Karst hazard assessment in the design of the main gas pipeline (South Yakutia)

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Abstract. The paper represents the description of the zonal and regional geological factors of geoengineering conditions which characterize the territory in South Yakutia crossed by the designed main gas pipeline. Cryogenic processes and karst are considered to be the most dangerous hazards for gas pipeline maintenance. Karst hazard assessment of the gas pipeline section made in the course of the research has involved a complex of geological methods: geoengineering, geophysical, hydrogeological, and mapping. Sections prone to karst development have been identified. The authors have suggested the measures to protect potentially hazardous sections and to ensure timely informing on sinkhole collapses.

1. Introduction

1.1. Significance of the problem

Constructing gas pipelines in the areas characterized by unfavourable environmental conditions, such as boggy areas or zones of ever-frozen subsoil, is a current challenge in the field of hydrocarbons transportation. The issue is particularly important when the pipelines are constructed in the territories with frozen karst, for instance, the Lena tableland in South Yakutia. To prevent gas pipeline failures, it is necessary to develop the measures which ensure timely informing on sinkhole collapses.

The karst phenomenon has been researched in the works of many Russian and foreign scientists. This is due to the fact that karst zones are varied and widely spread. In the works by N.A. Gvozdetsky [3, 4], G.A. Maksimovich [8] the following questions were discussed: solubility of karst rocks under different physiographic and geological conditions, the mechanism of karst collapse, stability assessment in karst areas, the methods efficient to detect karst cavities in the course of land development, etc.

The objective of this paper is to assess karst hazards for the first section of the main gas pipeline «The Power of Siberia» with the complex implementation of different geological methods: geoengineering, geophysical, hydrogeological, and mapping. On the basis of the data analysis sections prone to karst development have been identified and the appropriate measures have been suggested to protect potentially dangerous sections and to ensure timely informing on sinkhole collapses.

1.2. Object of study

The study area is located in Lensk Ulus, the Republic of Sakha (Yakutia). The description of geoengineering conditions is provided on the basis of the archive materials, which contain the data obtained by VostSibAGE, Promneftegazproyekt, Ingeokom, Fundamentproyekt, SPF DIEM, Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS) in the course exploration work for pipeline route in 2010-2012. The length of the track was 160 km. The region is poorly studied and the lands are poorly reclaimed.

The climate of the region is sharp continental, with lukewarm summer and severe dry winter. The average annual air temperature is –5.6-6.2 °C. The annual amount of precipitation is 346-409 mm, 75% of which fall during the warm period.

In terms of geomorphology, the gas pipeline route stretches through the Prilensk erosive tectonics plateau bounding with Patom highland in the southeast and with the Leno-Vilyuysk basin in the north and northeast. The surface of the plateau is 400-600 m above sea level and is tilted gently to the northwest. The highest point above the sea level is Byugyuekh watershed divide (554 m) and the lowest point is the valley of the river Nuia (243 m). The erosion and denudation landform is predominant. It is represented by Lower-Middle Cambrian sediments of steeply-sloping plateau and Upper Cambrian and Ordovician sediments of the ripple-semi-sloping plateau.

In terms of tectonics, the region is located in the southern part of the Siberian platform, beginning from the Nepsky arch of the Nepsko-Botuobinsk anticlise and moving to Predpatomsk depression. The area is composed of Cambrian and Ordovician sediments as comb-shaped folds extending to the north-east along the border of Baykal-Patom mantle folded formation. The folds are fractured predominantly with south-east thrusting. There are also transverse steeply dipping submeridional strike fractures. Two sections of the track cross the zones of Jurassic sediments overlying Lower Paleozoic sediments with angular unconformity. The summary information on the region geology is represented in table 1.

Table 1. The geology of the region.

№	Sediment age *period* – thickness, m	Lithologic composition of sediments
1	Cenozoic *Quartenary*	Low ice-content clay loam, sand clay, pebble, gruss, peat
2	Mezozoic *Jurassic* – 90	Diversely-grained sand with sandstone and conglomerate lamina
3	Paleozoic *Ordovician* – 300 *Cambrian* – 1300	 Aleurolite, argillite, Limestone, dolomite

On the seismic zoning map the track crosses the zone with seismic intensity of 6 points of MSK-64 scale.

Within the zone, country rocks and quaternary sediments are identified. Country rocks are of two formations: Lower Cambrian carbonate and Middle Cambrian and Ordovician terrigenous-carbonate. The following genetic types are found among Quaternary sediments: alluvial, alluvial-diluvial, diluvial-proluvial, diluvial-colluvial, colluvial, eluvial, eluvial-deluvial, and biogenic.

The region is within the area of insular permafrost. The lowest annual permafrost temperatures (up to –1.7 °C) are characteristic for valley bottoms and the lower parts of slopes, while the highest temperatures (0 – minus 0.6 °C) are characteristic for watershed and tops of smooth slopes. Thermal radiation subgelisols are typical for high watershed and fractured carbonate rocks slopes. Channel subgelisols are typical for stream valleys, especially within the zones of tectonic fractures and karst zones within the carbonate rocks of the channels.

Preferentially, island nature of distribution of permafrost within the territory and limited distribution of icy soil predetermined nature of development of cryogenic processes – dominance of the one-year, seasonally failing cryogenic educations – river sleets, one-year hillocks of a frost heaving, arising not annually and changing places of the education depending on freezing conditions. Cryogenic processes have local distribution and are coordinated generally for the bottoms of valleys.

The insular permafrost and scarce icy ground of the region result determined the character of cryogenic processes: one-year cryogenic formations, which break on-season, are predominant – flood icing and one-year frost mounds, which emerge from time to time and change the place of emergence.

Karsts are widely spread in carbonate formations. Intensive karst development takes place due to fissured lands and fractured rocks. Karst development is caused by dissolution of carbonate rocks by surface and ground waters. The process is intense in fractured zones of smooth carbonate kettle back, which is the anticlinal core. Cambrian carbonates include sulphate of lime, cube spar, limestone, and as a result, both the thickness and the extension of karst zones vary significantly.

In the course of exploration different forms of karst were identified – karst windows and sinking streams. The diameter of the karst window is from 10 to 50 m and the depth is from 0.5 to 3.3 m. The process of karst development within some windows is quite intense which is indicated by recently fallen trees and sinks 5 m in width and 3 m in depth. The 10 m well drilled within the karst window revealed uncovered loam soils and sandy medium gravel clay, while no hard limestone, supposed to occur at the window periphery at the depth of 1.5– 3.0 m, were identified. Ground waters were neither found.

Sinking streams can be observed in slightly sloping depression which stretches along the kettle back slope for 1 km. The well drilled at the edge of the depression uncovered homogeneous formation of medium gravel loam soils while country rocks were not identified. Neither were ground waters found.

The channel karst was identified on the left bank of the river Tokunda. At the interval between 10 and 13 m below 3 m layer of medium hard limestone, a decompressed zone, was found. It was filled with sandy clay with noncoherent limestone clasts. Ground waters were not found. The zones of potential karst hazard are smooth carbonate formations (watershed divides, gentle slopes, and valley bottoms). Slope and erosion exogenous process, as well as bogging and suffusion, are less intense within the study area.

2. Methodology

2.1. Choice of methods and work sequence

One of the key issues in karst research is karst related zoning. The average annual intensity of karst sinkhole development (number of sinkholes / km^2 per year) was suggested by Z.A. Makeev [7] in 1948 and has been the conventional measure to assess karst hazard for a long time. We support the idea of V.S. Lukin that the appropriate methods to assess karst hazard are different for different zones; for instance, to assess karst hazard in Kungur territory, the basic criterion is the diameter of the sinkhole [10].

Since the data on intensity of karst sinkhole development, sinkhole diameter, and sinkhole age are not enough to assess karst hazard in the study area, we suggested assessment on the basis of the integral criterion of potential karst development.

To provide rationale for the karst hazard criteria, we analysed the data collected from various karst areas. The data analysis allowed recognizing the evidences of karst hazard – lithological composition of rocks, massif's hydrogeological characteristics and fracturing (table 2).

Table 2. Evidences of potential karst sinkhole development.

№	Evidences
1	Surface karst landforms
2	Dissolving capacity of natural waters
3	Zones of loosened ground, identified through geo-electrical and velocity anomalies
4	Intensive vertical filtering of underground waters
5	Existence/absence of the aquaclude superposing soluble rocks

To assess the karst hazard of the area, firstly, the well columns indicating data on karsting rocks and aquacludes were identified. The zones of surface karst and water sampling points were reflected in the base map.

Secondly, equilibrium and non-equilibrium states of the system “natural waters – soluble rocks” were studied to assess the dissolving power of natural waters.

At the next stage, geophysical survey data were analyzed and the zones of loosened ground were identified through geo-electrical and velocity anomalies. Finally, the karst related zoning map of the study area was designed.

2.2. Hydrogeological research

The assessment of karst hazard and the intensity of karst development was done on the basis of laboratory study of waters sampled in 2010-2012 with the application of hydrogeochemical methods.

The underground waters are characterized by sporadic distribution. The waters within thin and marginal diluvial formations at slopes are found at the depth of 3-5 m; in terms of content, they are hydrocarbonate, magnesium-calcium, and sodium-magnesium-calcium. Aquaclude is hard and medium hard soil, sometimes multi-year.

The waters within diluvial-proluvial formations at slopes are associated with over- and inter-permafrost subgelisols. Water-bearing soil are medium gravel clay loams and brash.

The calculation of water equilibrium was done with the method by Garrels and Christ [2] for the temperature of 25°C and the pressure of 0.1 MPa. Thermodynamic modeling is done on the basis of HydroGeo software [1]. In the process of modeling only the minerals widely spread within the study area were considered. The issue of mineral matter transformation under the given hydrogeochemical conditions was considered on the basis of non-equilibrium index (SI). As the saturation with any chemical bonding increases, the non-equilibrium index decreases tending to zero; in case of over-saturation the index value is positive; zero value signifies equilibrium.

Table 3. Average value macro component composition (мg/l), pH and total salt content (g/l).

Component	Types of water	
	surface	ground
pH	7.2	7.1
$(HCO_3)^-$	182	335
$(SO_4)^{2-}$	69	84
Cl^-	7.5	11
Ca^{2+}	53	78
Mg^{2+}	18	29
$Na^+ + K^+$	10	16
M	0.2	0.54
$CO_{2\ aggresive}$	15.4	14.7
Number of test	7	23

The data of chemical analysis made on the basis of HydroGeo software allowed identifying equilibrium and non-equilibrium states of the system calci-spar – underground water. On the basis of data obtained, non-equilibrium index dependency graph of $CaCO_3$ mineralization was designed. The dependence was described through logarithmic equation with the coefficient of correlation $R^2 = 0.41$. The waters with mineralization higher than 0.6 mg/l are saturated with calci-spar, and within these zones, there is no hazard of karst development or the process in not intense.

2.3. Geological survey

On the basis of vertical electrical sounding survey geoelectric models of the upper part of the section up to the depth of 15-20 m over the winter period were studied. In this depth interval geoelectric sections are approximated with three-four-layer models. The first geoelectric layer within the upper interval of the section is of high-resistivity, with the thick seasonally-frozen interlayer. The specific electric resistance of the soil (ρ) is from 400 to 800 Ohm·m. The geoelectric layer thickness varies from 0.5 to 4 m, with the increase in the depressed areas. According to the data of the seismic survey (SRM), the velocity of P-waves within the interval preceding the first rigid border (V_1) is from 500 to 1800 m/s. The zones, where according to seismic survey data the refractor velocity is abnormally low ($V_2 \leq$ 1800 m/s,) are thick layers of friable eluvial ground (loosened ground). There are 48 zones of this type on the track. Geoelectric layer characteristics are represented in table 4.

Table 4. Geoelectric layer characteristics.

Layer	Characteristics
1	Seasonal-frozen layer – peat, loams, sandy loams of different consistence and cryostructure Thickness 0.5-4 m ρ_1= 400-800 Ohm·m V_1=500-1800 m/s
2	Rubbly, crushed, clumpy eluvial soil, loams of different consistence and cryogenic characteristics Thickness 1-7 m, ρ_2= 80 -200 Ohm·m V_2=1100 - 3900 m/s.
3	Hard carbonate rocks (limestone, dolomite, marl) Thickness 5-10 m, ρ_3= 600 Ohm·m V_3=2500 – 3900 m/s.
4	Zones of interbedding of the dense lithological varieties of dolomite, limestone and marls, clay and soapstone ρ_4= 80-220 Ohm·m V_4=2000 – 4600 m/s.

2.4. Karst hazard mapping

To design the karst related zoning map, it was necessary to identify the values of the model parameters on the basis of characteristics represented in table 2. The data points were grouped through calculation of the integral criterion for a characteristic presence or absence. If the characteristic was absent, the zone was considered potentially dangerous.

3. Results

3.1. Data analysis

The pipeline route is split into sections which are considered hazardous, potentially hazardous, and unhazardous in relation to karst development. Hazardous zones are those with karst landforms, with no aquaclude superposing soluble rocks or with the thickness less than 5 m. Potentially hazardous zones are those composed of loosened rocks, with the aquaclude superposing soluble rocks or with the thickness from 5 to 10 m. Unhazardous zones are those with the aquaclude superposing soluble rocks.

3.2. Recommendations on gas pipeline protection

To protect potentially hazardous sections and to ensure timely informing on sinkhole collapses, the following measures recommended:

- shutting off karst cavities and loosened ground zones with high-strength and low-deformation geosynthetic materials;

- soil stabilization by biocement injection fixing; the advantage of this method in comparison with other methods of chemical stabilization is low viscosity of the slurry and its deep penetration into porous ground;
- constructing bored piles with lodgement and steel cable rope;
- implementing a reliable alarm system to indicate the changes in the stressed-deformed state of the pipeline.

4. Conclusion

The lack of study area data makes karst related zoning conditional and requires further exploration. To update the karst related zoning map, continuous monitoring of karst development is relevant. To describe geological objects, the advantages of GIS technologies should be used, namely, spline functions, which are flexible, relatively simple and easy to use.

References

[1] Bukaty M B 1997 Development of the software in the field of oil and gas hydrogeology *J. Investigation and protection of a subsoil* **2** 37
[2] Garrels R M and Christ C L 1968 *Solutions, minerals, equilibria* (Moscow: Mir) p 368
[3] Gvozdetsky N A 1981 *Karst* (Moscow: Myisl) p 214
[4] Gvozdetsky N A 1988 *Karst landscapes* (Moscow: Moscow State University Press) p 112
[5] Zverev V P 2007 *Underground waters of crust and geological processes*. (Moscow: Scientific world) p 256
[6] Katayev of V N 2001 *Methods and practice of comparative and evaluation karst division into districts* (Perm: Perm State University Press) p 85
[7] Makeev Z A 1948 Principles of engineering-geological division into districts *J. Karstovedeniye*. **4** 43
[8] Maksimovich G A 1963 *Karst bases.* (Perm: Perm State University Press) vol 1 p 443
[9] Falcons D S 1962 *Main conditions of development of a karst* (Moscow: Gosgeoltekhizdat) p 322
[10] Tolmachev V V and Royter F 1990 *Engineering karst* (Moscow: Publishing house Subsoil) p 151
[11] Homenko V P 2012 Normative assessment of karst danger: a crisis situation *Geotechnical problem of design of buildings and constructions on the karst danger territories: Proc. Int Conf. (Ufa).* (Ufa: Bashniistroy) pp 240–45
[12] Scherbakov S V and Katayev V N 2011 An integral assessment of karsto-danger of the urbanized territories (on the example of Kungur) *Scientific notes of the Kazan university. Series Natural sciences* **153** (1) 203
[13] Fleury S 2009 *Land use police and practice on karst terrains: living on Limestone* (Dordrecht: Springer Science) p 153
[14] Smith P 2007 *The fundamentals of piping design: drafting and design methods for process applications* (Houston: Gulf Publishing Company) p 214