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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

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DEFORMATION OF RAILWAY SUBGRADE UPON PERMAFROST AND STABILIZATION MEASURES

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The paper presents results of experimental studies of subgrade deformation in permafrost areas and measures for its stabilization. Deformation results from heat transfer changes caused by railway construction and operation. An embankment loads the cryotic soil like a hot press which lowers the permafrost table to 6–10 m below the superstructure and causes melting of ground ice. The subsequent extrusion of thawed yielding muddy soil from beneath the subgrade leads to decades-long soil subsidence. As a result, the subgrade experiences settlement and lateral spreads, especially in poorly drained soils with a moss-grass-peat cover. As shown by experiments, native soil under the subgrade is mechanically weak and prone to rheological changes (plastic flow) that induce uneven subgrade settlement. Moisture migration in thawing soil is driven by thermo-electrokinetic forces in thermally anisotropic capillary systems. Possible subgrade stabilization measures include ground freezing under slopes and creating mechanical barriers to soil extrusion. A number of respective engineering solutions have been suggested and experimentally tested.

Railway subgrade, permafrost, subgrade settlement and lateral spreads, soil freezing, retaining structures

INTRODUCTION

Totally more than 5000 km of railroads in Russia are located in permafrost areas and have been operated from 30 to 100 years. Construction of embankment and track structures changes heat transfer conditions in the ground underneath. The permafrost table becomes deeper, irrespective of the overburden thickness (Fig. 1), as a result of surface warming and thawing in the absence of shadow and evaporation by plants, as well as rapid thawing due to moisture contents lower in the subgrade than in the natural soil. The loose draining subgrade fill and wet soil warm up times more strongly than the natural ground surface: from 4 to 16 °C and 0.4 to 6 °C, respectively, in the day cycle [*Dydyshko, 1991a*].

A subgrade loads cryotic soil like a hot press which lowers the permafrost table, to 6–10 m below the embankment surface in the case of the Baikal-Amur railway (data by Dydyshko). Thawing leads to the formation of taliks in the subgrade and at its base between the active layer and the permafrost table. Frozen ground beneath the subgrade warms up to about –1 °C.

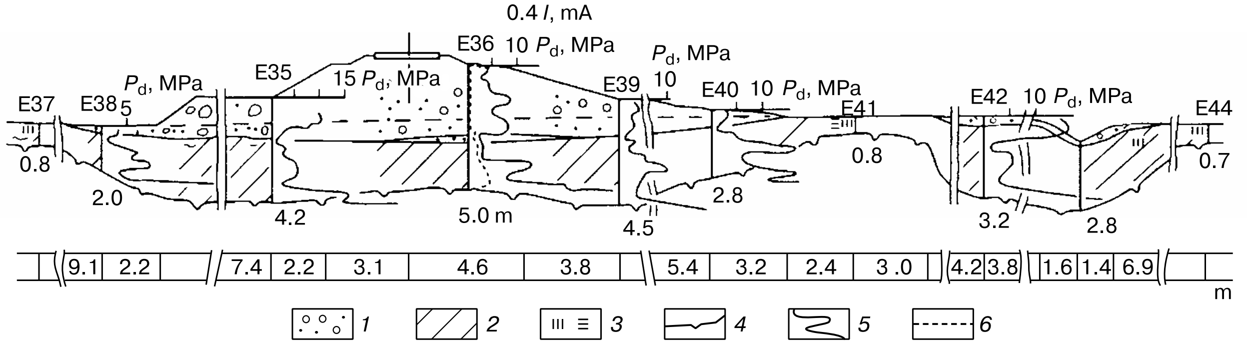

Fig. 1. Engineering-geological cross section of settling subgrade upon bog.

1 – draining soil (subgrade); *2* – clayey natural soil; *3* – peat; *4* – permafrost table; *5* – conventional penetration resistance (P_d, MPa); *6* – current (I, mA), Far East railway; E35 to E44 are sounding points.

Such a setting occurs in the southern part of the permafrost zone, in eastern and northern Russia. The depth to permafrost under railroads may reach 15 m (e.g., in the Noyabrsk–Korotchaevo district of the Sverdlovsk railway).

In the natural conditions of northeastern Russia, the ground temperature at the depth of zero annual amplitude is from –1 to –3 °C; the active layer thickness is from 0.6 to 1.5 m, depending on soil type and vegetation-peat cover; the permafrost thickness reaches 50–100 m [*Sergeev, 1976; Kozlovskiy, 1988*].

As the depth to permafrost increases, ground ice melts out (Fig. 2) and the thawing soil subsides [*Roman, 2002*]. The related initial settlement of the subgrade is followed by its decades-long deformation with further settlement and lateral spreads resulting from extrusion of yielding unfrozen clayey soils (Fig. 3).

Subgrade settlement occurs over 800 km of railroads, mostly in the Far East railway (75 %) and less often along the East Siberian (13 %), Northern (6 %), Transbaikalian (4 %), and Sverdlovsk (1 %) railways. The average size of individual deformed sites reaches 400 m.

DEFORMATION FORM AND CAUSES

Surveys by a method that combines dynamic probing and electrical logging (EDP) [*Dydyshko, 1991a*] reveal 0.1–0.3 m thick yielding soil beneath loose draining fill. The mechanically weak soil, with a deformation modulus of <10 MPa [*CPI-36, 2004*], lies upon stronger ground. This setting is common to clayey soils of any kind, irrespective of initial natural collapsibility. Thawing soil gains excessive moisture due to migration of film water in capillaries driven by thermoelectrokinesis, a phenomenon discovered by *Dydyshko* [*1991b, 1992*]. This phenomenon (detailed information is presented at the website *Thermoelectrokinesis.ru*) consists in migration of film water toward the colder side driven by the electric potential difference that arises in the presence of a temperature gradient (electric double layer); the temperature gradient at the seasonal thaw boundary reaches 4 °C/m.

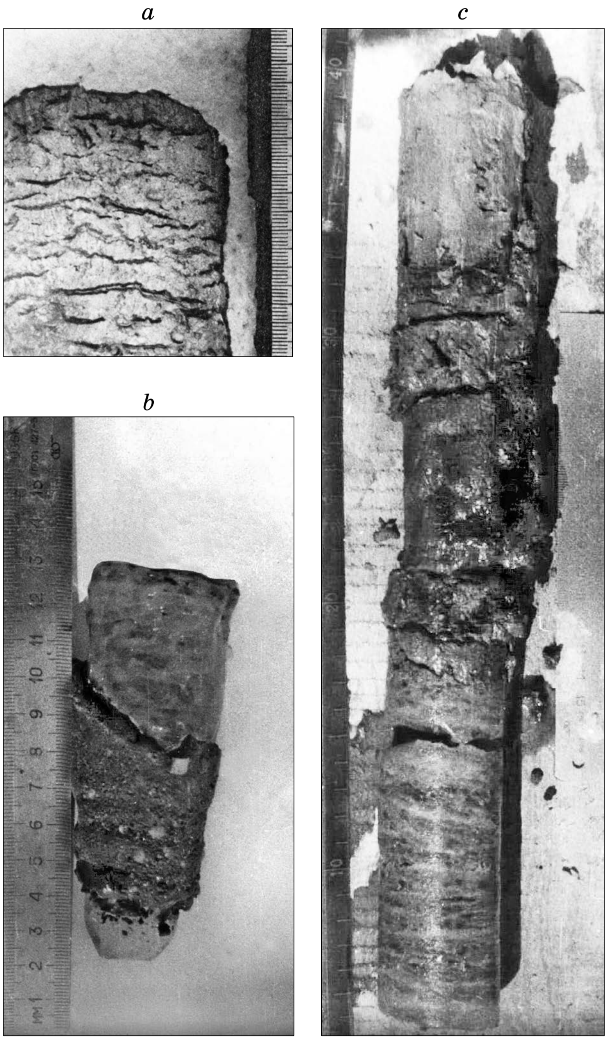

Fig. 2. Layers of segregation ice in clay silt (*a*) and clay silt with rubble (*b*); 3.2 m thick ice layer at the boundary with peaty clay silt (*c*).

Separate subgrade elements move down and laterally off the track centerline, i.e., experience, respectively, settlement and lateral spreads (Fig. 4, *a*)

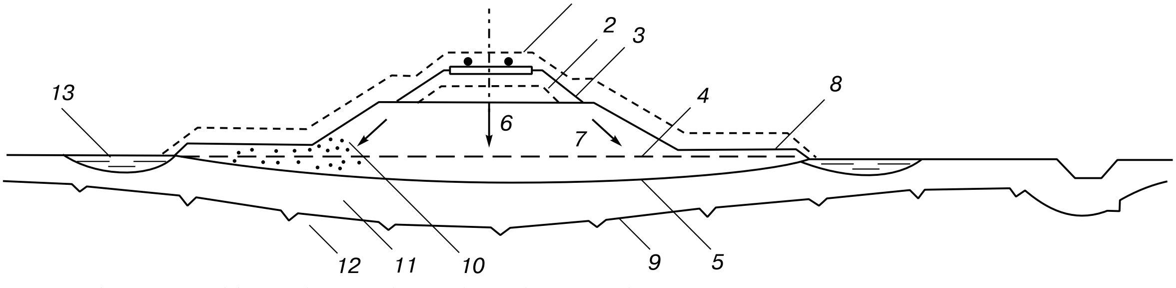

Fig. 3. Settlement and lateral spread of subgrade upon thawing permafrost.

1 – initial position of subgrade and ballast section; *2* – same, after settlement; *3* – same, after remediation (track raising); *4* – initial subgrade base; *5* – same, after settlement; *6*, *7* – direction of motion of the track center (*6*) and sides (*7*); *8* – benches; *9* – permafrost table; *10* – subgrade draining soil; *11* – unfrozen clayey soil; *12* – frozen clayey soil; *13* – lows filled with water.

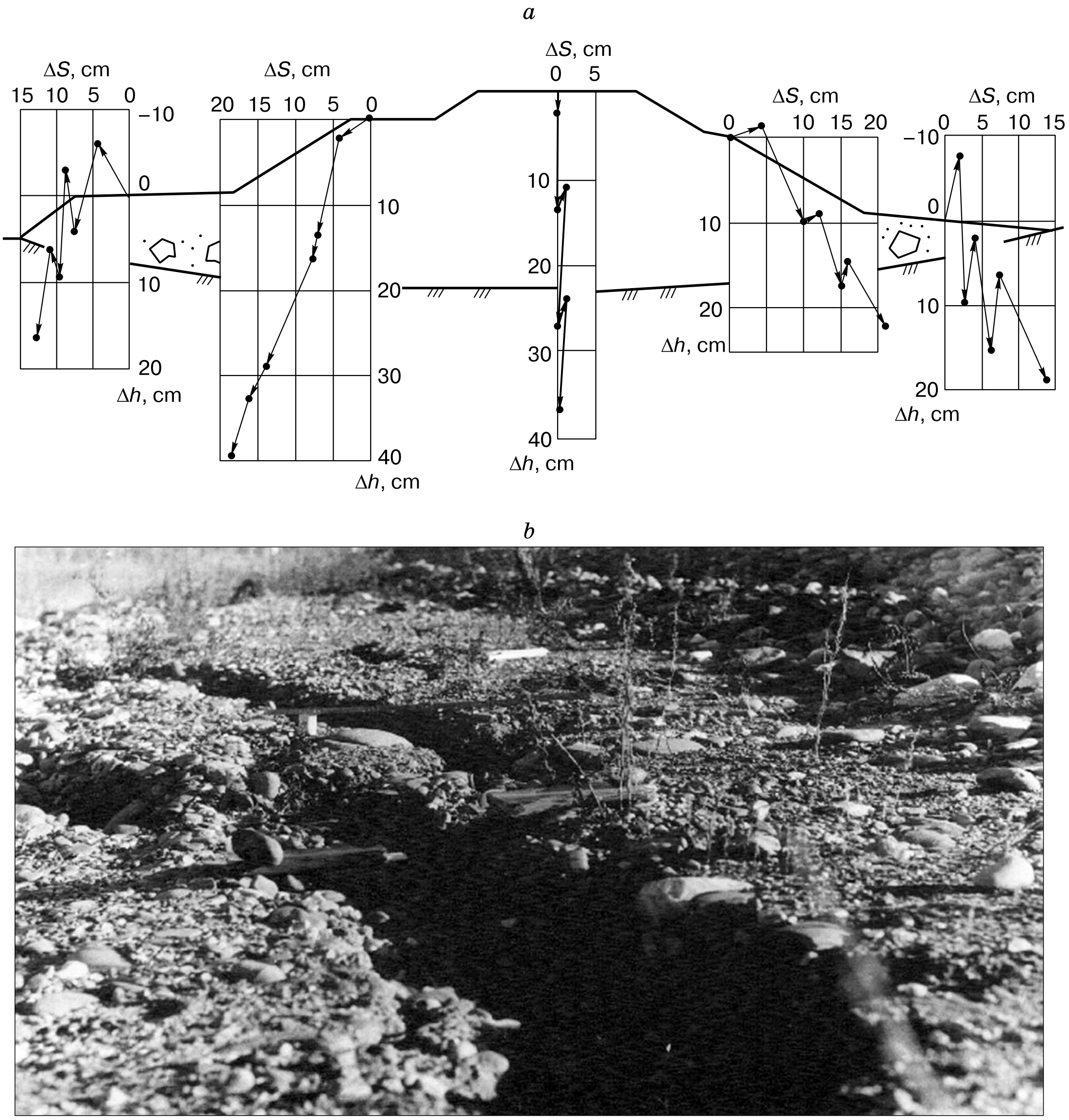

Fig. 4. Vector of motion of embankment surface in its different parts in seasonal (autumn–spring) cycles for three years (*a*) and cracks on the sides (*b*).

Δ*S*, Δ*h* are lateral and vertical motions, respectively.

sometimes leading to rupture and formation of cracks, up to 30 cm wide or wider (Fig. 4, *b*). Uneven settlement reaches 100 to 300 mm per year (about one third in November–December). The deformation is caused by changes in temperature gradient direction and in flows of migrating film water from super-wet unfrozen soil toward the freezing front. In the winter season, such soil undergoes heaving to 30–50 mm.

The thermal effect of the subgrade extends to ~2 m off its edges if the natural soil surface remains undisturbed. The permafrost table subsides in places where this surface is covered with a mineral fill (Fig. 1, survey point E42). Similar permafrost degradation occurs in the case of water-logged surface. Installation of 3 m wide benches (which takes up to 20 % of subgrade costs) and creation of new drain ditches pre-filled with draining soil expands the zone of thermal disturbance and water-logging, which interferes with the natural river and groundwater flow patterns.

Thawing is additionally caused by the absence of water guides within natural surface lows (up to 1/3 of the total amount of culverts in the eastern segment of the northern W–E part of the Far East railway), which leads to stagnation of water and its percolation through the subgrade.

The regulations for design and construction in permafrost imply bridging and tubing outside natural water streams, with filling and channel changing in the latter.

Taking into account the negative experience, the construction norms for engineering structures [*CES C-01-95, 1995*] include design of culverts in all natural depressions (at every 500 m in poorly drained places), but neither filling natural streams nor changing their channels are allowed. The ground should be kept frozen in areas of complex permafrost conditions (>0.1 relative soil subsidence, thermokarst, and ground ice to 4 m below the surface).

The presence of experimentally detected weak soil beneath subgrade and benches is the main cause for rheological changes (plastic flow) of soil and uneven subgrade settlement.

Settlement and lateral spreads occur most often on poorly drained soils with a moss and grass-peat cover. Deep uneven settlement affects primarily the subgrades that are located in 200–500 m medallion-shaped depressions, with weak low trees (under 3 m), surrounded by large mixed forests, which are widespread in all studied permafrost areas.

SUBGRADE STABILIZATION

In accordance with its causes, the subgrade deformation can be mitigated by thermal and mechanic stabilization: keeping the ground frozen at the slope toes and creating mechanic barriers to extrusion of yielding soil. The required thermal regime can be maintained with long thermosyphons (used at the 267, 489, 366, and 330th km of the Noyabrsk–Korotchaevo district, etc.) and heat insulation by plastic foam (211 and 212th km of the Tynda–Berkakit district), peat, and other materials. Mathematical and physical modeling of heat transfer makes basis for various engineering solutions in this respect.

Mechanic stabilization of settlement-prone subgrade upon degrading permafrost implies remediation of adjacent areas, draining, and installation of retaining structures. The remediation measures include filling stagnant-water thermokarst depressions, thaw lakes, abandoned river channels, bridge clearance, and approaches to malfunctioning culverts; the fill may consist of peat, peaty clay silt or wood wastes (wood dust, chips, bark residue, or branches). Other measures are draining (channeling water away from depressions along or across the trackline) and reinforcement of the existing drain ditches by laying and fixing geotextile on their bottom and sides and pouring over suspension of local native soil.

It is also reasonable to create a separate system of special drains, besides the existing culverts. One drain in such a system, made of a rolled 1–1.5 m wide strip of needle-punched geotextile, without thermal treatment (1 m^2 of such geotextile weighs 500 g), is embedded to 0.2 m at the slope toe. Another drain, made of perforated polymer tubes, is set to a depth of 1 to 3 m into a mechanically cut slit trench, together with a strip of geotextile. Then longitudinal drains are installed between culverts, and transversal drains are laid in bridge clearance extending them to a distance of 100–200 m toward the low side.

Filtering slits made of selected mechanically strong stone are set up in places where longitudinal drainage from lows in the high sides is difficult. Trees and shrubs are preserved within the drainage area while making vegetation-free fire breaks is not recommended.

In addition to the above stabilization measures (keeping soil frozen by heat insulation and thermosyphons, or crushed-stone filling on slopes), rapid uneven settlement and lateral spreads of subgrades can be mitigated with the use of goffer retaining structures [*Dydyshko and Mariomaa, 2008*], hollow-core constructions [*Tsukanov et al., 1983*], and draining fill instead of native soil at the toe of slopes (benches) [*Engineering Guidelines, 1993*].

EXPERIMENTAL TESTING OF ANTI-DEFORMATION STRUCTURES*

Plastic foam heat insulation. Heat insulation of subgrades in the southern permafrost zone, made with reference to 2D thermal-engineering calculations, consisted of plastic foam plates (⩾20 cm thick) laid in several layers next to one another, with at least 30 cm overlap, over 6 m on each subgrade side. According to theoretical calculations and field measurements of fill and ground temperatures, frozen ground forms beneath the middle parts of the insulation plates (Figs. 5, 6). For instance, the thaw depth in thus insulated railroad segments at 211–212 km of the Tynda–Berkakit district were 2.7 m in four years and 2.8 m in 18 years, while the ground temperatures at a depth of 6 m (thaw depth in the absence of insulation) was, respectively, –1.0 and –0.6 °C (measured together with people from the Permafrost Station, Center for Monitoring of Railroads).

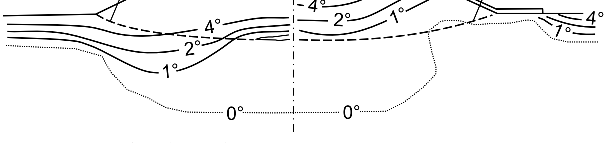

Fig. 5. Calculated quasi-stationary temperature fields (°C) in subgrade and natural soil on 1 October (19.5 yrs).

a: natural state; *b*: insulated by plastic foam; *1* – heat insulation; *2* – subgrade-natural soil interface.

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* The experimental results for all engineering solutions mentioned hereafter have been obtained by the author.

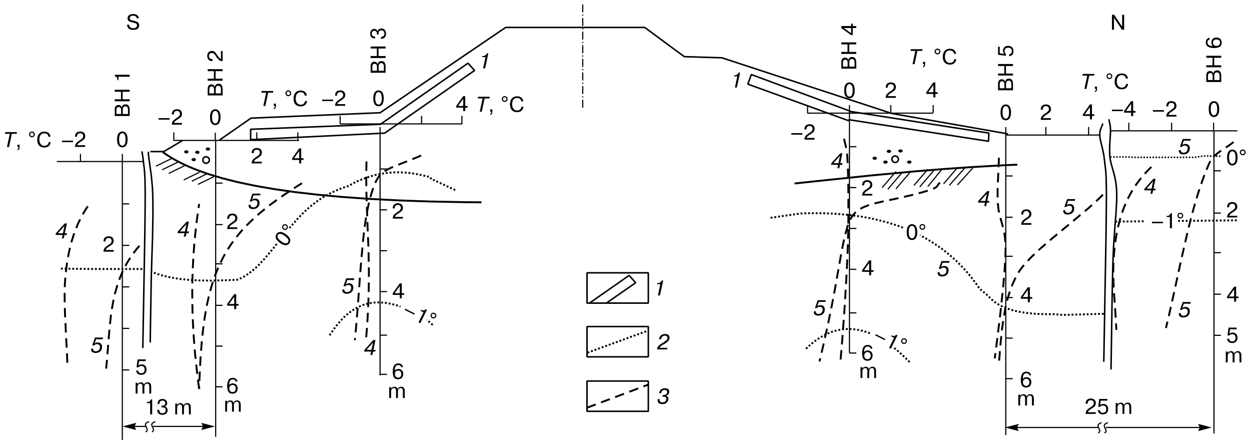

Fig. 6. Temperature fields and curves (*2*, *3*) in the section across subgrade and natural soil, with plastic foam insulation (*1*).

4, *5* – periods of maximum freezing and thawing in the last year of observations.

Plastic foam insulation plus long thermosyphons. The efficiency of heat insulation can be further improved by placing long thermosyphons in addition to plastic foam plates. The evaporators (inclined components) are laid either track-parallel (case 1) or track-orthogonal, in transversal trenches (case 2) beneath the plastic foam layer, while the condensers are set vertically.

The temperature regime of deforming slopes after installation of thermosyphons (case 2) was estimated (by Dydyshko) for 1374th km of the road, Kazankan switch, near the Severomuisk station of the Baikal-Amur Railway (Fig. 7).

Evaporator tubes are laid at a depth of 0.6 m in transverse trenches filled with soil; 0.15 m thick plas-

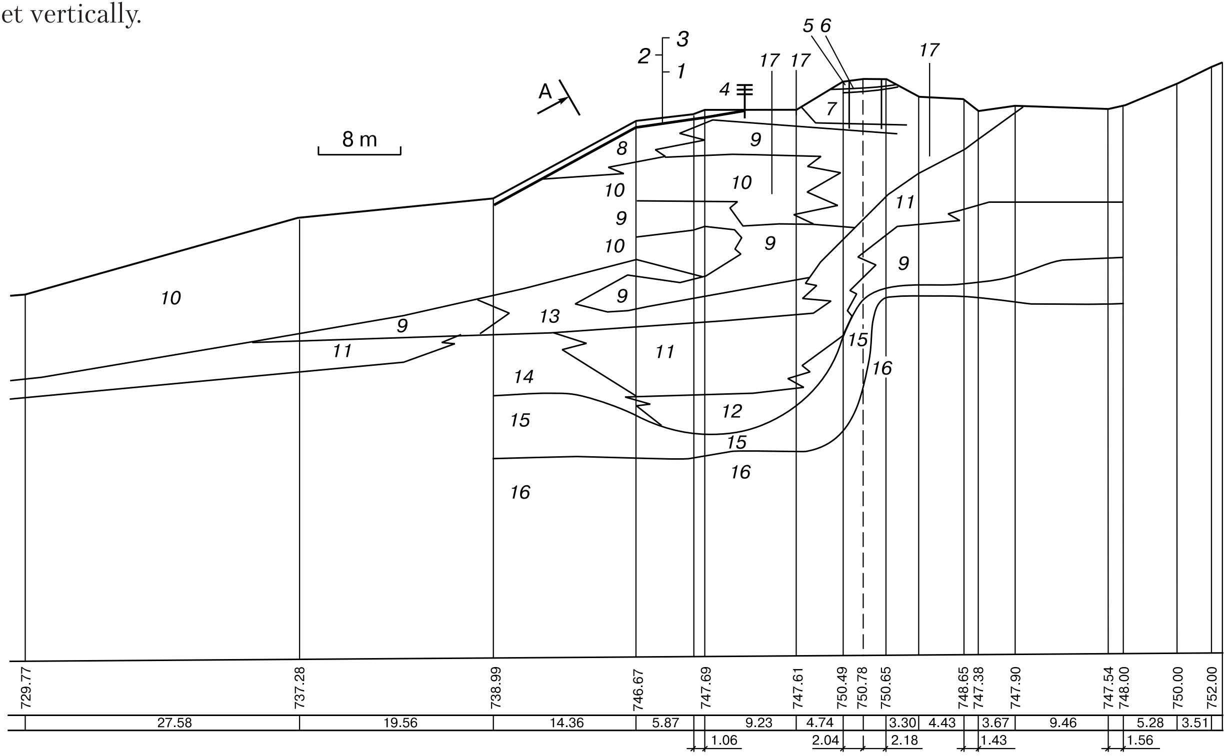

Fig. 7. Cross section of subgrade on a hillside slope at the 1374th km of the Baikal-Amur Railway stabilized with long thermosyphons and plastic foam insulation.

1 – evaporators; 2 – plastic foam; *3* – draining soil; *4* – condensers; *5* – debris; *6* – sand; *7* – blocky soil; *8* – rubbly soil; *9* – gravelly silt; *10* – silt-cemented rubbly soil; *11* – yielding silty soil upon thawing; *12* – plastic silty soil upon thawing; *13* – silt with pebble; *14* – pebbly soil; *15* – weak weathered granite; *16* – strong granite; *17* – vertical thermosyphons. Numerals in the figure bottom refer to elevations (numbers above) and distances (numbers below), in m.

tic foam is laid on the top and is buried under 0.2–0.3 m of draining material.

The calculations were made starting on October 1, at the end of the warm season. Ground temperatures in the subgrade and at its base were assumed to be 0.5 and –0.5 °C, respectively. The temperature patterns over the section A (Fig. 7), in 5 year intervals on October 1 are shown in Fig. 8, *a*, *b*.

At the subgrade temperature 0.5 °C (unfrozen soil), a frozen zone, at least 1 m thick, forms in a year and thickens up progressively to more than 2 m in 2 years and 6 m in 5 years. A colder subgrade (–0.5 °C) cools down faster, and the plastic foam thickness may be reduced to 0.1 m. Vertical thermosyphons (*17* in Fig. 7) have failed to provide stabilization at this site.

Heat insulation by peat and wood wastes. This kind of insulation is made as fill on slopes, with a triangular transversal profile having its top at the em-

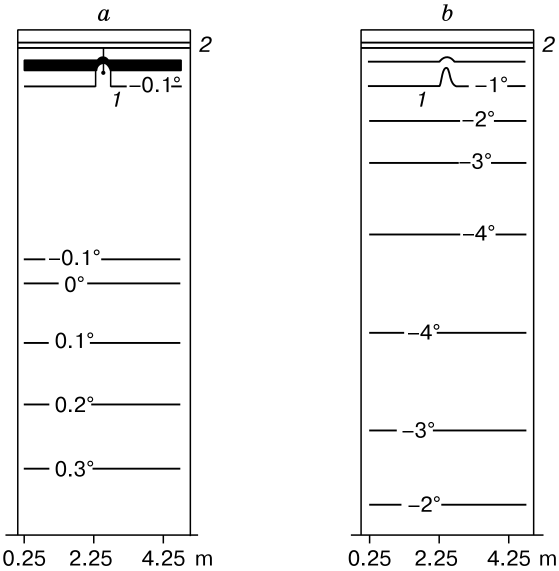

Fig. 8. Temperature field in subgrade in 5 years, at the end of the warm season, for initial temperatures 0.5 °C (*a*) and –0.5 °C (*b*).

1 – long thermosyphon; *2* – plastic foam; numerals on curves are temperatures in °C.

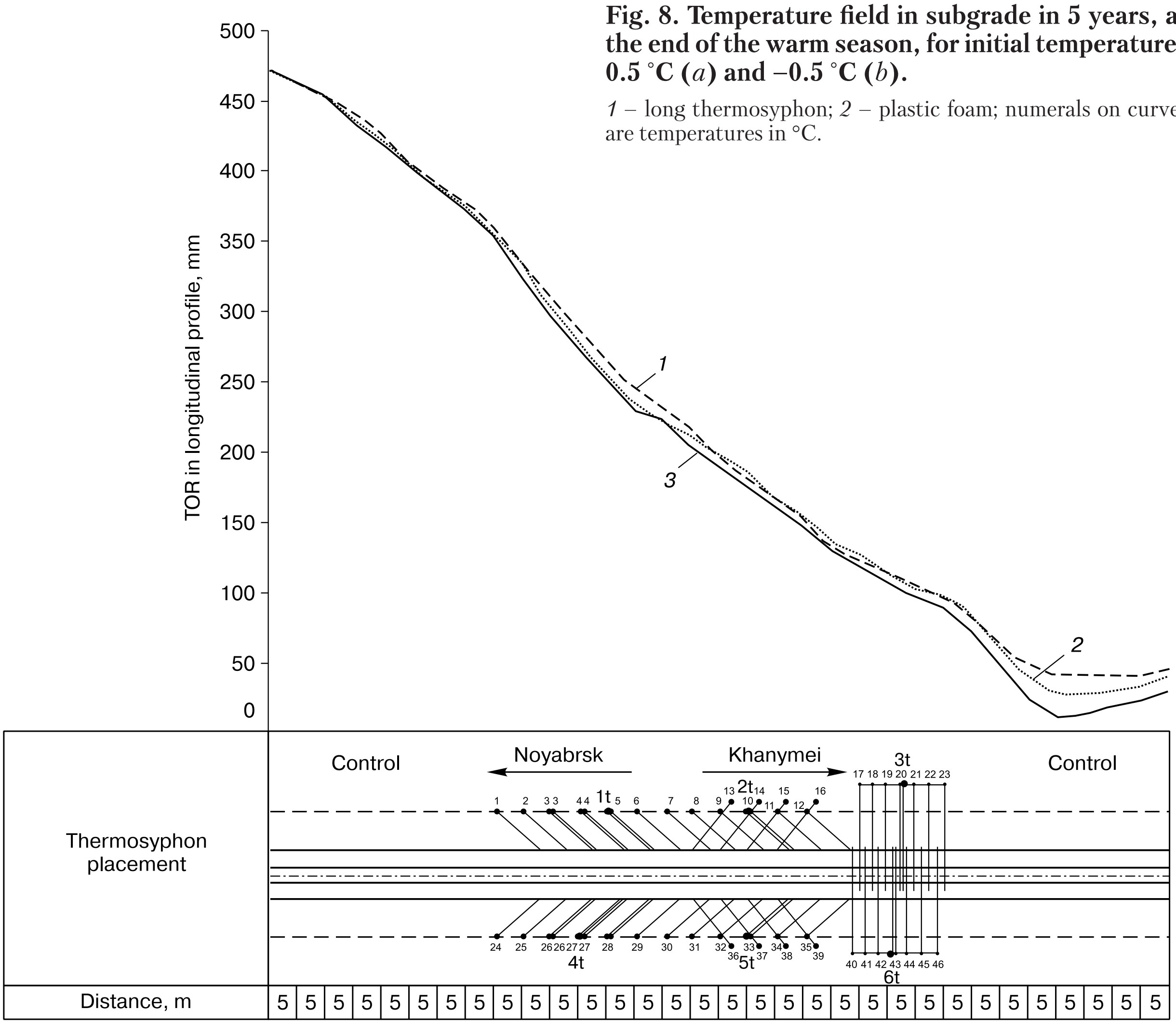

Fig. 9. Placement of thermosyphons and a longitudinal track profile, 267th km.

1 – September 2005; *2* – April 2006; *3* – September 2006; 1t–6t are logged boreholes. TOR = top of rail.

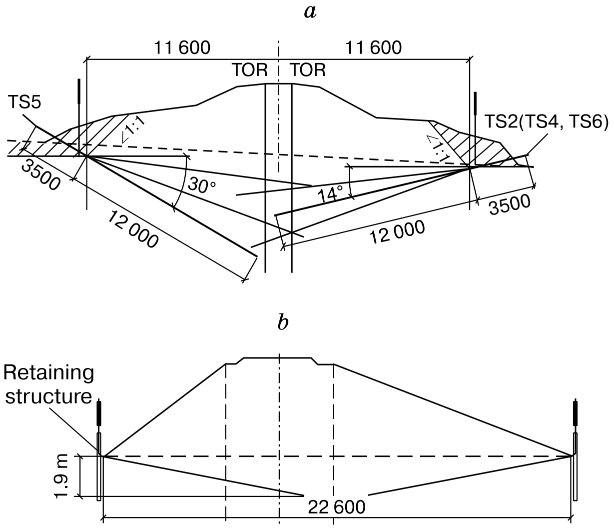

Fig. 10. Placement of long thermosyphons at 489th (*a*) and 366th km (*b*).

TOR = top of rail.

bankment edge and the base at least 3 m below the slope base. The fill is covered with a 0.2 m thick layer of local soil or with geotextile impregnated with a native soil suspension.

Fill on slopes. The slopes are covered with 0.8 to 1.2 m thick selected crushed stone with high erosion strength, in the absence of snow drift and snow depth on the slope within 0.4 m.

Design of long thermosyphons. Thermal stabilization follows the norms of *CPI-40* [*2009*], with long thermosyphons installed at sites of subgrade settlement, in the conditions of

– paludal areas (various terrain elements) where subgrade upon thawing permafrost is subject to uneven (more than 20 mm/yr) settlement;

– thaw lakes and water streams crossed by subgrades;

– bridge pier vicinity.

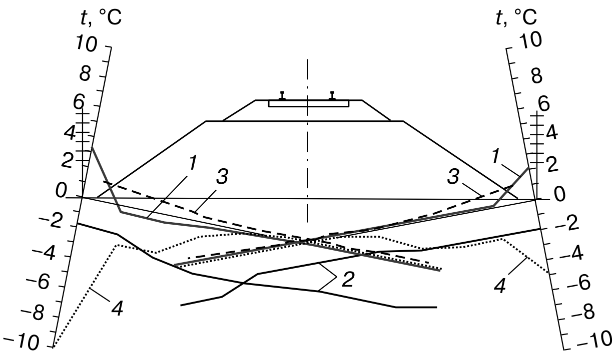

Fig. 11. Temperature patterns along thermosyphons in logged boreholes 3t and 6t (Fig. 9).

1 – September 2005; *2* – April 2006; *3* – September 2006; *4* – October 2006.

Long thermosyphons are made of steel pipes, 60 mm in diameter, or aluminum alloy pipes, 32 mm, with Freon-22 used as the coolant. They consist of inclined evaporators laid in the ground and vertical finned condensers above the ground surface.

Retaining structures are made of steel pipes, 110 mm in diameter, installed track-parallel in accordance with the location of condensers. The pipes, spaced at 1.25 m, are embedded vertically into the soil to a depth at least 5 m and are connected on the top by pipes of the same kind laid horizontally.

Subgrade stabilization can be provided by long thermosyphons with or without retaining structures.

The vertical condensers are 2.3 m long, placed >7 m far from the tracks; the evaporators are 9 m long placed at 11° to the track, at >2.5 m between the track centerline and the end of the evaporator (surface projection). The installation of evaporators beneath the subgrade ensures additional thermal resistance of soil necessary for preventing summer thawing of the stabilized frozen part.

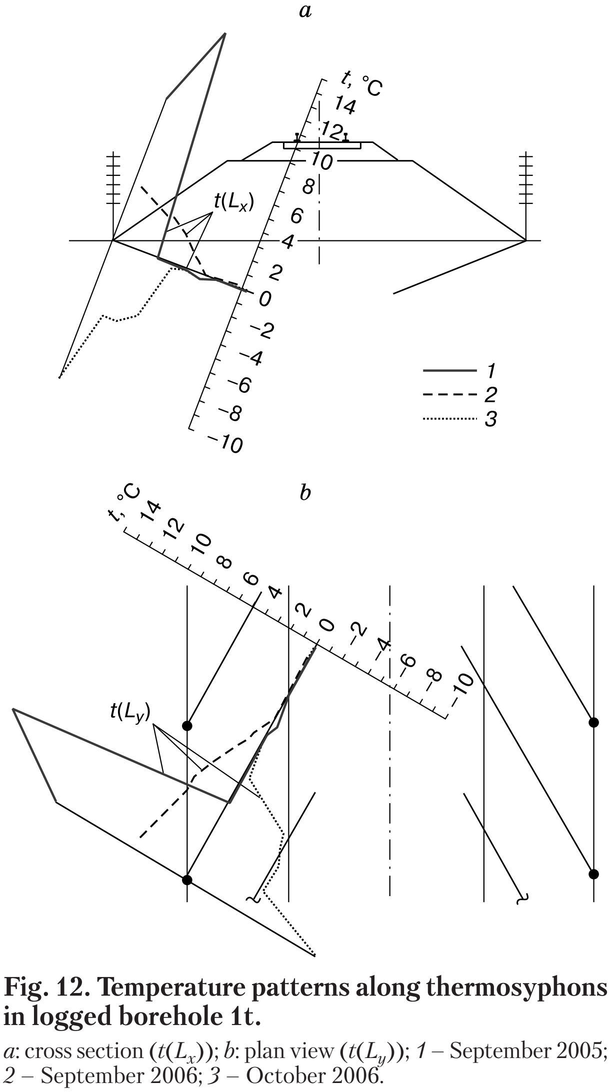

Fig. 12. Temperature patterns along thermosyphons in logged borehole 1t.

a: cross section ($t(L_x)$); *b*: plan view ($t(L_y)$); *1* – September 2005; *2* – September 2006; *3* – October 2006.

In the case when long thermosyphons are used without retaining structures (case 2), the evaporators are placed either at an angle to the track (in forward or backward directions), or orthogonally to the track, beneath the track structure and on sideways.

The *VNIIZHT* and *Fundamentproekt* teams installed long thermosyohons in 2005, in all possible ways according to the design by the author (Fig. 9), at the 267th km of the Noyabrsk–Korotchaevo district of the Sverdlovsk railway where the subgrade was deforming at 300 mm/yr. Figure 9 shows thermosyphons 1–46 and temperature logging boreholes 1t–6t; Figure 10 shows such structures installed in other districts of the Sverdlovsk railway. The deformation stopped after the installation of the thermosyphons.

The length and dip of the evaporator tubes depend on local conditions in the places of filled streams, thaw lakes, and in places where the subgrade approaches bridge piers.

The temperature of subgrade measured in the time of maximum freezing at the 267th km of the railway varies from –4 to –1.5 °C and is below 0 °C in autumn (Figs. 11, 12). Independent measurements by

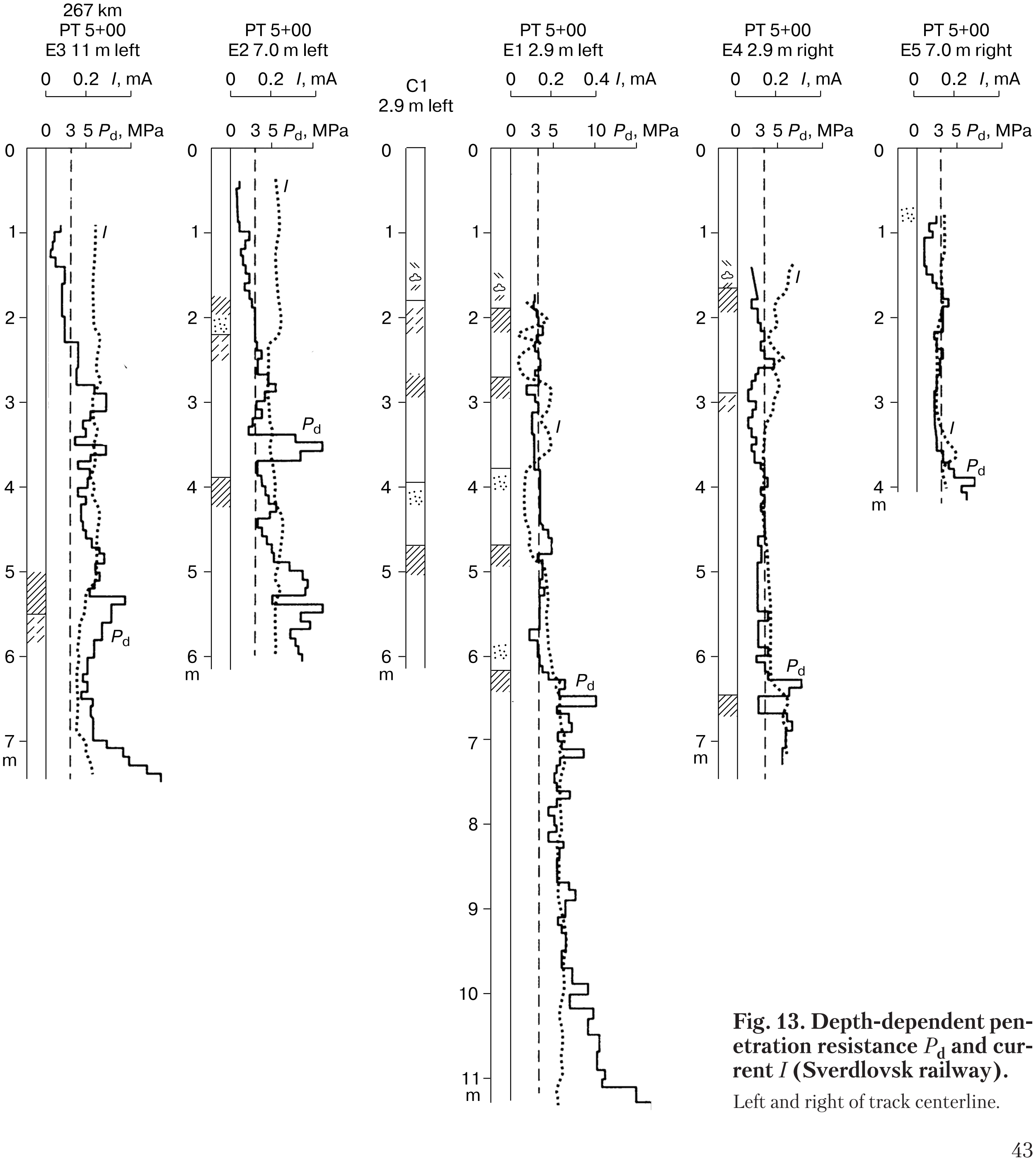

Fig. 13. Depth-dependent penetration resistance P_d and current I (Sverdlovsk railway).

Left and right of track centerline.

EDP and ground temperature logging in the time of maximum thawing in 2007 showed a 3 m depth to permafrost on the track sides above the thermosyphons. According to 3D calculations, the 0 °C isotherm is located at the depth 2.7 m.

Subgrade settlement occurred at the 489th km in the place of the filled channel of the Tydeyotta River. The new channel was displaced to reach the bridge built off the river. In 2003 and 2007, thermokarst cave-in of the subgrade occurred 1 m far from the rail-

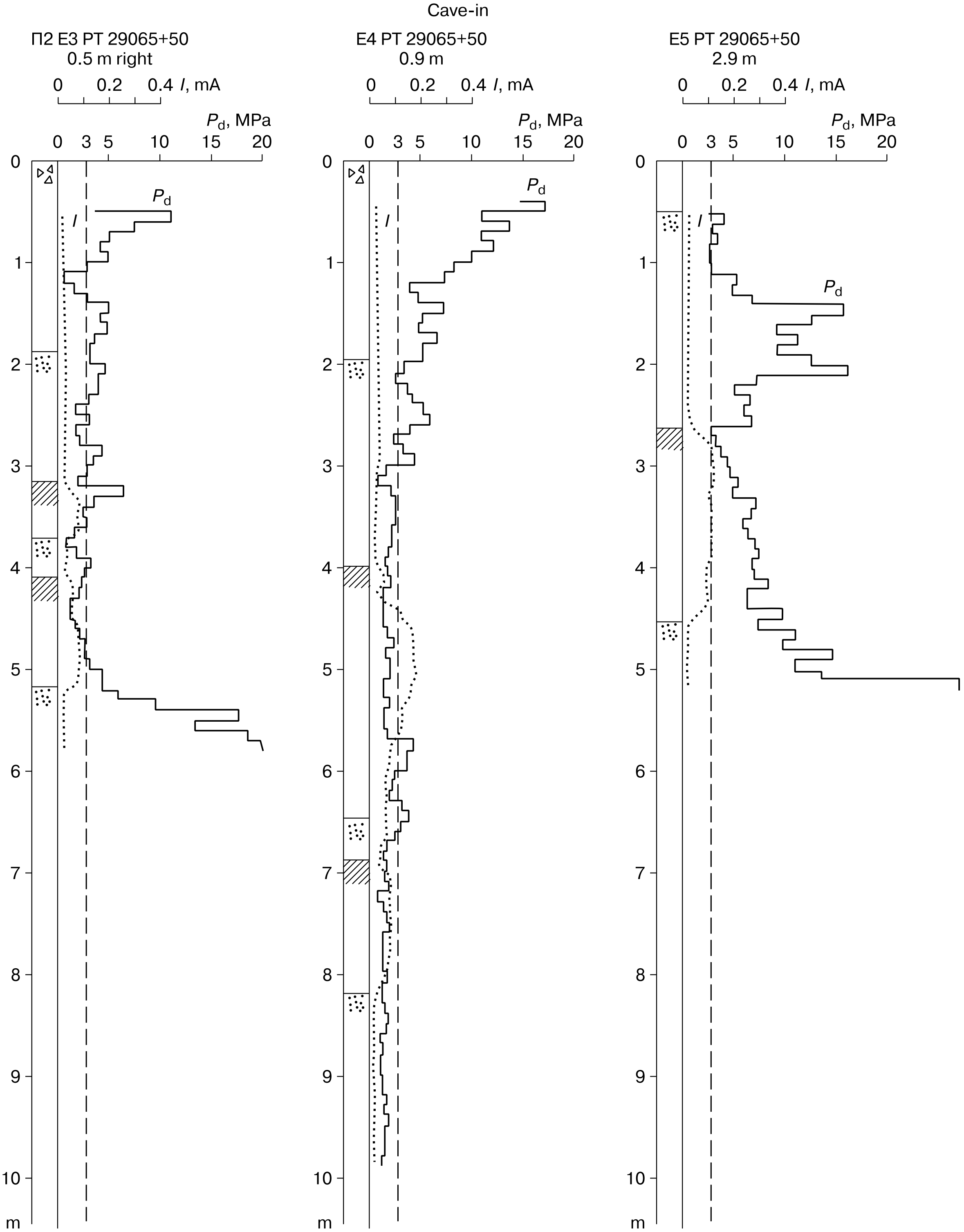

Fig. 14. Depth-dependent penetration resistance P_d and current I (Far East railway).

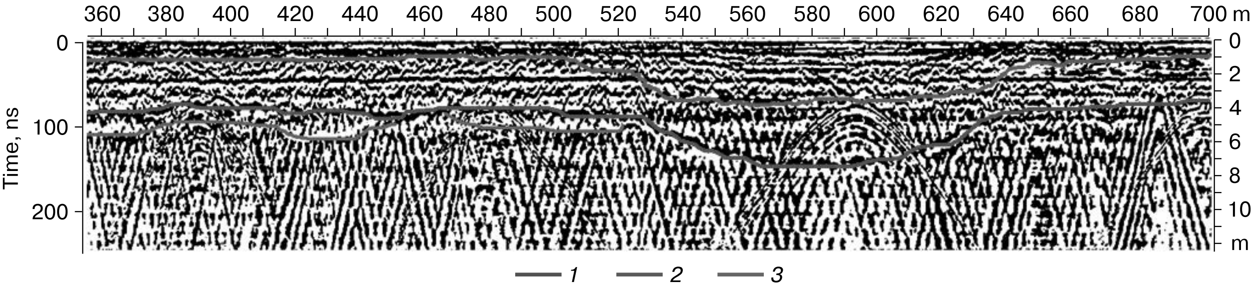

Fig. 15. GPR section along the track centerline (267th km, PT3+55–PT7+00, Sverdlovsk railway).

1 – subgrade base; *2* – ballast base; *3* – soil type interface.

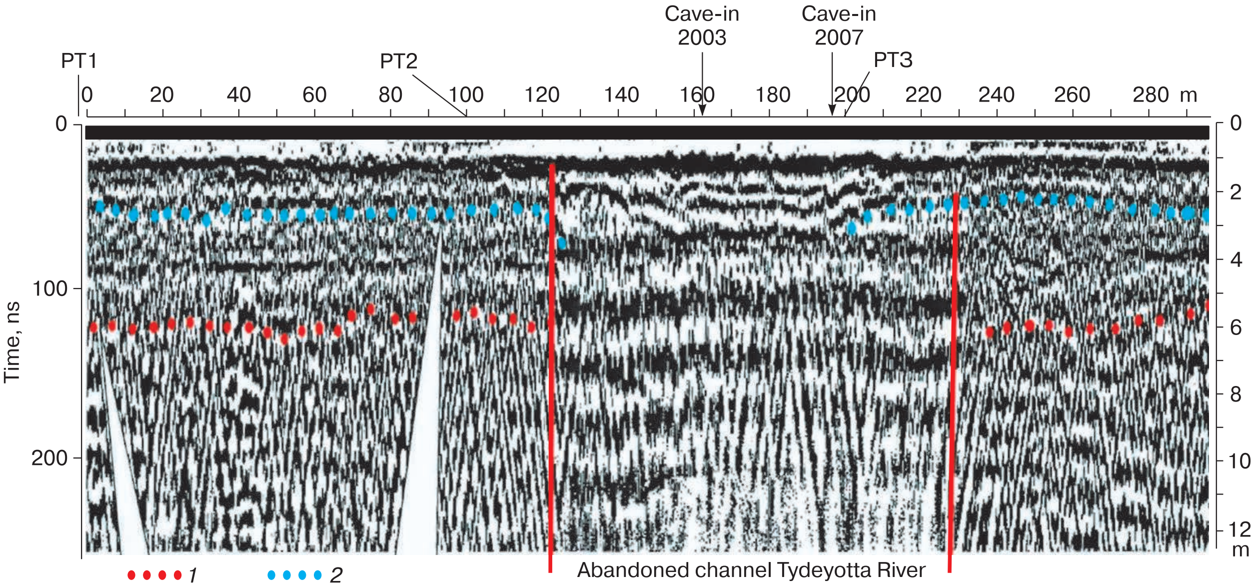

Fig. 16. GPR section along the track centerline (489th km, PT1–PT3, Sverdlovsk railway).

1 – subgarde base; *2* – ballast base.

track structure (left of the line) and inside it, respectively.

In order to mitigate settlement and prevent cave-in, thermosyphons were installed at every 2.25 m on both sides of the embankment, in two rows in height, with 12 m long evaporators (Fig. 10, *a*). The settlement at the 489th km stopped after stabilization, and no cave-in repeated. The amount of surfacing did not exceed 10 mm. The ground temperature in logged boreholes was below 0 °C during the thawing season.

The parameters of stabilization structures (length, depth, etc.) are specified according to results of GPR and EDP engineering-geological surveys [*CPI-36, 2004*].

The penetration resistance (P_d) and types of soil were inferred from electrical current (I) EDP measurements in places of settlement, including the caved-in sites and areas outside them (Figs. 13, 14). The sounding points E are shown in the figures separately for each site, with indication of their numbers, locations along the line (point + m), direction and distance (m) orthogonally off the track centerline.

Fig. 17. Drilling of an inclined borehole (by a UKB-12.5/25 drill).

Fig. 18. System of long thermosyphons after installation (*a*) and in winter season (*b*).

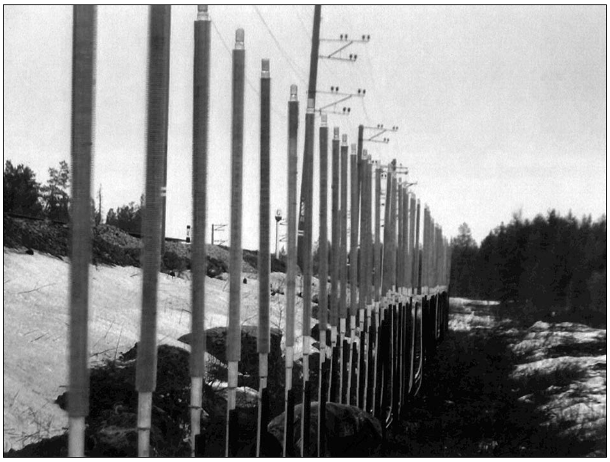

Fig. 19. System of aluminum thermosyphons after installation (366th km, Noyabrsk–Korotchaevo district).

Soils are considered to be weak at $P_d \leq 3$ MPa. For instance, weak soils were revealed to a depth of 7 m at the 267th km of the Sverdlovsk railway, within the main site (2.9 m on the left and on the right). This result is consistent with GPR data (Fig. 15) which revealed weak soil between points PT5+20 and PT6+40. The surveys were performed using the LOZA georadar [*LOSA..., 2012*] with its electromagnetic signals not attenuating in clayey soil.

GPR data are used to contour sites subject to deformation marked by changes of EM wave propagation patterns (Figs. 15, 16).

In the case of cave-in, hazard is mitigated by grouting at every 0.4–0.7 m over the caved-in area, through pipes, 75 mm in diameter, rammed with a conical tip which is left in the ground afterwards; during the grouting procedure, the pipes are lifted and then re-installed.

The photographs of Figs. 17–19 show, respectively, drilling for the installation of long thermosyphons (Fig. 17) and structures installed at the 267th (Fig. 18) and 366th km (Fig. 19) along the Sverdlovsk railway.

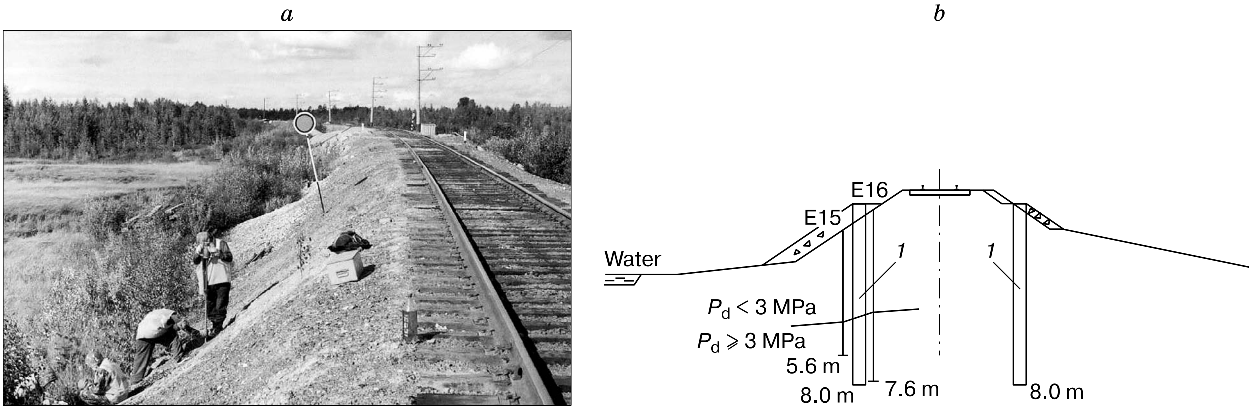

Fig. 20. EDP inspection of deforming subgrade slopes (*a*) and goffer retaining structures (*1*) installed for subgrade stabilization (point PT 3358+56, Sverdlovsk railway) (*b*).

Goffer retaining structures used for stabilization of subgrade upon thawing permafrost are fabricated following the regulations of *CPI-38* [*2006*]. Figure 20 shows EDP inspection of deforming subgrade and goffers placed at every 3 m, at 20° (in plan view) to the track line, for its stabilization.

Main issues concerning the design of subgrade stabilization structures in permafrost areas were discussed in previous publications [*Dydyshko, 2011, 2014*].

CONCLUSIONS

Experimental studies including geophysical surveys by the methods of dynamic probing combined with electrical logging (EDP) and ground penetrating radar (GPR), as well as thermal-engineering modeling have revealed the causes of deformation in subgrade upon thawing permafrost. The permafrost table subsides to a depth of 6–10 m below the superstructure after railway construction as a consequence of heat transfer changes. Deformation results from melting of ice layers and lenses in the underlying ground (initial settlement) and rheological changes leading to extrusion of weak yielding soils from beneath the subgrade (long-term settlement). The stabilization methods include freezing the soil at the base of slopes or creating a mechanic barrier to extrusion of yielding soil.

A system of logistic and engineering measures was suggested for remediation of areas along railroads, drainage, and installation of retaining structures.

Field surveys and theoretical calculations made basis for design norms and regulations for stabilization engineering solutions (long thermosyphons, plastic foam heat insulation, goffer retaining structures, etc.). The normative documents for subgrade stabilization have been approved for use, and the solutions have been patented.

It will be reasonable to set up a long-term program for stabilization of railway subgrade upon permafrost to improve the transportation safety and reduce the operation and maintenance costs incurred by *OAO RZD*. No less than 25 km of stabilization structures have to be installed yearly, with the costs 200–300 million rubles per year. The predicted cost efficiency due to stabilization may reach ~2500,000 rub/km.

References

CES C-01-95, 1995. Construction Engineering Structures: Railways, tracks 1520 mm. Approved by the Order of the Ministry of Railroads on 25.09.95, No. 14C, effective since 01.01.1996. Transport, Moscow, 87 pp. (in Russian)

CPI-36, 2004. Determination of mechanical properties of ballast and subgrade soils. Approved by the Department of Railroads, OAO RZD on 30.01.2004. Transport, Moscow, 84 pp. (in Russian)

CPI-38, 2006. Engineering guidelines and design documents on methods of railroad stabilization (for experimental use). Approved by the Department of Railroads, OAO RZD on 18.12.2006. VNIIZT, 74 pp. (in Russian)

CPI-40, 2009. Engineering guidelines for mitigation of subgrade settlement on permafrost by freezing of thawing soils by long thermosyphons. Approved by the Department of Railroads, OAO RZD on 03.07.2007. NIITKD, Moscow, 40 pp. (in Russian)

Dydyshko P.I., 1991a. Deformation of subgrades in paludal areas, its mitigation and prevention. ZH.-L. Transport. Ser. Put` i Putevoe Khoziaistvo, Issue 4, 17–32.

Dydyshko, P.I., 1991b. Thermoelectrokinetics in thermally anisotropic capillary systems. Zhurn. Fiz. Khimii 65 (12), 3169–3188.

Dydyshko, P.I., 1992. Thermoelectrokinetics in soils and other thermally anisotropic capillary systems. Vestnik VNIIZHT, No. 1, 12–17.

Dydyshko, P.I., 2011. Railway Subgrade Design. A Handbook. Intekst, Moscow, 152 pp. (in Russian)

Dydyshko, P.I., 2014. Railway Subgrade. A Handbook. Intekst, Moscow, 416 pp. (in Russian)

Dydyshko, P.I., Mariomaa, P., 2008. A method for subgrade stabilization by retaining structures of channelled plate steel. Patent 2374392. Patent Holder OAO RZD. Claimed on 19.05.2008. Published on 27.11.2009, Bull. 33.

Engineering Guidelines, 1993. Stabilization of Deforming Railway Subgrade upon Thawing Permafrost. Approved by the Main Administration of the Ministry of Railroads on 11.05.1993. Moscow, 98 pp. (in Russian)

Kozlovskiy, E.A. (Ed.), 1988. Geology of the BAM Zone. Book 2. Hydrogeology and Engineering Geology. Nedra, Leningrad, 447 pp. (in Russian)

LOZA Georadar System for Detection of Layer Boundaries, 2012. OOO "Kompaniya VNIISMI", Moscow, 1 pp. (in Russian)

Roman, L.T., 2002. Mechanics of frozen soils at the turn of the 21st century. Kriosfera Zemli VI (1), 3–16.

Sergeev, E.M. (Ed.), 1976. Engineering Geology of the USSR. Book 2. West Siberia. Moscow University, Moscow, 496 pp. (in Russian)

Tsukanov, N.A., Passek, V.V., Zakovenko, V.V., Dydyshko, P.I., Evstigneev, R.I., 1983. Filling of Embankment Slopes. Patent 1139176. Claimed on 19.09.1983. Published on 27.10.1995. Patent Bureau of the USSR. (in Russian)

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