Some geocryological problems of railways and highways on permafrost of Transbaikal and Tibet

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ABSTRACT
Over the last 12 years significant new construction of railroads and highways has occurred in Transbaikal and the adjacent territories, including China. Examples of geocryological problems associated with selected railroad and highway locations are presented. Operational reliability, assessment and monitoring needs are discussed. Emphasis is given to providing comprehensive geocryological exploration efforts, utilizing innovative and intelligent design solutions, allowing for timely and quality construction procedures as well as making provisions for necessary ongoing maintenance. Experience with anti-deformation measures, used for both the Russian and Chinese railroads and highways, utilizing both active and passive methods for strengthening the embankments on ice rich permafrost, is also presented. In addition, technical solutions involving anti-frost heaving devices for electrical contact-line railway and power line tower supports, is reviewed.

RÉSUMÉ
Au cours des 12 dernières années importants travaux de construction de nouvelles routes et des chemins de fer a eu lieu en Transbaïkalie et dans les territoires adjacents, y compris la Chine. Exemples de problèmes liés à géocryologiques de chemin de fer et les lieux choisis la route sont présentés. La fiabilité de fonctionnement, l'évaluation et des besoins de surveillance sont discutés. L'accent est accordée à la fourniture complète les efforts d'exploration géocryologiques, en utilisant des solutions de conception novatrice et intelligente, permettant des procédures de construction en temps utile et de qualité ainsi que des dispositions qui pour la maintenance nécessaire. L'expérience de la lutte anti-déformation, utilisé à la fois pour les chemins de fer russes et chinois et les autoroutes, utilisant à la fois active et passive des méthodes pour renforcer les digues sur la glace du pergélisol riche, est également présenté. En outre, les solutions techniques impliquant des dispositifs anti-gel pour le soulèvement de chemin de fer de contact ligne électrique et la tour de ligne électrique prend en charge, est passée en revue.

1 INTRODUCTION

The history of railways constructed in permafrost regions exceeds more than 100 years: Transbaikalian, Amur, Alaska, Norilsk, Gudson, Labrador, Baikal-Amur (BAM), Amur - Yakut (АЯМ), Yamal and some other railways in Russia, USA and Canada. Construction of each of these railroads provide examples of frozen ground construction and attempts to provide stable subgrade soils in areas of permafrost and deep seasonal freezing.

Construction in China of the Qinghai-Tibet Railway along the Golmud-Lhasa segment occurred in 2000-2006. This is the newest stage of major railway construction involving conditions of permafrost and deep seasonal freezing of the soils. The project has included new, large scale attempts to solve some of the specific problems.

The author was involved with Chinese experts on addressing problems of geocryological concerns along the Qinghai-Tibet Railway and the Qinghai-Tibet Highway over the last 15 years and, in Russia, has been actively engaged in these problems since 1986. Results of his research are reflected in more than 70 technical papers and reports, as well as 5 monographs published in the USSR, Russia, the USA, Canada, Norway, China, Japan, and Finland. Information from these projects and various studies are briefly reviewed in this paper.

2 GEOCRYOLOGICAL PROBLEMS ASSOCIATED WITH RAILROADS

The thaw settlements of the embankment and the frost heaving tower supports are most important geocryological problems associated with railways.

2.1 Thaw settlements of the embankment

There has been very limited success in building a railway line that would not undergo deformations resulting from thawing of ice rich soils or frost heave induced by freezing of wet foundation soil.

These problems are characteristic for all railroads regardless of the length of time in operation. The Transbaikalian Railroad has been in operation more than one hundred years, the BAM and the Amur-Yakutsk Main Line - well over tens of years, and the connecting lines Chara-Cheena and Ulak-Elga - only several years. The Qinghai-Tibet railway has only recently been completed.

One of the major problem areas on the Transbaikalian Railroad, located at route segment 6277 to 6278 km, is shown in Fig. 1.

Figure 1. Deformations of a track of Transbaikalian Railroad, km 6278, March, 2009

This segment is known as the “golden” kilometer. At this location, continuing deformation of the embankment and rail-sleeper grating has been occurring since 1949. Train speed limitations of 40 km/h, and sometimes as low as even 15 km/h, have been imposed since 1969, while addition of ballast and rail adjustments are executed annually.

In some places, the ballast has already subsided 5 to 6 m and subsidence of the rail bed has not ceased. This condition is expected to continue for many years, since the embankment was constructed on permafrost soils having a thickness of 25 to 30 m.

On the East Siberian Railroad in the region of the Kazankan sidings at 1374 km on the BAM, major railway track deformation has been taking place for nearly two decades. From the original four track lines on this segment, only one remains in service; however, as shown in Fig. 2, it also requires nearly continual maintenance and recurrent refitting. For the last seven years, 360 million rubles (about 15 million dollars) have been spent to refit this section of the railroad, but the problem of stabilization remains unsolved. Train speeds are still limited to 15 to 40 km/h, since the threat of unacceptable deformation of the track on this side hill-slope remains. Since this segment of the BAM is electrified, it is critical that the electric contact net and supporting power line towers be repaired as well.

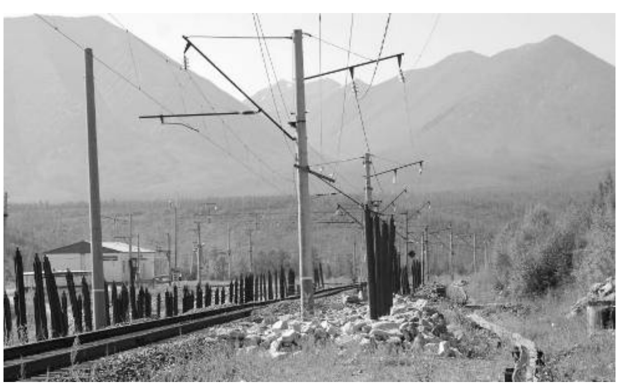

Figure 2. Area of severe deformation on the East-Siberian Railroad at 1374 km of BAM, August, 2008

To the north of the Transbaikalia, the Chara-Cheena railway line was constructed in 2001. The route extends over an area having extremely complex engineering-geocryological conditions involving ice rich permafrost. In some areas, the underground ice has a thickness of 5 to 10 m. An example of this railway track deformation is shown in Fig. 3.

Figure 3. Thaw settlement of embankment of the Chara-Cheena Railroad, May, 2010

The thawing of permafrost soil under railroad embankments is usually caused by: 1) increased absorption of solar radiation into the subgrade when compared to the natural surface; 2) the infiltration of precipitation through the embankment; 3) an increase in the thickness of snow cover at the base of the embankment and adjacent area; and 4) the migration of surface and subsurface water into the body and base of the subgrade in side-hill slope areas.

Several methods of strengthening the base of embankments on ice rich permafrost have been developed. These methods cause a decrease in the average annual temperature of soils and assist in preserving the permafrost state in a way that reduces warming and improves cooling impacts.

These technical solutions have been presented in articles, reports and monographs, both in domestic and foreign publications (Kondratiev 1994, 1996, 1998, 2002, 2004, 2006 and 2008). The solutions have been applied on experimental projects while constructing; 1) the Amur-Yakutia trunk line, 2) the connecting Ulak-Elga railway line, and 3) a feasibility study of stabilization measures for use on the Transbaikalian Railroad. Some of these solutions have also been applied on the Qinghai-Tibet Railway in China. An example of the sun-precipitation protective shed, applied to side slopes, is shown in Fig. 4.

Figure 4. Sun-precipitation protective sheds on the Qinghai-Tibet Railway, August 2006

Data from observations at the full-scale site indicates temperature reductions ranging from 3 to 5ºC in the subgrade soil (Fig. 5). This cooling influence serves to improve the stability of the subgrade soil on the highly ice rich permafrost soil (Niu & Shen 2006; Feng Wenjie, Ma Wei, 2006; Feng Wenjie et all 2009).

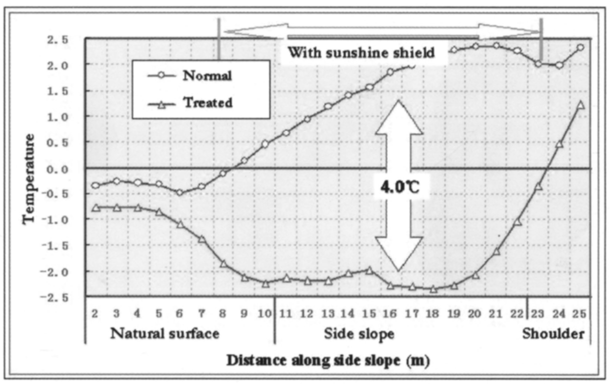

Figure 5. Cooling influence of the sun-precipitation protective sheds, constructed on the embankment slopes of the Qinghai-Tibet Railway (by Niu & Shen 2006).

Application of sun-precipitation protective sheds has also been accomplished on Russian railways. On the Amur-Yakut Railway, at the approach to the Lena River, where for tens of kilometers of the railroad there exists a so-called “ice complex”, having a thickness of tens of meters.

Excavation or mechanical pre-thawing of this ice thickness is considered to be impractical. Therefore, it has been concluded that this section should be protected from thawing during all periods of railroad operation.

In 2007, a technical study of the application of sheds for preventing degradation of ice rich permafrost, at the base of an embankment along the Tommot-Kerdem Railway, was initiated at five separate sites. These involved three embankments having heights of 3.48, 6.64 and 7.31 m and two excavations having depths of 2.38 and 5.5 m.

For comparison, at the same sites, thermotechnical calculations of the cooling influence of convective stone/rock covering on the embankments and excavated slopes were executed. Results were found to show a higher efficiency with the sun-precipitation protective sheds for cooling soils in the subgrade of an embankment and prevention of degradation in the underlying permafrost soil, particularly when used in combination with dolomite powder (light-reflecting painting) placed on the surfaces of the basic platform and employment of an antifiltering membrane underneath. Results further indicate that:

• On slopes of both embankments and excavations, the shed only application provided a decrease of 10 to 31% (average 22.4%) in the depth of the bedding and cover over the permafrost soils along the axis in comparison with the rock covers.

• On the slopes of both embankments and excavations, use of sheds in combination with dolomite powder painted on the surface of the basic platform provided a 25 to 35% (average 30.6%) decrease in the depth of the bedding and cover over the permafrost soils along the axis in comparison with the rock covers.

• On the slopes of both embankments and excavations, use of sheds in combination with the dolomite power painted on the surface of the basic platform and with placement of antifiltering membrane underneath provided a 28 to 40% (average 34.6%) decrease in the depth of the bedding and cover over the permafrost soils along the axis in comparison with the rock covers. In this case, cooling of the embankment and subgrade soil occurs more rapidly than at sites having rock covers. After only 5 years the subgrade soils and a substantial part of the body of the embankment exist in the permafrost state, whereas under the rock covers the embankment remained unfrozen and complete freezing will only occur after 50 years.

Thermotechnical calculations for the Amur-Yakut Highway, as well as experimental research in Tibet, demonstrate that sun-precipitation protective shed applications represent an effective treatment as an anti-deformation device for embankments on railroads at sites containing icy permafrost soils. The positive effect of the shed application is accomplished by both allowing the intensive winter cooling of the embankment and its subgrade, and by both the reduction in infiltration of summer precipitation and the exclusion of direct solar radiation. This helps to preserve the higher strength properties of the frozen soils in the subgrade during all periods. Thus, the design of an embankment becomes simpler, traffic volume and safety improves, and maintenance and repair needs decrease.

On the BAM sun-precipitation protective sheds are used since November 2009.

Operational reliability of railways and highways in regions of permafrost is predetermined by the choice of constructive-technological solutions and the methods of effective execution during construction and subsequent maintenance operations. Constant protection of roads, particularly in areas of ice rich soil, from adverse engineering-geocryological processes is important in order to provide stability and maintain traffic design speeds. To be most effective, such protection needs to be carried out systematically with emphasis on engineering and geocryological monitoring of the routes.

This includes providing regular reviews and controls, technical analysis, and providing estimations and forecasts of changes in freezing conditions. Such a procedure allows detection and mitigation of undesirable and adverse cryogenic processes. The concept of such a monitoring system was developed for the constructed Berkakit – Tommot – Yakutsk railroad (Kondratiev and Pozin 2000). In 2001, the concept and process were presented in Beijing and then applied to the Qinghai-Tibet Railway route.

2.2 Frost heaving tower supports

The provision and effective utilization of basic facilities of railways in areas of a permafrost and deep seasonal soil freezing is associated with significant difficulties. As an example, on the Transbaikalian Railroad during the past 10 years (1997 to 2006) at least 17,192 power line tower supports required corrective repairs and 3,294 were replaced. In most cases deformation of support structures were caused by frost jacking within wet friable sediments of seasonally thawed (STL) or seasonally frozen (SFL) layers. Fig. 6 provides an example of the extent of tower deformation.

Figure 6. Adverse deformation of power line tower supports along the electrified section of the Transbaikalian Railway, March, 2010

In responding to this problem, a patented solution for an anti-frost heaving measure was developed for the purpose of decreasing the influence of frost heaving forces. This is accomplished by the simultaneous increase in lateral forces on the tower support in STL by freezing and by cooling within long term frozen soils by means of: a) thermosyphon support in STL, inserted into a hollow reinforced concrete support or metal base, b) wrapping of an anti-frost heaving sleeve made of nonfreezing grease and a protective casing made of frost-resistant material, c) placement of heat and hydroinsulation at the soil surface around the support, and d) inclusion of a sun-precipitation protective shed around the support and anti-frost heaving sleeve (Kondratiev, 2005).

The anti-frost heaving device design for a metal tower support having a screw base (as shown in Fig. 7) consists of three basic elements: the thermosyphon, the thermal insulation and the anti-frost heave sleeve.

In October, 2003, anti-frost heaving devices consisting of the thermosyphon structure and a 1.25 m long anti-frost heaving sleeve were installed on five tower support pile bases along the Erofey-Pavlovich-Sgibievo segment of the Transbaikalian Railroad.

Work on placing the insulation layer around the support bases and protective soil cover was performed in April, 2004 after allowing maximum winter freezeback of the soil around the metal support bases. The elevated portion of the supports was then painted with a white cover.

Analysis of the data recovered since November, 2004 shows, owing to the cooling influence of the thermosyphons, that soil freezing near the base (at 0.1 to 0.2 m from the surface) occurred more quickly than at 0.55 to 0.65 m. Around one support, the frozen soil mass that normally by late autumn thaws to a depth of 2.5 to 4 m, was found to preserve the soil in a constantly frozen state around the lower portion of the support at a depth of 1.5 to 3 m.

Periodic level surveys were conducted on the top part of the tower supports and have shown that the tower bases having anti-frost heaving devices have remained stable under the varying conditions of soil freezing and thawing cycles. Measurements indicate the vertical movement does not exceed 10 mm, based on a measurement accuracy of a Class III level survey. Whereas, 20 to 30% of the tower bases not having anti-frost heaving devices have begun to heave after 2 to 3 years following installation. Their vertical moving for five annual cycles of freezing-thawing has ranged from 10 to 280 mm.

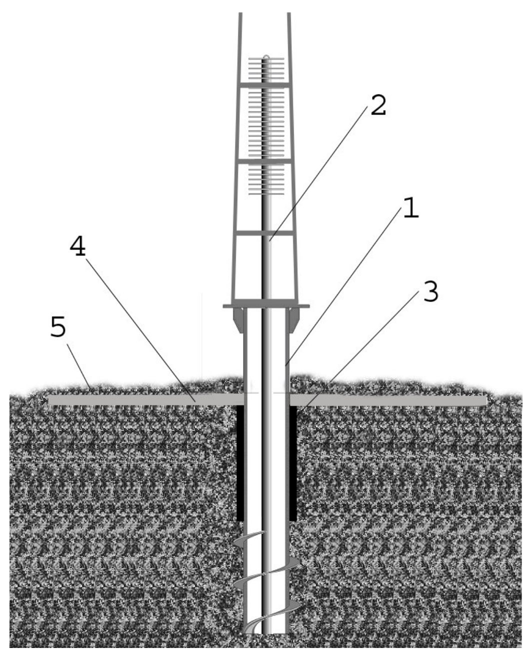

Figure 7. Metal support with screw base (1) with thermosyphon inset (2), anti-frost heaving sleeve (3), thermal insulation (4),covering soil layer (5)

Following verification of the experimental anti-frost heaving devices for the tower support bases, applications have now been extended to electrified rail line projects such as the Karimakaya – Borzya, Burinda – Magdagachi, Mogocha – Amazar, Chernovskaya and Karimskaya stations. This solution also has the potential for use on other type tower structures such as signal system devices, high voltage transmission lines, communication structures and also elevated pipelines which are exposed to the negative influence of soil frost heaving.

3 GEOCRYOLOGICAL PROBLEMS ASSOCIATED WITH HIGHWAYS

Problems with embankment stability of subgrade soils are characteristic for highways within permafrost regions as well. Particularly, for the newer "Amur" Highway extending from Chita to Khabarovsk (shown in Figs. 8 through 11) and the Qinghai-Tibet Highway (shown in Figs. 12 through 15).

3.1 The federal "Amur" - Chita to Khabarovsk Highway

This highway is one of the largest contemporary construction efforts in Russia. Construction of the road, having a length of 2,165 km began in 1978 and is planned for completion in 2010. However, even now many sections of the road are subject to constant repairs that are not always successful. As an example, the high embankment on the "Amur" Highway where it passes over Chichon Stream at 247 km is presented. Here the uneven subsidence of the 20 m high embankment has been observed since May, 2001, soon after the delivery of this highway section. Since that time, as evident in Fig. 8, subsidence of the road surface in some places has approached about 2 m, in spite of the periodic addition of soil and the releveling to profile grade.

Both transverse and diagonal cracks, having widths of up to 15 to 20 cm, are opening within the roadway, shoulders and embankment slopes. The pavement surface is also highly deformed. This highway section is in a very distressed condition. The traffic speed for vehicles is now limited to 40 km/h for this section while the designated design speed is 100 km/h.

During September, 2006 the innovation repairs of this 200 m failing section, as shown in Fig. 9, was completed.

Figure 8. A section of road on the "Amur" Chita to Khabarovsk Highway, km 247, before repairs, July, 2006

Figure 9. Same section of road on the "Amur" Chita to Khabarovsk highway, km 247, one month after completing innovative repairs, October, 2006

Almost 10 million rubles have been spent on repairs to date, however, as shown in Fig. 10, deformation of the embankment section continues. The subgrade soil in this section consists of 15 to 20 m of permafrost with the larger part being ice rich soil, that settle and flow upon thawing. As a result, permafrost degradation and corresponding deformation of the road under the prevailing conditions is expected to continue indefinitely.

Figure 10. Same section of road on the "Amur" Chita to Khabarovsk, km 247, eighteen months after completing innovative repairs, March, 2008

Figure 11. Same section of road on the "Amur" Chita to Khabarovsk, km 247, eight months after completing last repair and asphalting, May, 2010

There are a number of other such examples along the "Amur" Highway. Since much of the route passes through the southern fringe of discontinuous permafrost and also lies within a region of deep seasonal soil freezing, it is evident that an ongoing change in permafrost conditions and deep seasonal freezing will continue. Thus, it is important to identify permafrost conditions along the route, develop systematic means to address or control the cryogenic dynamics that adversely influence elements of the roadway, and to initiate the timely application of protective measures. Therefore, in order to provide for a more effective operation of this highway, the system of engineering-geocryological monitoring of the “Amur” Highway was developed under the designation SIGMA “Amur”.

In 2006, the TransEGEM organization developed and submitted to Rosavtodor the concept of SIGMA “Amur”. Following is a summary of the developed concept (Kondratiev et al. 2007):

- The SIGMA “Amur” structure includes: information gathering, processing and analysis of information, assessment and information storage, forecasting and projection of protective measures, and application of protection (implementation of protective measures).
- The operating scheme of SIGMA “Amur” provides for a number of regular procedures arranged into cycles for data gathering and processing, assessment of hazardous engineering-geocryological processes, forecasting their future development and management of unfavorable processes.
- The operating structure of SIGMA “Amur” consists of several subsystems designed for different purposes: hierarchical, project monitoring and operating subsystems, productive work, methodical and technical support.
- Primary subjects of SIGMA “Amur” engineering-geocryological inquiry consists of three interrelated parts: geology-geographical, permafrost and highway conditions.
- The overall program of the SIGMA “Amur” organization emphasizes optimal structure and consistency in practical operations, both with regard to organization and function.
- The plan is to implement a complex program with the aim to set up SIGMA “Amur”. The program has three stages: preliminary stage, set-up of information database, and the stage of SIGMA “Amur” operation.
- Address proposals on the organization of SIGMA “Amur” operation.

The early creation and functioning of SIGMA "Amur" was intended to provide a more reliable and safe highway that will reduce less unproductive expenditures and improve its operations. Without application of such a concept, the “Amur” Highway will be subjected to continuing repairs, constant traffic speed limitations for vehicles and major financial and material losses.

Another problem in building roads in Russia cryolite zone is the problem of building passages through poorly defined and small drainage channels, unit recently, on those route segments containing permafrost soil and icings, preference has been given to constructing small and medium size bridges - even in those cases where there was limited exposure to potential ice mound development and validation of actual subsurface conditions might be available. Various forms of culverts were only utilized within evident waterless valleys and, most usually, only in traditional ways involving standard round 1.5 m reinforced concrete pipe sections having 1-4 pipe passages at a drainage crossing. On occasions rectangular sections having 2.0 x 2.0 m openings have also been used. Corrugated metal pipe was seldom utilized.

In 2003, it became obvious that extensive use of short and medium size bridges on undefined and small drainage passages would delay the desired schedule for construction of the Federal Road “Amur” Chita-Khabarovsk and were not suitable both technically or economically.

In general, there was insufficient information on permafrost conditions for different parts of the road through those passages having some watercourses widths of up to 4 and 5 m. Along the route segments lying between 1008km and 1020km concerns with icing building resulted in initial plans for three and four span bridges having lengths between of 55 and 97 m. Subsequently, additional subsurface investigation and research work was initiated and thus allowed further assessment of icing potential and the opportunity to develop measures for reducing the risk of drainage and structural failures. As a result large diameter corrugated metal pipe were justified for application at these drainage crossings.

During the period from 2003 to 2008 a total of 138 structures were planned for the “Amur” road. A total of 15 corrugated metal pipe culverts were constructed. Pipe shapes involved circular pipe diameters ranging from 1.5 up to 4.30 m, an both ovoid and arch sections having widths of between 1.94 and 10.72 m. Heights ranged from 1.6 to 7.81 m and had equivalent diameters of 1.72 up to 7.5 m. The length of the pipe crossing varied from 21 to 70 m. Inclines along these watercourses varied from 0.01 to 0.05. Pipe wall thickness ranged from 2.75 to 7 mm. Height of the fill above the pipe sections varied from 1.1 to 16.09 m. Discharge through these pipe sections ranged from 1.07 to 147 m^3/sec.

3.2 The Qinghai-Tibet Highway

In the 1950’s the Qinghai-Tibet Highway was constructed with a gravel-crushed stone coating. In the 1980’s, it was reconstructed, and in may sections, asphalt pavement was applied. This black pavement surface accelerated degradation of permafrost within the subgrade, producing significant surface deformations in those sections having ice rich soils (Fig. 12).

Figure 12. The Qinghai-Tibet Highway, October, 2002

Also those subgrades, having frost heaving soils were adversely impacted (Wu et al. 1988).

Recently, the highway was reconstructed to meet contemporary high speed vehicle standards. The highway, in essence, traverses parallel with the Qinghai-Tibet Railway. The highway has a hard-surfaced pavement and utilizes anti-frost heaving measures in the sections having ice rich soils. At some of these locations, thermosyphons have been placed in the form of one (Fig. 13) or two (Fig. 14) lines along roadway shoulders,

Figure 13. One line of thermosyphons along the Qinghai-Tibet Highway, September, 2004

Figure 14. Two line of thermosyphons along the Qinghai-Tibet Highway, August, 2006

However, as can be seen in Fig. 15, some embankment problems have begun to occur. It is also expected that the thermosyphons will not protect the road from the thermokarsts, because of their limited radius of cooling.

Figure 15. Deformation and displacement of an embankment slope on the Qinghai-Tibet Highway as a result of permafrost degradation outside the influence area of the thermosyphons, August, 2006

4 CONCLUSIONS

In conclusion, it is felt that the above information again demonstrates that in order to achieve stable and reliable transportation routes in regions of permafrost and deep seasonal frozen soils, it is critical that a system be utilized to provide comprehensive geocryological exploration and evaluation, uses innovative and intelligent design solutions, allows timely and quality construction procedures and provides for necessary ongoing maintenance.

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