Approaches to Engineering Geocryological Zonation of the Republic of Sakha (Yakutia)

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Abstract. This paper describes the engineering geocryological zoning of the Republic of Sakha (Yakutia) which was performed based on analysis of the main controlling factors and their cartographic generalization. Several schematic maps were compiled depicting topography (landforms), geocryological processes, soils and rocks, permafrost conditions and seismicity. The types of engineering geocryological conditions were assessed and scored to classify areas by suitability for engineering. The paper begins with a brief Introduction which clarifies the objectives and importance of the research. The Methods section describes the ranking of control factors adopted for the convenience of zonation. The next section discusses the factors controlling engineering geocryological conditions in Sakha (Yakutia). The Results and Discussion section describes the series of maps produced comprising: a map of morphostructural zonation, a zonation map of geocryological processes intensity, a zonation map of ground and permafrost conditions, a map of seismic zonation. It also presents an integrated analysis of the controlling factors and concludes that the Coastal Lowlands and Shallow Seashelf Region is most challenging for engineering. For further refinement of engineering conditions, it seems advisable to prepare permafrost-landscape, geomorphological and other regional maps that would be useful for assessing economic feasibility of projected developments in the Republic of Sakha (Yakutia).

1. Introduction
Engineering geocryological zonation is a method used in engineering geocryology which deals with the geological environment of engineering structures in permafrost areas. The engineering geocryological conditions are controlled by the properties of frozen and thawing materials, permafrost-related geological processes, condition of intra- and subpermafrost aquifers, and rapid temporal variability of ground temperature distribution [1]. The purpose of the engineering geocryological zonation of the Republic of Sakha (Yakutia) is to provide background information for the planning of land-use, selection of transportation and communication alignments, and feasibility evaluation of proposed developments, as well as for the assessment of geological hazards for mitigation and prevention. This study is particularly important and necessary in view of accelerated development of northern areas, including the Arctic. Analysis of engineering-geocryological...
conditions involves the upper 10-20 m layer within which permafrost can influence or be influenced by the existing or new engineering work in Sakha (Yakutia). This depth coincides with the depth of annual temperature variation in the study region.

2. Methods
For the convenience of zonation, the types of engineering-geocryological conditions were ranked. The highest classification taxon, the Region, was assigned to major landforms. The second rank unit - the Province - was allotted to smaller landforms and associated geocryological processes. The third, lower taxonomic level – the Area – was used to depict the soil and rock units. The District taxon was used to show the geocryological characteristics of soils and rocks. Hydrogeological conditions and seismicity were depicted on inset maps, outside the ranking system.

3. Factors controlling engineering geocryological conditions in the Republic of Sakha (Yakutia)
Popov [2, p. 8] states that characterization and evaluation of engineering geological conditions for construction should highlight: a) structure and constituents of the earth's crust; b) structure of the earth crust surface; c) ground water; and d) modern geological processes. Trofimov [3] writes that engineering geological conditions are usually considered as a set of modern geological characteristics (parameters and factors) that determine the conditions for engineering site investigations, as well as for construction, operation and maintenance of engineering structures (narrow approach), or the conditions for engineering-related economic activity in general (broad approach). According to Trofimov and Averkina [4], engineering geological (geocryological) conditions comprise the following components: 1) the geological structure of an area and the nature of constituent rocks; 2) relief; 3) hydrogeological conditions; 4) permafrost conditions; and 5) modern geological processes. Trofimov [5, p. 34] redefines I.V. Popov's law of regional engineering geology as follows: "The modern features of the Earth's engineering geological structures are determined by their geological history, the present-day structural and tectonic setting, and current climatic conditions, as well as the character of human impacts in land-use areas". The structural zones control a set of specific formations characterized by the features of magmatism, hydrogeological conditions and modern geological processes [6, 7]. The geodynamic factor determines the spatial distribution of the main morphostructural elements: lowland, plateau and mountain regions. The present-day geodynamics of Sakha (Yakutia) is controlled by the current boundaries of the Eurasian and North American plates in the eastern half of the area [8] and the Baikal-Stanovoy Fold-and-Thrust Belt in the south [9]. The morphostructural factor controls the intensity and types of exogeneous processes, as well as the ground conditions. It is this factor that determines the degree of difficulty for construction and operation of engineering works. The geocryological factor exerts a direct effect on the geological medium, especially on the ground conditions [1]. The hydrogeological factor depends to a large degree on geocryological conditions. The map area is mostly underlain by continuous permafrost and the dominant water type is ultra-fresh water of the active layer. Seismicity is closely related to the geodynamic factor and the zonal climate which control the periglacial areas of active glacial isostatic movement. All the factors are interrelated and affect determine the entire complex of engineering geocryological conditions.

4. Results and discussion
4.1. Morphostructural (geomorphological) zonation
Considering its size, morphostructures (regions) were adopted by the authors as first-order taxonomic units. Five regions were recognized within the map area [10]: a) Coastal Plains/Lowlands and Shallow Seashelf Region [9, p. 12-18, 11, 12]; b) Central Siberian Plains and Plateaus Region; c) Baikal-Stanovoy Region; d) Verkhoyansk-Chukotka Region; and e) Trans-Regional Areas include valleys of the major rivers (Lena, Indigirka, and Kolyma). The proposed classification is close to the one presented in Ershov [1]. Based on surface elevation, size and spatial position of the morphostructures, as well as their landscape characteristics, the regions were subdivided into smaller taxonomic units -
provinces. In total, about 90 provinces were recognized. The table 1 presents numerical scores indicating the relative difficulty for engineering (other things being equal) in relation to relief complexity in the main types of morphostructural regions and provinces.

**Table 1.** Morphostructural province types.

| Landforms and their origin         | Plains  | Plateaus | Mountains |
|-----------------------------------|---------|----------|-----------|
| Aggradation (alluvial, fluvioglacial) | Low - 4 | -        | -         |
| Denudation and aggradation         | Middle and elevated – 3 | -        | -         |
| Denudation and aggradation         | High - 1 | -        | -         |

**Table 2.** A part of the table describing morphostructural zones and associated geocryological processes.

| Morphostructural zonation units                  | Intensity score of geocryological processes | Zonal-sectorial landscape type | Set of processes and their intensity score |
|-------------------------------------------------|---------------------------------------------|--------------------------------|------------------------------------------|
| I. Coastal Plains/Lowlands and Shallow Seasheelf Region |                              | Arctic and Subarctic |                                      |
| Provinces:                                       |                              |                                |                                      |
| I-1. Anjou and De Long Islands                   | 5                            | mm-m³ Ta₂₃,₃E₄₂,₂T₂₃,₂T₂H₂ |                                      |
| I-2. Lyakhovsky Islands                          | 5                            | mm-m Ta₂₃,₃E₄₂,₂T₂₃,₂T₂H₂ |                                      |
| I-3. Bolshoy Begichev Island                     | 4                            | mm-m Ta₂₃,₃T₂₃,₂H₂₃E₂₂,₂S₂  |                                      |
| I-4. Mamontov Klyk Peninsula                     | 5                            | mm-m Ta₃₄,₃T₃₄,₂H₃₃E₂₂,₂S₂  |                                      |

*Letter symbols after Ershov [1, Table 5.2, pp. 183-187]: mm - moderately maritime, mc – moderately continental, c – continental, sc – strongly continental.

4.2. Zonation by intensity of geocryological processes

To illustrate the characterization of geocryological processes, table 2 presents a part of the table compiled for the entire area of Yakutia. Geocryological processes are classified in terms of hazard level into: Class 1 - very low, Class 2 - low, Class 3 - moderate, Class 4 - high, and Class 5 - very high [1]. A procedure described in Ershov [1, table 5.3, p. 188] was adopted for areal process intensity classification. Abbreviations used to denote geocryological processes are: T - thermokarst, H - frost heaving, I - relative icing coverage, S - solifluction, E - earth flow, Te - thermal erosion, Ta - thermal abrasion.

**Table 3.** Elements of the ground component of engineering geocryological zonation.

| Frozen and cryotic rock class | Group | Type and variety groups |
|------------------------------|-------|-------------------------|
| Solid rocks                  | Siliceous | Intrusive rocks of all groups, extrusive traps, metamorphic rocks -1 |
4.4. Zonation by permafrost conditions

The ground temperature range between 0 and -2°C is used as an attribute to identify permafrost conditions for construction purposes. This temperature range controls the plastic properties of frozen soils, determining if the soil is in a solid frozen or plastic frozen state (table 4). Estimated complication of engineering geological conditions in relation to ice content and temperature is given in brackets.

**Table 4.** Characterization of permafrost conditions.

| Material     | Ground temperature, °C | Condition     | Ice content |
|--------------|-------------------------|---------------|-------------|
| Soils        | Below -2°C              | solid-frozen  | A(1)        |
|              | 0 to -2°C               | plastic-frozen| B(2)        |
|              | Above 0°C               | unfrozen      | C(4)        |
| Rocks        | Below -0°C              | dry frozen    | D(2)        |
|              | 3-10 m, occasionally >10 m | Sulfates (in the transition zone) | E(3)        |
|              |                        |               | F(5)        |
|              |                        |               | G(4)        |
|              |                        |               | H(0)        |
|              |                        |               | I(1)        |
|              |                        |               | J(2)        |

4.5. Hydrogeological zonation is based on the type and aggressiveness of intra- and suprapermafrost water. Suprapermafrost water in the map area is mostly calcium bicarbonate type and is not chemically aggressive [15, 16, 17, 18, 19]. Mineralized water springs with dissolved-solids concentrations averaging 4 g/l occur in the Baikal-Stanovoy Region. They are confined to areas of discontinuous and sporadic permafrost and contain elevated sulfate levels (table 5).

**Table 5.** Characteristics of hydrogeological conditions.

| Permafrost type | Depth to suprapermafrost water and groundwater | Predominant aggressive agent in groundwater | Engineering complication score |
|-----------------|-----------------------------------------------|--------------------------------------------|--------------------------------|
| Continuous      | <3 m, >3 m in fault zones                     | Non-aggressive                             | 1                              |
|                 | <3 m and <10 m in intrapermafrost taliks      | Non-aggressive                             | 1                              |
|                 | 3-10 m, occasionally >10 m                    | Sulfates (in the transition zone)          | 3                              |
| Discontinuous   | 3-10 m, occasionally >10 m                    | pH (periglacial dunefields)                | 3                              |
| Sporadic        | >10 m                                         | Sulfates                                   | 3                              |
4.6. Seismic Zonation was differentiated based on earthquake intensity. About half of the area lies in the zones with intensity of 6 or higher. Earthquakes with intensity of 5 can occur in other parts of Yakutia (table 6).

Table 6. Predominant earthquake intensity in the engineering geocryological regions, Sakha (Yakutia).

| Region                                      | Earthquake intensity | Estimated score for the region |
|---------------------------------------------|----------------------|---------------------------------|
| I. Coastal Plains/Lowlands and Shallow Seashelf | 9-5                  | 9                               |
| II. Central Siberian Plains and Plateaus    | 5                    | 5                               |
| III. Baikal-Stanovoy Fold-and-Thrust Belt   | 9-6                  | 9                               |
| IV. Verkhoyansk-Chukotka Region             | 9-7                  | 9                               |
| V. Trans-Regional Areas - major river valleys | 6-7                  | 7                               |

4.7. Integrated Analysis of Engineering Geocryological Factors

As an example, table 7 presents a comparative assessment at the scale of region, the largest zonation unit. A conventional approach to evaluating engineering conditions for permafrost areas well described in the literature [1, 20] has been adopted. It should be noted that these estimates provide a very first approximation and do not take into account the economic importance of the regions.

Table 7. Comparative assessment of the mapped regions in terms of difficulty for engineering.

| Region                                      | Engineering difficulty score |
|---------------------------------------------|------------------------------|
|                                             | Topography | Geocryological processes | Ground conditions | Permafrost conditions | Hydrogeological conditions | Seismic conditions | Total score |
| I. Coastal Plains/Lowlands and Shallow Seashelf | 4         | 5                        | 10                 | 4                    | 1                        | 9                  | 33          |
| II. Central Siberian Plains and Plateaus    | 3         | 3                        | 6                  | 4                    | 3                        | 5                  | 24          |
| III. Baikal-Stanovoy Fold-and-Thrust Belt   | 9         | 2                        | 6                  | 4                    | 3                        | 9                  | 33          |
| IV. Verkhoyansk-Chukotka Region             | 12        | 4                        | 2                  | 1                    | 1                        | 9                  | 29          |
| V. Trans-Regional Areas - major river valleys | 4         | 3                        | 7                  | 1                    | 1                        | 7                  | 23          |

5. Conclusions

As is seen from the above Table, the major river valleys (score 23) and the Central Siberian Plains and Plateaus (central Yakutia) (score 24) have the most favorable engineering geocryological conditions. The worst conditions for engineering activities exist in the Coastal Plains/Lowlands and Shallow Seashelf Region, as well as in the Baikal-Stanovoy Belt (score 33). Its land area is dominated by very ice-rich permafrost with a complexity score of 10 points. High seismicity is mostly characteristic of the Laptev Sea area. Thermokarst processes present the most serious danger. The average rate of thermokarst (0.5-2 m/a) can be inferred from size of the largest thaw features (5-20 km) and length of the Holocene Optimum (10,000 years) which followed the Sartan Glaciation. However, actual present-day rates can be significantly higher due to positive feedbacks between surface are temperature and thermokarst. In some years, thermal abrasion rates as high as several tens of meters have been reported for the region. The factor of endogenous relief dynamics also needs to be verified by further research. For example, repeated geodetic measurements by Bocharov et al. [12] indicate that the Laptev Sea coast is experiencing glacial isostatic uplift. Consideration of these phenomena would add to the rated engineering complexity for the Coastal Lowlands.
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