blocky-rubble stratum is saturated with water, and this fact favors the occurrence of landslide processes. The thickness of the Quaternary formations towards the thalweg of the river increases and the multimeter side cutting on the part of the hanging road shelf will cause a gravitational slide of the overlying loose mass.

Figure 5. Members of the Geophysical Institute at work with Georadar

Figure 6. Geologic-geophysical profiles of the route sections on the eastern slope of Zemegendon River 300 m away from the thalweg

Figure 7. Geologic-geophysical profiles of the route sections of the eastern slope of the gas pipeline route from the mouth of the river Kozikomdon
As a result of the analysis of the spatial variability of particular indicators of the physical and physical-mechanical properties of soils determined by laboratory methods, taking into account the data on the geological structure and lithological features of soils in the area of the projected gas pipeline 20 engineering-geological elements have been identified, the tensile strength of which varies from 18 MPa to 300 MPa. Such a wide range of properties implies the development of special conditions for the successful implementation of the project. In this regard, a very important step is the organization of local environmental monitoring, which involves determining the main components of the environment that need monitoring [30, 31], determination of background values or initial data on the day of the beginning of the facility construction and realization of stationary observations to determine changes in indicators of the environment state. The proposed line of the road shelf cutting, located on the eastern slope of the Zemegendon River valley significantly upward the river, unfortunately, was not taken into account in the construction of the route. The cutting was carried out near the river, which caused intense lateral infiltration of groundwater, removal of loamy cement and activation of landslide processes along the entire cutting line.

The actions program of the environmental monitoring group during the construction stage was limited to the following:

- preventing unauthorized use and land pollution outside the boundaries of the branch for storage of materials and discharge of oil products onto the ground [32];
- monitoring the use and reclamation of temporary allotment areas for construction objects.

The actions program of the environmental monitoring group during operation consists in monitoring the emission of pollutants from pumping stations, emergency points and launch sites.

6. Conclusion

The gas pipeline route in the range of PK 231 + 00 – PK 264 + 00; PK 283 + 00 – PK 339 + 00 and PK 560 + 00 – PK 665 + 00 passes through the territory of the North Ossetian State Reserve (beech, oak, linden, pine, yew, alder, aspen).

Line of precipitation which may cause a landslide is equal to 30-50mm/day; daily precipitation up to 70 mm/day occurs once in 10–15 years.

The background seismicity of the route area of the projected gas pipeline is equal to 9 points. This area is characterized by a high hazard level of exogenous geological processes development (mudflows, landslides, rock slide-scree and erosion processes, avalanches, carst).

The total length of landslide and rock slide-scree plots is 30052 m, and avalanche-hazardous is 5815 m. The total length of areas with shallow groundwater occurrence (less than 3.0 m depth) is 9525 m, as a rule, in alluvial and diluvial sediments.

The total length of areas with shallow rock bedding (depth less than 2.0 m) is 23054 m. The gas pipeline route in the range of PK 256 + 00 –PK 1100 + 00 is intersected by 12 powerful tectonic zones (from 100 to 2500 m) of a regional scale, which are still active today. Zones of the newest seismic dislocations were recorded both on the northern and southern slopes of the Glavnyi (Main) ridge, indicating high-intensity seismic shots.

This leads to the formation of the Action Program of the environmental monitoring group at the construction stage, which was to prevent unauthorized use and land pollution outside the boundaries of the branch for storage of materials and discharge of oil products onto the ground and providing monitoring of the use and reclamation of the temporary allotment areas for construction objects.

The actions program of the environmental monitoring group during operation consists in monitoring the emission of pollutants from pumping stations, emergency recovery points and launch sites.

Thus, in order to exclude possible accidents in mountain conditions, it is absolutely necessary to conduct special studies in the development of the project of laying the pipeline route along the so-called "weak" low-strength soils and the creation of a system of instrumental and visual monitoring of the condition of the underlying pipeline array.
References

[1] Qi S S, Hao F H, Ouyang W and Cheng H G 2012 Characterizing landscape and soil erosion dynamics under pipeline interventions in Southwest China, 18th Biennial Isem Conf. on Ecological Modelling for Global Change and Coupled Human and Natural System. Proc. Environmental Sci. Z. Yang and B. Chen (eds.) pp 1863–71

[2] Sahley C, Vildoso B, Casaretto C, Taborga P, Ledesma K, Linares-Palomino R, Mamani G, Dallmeier F and Alonso A 2017 Quantifying impact reduction due to avoidance, minimization and restoration for a natural gas pipeline in the Peruvian Andes Environmental Impact Assessment Review 66 53–65

[3] Lidskog R and Elander I 2012 Sweden and the Baltic Sea pipeline: Between ecology and economy Marine Policy 36(2) 333–8

[4] Zaks T, Burdzieva O and Zaalishvili V 2019 Impact of Noise, Gamma Radiation and other Geophysical Factors on Population Health Akustika 32 206–10

[5] Alborov I, Burdzieva O and Zaalishvili V 2019 Technology for the Maintenance of Acoustic Comfort on the Transcaucasian Highway in the Zone of the Residential Areas Adjusting the Motor Road Akustika 32 211–5

[6] Zaalishvili V, Dzhgamadze A, Gogichev R et al 2018 Changes in the Qualitative Characteristics of Groundwater of the Ossetian Artesian Aquifer Int. J. of Geomate 15(51) 22–30

[7] Burdzieva O G, Zaalishvili V B, Beriev O G et al 2016 Mining Impact on Environment on the North Ossetian Territory Int. J. of Geomate 10(19) 1693–7

[8] Zaalishvili V B, Melkov D A, Dzeranov B V et al 2018 Integrated Instrumental Monitoring of Hazardous Geological Processes Under the Kazbek Volcanic Center Int. J. of Geomate 15(47) 158–63

[9] Shempelev A G, Zaalishvili V B and Kukhmazov S U 2017 Deep structure of the western part of the Central Caucasus from geophysical data Geotectonics 51(5) 479–88

[10] Zaalishvili V B, Nevskaya N I, Nevskii L N et al 2015 Geophysical fields above volcanic edifices in the North Caucasus J. of Volcanology and Seismology 9(5) 333–8

[11] Rogozhin E A, Gorbatikov A V, Zaalishvili V B et al 2015 New data on the deep structure, tectonics, and geodynamics of the Greater Caucasus Doklady Earth Sci. 462(1) 543–5

[12] Gorbatikov A V, Rogozhin E A, Stepanova M Yu et al 2015 The pattern of deep structure and recent tectonics of the Greater Caucasus in the Ossetian sector from the complex geophysical data Izvestiya Physics of the Solid Earth 51(1) 26–37

[13] Zaalishvili V B, Nevskaya N I and Mel'kov D A 2014 Instrumental geophysical monitoring in the territory of northern Caucasian Izvestiya Physics of the Solid Earth 50(2) 263–72

[14] Milyukov V K, Yushkin V D, Kopav A V, Zaalishvili V B et al 2014 Monitoring Current Vertical Movements of the Northern Caucasus by Absolute and Relative Gravimetry Measurement Techniques 56(10) 1105

[15] Akoeva L A and Zalikhanov M Ch 1987 Natural phenomena in the Caucasus and their intensification under the influence of economic activity (Moscow: Hydrometeoizdat) Khashirova T Yu, Lamerdonov Z G and Kuznetsov E V 2007 The conceptual model of the protection of mountain and foothill landscapes as a natural and man-made environmental management complex Melioration and Water Economy 6 43–6

[16] Zerbaliev A M and Guseynova M R 2009 Study of anti-erosion technology of gravity irrigation of land Environmental Management 2 43–8

[17] Agibalova V V 1983 Mudflows in North Ossetia (Ordzhonikidze: Ir)

[18] Kononova N K and Malneva I V 2003 The occurrence of emergency situations caused by the development of dangerous geological processes in the North Caucasus, and their forecast for the next decade Problems of forecasting emergency situations: Reports and speeches at the II sci. and pract. conf. (23 October 2002) (Moscow, Center Antistikhiya Ministry of Emergency Situations of Russia) pp 160–6
[19] AS USSR, Schmidt Institute of Physics of the Earth 1976 *New catalog of strong earthquakes on the territory of the USSR from ancient times to 1975* (Moscow: Nauka)

[20] Zalikhanov M Ch 1981 *Snow-avalanche regime and prospects for developing the mountains of the Greater Caucasus* (Rostov-on-Don) 376 p

[21] Socratov S A, Seliverstov Yu G, Shnyparkov A L et al 2013 Anthropogenic influence on avalanche and mudflow activity *Ice and snow* 2(122) 121–8

[22] Zaalishvili V B and Vorobiev V G 2006 Monitoring of glaciers and determination of the boundaries of avalanche danger in mountain areas *Earthquake Engineering. Safety of buildings* 6 32–6 (Moscow: VNIINTPI)

[23] Oliveros F, Hernandez E and Soto G 2017 Application of geotechnical criteria for the occurrence of earth flows (avalanches) on the right of way of pipeline transportation system of Camisea in the coast zone of Peru *Proc. of the ASME 2017 Int. Pipeline Geotechnical Conf. IPG2017* (25–26 July) (Lima, Peru)

[24] Vladov M L and Starovoitov A V 2001 Interpretation of GPR data *Exploration and protection of subsoil* 3 11–4

[25] Paramonov N B, Shishkov D L, Zaripov M N and Egorov G A 2016 Processing of geolocation information *Issues of radio electronics* 3 74–9

[26] Alterman A D and Lushnikov N D 2018 Geolocation capabilities and its features *Theory. Practice. Innovation* 11(35) 15–9

[27] Kiselev D A 2018 Research methods for processing geolocation data. In the collection: Innovations in science and practice *Collection of articles on the materials of the VII Int. Sci. Pract. Conf* In 5 parts pp 258–61

[28] Angelici F M, Grimod I and Politano E 1999 Mammals of the Eastern Niger Delta (Rivers and Bayelsa States, Nigeria): An environment affected by a gas-pipeline *Folia Zoologica* 48(4) 249–64

[29] Jones I L, Bull J W, Milner-Gulland E J, Esipov A V and Suttle K B 2014 Quantifying habitat impacts of natural gas infrastructure to facilitate biodiversity offsetting *Ecology and Evolution* 4(1) 79–90

[30] Baynard C W 2011 The landscape infrastructure footprint of oil development: Venezuela's heavy oil belt *Ecological Indicators* 11(3) 789–810