Geophysical Monitoring of Engineering Constructions in Western Yakutia and Study of Coupled Problem of Temperature and Seepage Fields in Permafrost near Hydro Unit

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
For the last two decades on a number of Hydro Units in Western Yakutia, we observe seepage process compromising their secure. We present geophysical methods for verification of permafrost state near Sitikan and Vilyui Hydro Units. Complex includes electric, electromagnetic, ground penetrating radar, hydro location, thermal and radiowave (down-hole) measurements. Ground level and down-hole geophysical survey focused on detecting thawing zones (talik) in dam, its flank and tail-water zone. Long-term geophysical monitoring shows up spatial-temporal permafrost evolution and talik development in the flank shore of Sitikan dam. Detecting of inflow zone and seepage velocity performed for right-bank contiguity of Vilyui HPS-1. Alongside with field studies the numerical evaluations of conditions of originating permeable talik-zones (thawing) in a board zone of dam, was down. Numerically analyzed conditions causing origin and development of talik near reservoir: annual air temperatures, snow cover, annual water temperature in storage basin with depth, permeability evolution in frozen soil. Proposed model can be used for analyzing more complex situation.

RÉSUMÉ
Depuis les deux dernières décennies, un certain nombre de réservoirs de la Yakoutie Occidentale présentent des processus d'écoulement, menaçant la sécurité des réservoirs. Nous présentons dans cet article des méthodes géophysiques permettant la vérification de l'état du sol gelé (la merzlota) le long des réservoirs de Sitikan et de Vilui. Le complexe inclue des prises de mesure électriques, thermiques, électromagnétiques, acoustiques sous-marines, de radar à pénétration de sol (RPS) et des ondes radio ondulatoires. Les études géophysiques terrestres, ainsi que les forages ciblent la détection de zones de dégel (taliks) dans le barrage. Le suivi géophysique à long terme a permis d'observer l'évolution spatio-temporelle de la merzlota et le développement de taliks le long de la rive latéral du barrage de Sitikan. L'analyse des zones d'infiltration, ainsi que de la vitesse d'infiltration ont été réalisées le long de la rive droite de la station hydroélectrique de Vilui HPS-1. Des travaux de terrain ont permis d'évaluer, de manière numérique, que l'origine des zones de taliks perméables le long du rivage du barrage se situe dans la partie inférieure du barrage. Le problème de l'instabilité du transfert de masse et de chaleur dans un substrat fracturé et poreux saturé en glace et situé entre des couches de roches gelées et imperméables est proposé. La température annuelle de l'air, la couche de neige, la température annuelle de l'eau dans le réservoir en fonction de la profondeur, l'évolution de la perméabilité des sols ont tous été numériquement analysés. Le modèle proposé va permettre l'analyse de situations semblables plus complexes.

1 INTRODUCTION

Permafrost area is about 70% of the territory of Russia, the whole territory of Alaska, as well as a significant part of Canada and mountain Alpine regions. Regular water and energy supply in permafrost areas are vitally important conditions for inhabitants of the large North territories of Russia, Canada, US and Alpine areas of China. Artificial reservoir in permafrost conditions creates prerequisites for forming and development of talik zones acceleration in flank shore. Dam and flank shore stability is the key point for safety of reservoir (power pool, water supply, tailing pit, etc.). Similar problems may occur also with natural basins in cold regions – climate change may activate lake drainage and changes in permafrost.

To avoid water loss and Hydro Unit's stability in permafrost zone we need to use geophysical tools, including long-term monitoring for detecting talik development. Along with required temperature control different geophysical methods give information about variation of rock physical properties caused by thawing-freezing effect. Integrated geophysical monitoring allows observing time-space variability of physical fields reflecting evolution of frozen-thawed dam bedding and flank shores.

2 GEOGHYSICAL OBSERVATION

The study was conducted in Aichal-Mirni region of Western Yakutia, which one is region of a potential development of different types of anthropogenic loads.(Fig.1) They are connected with exploitation of kimberlitic pipes, construction and operation of hydro facilities, injection and dumping of underground waters, underground storage facilities for toxic waste, tailing dumps. Permafrost is very sensitive to natural and man-made influences. (Fig.2) In consequence of these circumstances thawing-filtration processes were observed on a number of hydro technical objects of Western Yakutia - Marha, Irelyah, Vilyui, Anabar, Sitikan, Kieng, Iyraaas-Yuryah. In our report we will present examples of geophysical observations on Sitikan Hydro Unit and Vilyui Hydroelectric Power Station. Sitikan HU (frozen type dam) provides water supply for Successful (near diamond pipe “Udachnaya”). Underflow talik-zone was established in the dam basement in 1995, after 20 years of reservoir operation (Kronik 1999). As a result, in present time, we have significant water loss from reservoir and serious problems with water management.

Construction of Viluy Hydroelectric Power Station (VHPS-1) was finished in 1967. It was first world large Hydro Unit Sitikan HU (frozen type dam) provides water supply for Successful (near diamond pipe “Udachnaya”). Underflow talik-zone was established in the dam basement in 1995 with rock fill dam on permafrost. In August 1996 temperature jump was fixed in observation holes in right-bank contiguity of VHPS-1. During few days seepage was formed. (Velikin & Snegirev 2004). This seepage exists up to the present in spite of special anti-filtration efforts. For last 20 years various geophysical investigations were carried out on many engineering constructions in Western Yakutia by Vilyui Permafrost Station (VNIMS). Priority interest was connected with methodology of geophysical survey of permafrost state and its change near hydro units. Some examples of these works we present below.

From many ground-level geophysical methods in permafrost study (Zikov 1999) the most useful for solving above mentioned tasks were selected Natural Field method (Semenov 1968) or Self Potential method (Erchul & Slifer 1989), Capacitive-Coupled Resistivity profiling or VCHEP method (Timofeev 1980, Hunter & Douma 2007,) Ground Penetrating Radar method (GPR) (Arcone et al. 1998)

Geophysical surveys were focused on main tasks:

I - eliciting and checking the position of inflow seepage near dam and coastal junction of dams, detecting and locating places of the most intensive thawing and seepage from the reservoir.;

II - investigation of talik geometry in frozen massif;

III - monitoring dynamics of progressing seepage in space and time.

Down-hole observations near hydro units included long-term regime temperature measurements including logger measurements. Long-term water level and temperature measurements in reservoirs on different depth were done too. Logging complex (electrical, flow meter survey, gamma logging, neutron-gamma logging, caliper measurement) (Zikov 1999) was used for petro physical studies

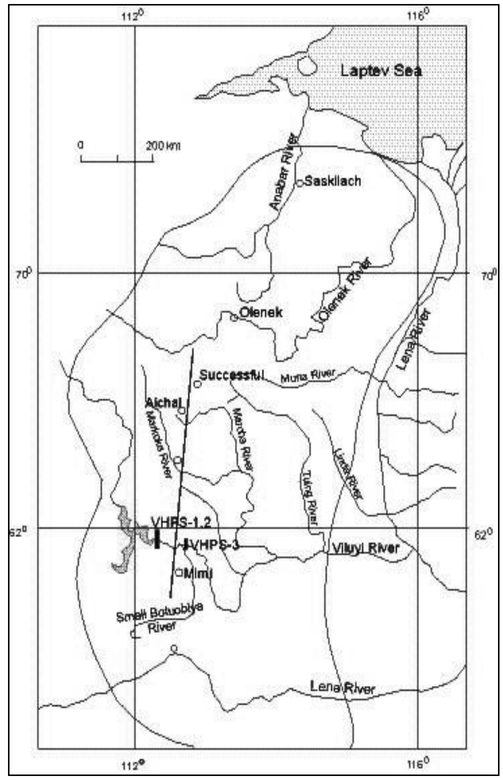


Figure 1. Case study areas: Sitikan Hydro Unit near Successful (Udachnaya) Pipe and Vilyui HPS -1&2. S-N oriented ecological profile (solid line) is shown below (see Fig. 2)

Radio Wave Geo-Introscopy (RWGI-ORWP) method (Istratov & Frolov. 2003) with thermo metrical data gave the possibility to monitor talik development. On the ground of geophysical survey geolcryological structure was studied and the binding of filtering spacing to definite lithological horizons was established. We present some results of geophysical survey in the cryolithozone.

2.1 Talik Detecting and Monitoring

Natural Field (Self Potential) method. The use of natural field (NF) technique was substantiated by the existing practice of filtering study in hydraulic structures beyond the cryolithozone, which proves the difference between the filtering flow according to natural electrical field and the containing medium. In this case NF has electro kinetic nature resulting from transportation of charges by water flow. Inflow zones correspond negative values of electro potential vice-versa outflow zones have positive values of NF (Semenov 1968, Zikov 1999, Erchul & Slifer 1989). With a network of electro prospecting profiles (observation step along profile 2,5m) was covered lower and upper tails, coastal zone, and ridge of the earth dam, water-coast and water zones of Sitikan Unit (Fig.3) Measurements were done relatively one of two stationary reference electrodes in the head race. In particular NF data obtained in the head race of Sitikan detect (by negative anomalies) infiltration zones in the earth dam, below spillway and along coastal line of right bank contiguity. Detecting of thaw zone of thaw zone in Sitikan right bank contiguity with electrical tomography method is presented on Figure 4.

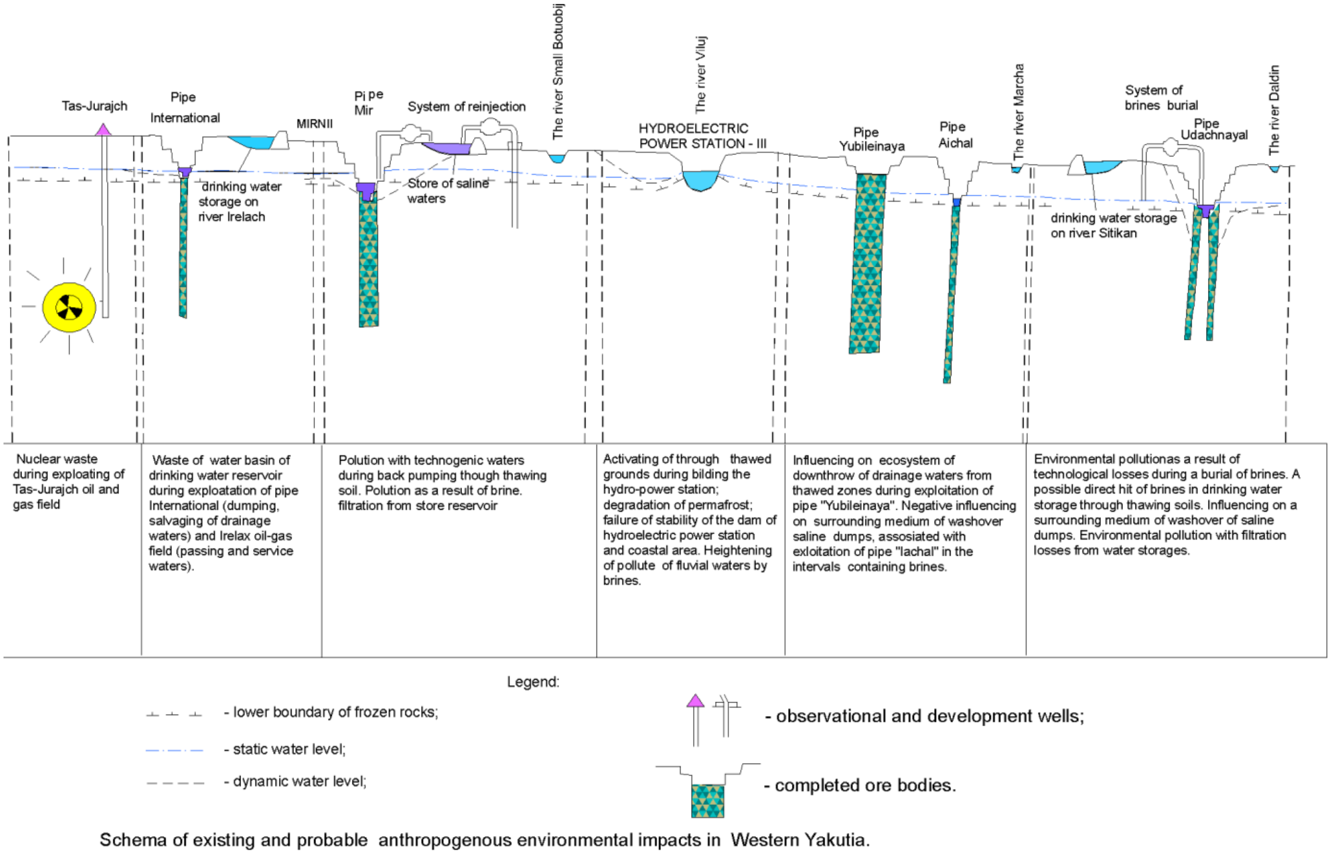


Figure 2. Schema of existing and probable man - made impacts in Western Yakutia

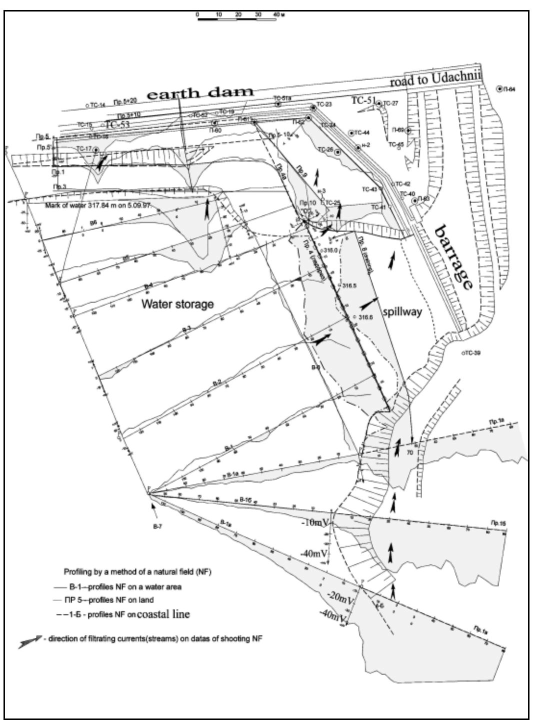


Figure 3. Sitikan Hydro Unit. Natural Field profiles on water, land and coastal zone. (Negative NF anomalies indicates inflow seepage zones)

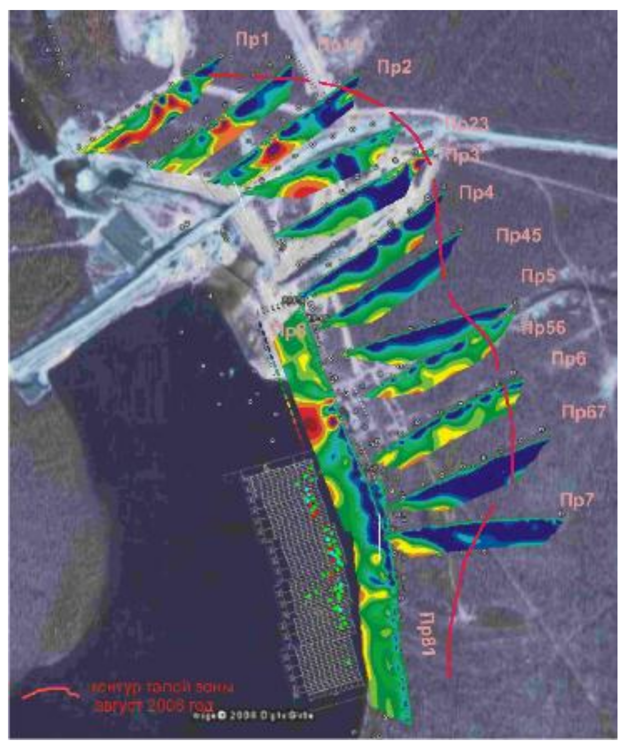


Figure 4. Sitikan Hydro Unit. Detecting of thaw zone (red line corresponds thaw zone outline for August, 2008) with electrical resistivity tomography (ERT).

Among many applied **surface geophysical** studies Capacitive-Coupled Resistivity profiling method (VCHEP) and Natural Field (Self Potential) methods data were the main source of information about propagation of inflow zones, talik's cut-out. The theory governing the VCHEP method has been discussed by Timofeev (1980).

Advantages of VHCEP method are high productivity and simplicity of measurements in cold region. There is no need for direct electrical contact between the transmitter and the ground (Hunter & Douma, 2007). Specially developed optional equipment "VCHEP" was used for survey. This facility permitted to get effective resistivity (ρ_ω), values directly during field observations via conversion of measured electric field parameters for ω = constant and selected unit configuration (Timofeev 1980, Zikov 1999). Later on this approach was realized in "OhmMaper" device (Hunter & Douma, 2007). "VCHEP" survey on Sitikan Unit was done with two frequencies – 8 and 12 kHz and square waveform signal in April 1997. In this time snow cover and frozen rocks do not permit use of any galvanic ground connection. Basic boundaries between frozen and thawed zones - shade zones, reflected in effective resistivity (ρ_ω) field for ω=8 kHz (Fig. 5).

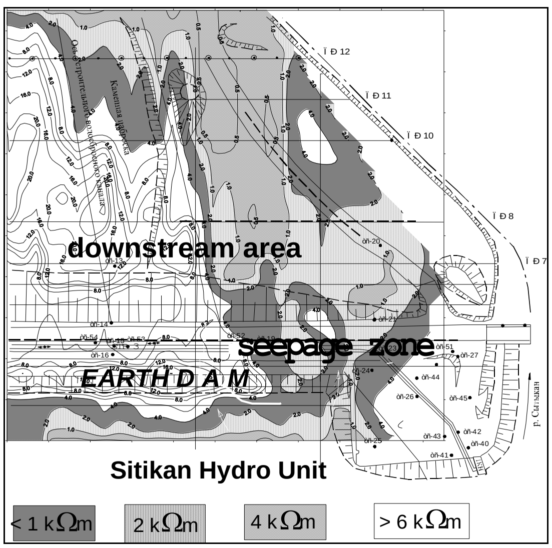


Figure 5. Spatial distribution of effective resistivity,ρ_ω kΩm (dipole length=10m, dipole-dipole spacing=20m, sampling step=2,5m, ω=8 kHz). Thawed zone determined with Capacitive-Coupled Resistivity profiling method (VCHEP) on Sitikan dam and tail-water. Shade zones (low effective resistivity) correspond to talik's contour

Self Potential (NF method) survey with "ERA-MAX" facility and pots was also carried out along water profile in Viluy HPS-1 headrace and on its bank. Several years of observations on these profiles showed significant change in form and amplitude of natural field graphs in association with different water level in headrace and discrepancy of observation lines. Nevertheless, in zone adjoining to right-bank contiguity the field abnormal part was well detected by signal form and amplitude. As a rule, seepage takes origin from structure and head race contact. It would be logically to suppose that just this anomaly was caused by seepage processes. Later on, test-methodical works proved that. Two contactless surveys were performed from water with the use of inflatable boat in a headrace of VHPS-1. Ground Penetrating Radar (Arcone et al. 1998) - above-water GPR survey with "SIR2000" and Side Plan Hydro location (Velikin & Snegirev 2004) with "GBO" facility. (Fig. 6). Both methods

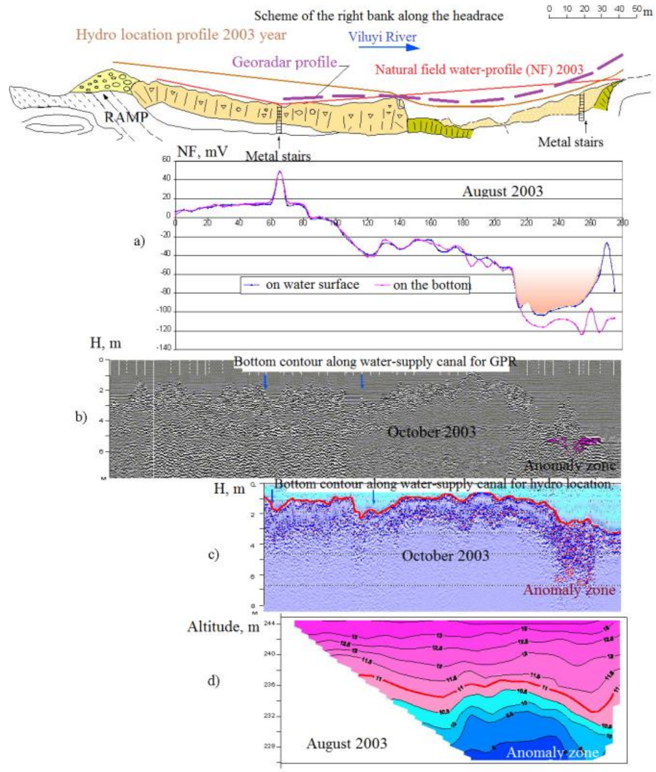


Figure 6. Study of seepage situation near VHPS-1 with water survey: a) Natural Field Method; b) GPR-method; c) Hydro location of side survey; d) Temperature measurements in the canal.

confirmed the anomalous zone distinguished from self-potential data in the head race. GPR- reflecting boundaries associated with water-filled cracks, reflections typical horizontal and vertical cracks being recognized on radargram. On bottom-surface picture obtained with hydrolocation the anomalous site was distinguished by occurrence of small depressions (slots) perpendicular to the shore. In geological structure of berm adjoining to head race a number of similarly oriented (orthogonal to shore zone) cracks were marked too. It is important that close spatial coincidence of anomalous zones found by Self Potential, GPR and Side Plan Hydro location methods was established. Detected zones at (242-238) m elevation coinciding with the depth of intensive seepage interval established also by thermometry (Velikin & Snegirev 2004).

Borehole observations. The first warning information (in 1995) about talik nucleation in the base of Sitikan dam was long-term temperature measurements carried out since 1990. Seasonal temperature field dynamics for flank of Sitikan dam – acting talik zone is presented on Figure 7. Network density of thermometric holes and irregularity of observations has hampered an estimation of spatial distribution of talik and seepage development. For processing all previous available temperature data were used. Besides, measurements were conducted in piezo borehole and on a water area, where earlier temperature observations were not conducted. It has allowed to fill up the skipped periods of observations in individual holes and to get a general evolution of talik zone. An example of active stage of talik section evolution for the period 2000 – 2006 is shown on Figure 8.

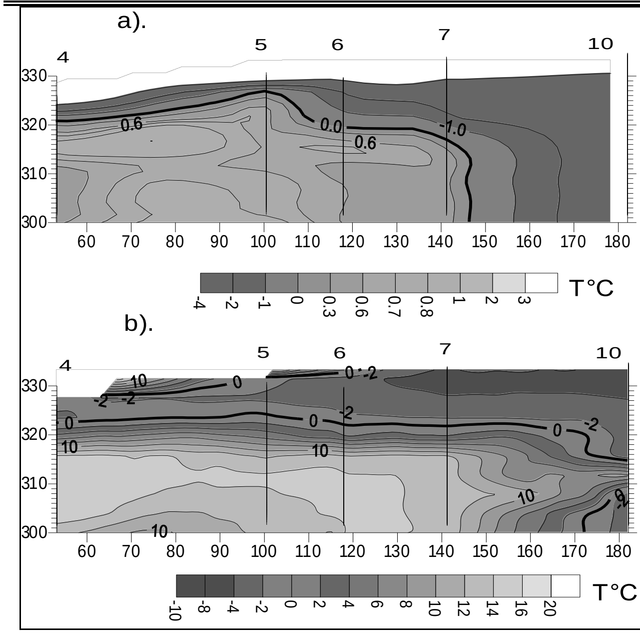


Figure 7. Dynamics of the ground temperatures within the reservoir flank of Sitikan dam along boreholes (4-5-6-7-10) in March of 2001 (a), August of 2001(b)

No going into details of contingency of Sitikan dam necessary to say that for the last decade many efforts (cementation, air and kerosene cooling, enrockment, etc.) were implemented to prevent consequence of seepage process. Some result is visible on Figure 8 on the left part of the earth dam. We also can see progressing talik in the right bank contiguity due to development of bypass filtration (Figures 7 and 8). For controlling *in situ* situation in seepage zone, tracer technique determination of flow rate with the use of colorings and electrolytes was used (Velikin & Snegirev 2004). NaCl solution was used as a tracer. Resistive potentiometer installed in observation borehole in a particular selected interval was used as a recorder for continuous measuring water resistance filling the borehole. Observations were carried out by two ways: (I) with filling a tracer in piezo borehole № 80 and measurements in downstream piezo borehole № 81; (II) with filling a tracer near the shore of head race of the right-bank abutment and observation in piezo borehole № 80. According obtained data the filtering rate was estimated ~ 50-60 m per hour that comprised a fairly significant value and should be considered when developing anti-seepage measures. (Fig.9). characteristics. Figure 10 illustrates logger measurements in piezo metric borehole № 81 of the right-bank abutment in comparison with data available on water temperature

Automatic temperature measurements in the boreholes using loggers are of special interest, as far as they permit to get information about position of seepage horizons and their dynamics in the head race of the dam. Figure 10 shows that general drop of reservoir water temperature determines a temperature decrease in filtration zone (236-232m) of

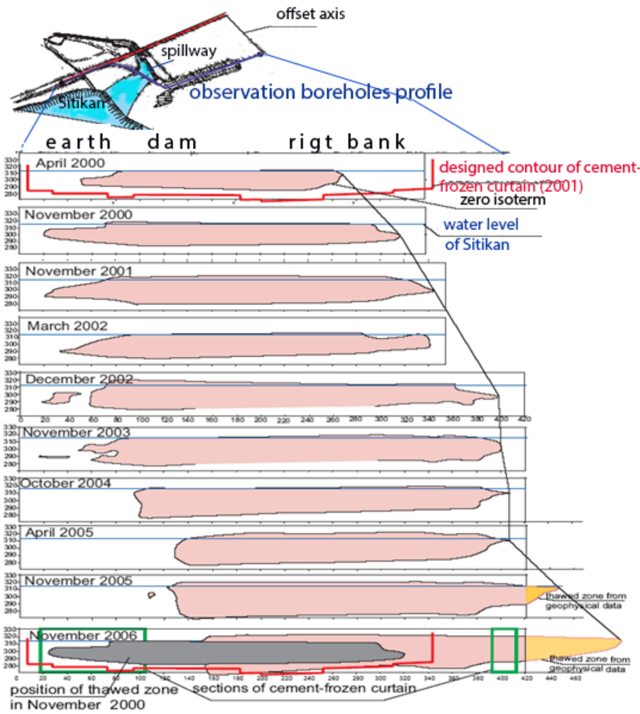
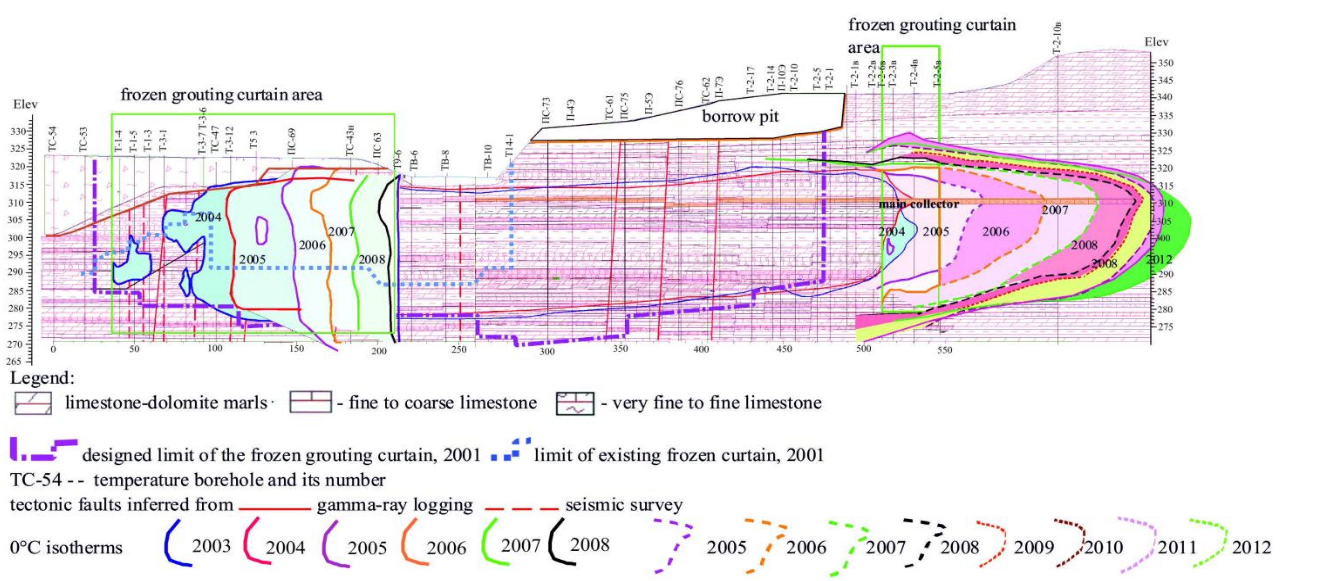


Figure 8. Up - Dynamics of thawed zone (talik) contour along borehole profile (solid line on the top scheme) for Sitikan Hydro Unit years 2000-2006 mainly by thermal data); Below (By Zhang & Velikin, 2014) –the same for Sitikan dam, the longitudinal profile showing geology and temperature distribution for years 2003-2012



massif. In the upper part of the hole logger data indicate on null or small temperature increase.

The analysis of available data showed high information content of logger temperature measurements. They may help to reveal reservoir intervals

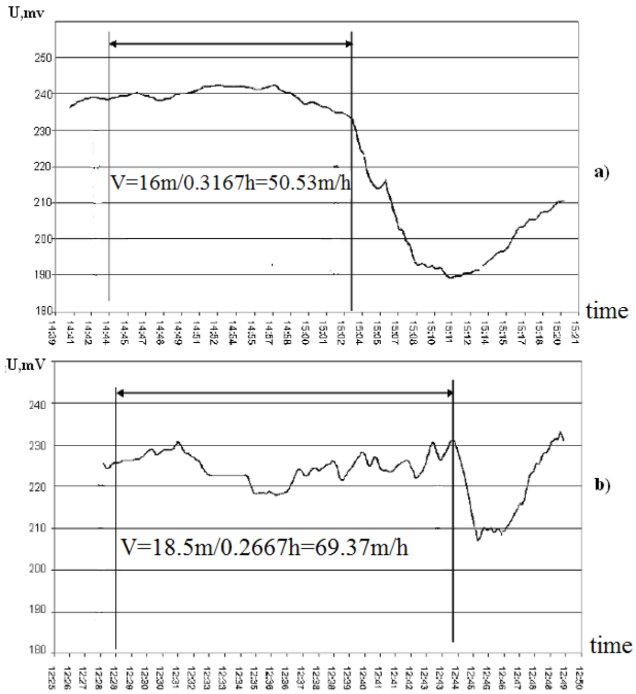


Figure 9. Determination of flow rate by Tracer Method (NaCl salination) in piezo metric boreholes 80 and 81 of right bank abutment of Viluyi HPS-1 in August 2004.

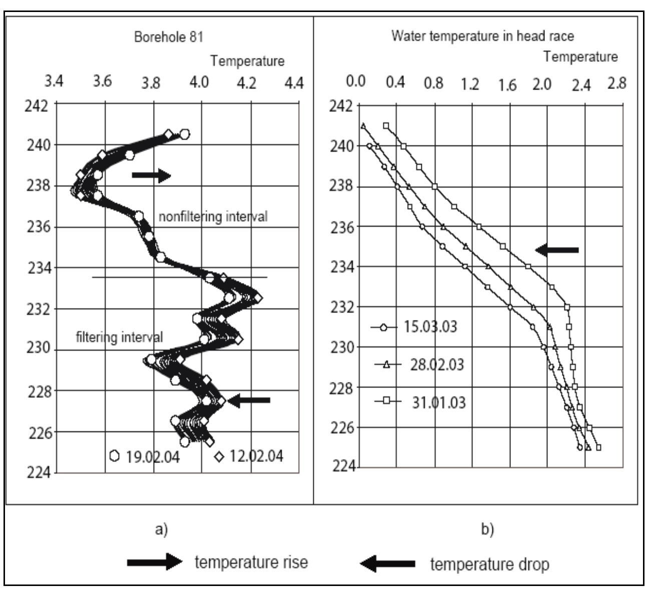


Figure 10. Revelation of filtering intervals by logger measurements: a) temperature measurements in piezo metric borehole № 81; b) water temperature in head race.in thermometric boreholes based on analysis of temperature dynamics, find out intervals, where in spite of the presence of positive temperatures, filtration flows are absent, and also to study the peculiarities of interaction between the rocks and water.

Radio wave geoinroscopy of inter-well space (RWGI) - way "of «visualization" of an internal structure of geological media in space between wells. A physic-geological basis of a method is the dependence of intensity of absorption of energy of radio waves by the rocks located on a line of distribution of a wave, from the electrical characteristics of these rocks: specific electrical resistance **(ρ)** and permittivity **(ε)**. The rocks having lower values of ρ and (or)ε, are characterized by higher absorption of radio waves.

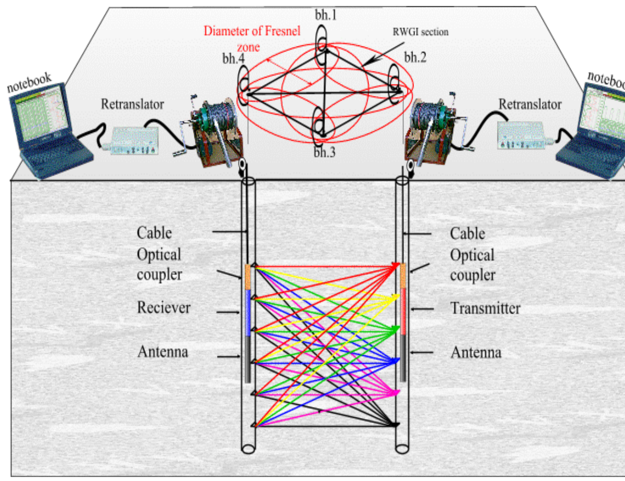


Figure 11 Geometry of Well-Well (WWGI) observation

Using an electromagnetic field in a range of radio frequencies, special technique of measurements and data processing, with tomographic image methods or wave restoration methods it is possible to detect and locate in inter-well space geological heterogeneity of relatively small sizes. The study of inter-well space can be executed in three variants of measurements:Well - Well (WWGI) - way of « tomographic survey» (Fig 11);Well - Surface of ground (WSGI) - radius of study on a surface is equal to depth of the well; One-well radio wave profiling (ORWP) - receiver and transmitter synchronously move in one well bore on fixed distance from each other. For geophysical monitoring in permafrost zone: the Radio Wave Geo-Introscopy (RWGI) - profiling and cross-borehole tests to study an inter-hole space and One-hole Radio Wave Profiling (ORWP) method was used. Theory, tools and measuring technique are described in Martian special volume (Istratov & Frolov 2003). The purpose of radio wave investigations was, first, to control the frozen rock thawing within the coastal zone of the reservoir and to assess the dynamics of the process, and second, to identify and to locate places of the most intensive thawing and seepage from the reservoir. Thawing process leads to a decrease of electrical resistivity (ρ). Besides, the saturation of the filtering layer must be reflected in an increase of relative dielectric permittivity (ε) within the same interval. If measurements are taken repeatedly at two frequencies along the borehole profile, the lower frequency data can give a picture of the rock electrical resistivity changes with space and time, thus providing an insight into the process of frozen rock mass thawing under influence of the reservoir. Measurements performed at high frequency permit to calculate effective values of relative dielectric permittivity (ε); the higher values from which will indicate layers of the most active filtration from the reservoir. The monitoring in Sitikan area has begun in 2000 and continues up to now. As an example, we consider the data obtained in 2001- 2002 near Sitikan Hydro Unit on (Figures 12, 13). In March and August 2001 and in March 2002 temperature measurements (Fig.6) were performed in the boreholes 4 to 10 oriented transversely to the shoreline of Sitikan water storage, as well as gamma logging and one-hole radio wave profiling (RWGI-ORWP) with the frequencies 1.25 and 31 MHz Repeated ORWP data were interpolated between holes (Fig. 12).

The holes are 35m to 45m deep, with polyethylene casing and inside diameter 65mm. Sections based on the repeated temperature measurements of the fractionally thawed coastal frozen massif in March and August 2001, show dynamics of the ground temperatures within the reservoir flank (Figures 7 and 13)

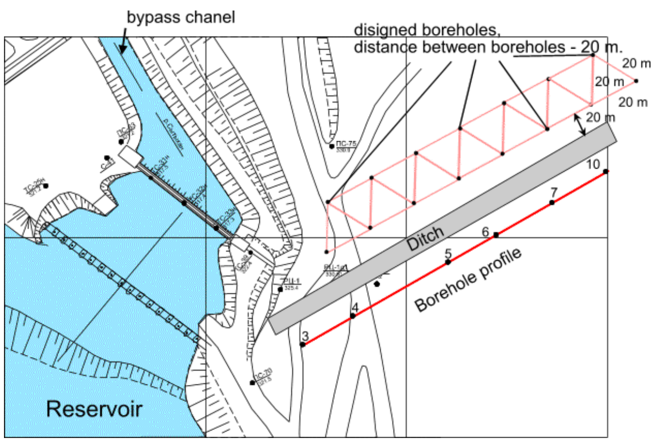


Figure 12 Geometry of radiowave observation near Sytikan

The geological section consists of carbonate rocks and (limestone, dolomites and marbles) varying in fissured zones clay content. Comparing the results received in March and August, 2001, it is possible to see not only the general promotion of "front of the lowered specific electric resistivity" in the direction of a hole 10, but also to allocate horizons of (309-311) m both (314-317) m and (321 – 324) m on which these changes occur most intensively. On section of effective values of dielectric permittivity, layers with the highest values of ε - intervals (311-314) m and (317-319) m and a in local area near hole 6 in interval (306-309) m correspond to high gradient zone of positive temperature. Along these permeable layers water from Sitikan penetrates deep into a coastal massif working in succeeding time like "secondary" heat source, distributing and accelerating process of frozen rocks thawing. However, in March 2002 (Fig.13) the resistivity of rocks in a section integrally increased. This phenomenon is connected with maximal freezing (frost penetration) of rocks, and minimum of water temperature in Sitikan storage. Visually it is tracked between holes 4 and 7 in a layer (314 – 317) m, in which one, relative heightening of resistivity (ρ) and below 314 m – decreasing of ρ, is observed. In March 2002 (time of minimal temperature of whole rock massif) the areas with heightened ε - values are narrowed and located near e borehole 6 on horizons (310 – 312) m and (322 – 325) m. This is connected with seasonal freezing of massif. However, the presence of local zones with heightened values of dielectric permittivity (ε) allows to guess existence of "year-round" liquid water phase zones - non- filtering level (322 – 325) m. and with bypass seepage from water storage through originally frozen massif on level (310-312) m, corresponding Sitikan water level in March = 314 m. Good correlation of geoelectric sections with the data of temperature observations shows not only direct dependence of electric properties of frozen-thawed state of massif, but also essentially higher sensitivity, and resolution of electric methods for detecting liquid water phase.

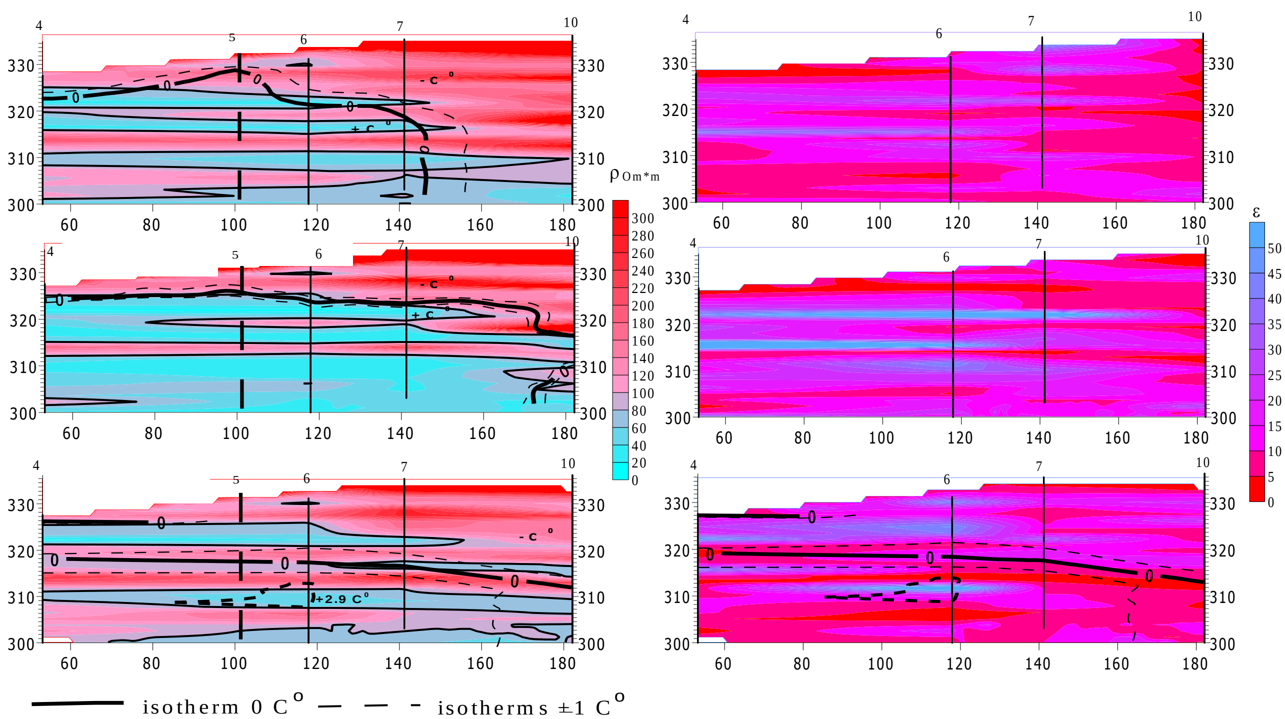


Figure 13. Examples of geoelectric sections of effective electric resistivity (ρ) – left, and relative dielectric permittivity (ε) – right, along boreholes profile (4 -5 -6 -7 -10) in a frozen massif crosswise shoreline of Sitikan Hydro Unit (Western

Yakutia, Siberia); RWGI-ORWP observations in: top – March 2001; middle – August 2001; bottom – March 2002 (for frozen rocks (ρ) is high & (ε) is low; for thawing- (ρ) is low & (ε) is high)

3 THERMAL MODELLING

Talik can be formed in permeable soils, and spread over impermeable soils. Its intensity is mostly controlled by the freezing conditions; e.g. if the talik localized under riverbeds, the talik may change to part-permeable type. A specific feature of artesian (head) aquifers is the predominantly upward movement of pressure head in permeable zones (disjunctives, karsts zones in carbonates, and fractured permeable zones in rocks). In the case of surface water basins, the pressure headwaters are constrained by the frozen dam with a set of engineering buildings, and including a by-pass channel (spillway) with waterway. This channel often has the role of a permanently-acting heat source in relation to the permafrost adjoining it. It is also possible to guess the presence of fractured water-saturated frozen rock strata (e.g. limestone) the rocks flanking the basin. Under frozen conditions the rocks are impermeable. Under thawing conditions, these strata may potentially become permeable, allowing filtration. In case of water storage on the one hand we have pressure headwaters constrained by frozen dam with a set of engineering construction. The non-steady problem of heat-mass transfer in fractured-porous saturated frozen Stratum (II), interlaying in frozen impermeable adjacent Strata's (I, III) is discussed. There is pressure head acting from Aquifer, explicating in thawing saturated Stratum (II) with allowance for seasonal variations of air-water temperatures on ground-water surface and inside Aquifer (Fig.14). Accurate interpretation of these data also needs taking into account seasonal water level change of Sitikan. According Petrunin & Milanovskiy (2005) and Milanovskiy et.al. (2011), from numerical analysis follows, that the process of thermal evolution of frozen strata can conditionally be separated into two basic and two transient stages (Fig.14). The first stage starts from the moment of infill of water storage and represents, as a matter of fact, installation of a thermodynamic equilibrium in absence of convection. It is quick enough, for 2 - 3 years is settled

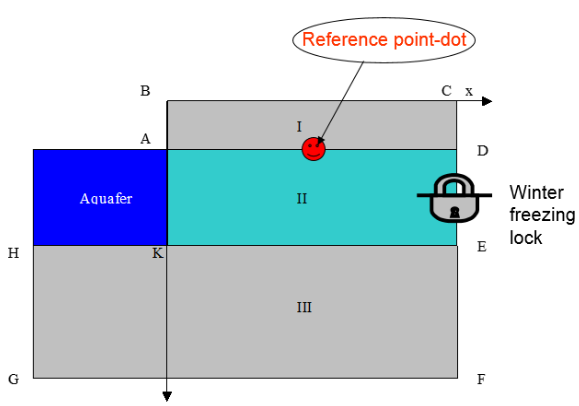


Figure 14. Schematic geometry of the model. (Winter freezing seepage lock- can be unlocked with crack in massif border or existing open through-massif fracture.

quasi-state conductive heat regime, at which seasonal variations of a thermal field quickly damp with depth according to Fourier Law, and the boundary summer fire-setting (thawing) a little bit migrates to the deep from season to season. From Figure 15 it is visible, that maximal seasonal temperature of reference point-dot on top of layer (middle of AD) of Stratum II in range 2-12 years lays in limits from -1^0C up to 0^0C, i.e. within the limits of temperatures, when the ice filling in pores starts to thaw and permeability of environment becomes distinct from zero. In this case if there is hydro head convective heat-mass transfer arises, which one is much more effective than conductive. This is the governing factor in our model for talik originating. The results of 2D thermal modeling indicate that talik development depends on specific thermal and hydraulic material parameters, water head, and thickness of frozen layer covering talik and winter snow blanket insulating ground rocks, seasonal temperature trend as well as of fracture presence in frozen media. In case of existing cracks in massif border or existing open through-massif fractures, talik development depends less on low winter temperature preserving seepage in this time Observed evolution of temperature field in talik zone in border part of Sitikan Unit is in general agreement with calculated temperature field. As it was mentioned above in a cold period for considered model filtration is "locked". It follows from K(transmissivity) value of Stratum II is equal to zero if temperatures, is lower -1^0 C. Actually exits of filtrate is carried out on local zones of fractures, which one remain permeable even and in a cold winter period. This circumstance was taken into account hereinafter at constructing more advanced model, by the introducing of the special conditions of permeability on boundary D-E. Such model includes a) open crack(s) on D-E boundary with limited length (5m) penetrating in frozen/thawed massif (Stratum II) or b) existing through-massif permeable channel (crack) in frozen Stratum II. We can observe both special cases. For case a) - after forming thawed zone we shall have all-year filtration without winter freezing "lock". The next case b) - talik development for winter periods with originally existing transparent crack in the basement of Stratum II. In this case filtration process runs much faster.

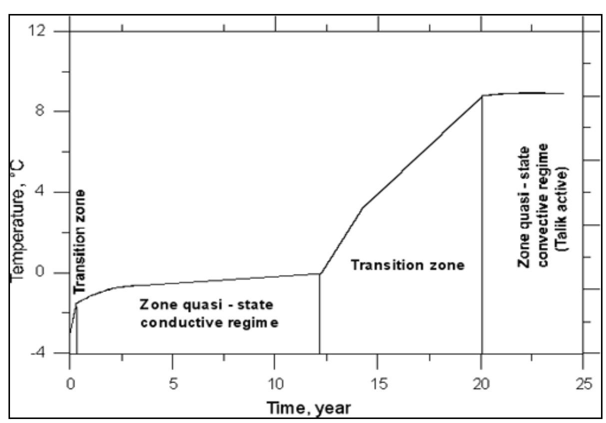


Figure 15. Variation of seasonal T-maximum in the reference point situated in the middle of the top of permeable zone (talik zone) with time. (By Petrunin & Milanovskiy, 2005)

An interesting case is “domino” model including more than one layer with Stratum II properties. If we have existing water head in “domino” model the thawing process runs deep into frozen massif due to combination of conductive and convective heating mechanism.

Geophysical data are testifying about different types of talik zones. Nevertheless they have very common characteristic feature - presence of triggering mechanism for talik initialization. For realization of this mechanism we need pre-talik temperature history, leading to pre-heating of the strata, existing fractures or pore channels (partly-open or ice cemented) and reservoir water head. For example, in Sitikan Unit case pre-talik history was about 20 years. Important factor for stability long-existing construction like hydro unit or waste confinement in permafrost zone is global climatic changes. Proposed simple model can be used for analyzing more complex situation.

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