Cryosphere Engineering:

Taking Permafrost Engineering as Examples in China

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Definition

Frozen ground:

Refers to various rocks or soil containing ice at 0 ℃ or 0 ℃ below.

Permafrost:

Is ground (soil or rock) that remains at or below 0°C for at **least two years**.

Classification of frozen ground

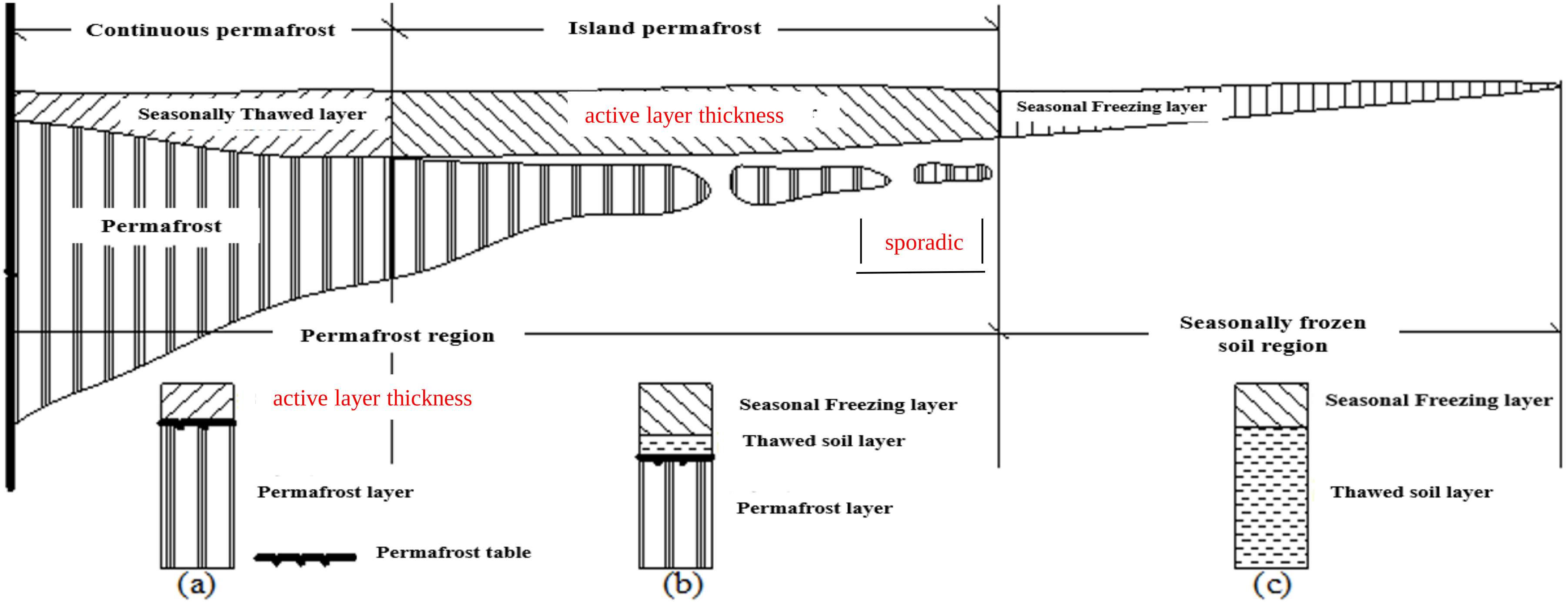
According to the existence time, it can be divied into

Short-term frozen ground (< several days), **Seasonal frozen ground** (≥1 month),

Permafrost (≥2 years)

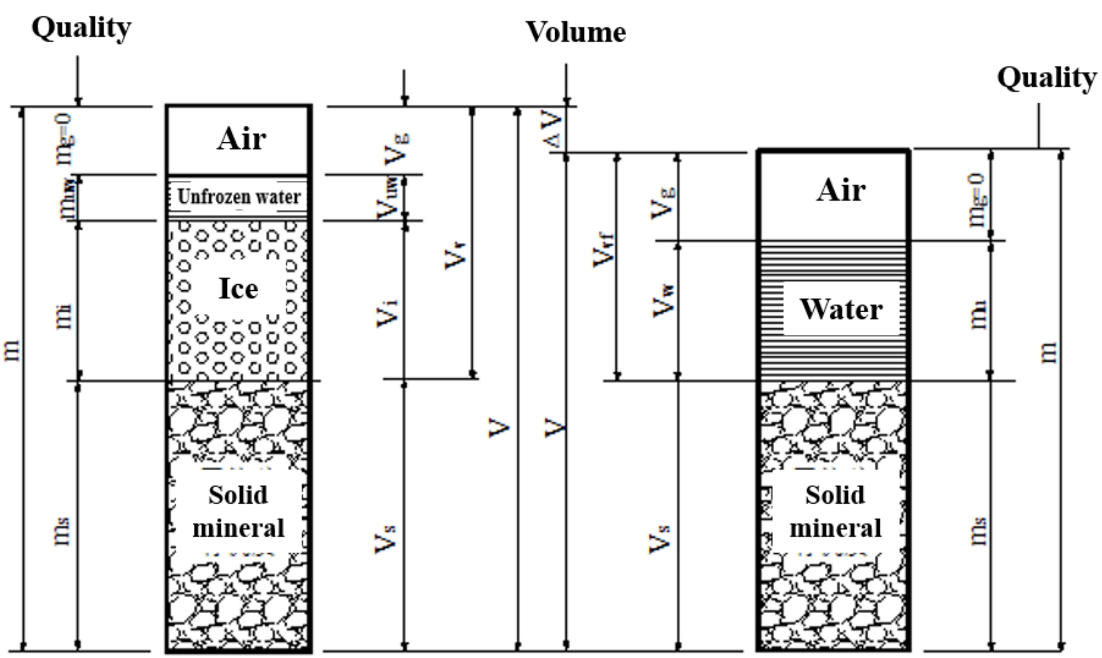
According to the degree of continuity of permafrost distribution：

Continuous permafrost, Discontinuous permafrost (island permafrost), sporadic .

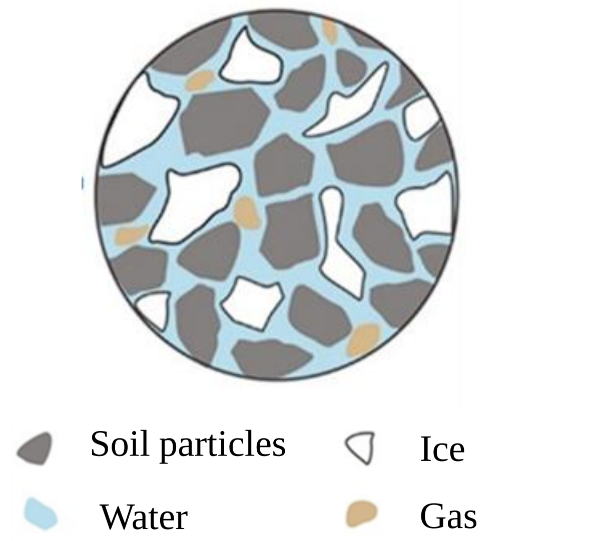


Components in Frozen ground

Frozen ground is a four-phase material composed of **solid particles**, **ice** , **unfrozen water** and **gas**.



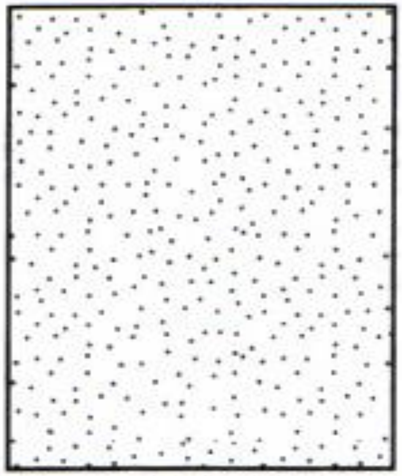
(a) Frozen soil (b) Thawed soil



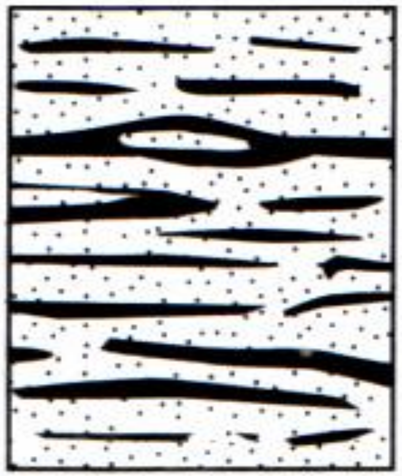
Cryostructure

Frozen ground (cryogenic) structure mainly includes integrated (uniform ice distribution), layered, network, vein, porphyritic and wrapped.

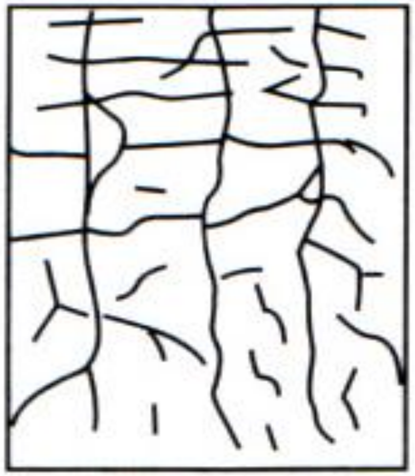
The ice-bearing rate (ice content), shape and conhesion with mineral particles are different in different cryogenic structures, which directly affect the engineering properties of frozen soils.



Integrated structure



Layered structure



Network structure

Formation of frozen ground

Frozen ground is formed in the process of heat and mass exchange in the lithosphere-soil-atmosphere system.

$$Q_g = K(dT/dz)$$

Q_g is the heat entered the soil layer, K is the thermal conductivity of the soil, dT/dz is the temperature gradient.

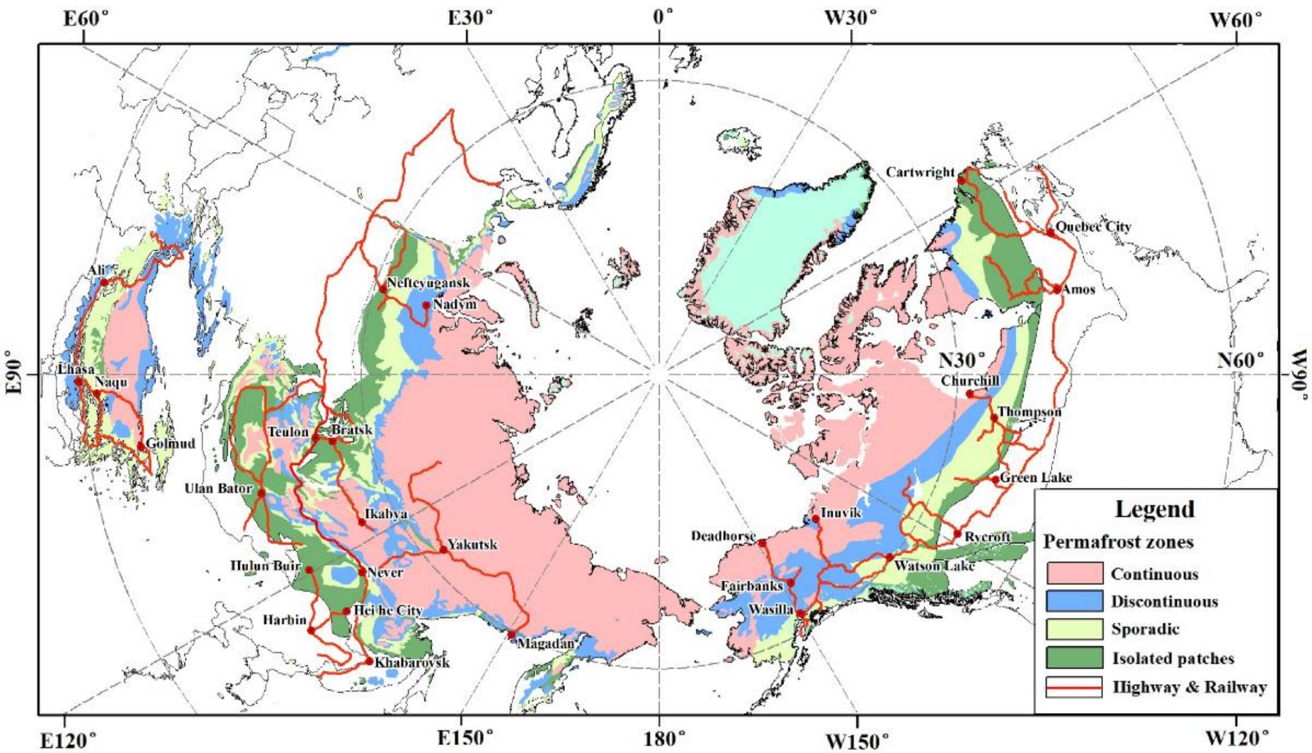
The formation of seasonal frozen ground and permafrost is closely related to the surface energy balance.

$$Q_n = (Q_i + Q_s)(1 - \alpha) - Q_e = LE + P + B$$

Q_n is Ground radiation balance;
Q_i and Q_s are direct solar radiation and scattered solar radiation respectively;
α is the ground reflectance;
Q_e is ground long wave effective radiation;
LE is the heat consumed in the total evaporation process (including soil water evaporation and plant evaporation);
P is heat consumed for the turbulent exchange between the surface and the atmosphere;
B is the heat flow through the ground

01 Definition, Distribution and Change of Frozen Ground

■ Distribution of permafrost--- where does permafrost occur?



Northern Hemisphere	Area ($\times 10^6 km^2$)	Southern Hemisphere	Area ($\times 10^6 km^2$)
Russia	11.0	Antarctica	13.5
Mongolian	0.8		
China	2.1		
Alaska	1.5		
Canada	5.7		
Greenland	1.6		
Total	22.7		13.5

Global permafrost is primarily distributed in the Northern Hemisphere, with the area of continuous permafrost accounting for about 1/4 of the land area of the Northern Hemisphere, and seasonal frozen ground areas covering about 27% of the land area of the Northern Hemisphere.

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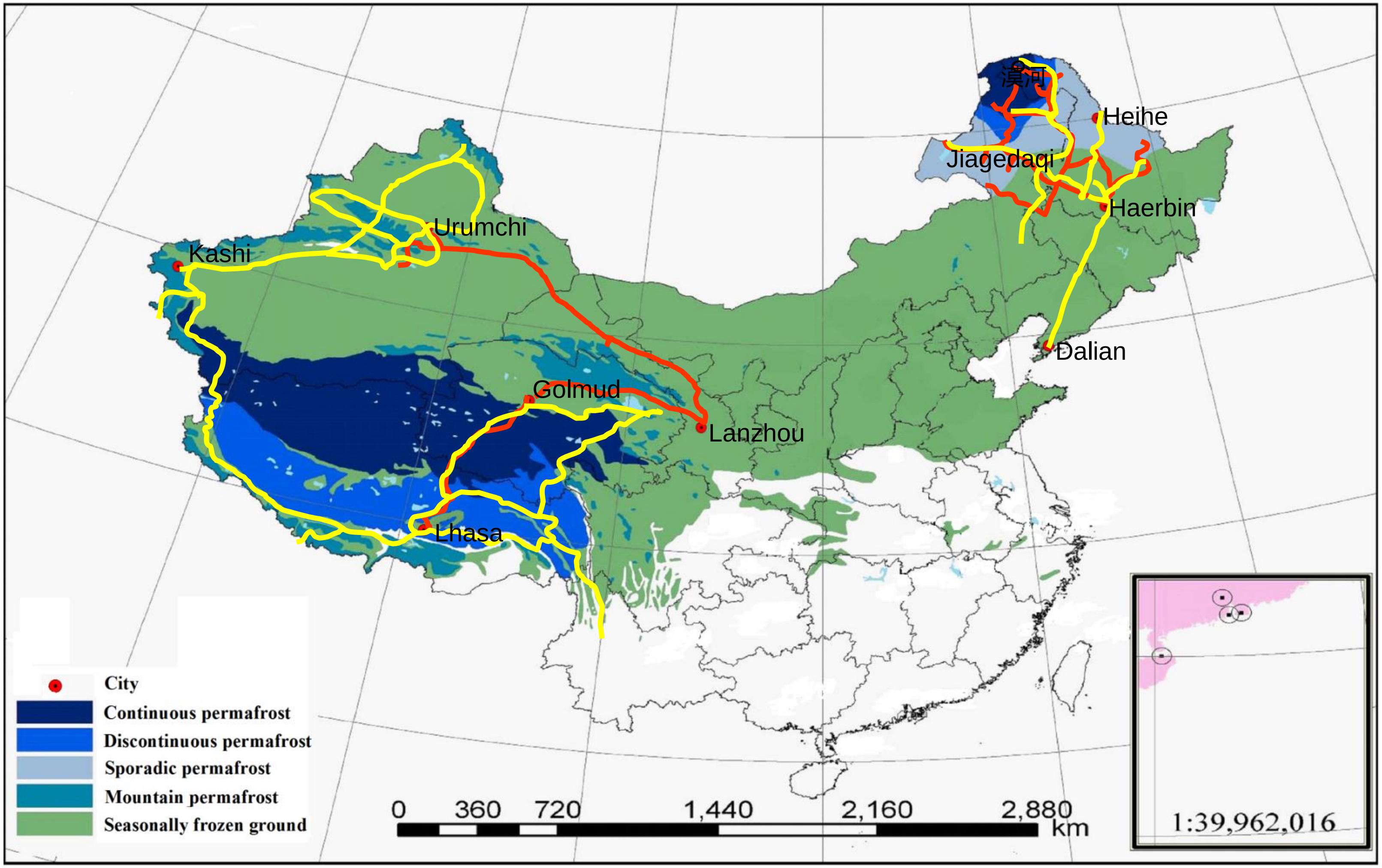
Distribution of permafrost



Permafrost in China is around 2.1 × 10^6km^2, 25% of the land territory.

Major cold region engineerign projects

China-Russia Gas Pipeline West Line

750 kV power transmission Line through Tianshan Mountains

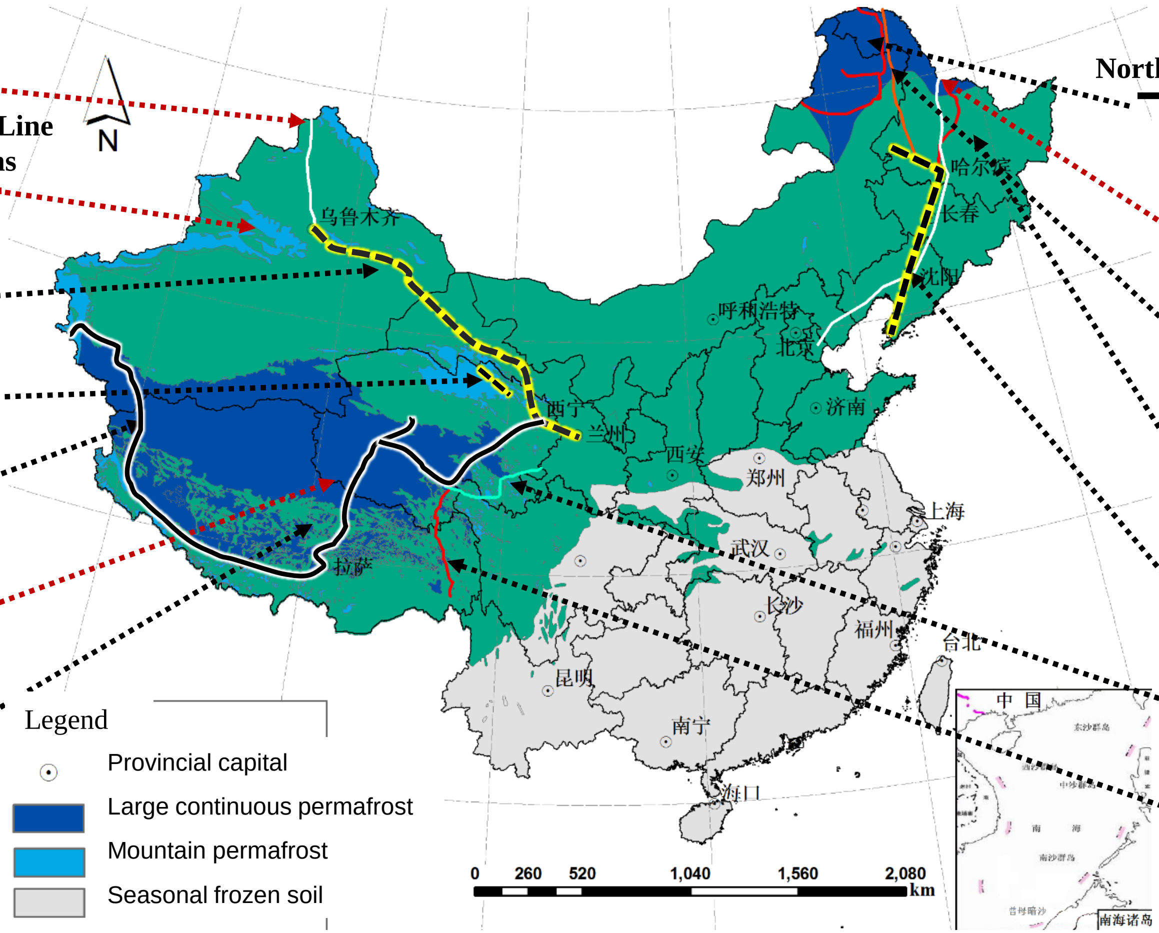
Lanzhou-Xinjiang High-Speed Railway

Chai-Mu Railway

Xinjiang-Tibet highway

Qinghai-Tibet expressway

Qinghai-Tibet railway, highway, power transmission line



Northeast highway in cold forest

China-Russia Gas Pipeline East line

China-Russia Crude oil pipeline

Heihe-Dalian Highway

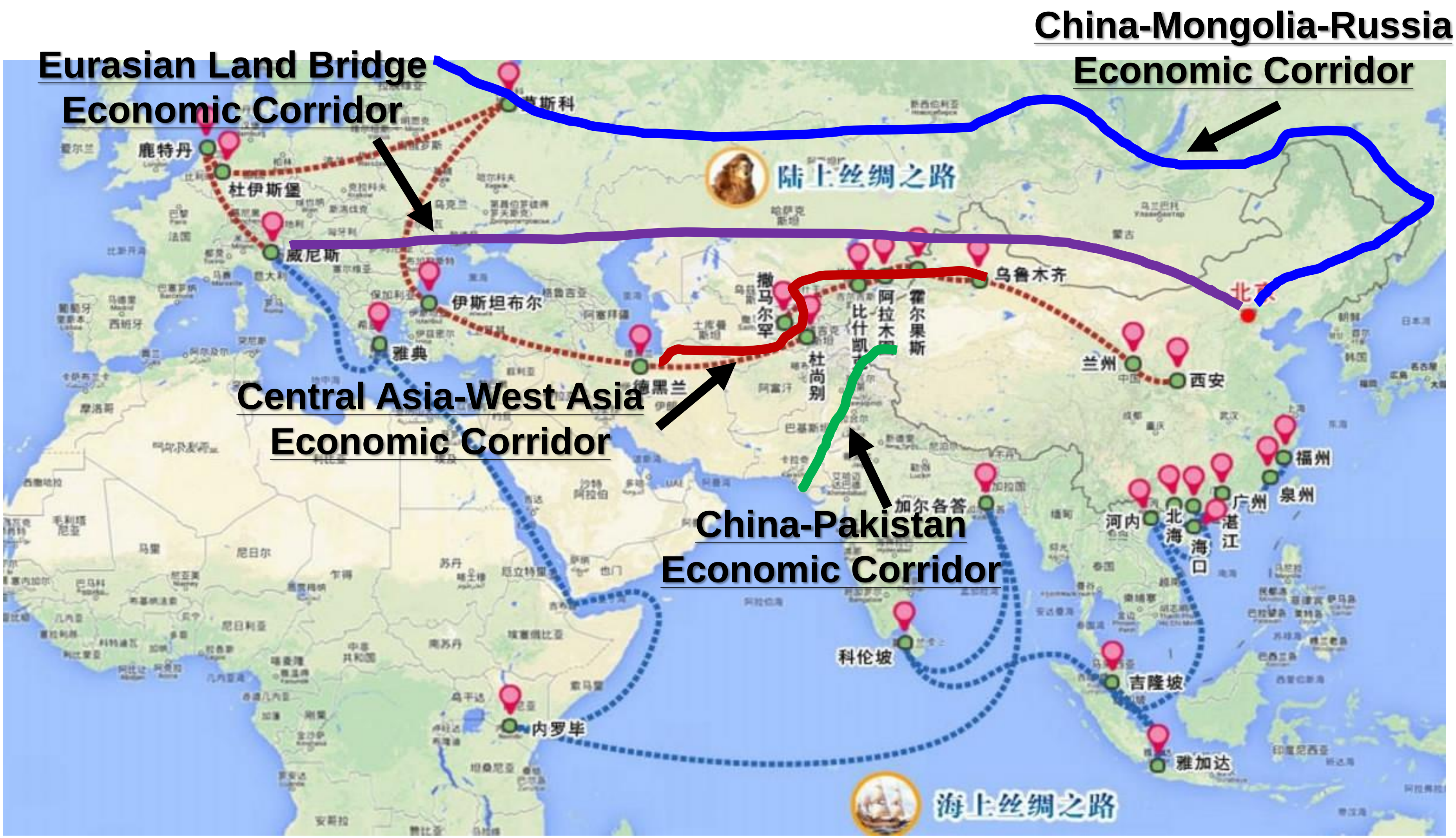
Harbin-Qiqihaer High-Speed Railway

West Route of South-to-North Water diversion

Qing-Kang Highway

01 Definition, Distribution and Change of Frozen Ground

Major engineerign projects along the belt and road in cold regions



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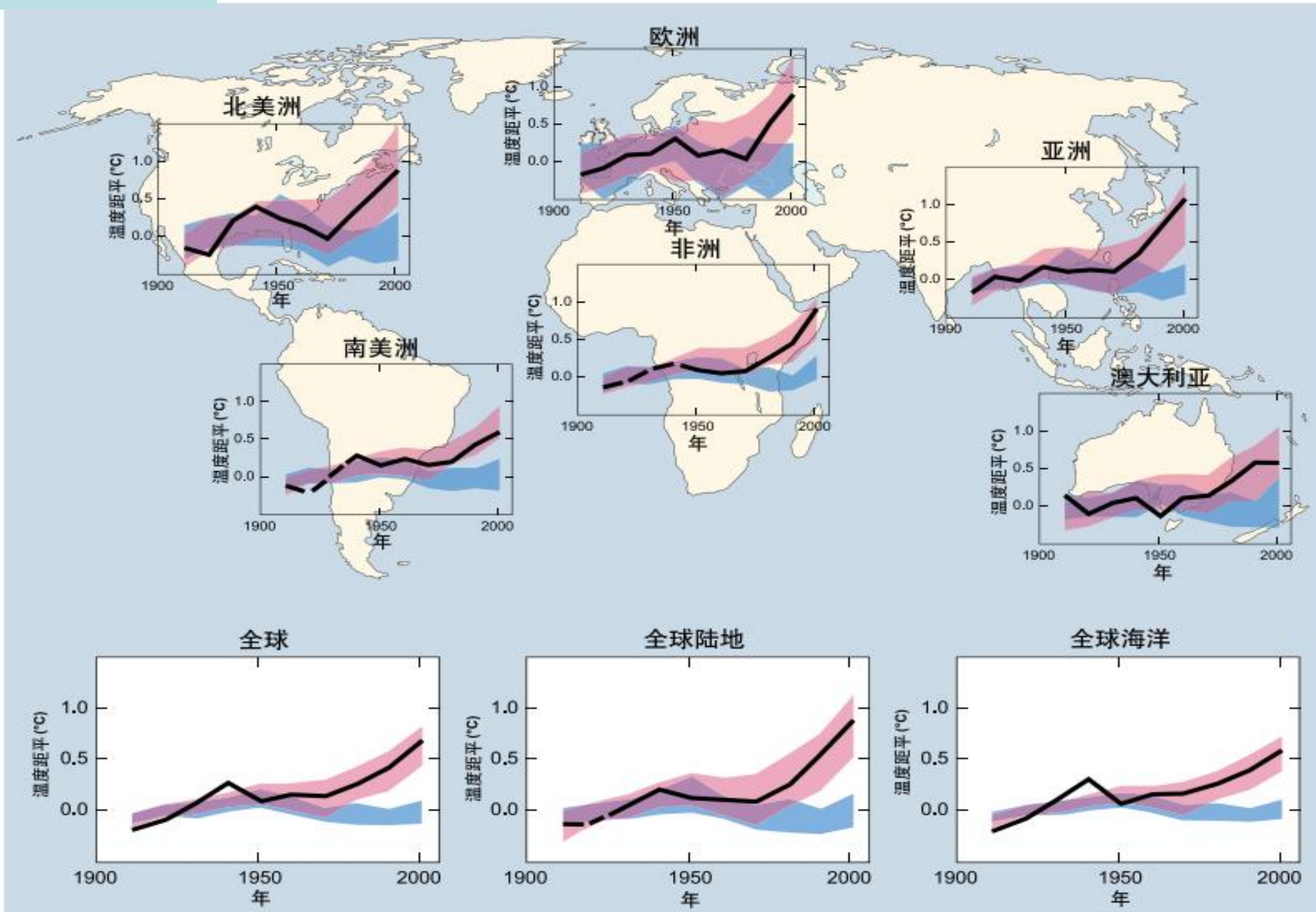
The IPCC report states

Global and continental temperature changes



观测结果

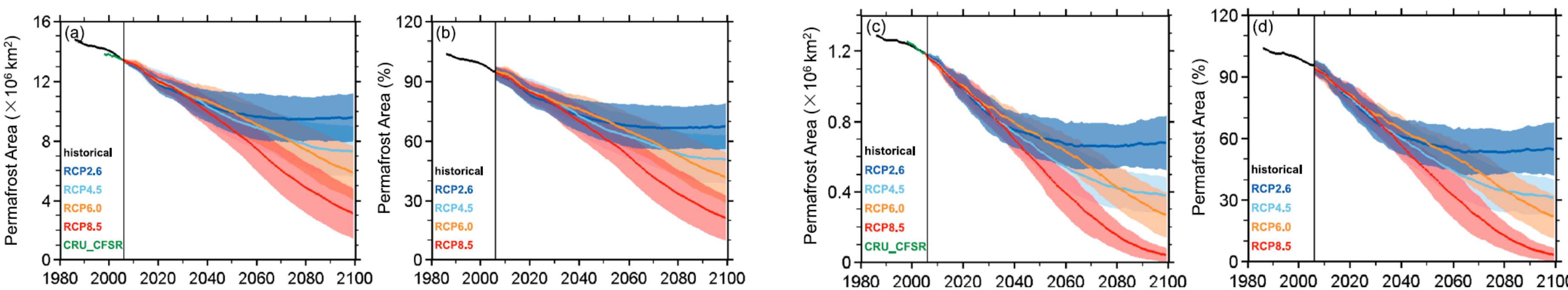
©IPCC 2007: WG1-AR4

The trend of global warming is obvious!

01 Definition, Distribution and Change of Frozen Ground

Permafrost changes

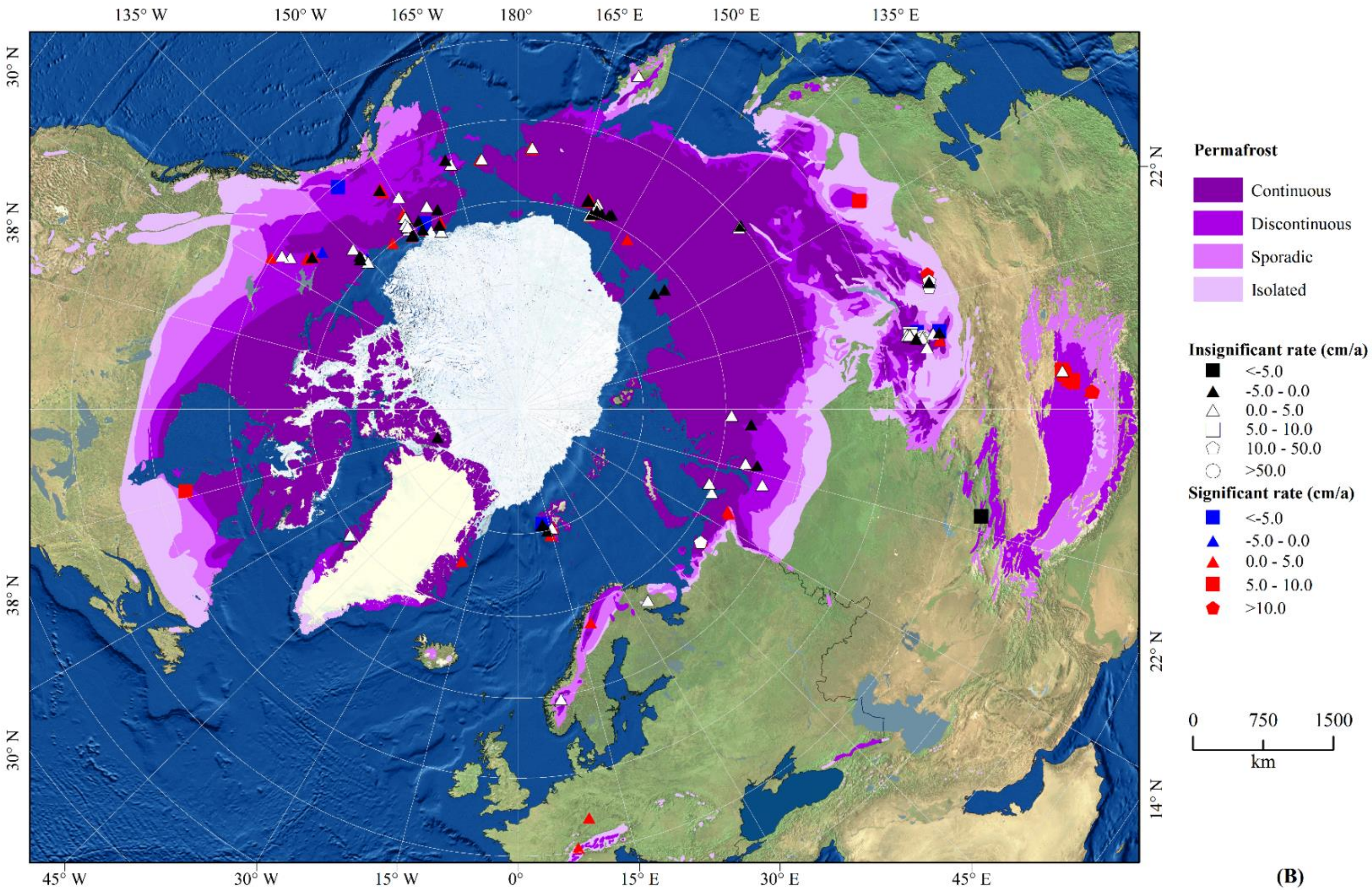
- Recent results showed a **reduction of the permafrost area** by 37 ± 11% (representative concentration pathway (RCP)2.6), 51 ± 13% (RCP4.5), 58 ± 13% (RCP6.0), and 81 ± 12% (RCP8.5) by 2080–2099, relative to the permafrost area during the period 1986–2005 (Slater and Lawrence, 2013).
- So degradation is still an enormous challenge facing in infrastructure design, construction, and maintenance in the permafrost regions.



Projected changes in (a, b) high-latitude and (c, d) high-altitude permafrost areas during the period from 1986 to 2099(Donglin Guo & Huijun Wang, 2016)

01 Definition, Distribution and Change of Frozen Ground

□ Spatial distribution of changing rates of active layer thickness (ALT) (Luo, et al., 2016)



ALT generally increased from the highly continuous permafrost zone to the southern fringes of discontinuous, sporadic and isolated permafrost zones, showing more dramatic in warm permafrost regions than those in cold permafrost regions.

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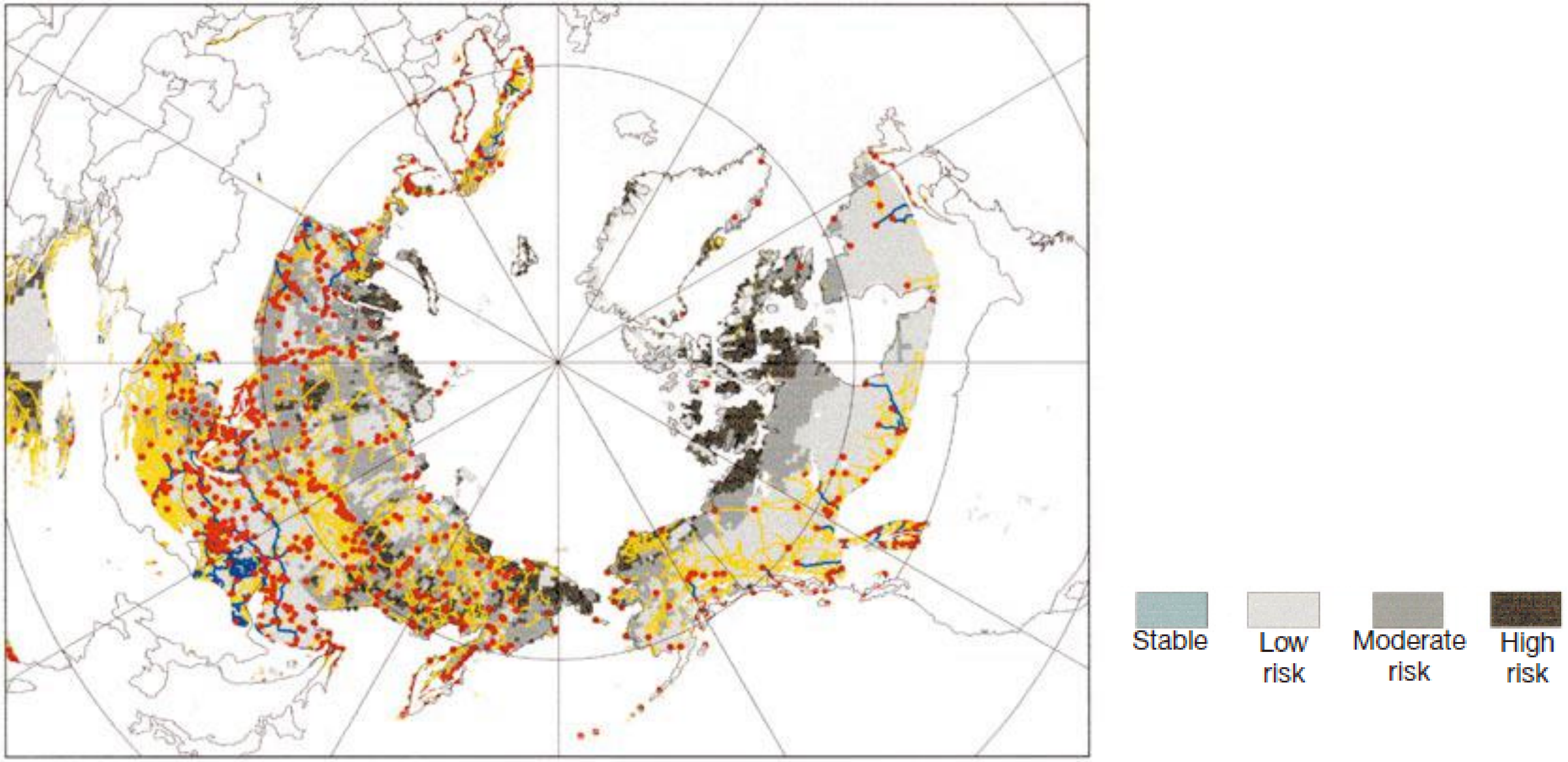
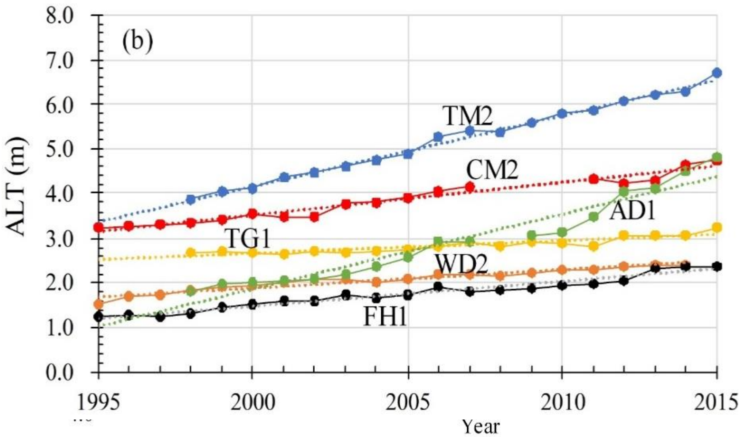
□ Subsidence risk from thawing permafrost (Frederick E. Nelson, et al., 2001)

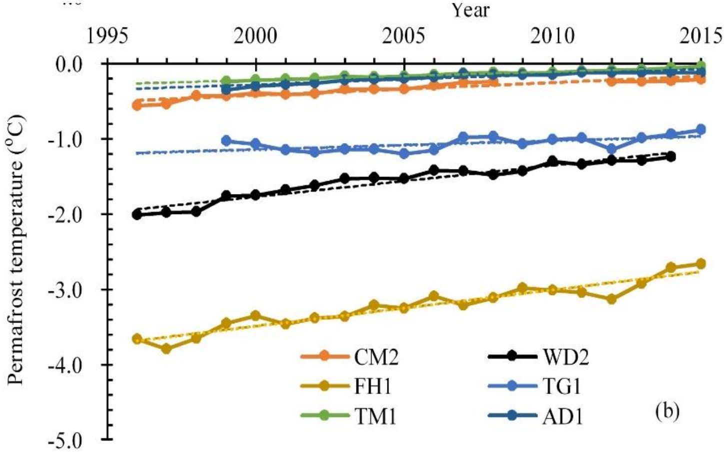


Permafrost hazard potential in the Northern Hemisphere.
Locations of existing settlements and transportation infrastructures:
roads and trails (yellow), railroads (blue), airfields (red);

01 Definition, Distribution and Change of Frozen Ground

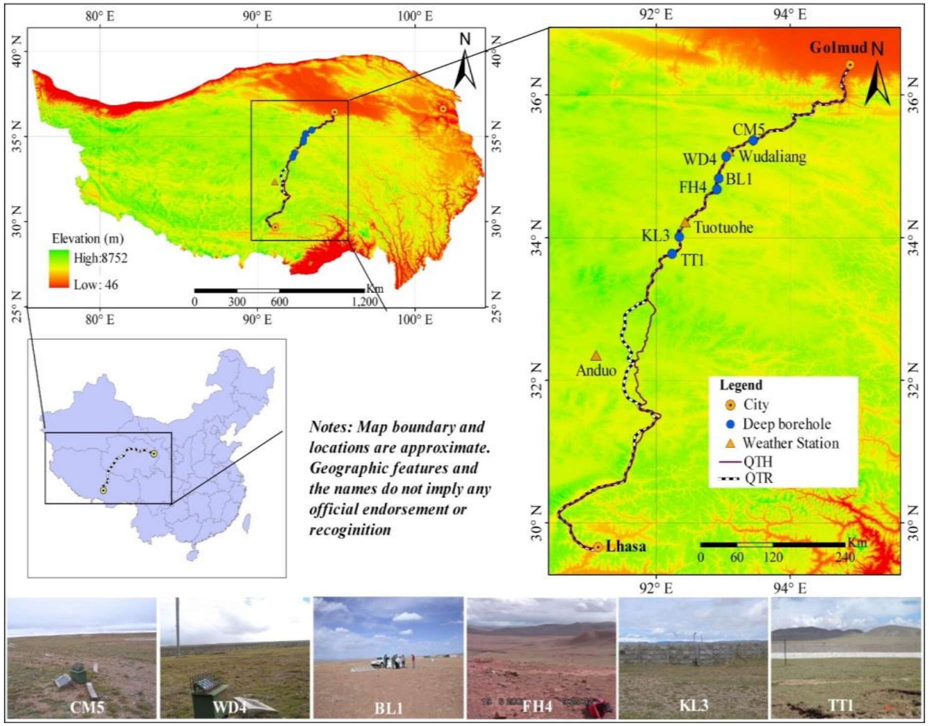
The Qinghai-Tibet Engineering Corridor:





MAGT(6cm): 0.09~0.48°C/yr,
mean:8.7cm/yr
Warm permafrost： 0.14°C/yr
Cold permafrost： 0.33°C/yr

ALT: 2.55~16.74cm/yr,
mean:8.7cm/yr
Warm permafrost： 12.4cm/yr
Cold permafrost： 4.0cm/yr



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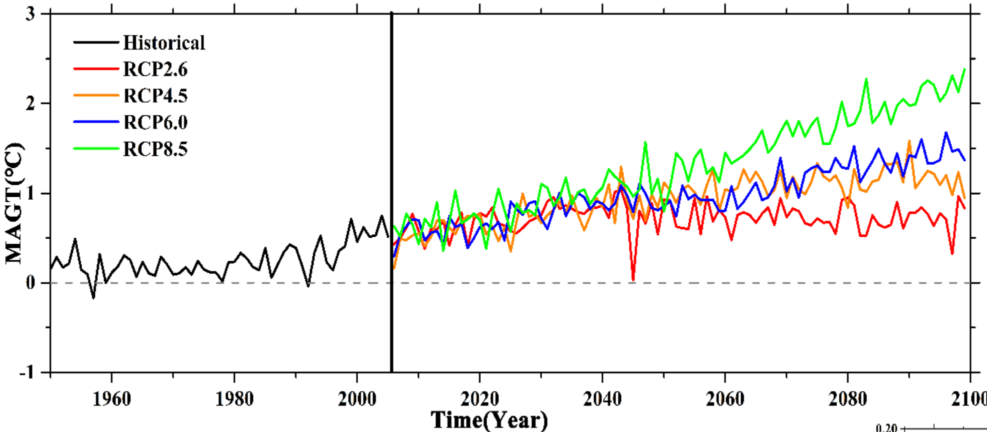
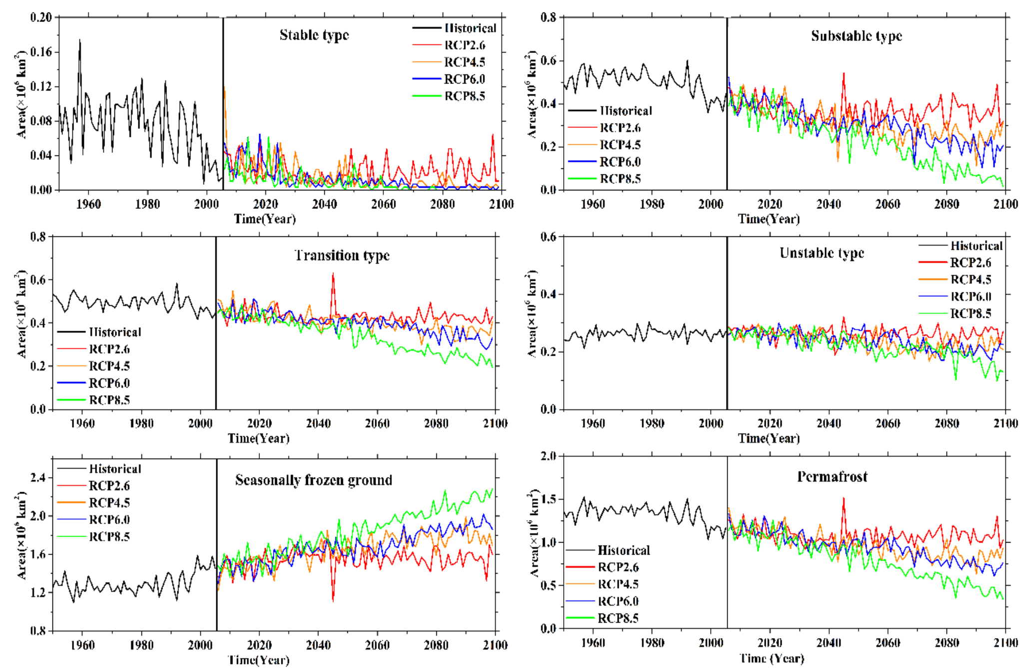
Permafrost degradation prediction of the Qinghai-Tibet Plateau (QTP):



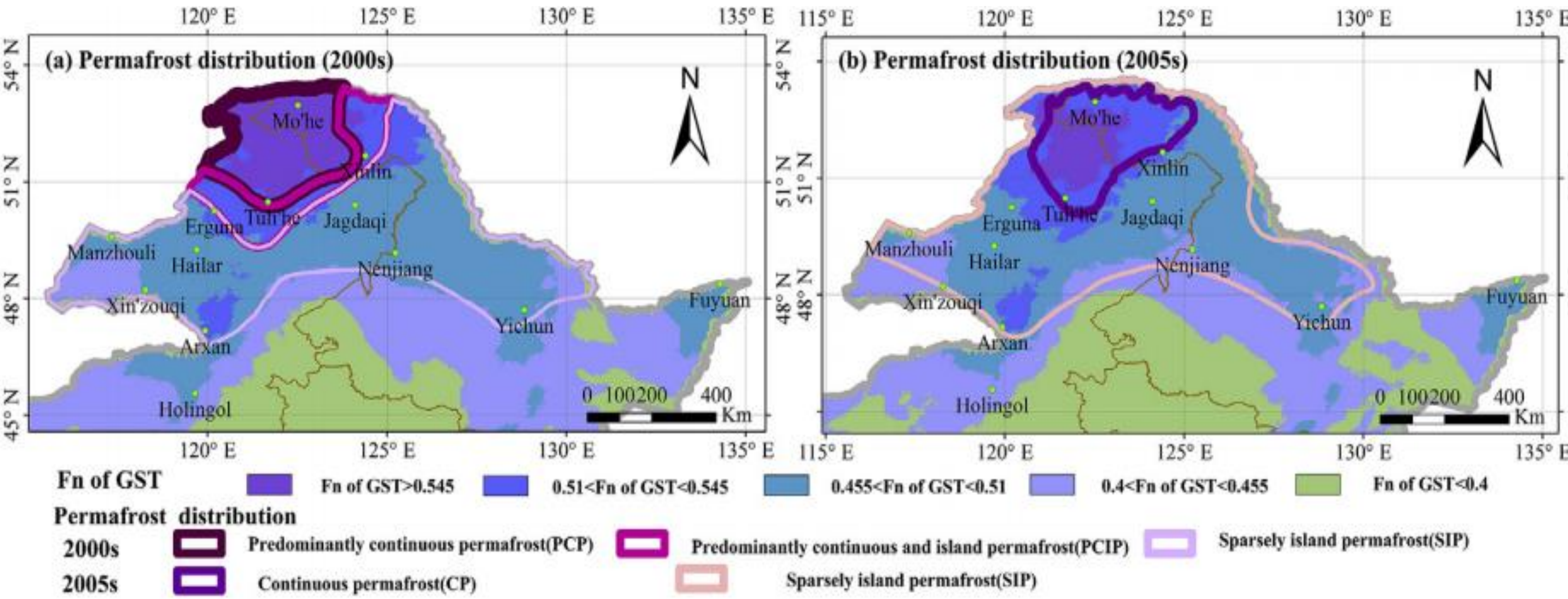
Prediction of the average permafrost area in 1950 – 2005， and the average permafrost area in 2006 - 2099 in four rcp scenarios.

The mean annual ground temperature (MAGT) variation and prediction simulation results over the QTP in four CO_2 Emission scenarios(RCP2.6, RCP4.5, RCP6.0 and RCP8.5) based on regional climate model (GFDL-ESM2M).



01 Definition, Distribution and Change of Frozen Ground

- The frozen soil in northern northeast China:



- From the 1980s to the 1990s, the permafrost extensively degraded by 43.3%.
- The area of predominantly continuous permafrost was $68 \times 10^3\ km^2$. Notably, high altitude played an important role in delaying the degradation of permafrost.

Zhongqiong, Z., Qingbai, et, al. (2019). Spatial distribution and changes of Xing'an permafrost in China over the past three decades. Quaternary International.

Mountain permafrost:

Permafrost of **Altai Mountain**： permafrost area is about 110× 10^3 km^2, the low limit of permafrost is 2200 m, where the mean annual air temperature is -6.8-5.4°C.

Tianshan permafrost： permafrost area is about 63× 10^3 km^2， The mean annual air temperature near the permafrost lower limit is about -2.0~-3.0° C. The maximum observed thickness of permafrost is 174 m.

Permafrost in **Qilian Mountains**： permafrost area is about 95× 10^3 km^2， The elevation of the permafrost low limit in the north-south slope is different, the north slope is 3,400-3,740m, the south slope is 3,700-3,950m. The mean annual air temperature near the lower limit is about -2.0~-3.0° C. The maximum observed thickness of permafrost is 139 m.

Huijun Jin, et al. "Impacts of Climatic Change on Permafrost and Cold Regions Environments in China."Acta Geographica Sinica 67.2(2000):161-173.

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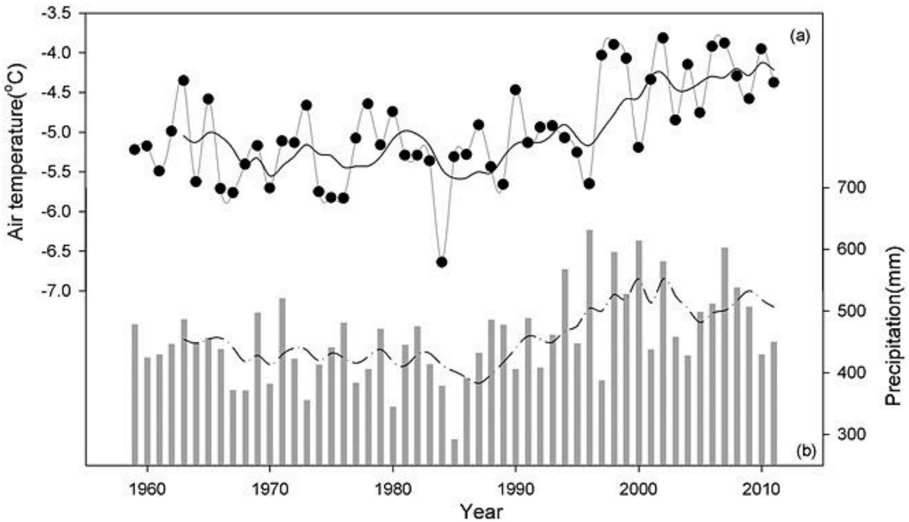
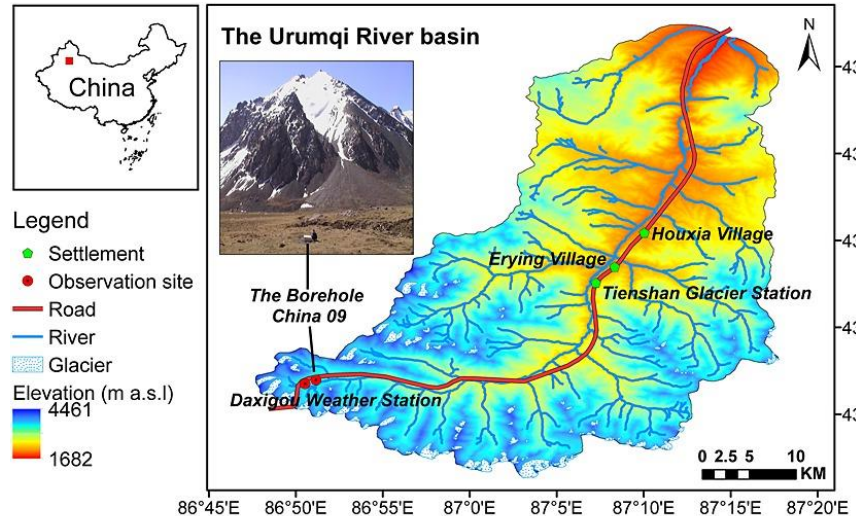
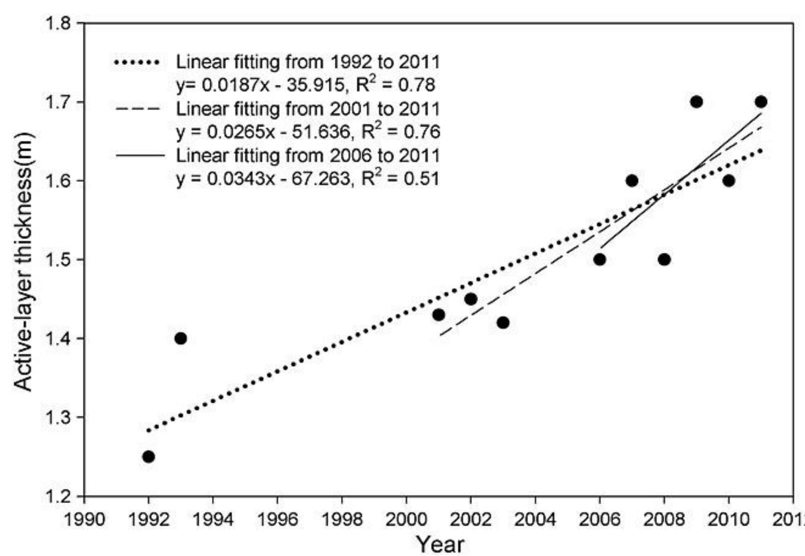
- The permafrost changes in the TianShan Mountains:



Annual mean air temperatures (AMATs) (a) and annual precipitation (AP) (b) observed by Daxigou Weather Station (DXG-st, 3540 m a.s.l.) from 1959 to 2011



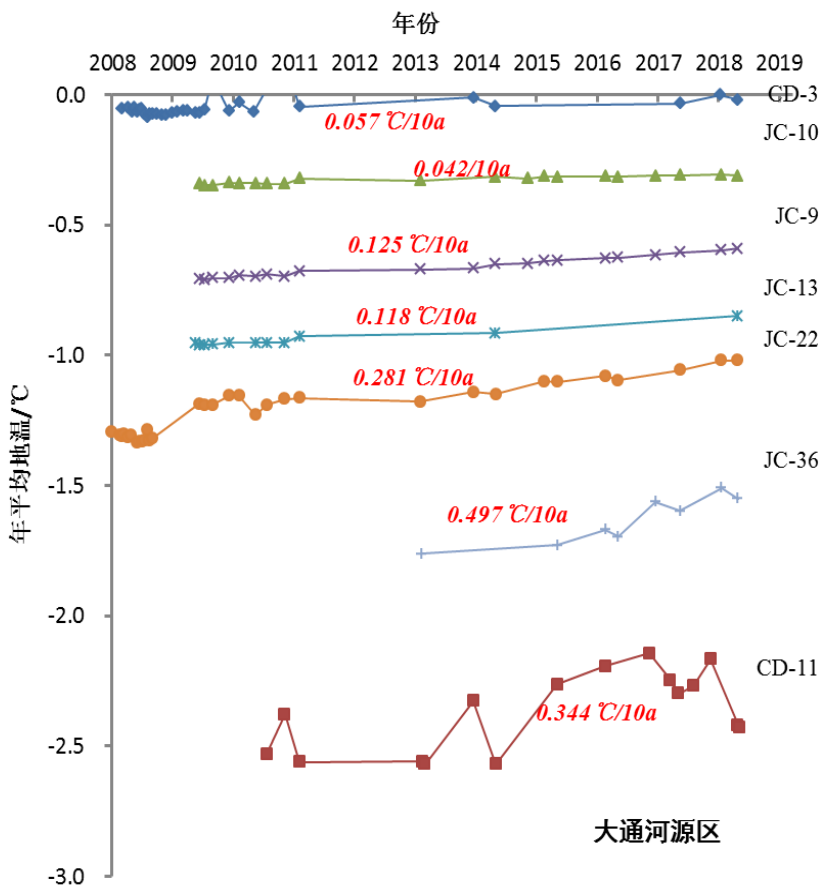


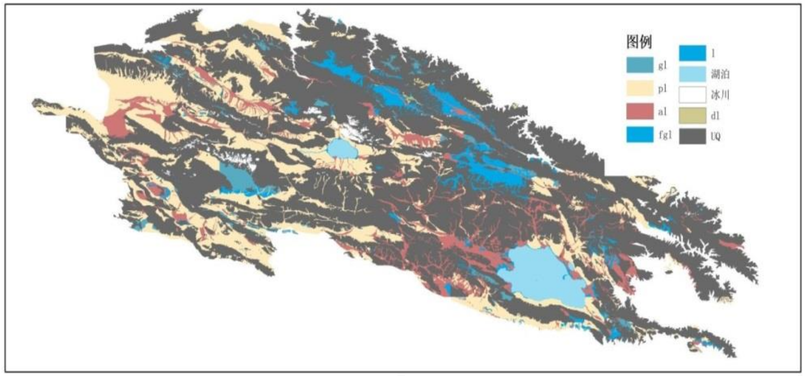
Active-layer thicknesses at the borehole China09

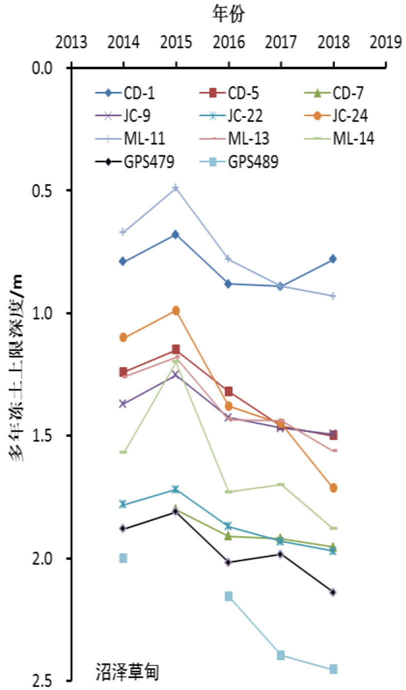
Liu, Guangyue , et al. "Permafrost Warming in the Context of Step-wise Climate Change in the Tien Shan Mountains, China." Permafrost and Periglacial Processes (2015):n/a-n/a.

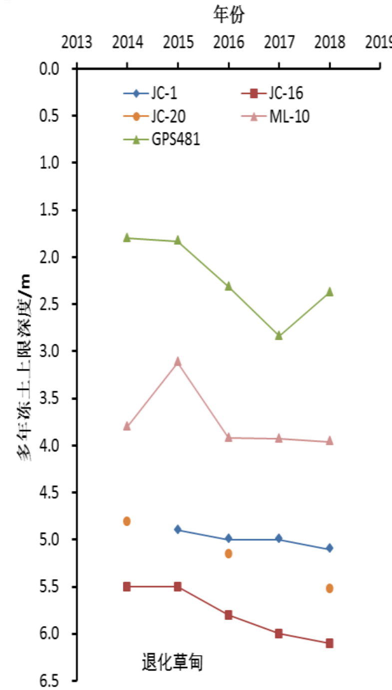
01 Definition, Distribution and Change of Frozen Ground

- The permafrost changes in Qilian Mountain :









The mean annual ground temperature and the table depth of the permafrost shows an upward trend.

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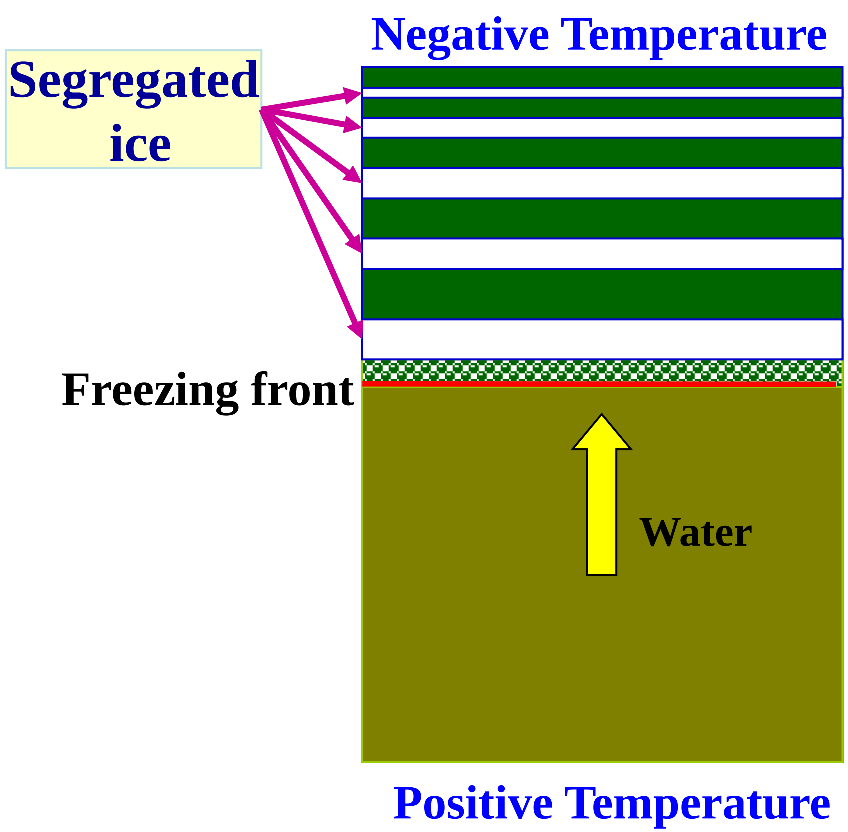
02 Impacts of Frozen Ground

Frost heave

The causes of **frost heave** include **the expansion (by 8 percent in volume) of the original water in soil** when it freezes; it also includes **the migration of water** in lower unfrozen soil during the soil freezing process and its accumulation on the frozen surface.



Temperature field equation:

$$\left(C + L\rho_i\theta_u \frac{\partial G}{\partial T}\right)\frac{\partial T}{\partial t} + L\rho_i G\frac{\partial \theta_u}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right)$$

Water field equation:

$$\left(1+\frac{\rho_i}{\rho_u}G\right)\frac{\partial\theta_u}{\partial t} + \frac{\rho_i}{\rho_u}\theta_u\frac{\partial G}{\partial T}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial\Theta}{\partial x}\right)$$

Frost heave

There are three basic factors for significant frost heave in soil, which are frost heave-sensitive soil, water supply and negative temperature.

Frost heave rate:

$$\begin{cases} \eta = \dfrac{\Delta z}{z_d} \times 100(\%) \\ z_d = h' - \Delta z \end{cases}$$

Δz ——Surface Frost Heave Amount(mm)

z_d ——Design Frost Depth(mm)

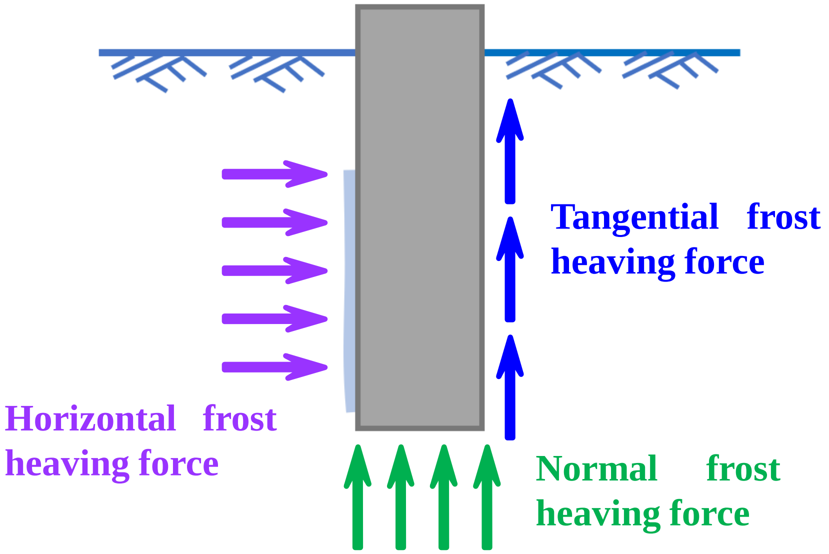
h'——Frozen Layer Thickness(mm)

Frost heave force

Normal frost heaving force: The upper part of the soil acts to the foundation when freezing, and the frost heave is limited, and the lifting force acting on the bottom of the foundation will be generated between ground and the foundation.

Tangential frost heaving force: The lifting force acting on the surface of the foundation side upward.

Horizontal frost heaving force: The frost heave force is along the direction of soil frost heave, parallel to the surface and perpendicular to the foundation surface.



■ Frost heave

➢ Engineering problems caused by frost heave

Uneven Frost Heave in Bridges

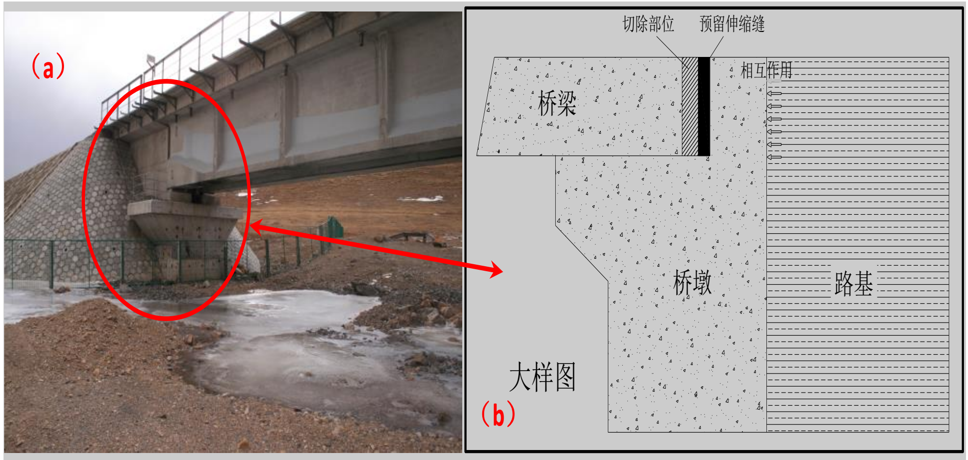
Frost Heave Damage in Channel Lining

Frost Heave Damage in Oil pipeline

Frost Heave Damage in Culvert

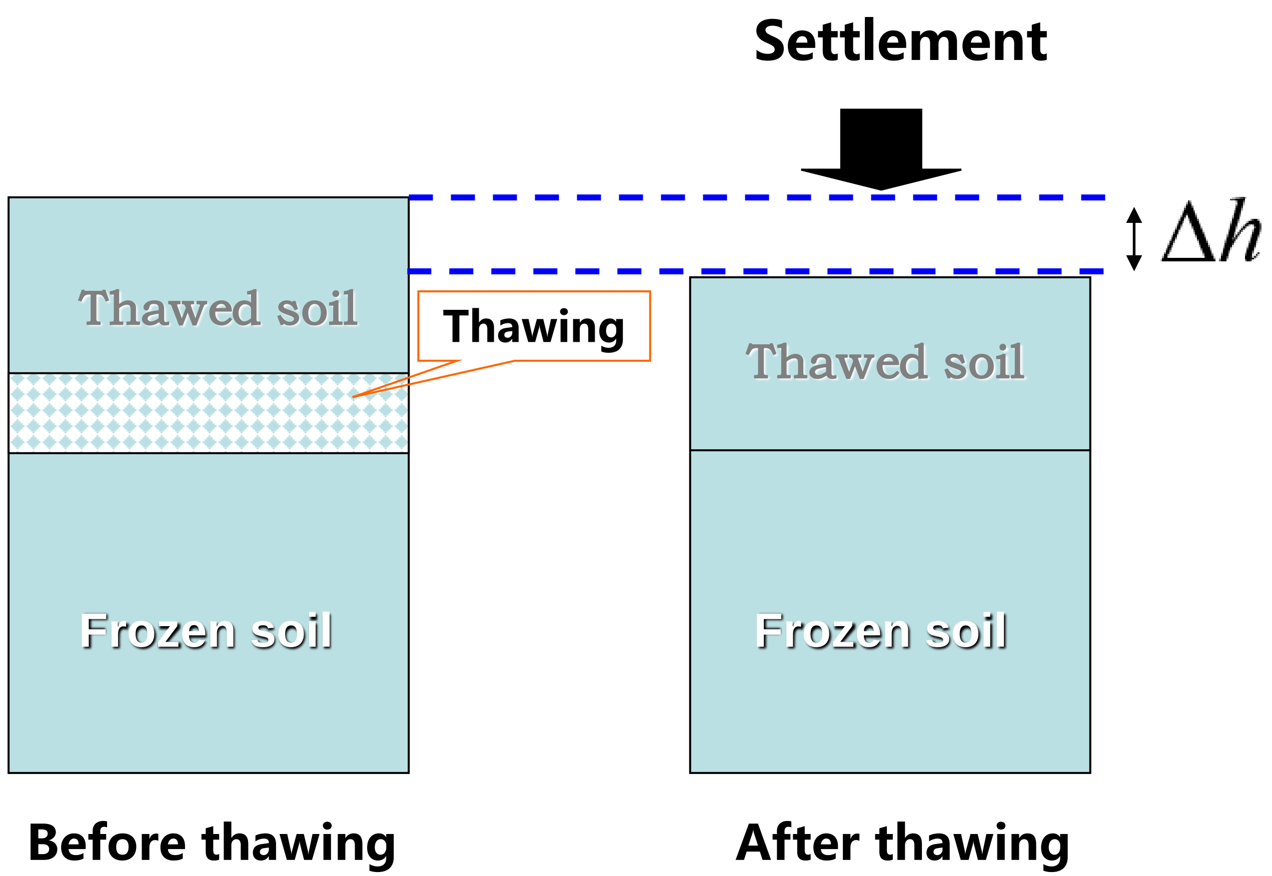
02 Impacts of Frozen Ground

■ Frost heave and icing



Thaw settlement

When frozen soil thaws, the volume of the ice turns into water and decreases by 8 percent, resulting in thaw settlement of the soil. If drainage and consolidation occur in the thawing area at the same time, it will cause compaction settlement of the soil layer.



Thaw settlement

Thaw Settlement Coefficient: $$\delta_0 = \frac{h_1 - h_2}{h_1} = \frac{e_1 - e_2}{1 + e_1} \times 100\%$$

h_1、e_1 ——Height (mm) and porosity ratio of frozen soil sample before thawing;
h_2、e_2——Height (mm) and porosity ratio of frozen soil sample after thawing。

Classification of permafrost thaw settlement

Mean thaw settlement coefficient δ_0 (%)	Thaw settlement degree (level)	Thaw settlement class
$\delta_0 \le 1$	I	Unthawing
$1 < \delta_0 \le 3$	II	Weak thawing
$3 < \delta_0 \le 10$	III	Thawing
$10 < \delta_0 \le 25$	IV	Strong thawing
$\delta_0 > 25$	V	Thaw collapse

■ Thaw settlement

➢ Engineering problems caused by thaw settlement

Uneven Thaw settlement in Highway

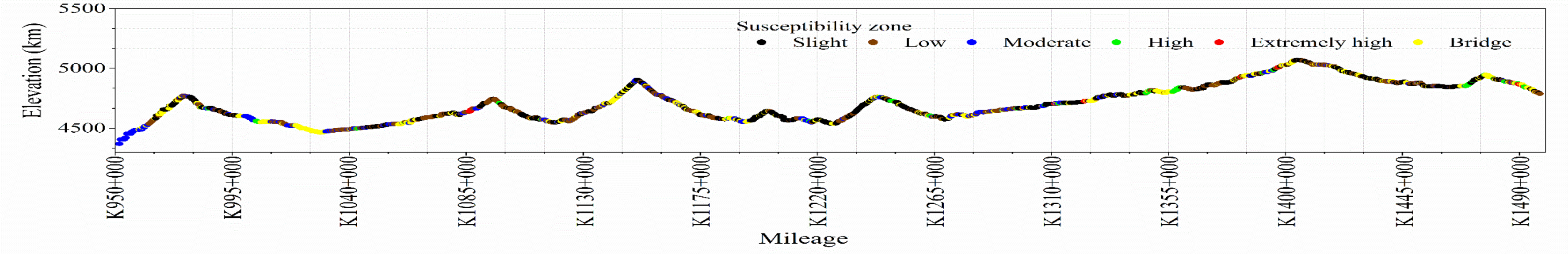
Uneven Thaw settlement in Railway

Thaw settlement in Buildings

Thaw settlement in Culvert

02 Impacts of Frozen Ground

■ Thaw settlement



02 Impacts of Frozen Ground

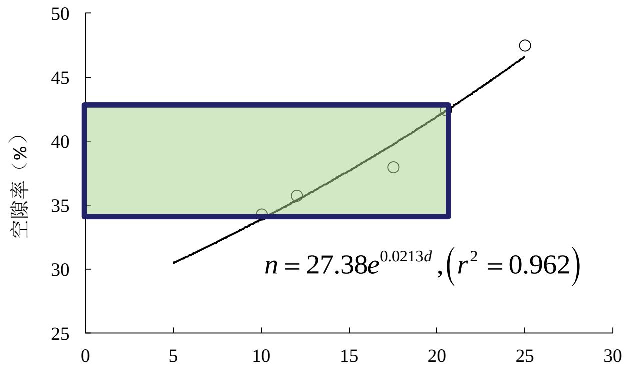
Photos photo by E.A. Kozireva, from lectures by Valentin Kondratiev in Lanzhou,2007

Photos from lectures by Valentin Kondratiev in Lanzhou,2007

Thawing settlement and crack damages to transportation infrastructures

02 Impacts of Frozen Ground

Freeze-thawing weather



Engineering design of cold areas

➢ In permafrost areas

Design Principles for Cooling Roadbeds and Lowering Permafrost Temperature

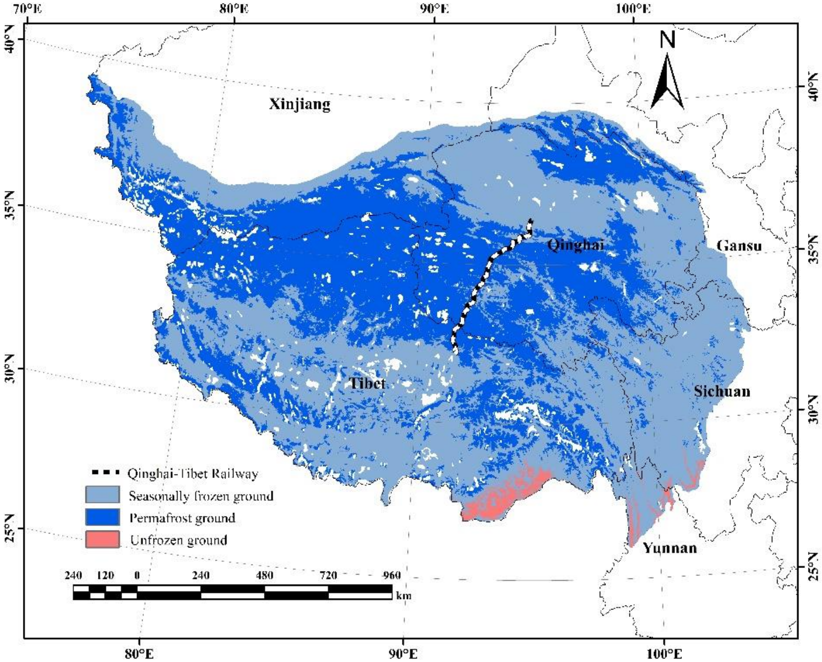
Breaking Through Traditional Design Principles

- **Permafrost Protection Design Principles**
- **Permissive Thawing Design Principles**
- **Pre-Thawing Design Principles**

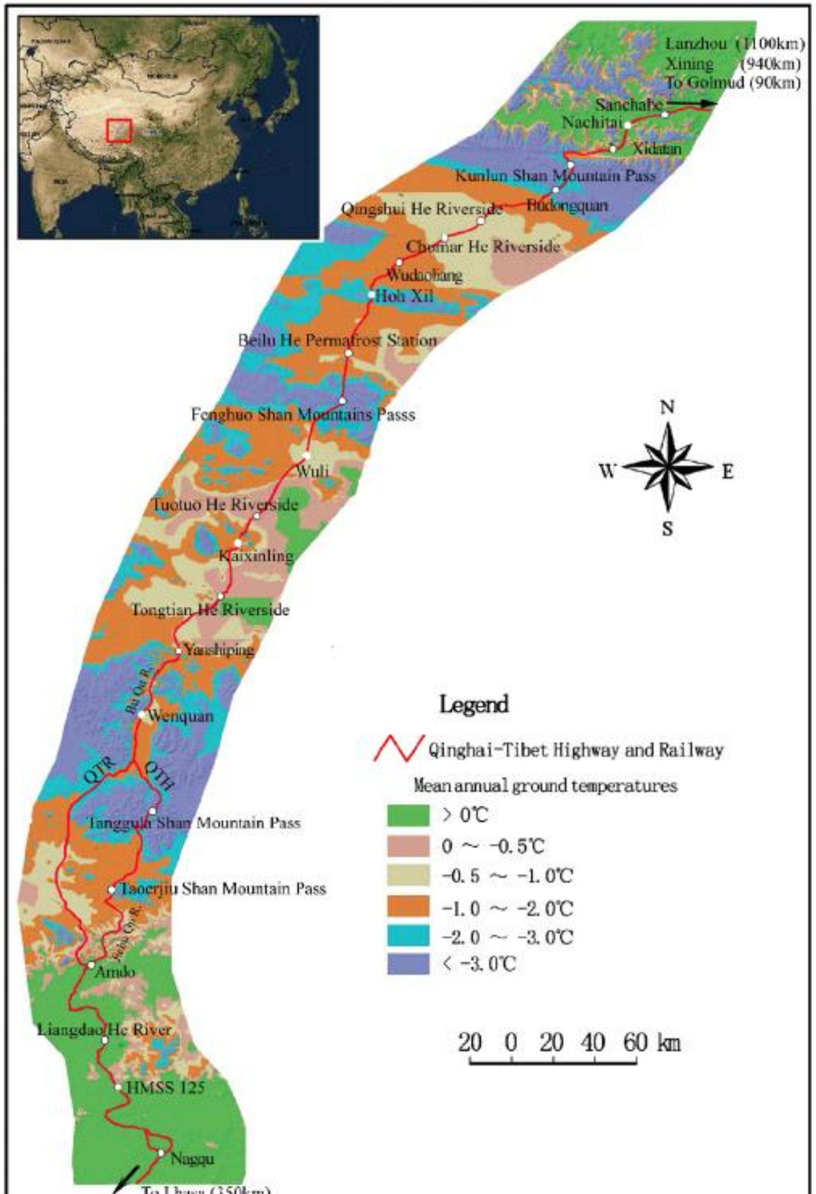
Contents

03 Qinghai-Tibet Railway

- The 1,956 kilometer-long Qinghai-Tibet Railway is the world's highest-altitude railroad. The Golmud-Lhasa section zigzags for 1,142 kilometers across the Kunlun and Tanggula mountain ranges. With the elevation mostly above 3,000 meters, 965 kilometers' tracks of the railway are laid at more than 4,000 meters above sea level, the highest point being 5,072 meters.



03 Qinghai-Tibet Railway



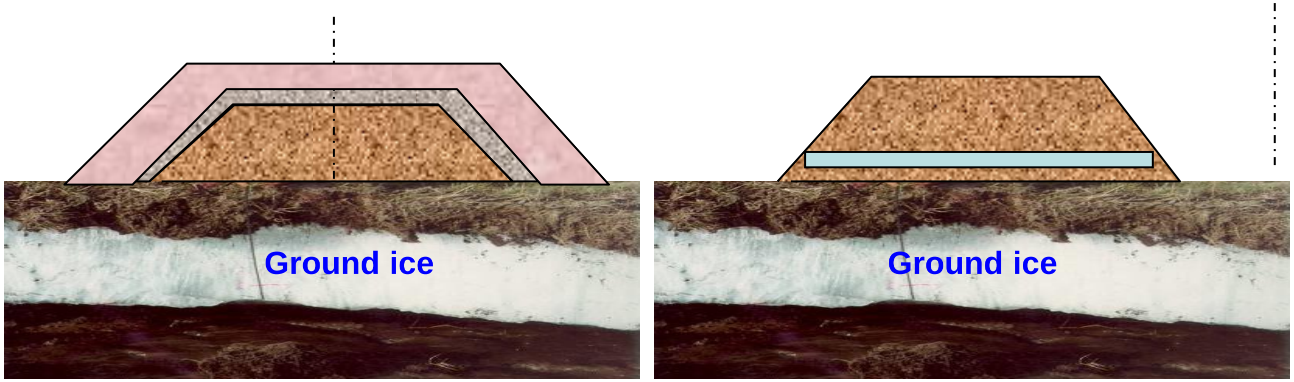
Characteristics of the permafrost environment on the Qinghai-Tibet Plateau:

- **Average altitude greater than 4,000 m (high)**
- **Annual average ground temperature less than -4 °C (cold)**
- **Annual average rainfall between 50 - 400 mm (dry)**
- **Single vegetation type, fragile ecological environment (fragile)**
- **Permafrost degradation leads to the development of thawing disasters and environmental deterioration (thawing disasters)**

The main design principle adopted in the construction of the Qinghai-Tibet Railway project is to protect permafrost.

Traditional passive methods

- To prevent thawing by increasing thermal resistance



Ice-lolly / ice-sucker
Covered by quilt

Increasing embankment height:

The minimum height

The reasonable height

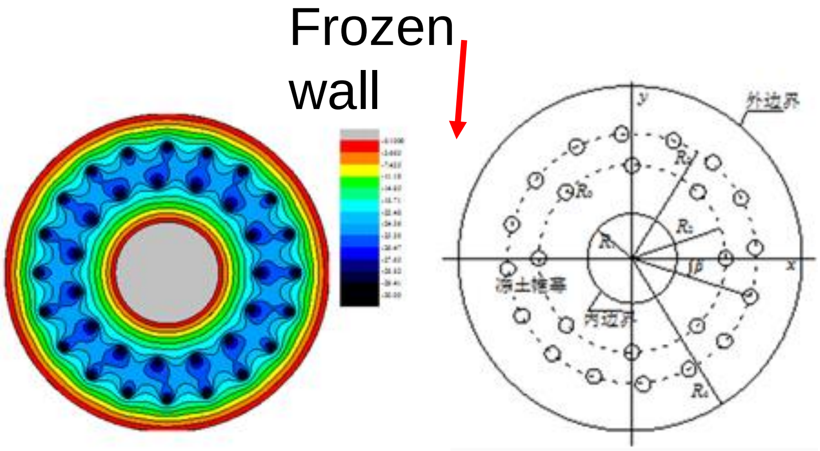
Add insulation layer: Equivalent to a certain height

I'm afraid high temperature
I'm afraid melting

Passive insulation method, even with using geotextiles, can only delay the permafrost thawing, but cannot ensure thermal and dynamic stability of the permafrost for a long time!

Changing to actively cooling methods

- Provide cold energy to the underlying permafrost

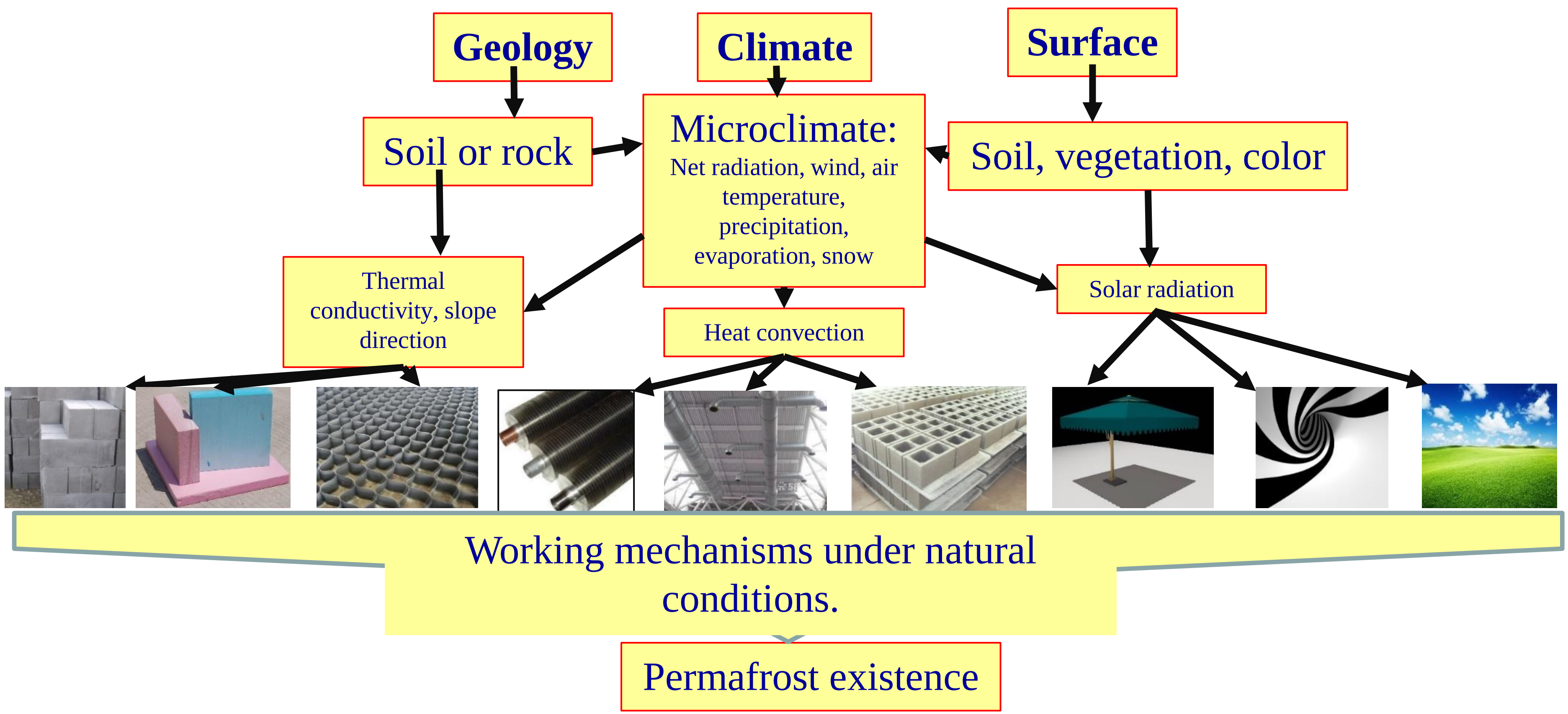


How to cool down the subgrade and the underlying permafrost ?

Artificial ground freezing— energy cost high !

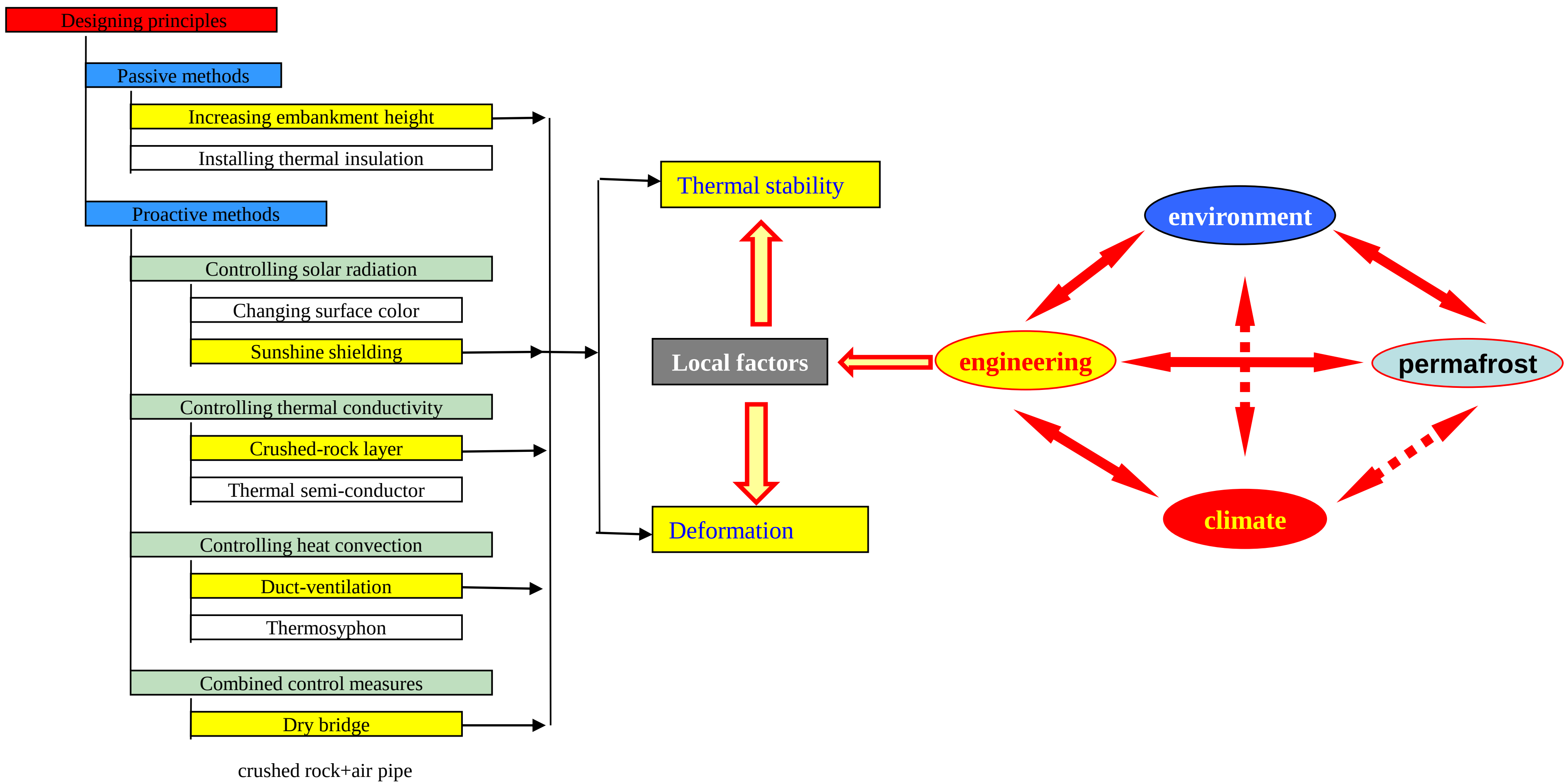
Changing to actively cooling methods

- What kind of local factors influencing the permafrost stability?



Changing to actively cooling methods

- Provide natural cold energy to the underlying permafrost

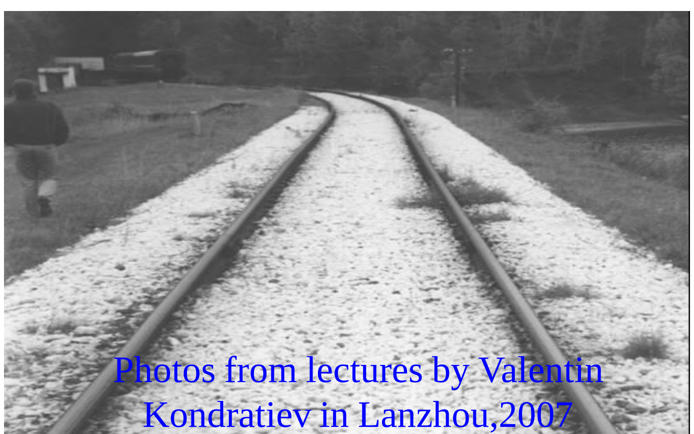


03 Qinghai-Tibet Railway

Controlling the solar radiation

- High albedo surfacing material

High albedo surfacing material test site along the QTH



Photos from lectures by Valentin Kondratiev in Lanzhou,2007

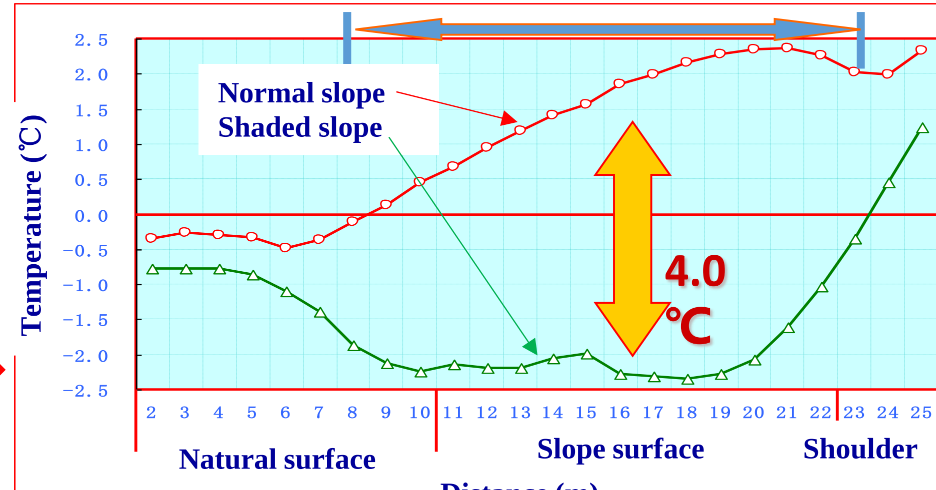
A bituminous surface treatment using light-colored aggregates in the Beaver Creek project (Guy Doré,2010)

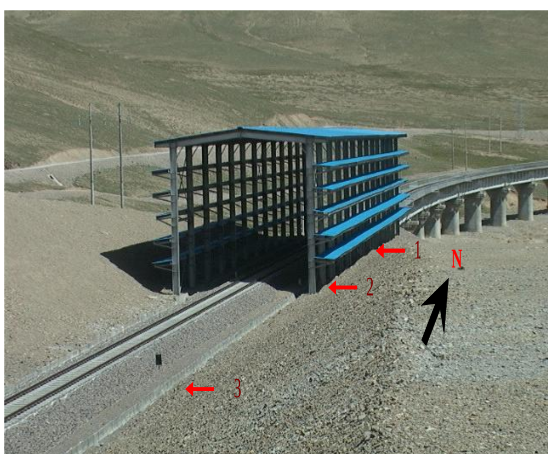
High albedo surfacing material test site in Salluit, Quebec, Canada

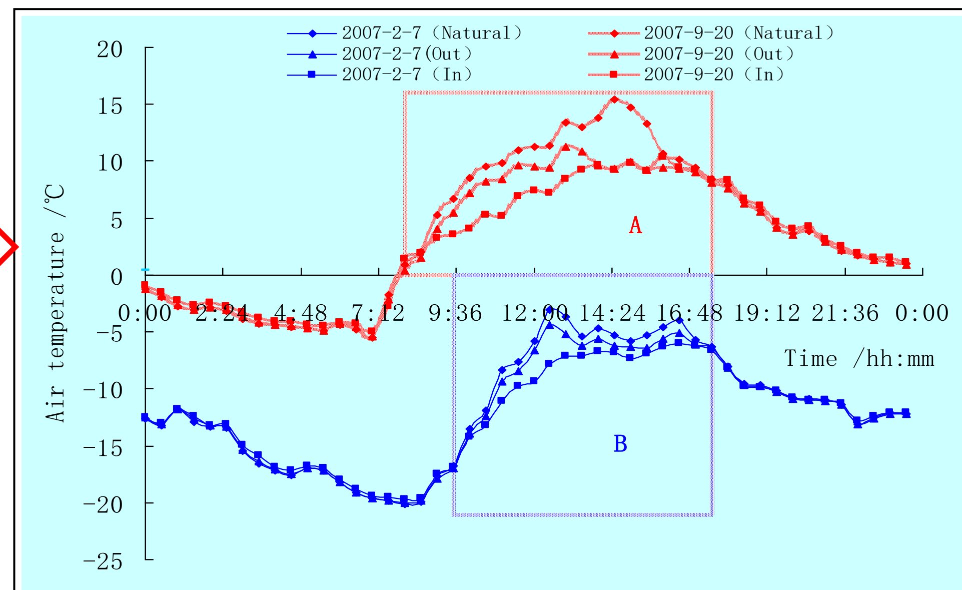
03 Qinghai-Tibet Railway

Controlling the solar radiation

- Shading boards and shed

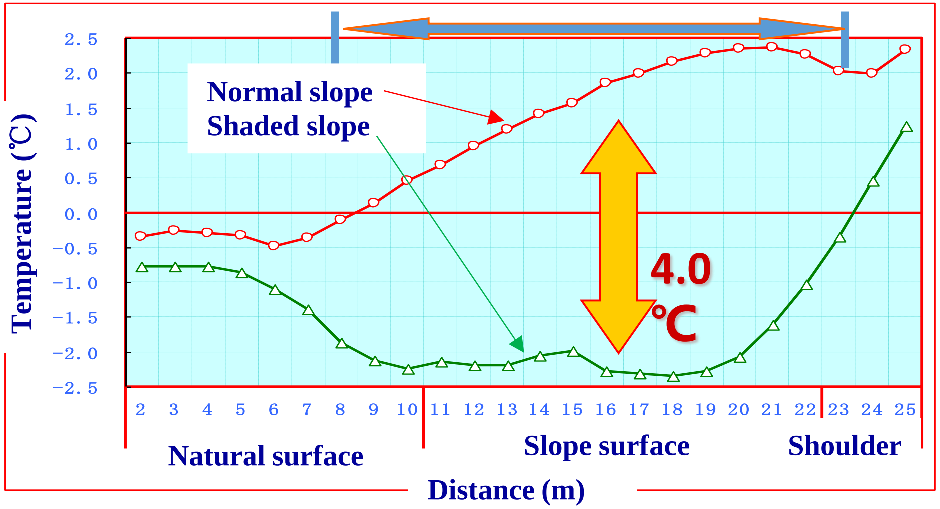


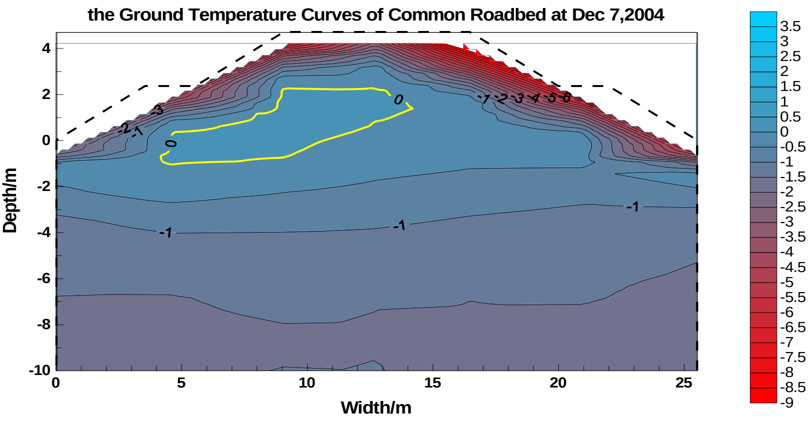


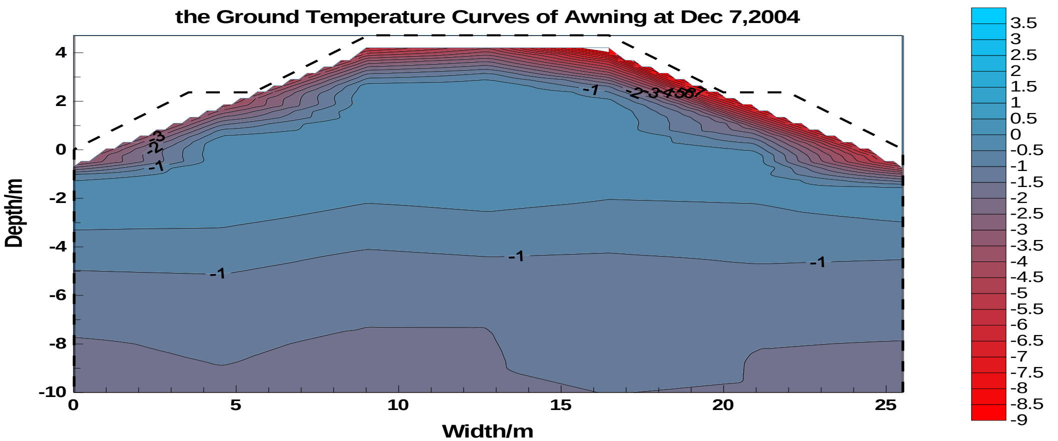


Controlling the solar radiation

- Shading boards







The shallow ground temperature is 3-5°C lower

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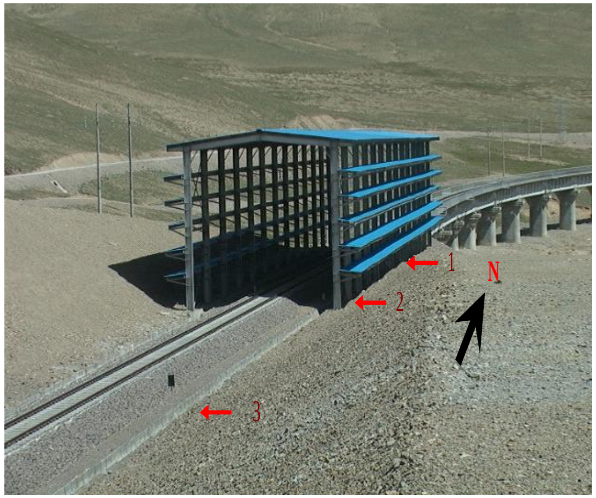
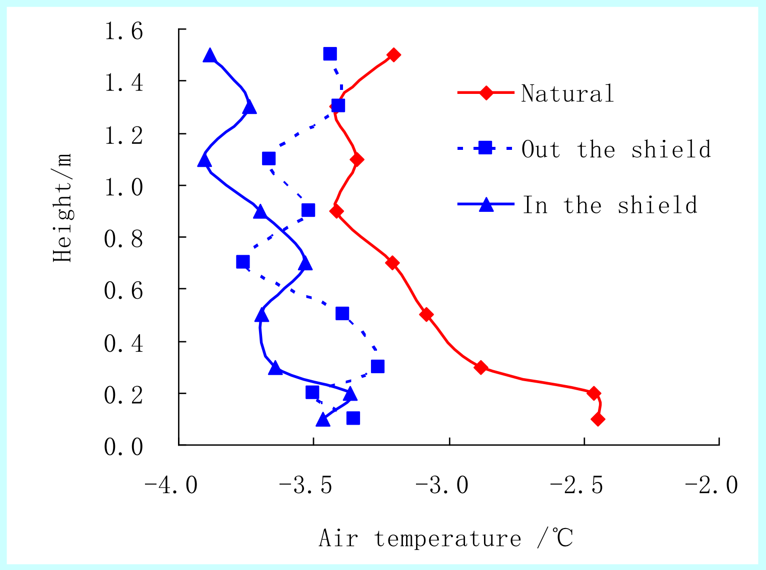
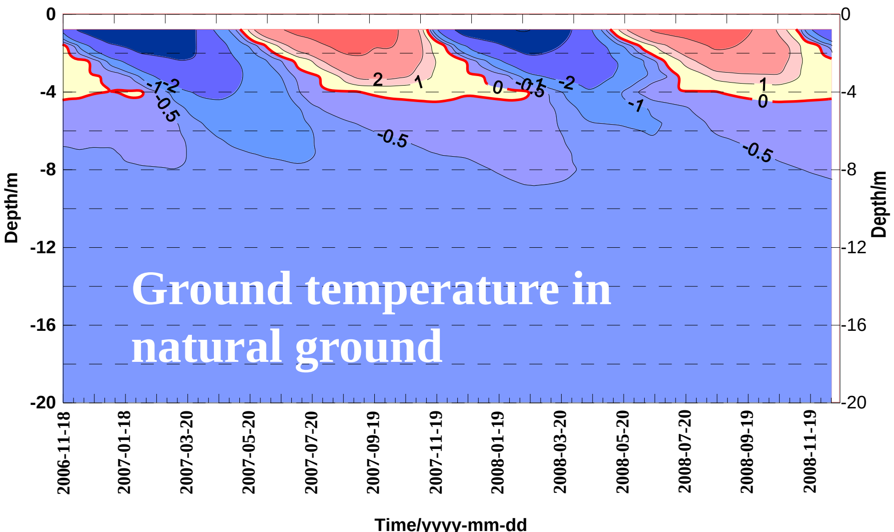
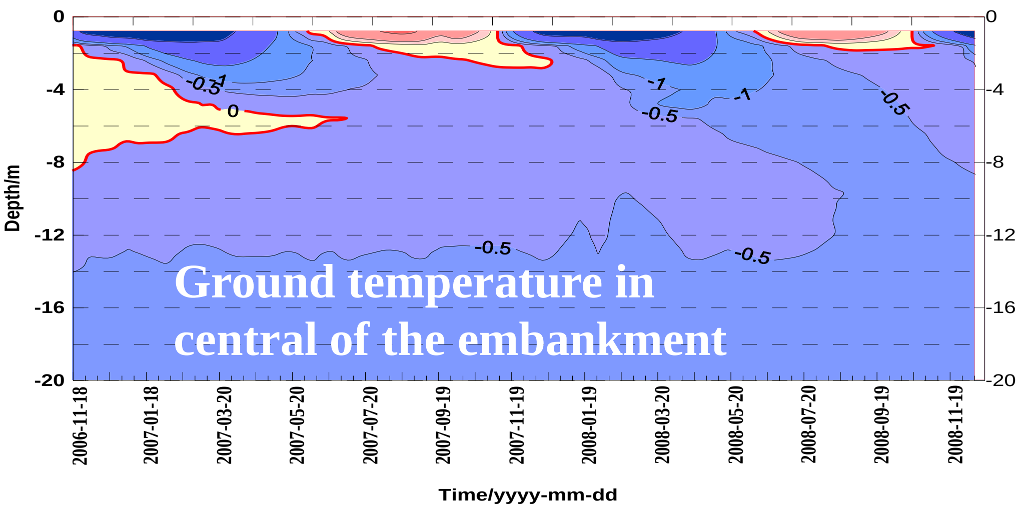
Controlling the solar radiation

- Shading shed





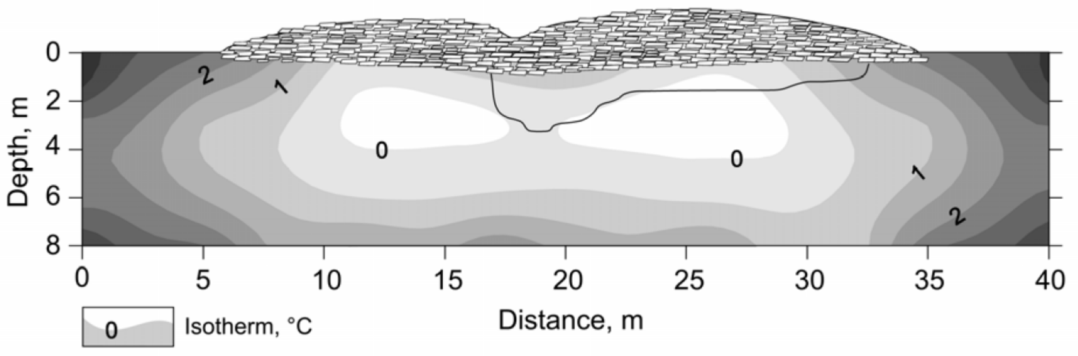




Controlling the heat convection

- Crushed rock embankment

Block fields, Scree, Kurum, Talus

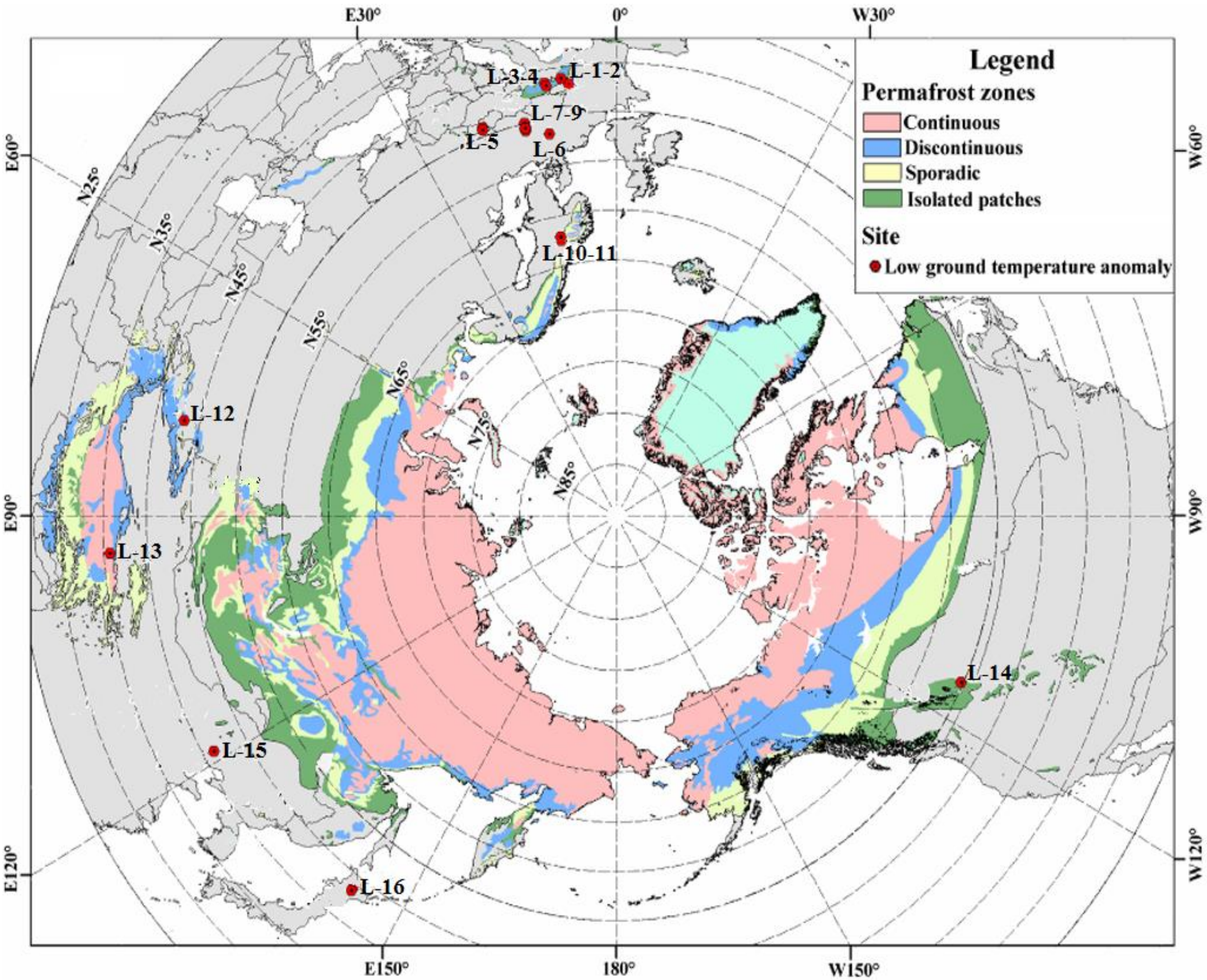


In Bukhtarma valley in Kazakhstan, of permafrost was found under a ancient tomb (2000-2500 years ago). Here the MAAT is 1.0-1.6 °C, and the seasonal frozen depth is 1.45 m. S. (Marchenko et. Al.,2006)

03 Qinghai-Tibet Railway

Controlling the heat convection

- Crushed rock embankment



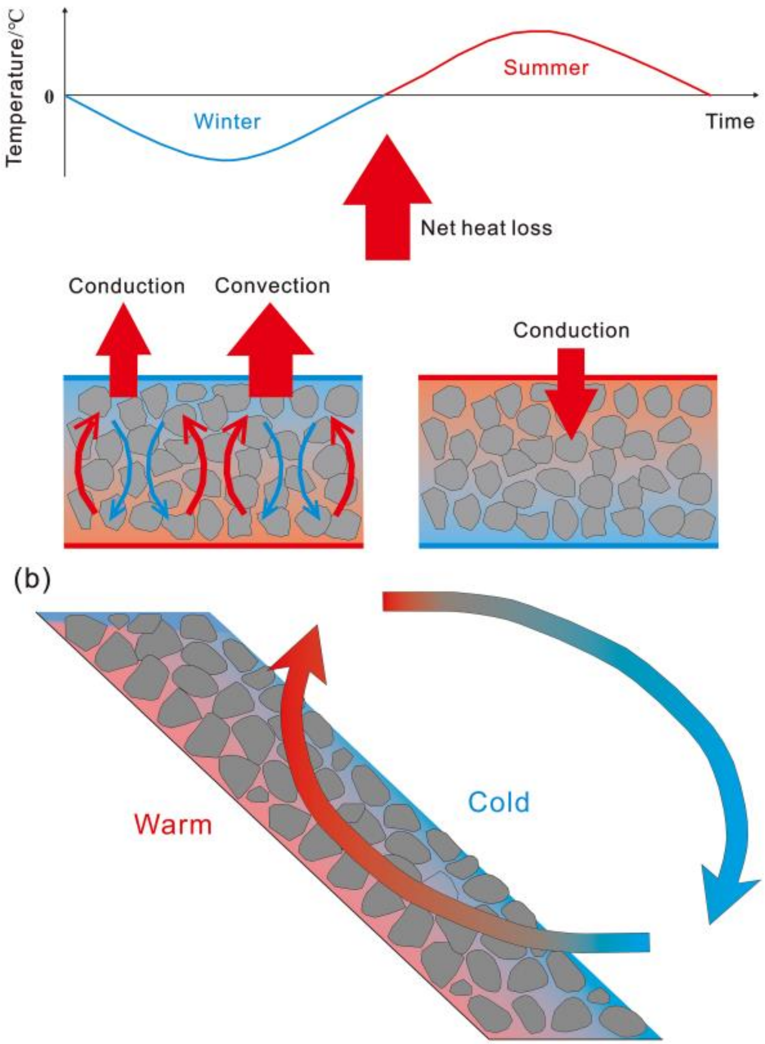
Distribution of low ground temperature anomalies outside of the continental permafrost bodies.

Many "cold earth", i.e. low ground temperature anomaly (LGTA, marked as L-number for short) have been reported to occur on scree or talus slopes spreading away from the present southern or lower limit of permafrost .

The studied robust permafrost site (marked as L-16) in North China is the southernmost in the Northern Hemisphere, except the one marked L-13, which is on the Qinghai-Tibet Plateau with much higher elevation (4,700 m a. s. l.).

Controlling the heat convection

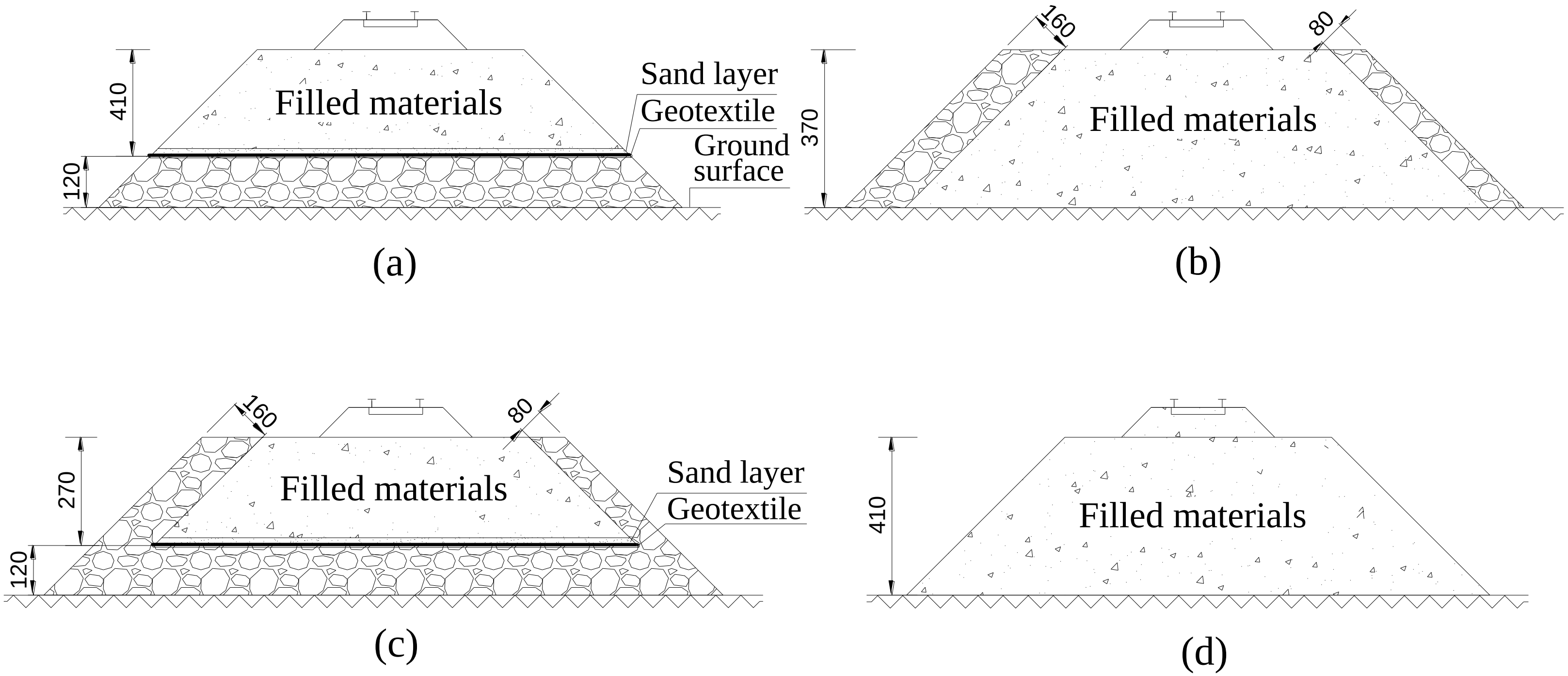
- Crushed rock embankment--There is a net heat loss in a year



Air convection embankment uncovered, Beaver Creek experimental road site, Alaska Highway, Yukon (Guy Doré,2010)

Controlling the heat convection

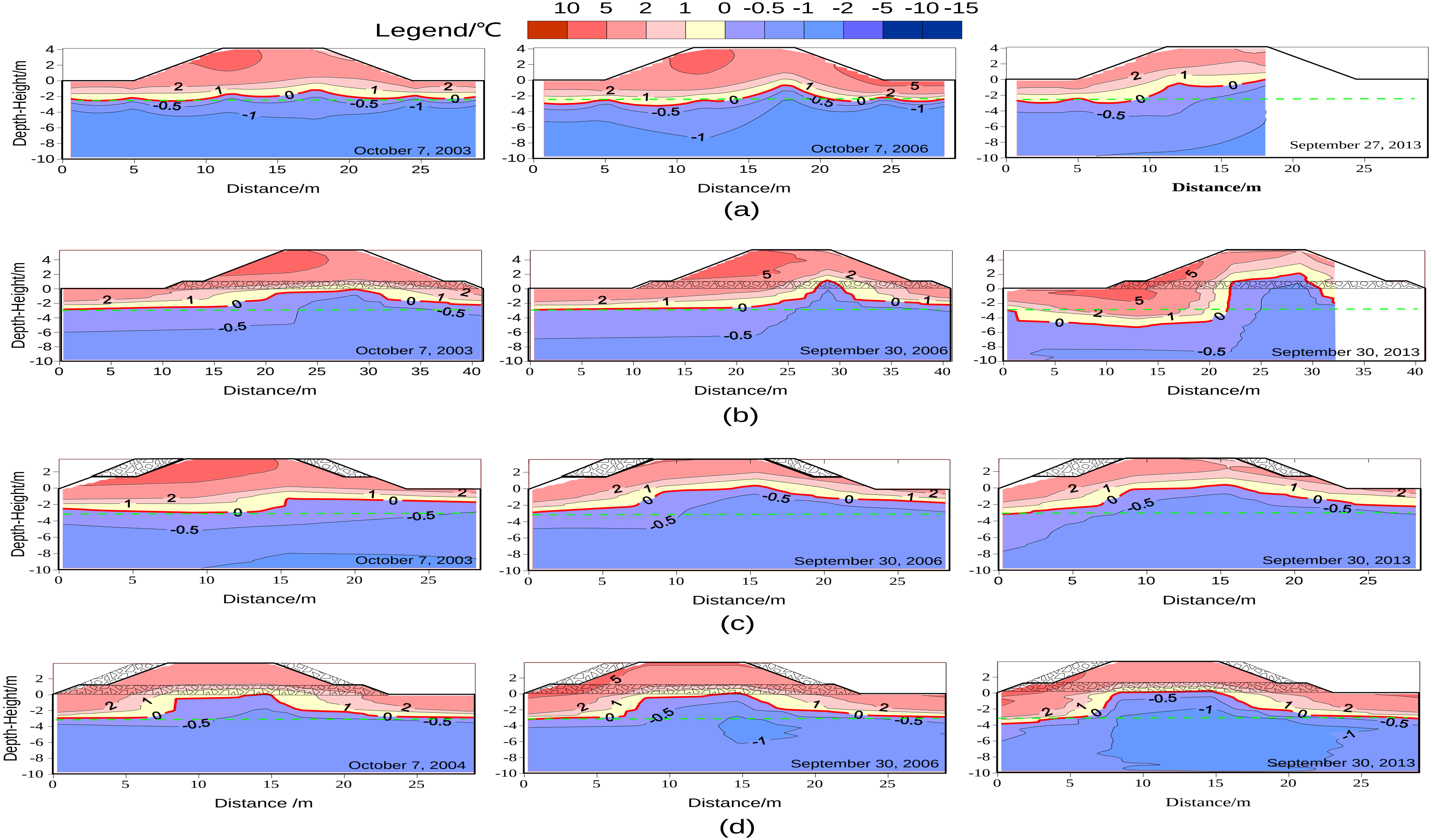
- Crushed rock embankment



03 Qinghai-Tibet Railway Engineering

Controlling the heat convection

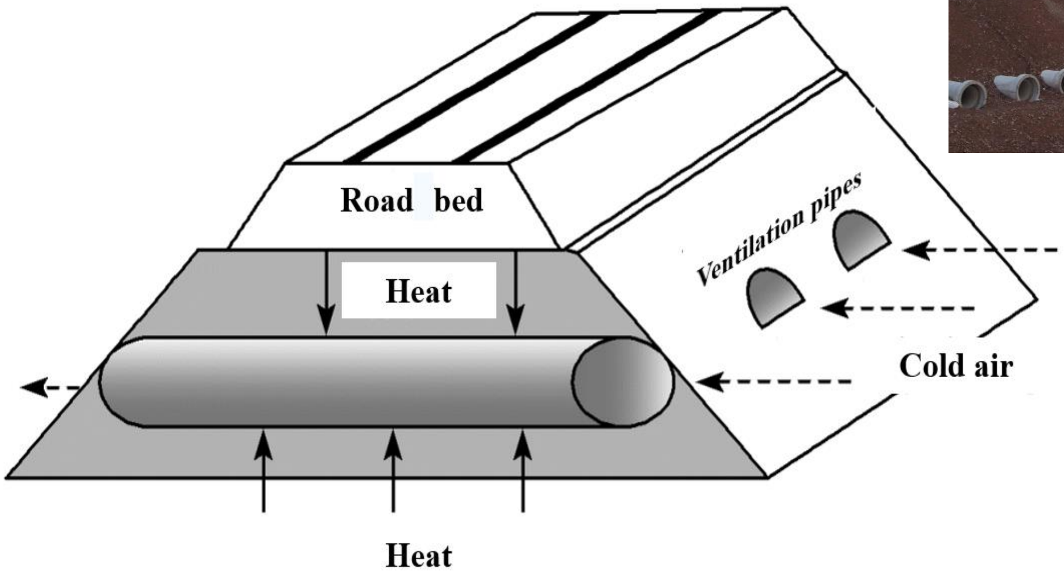
- Crushed rock embankment



03 Qinghai-Tibet Railway

Controlling the heat convection

- Duct-ventilated embankment



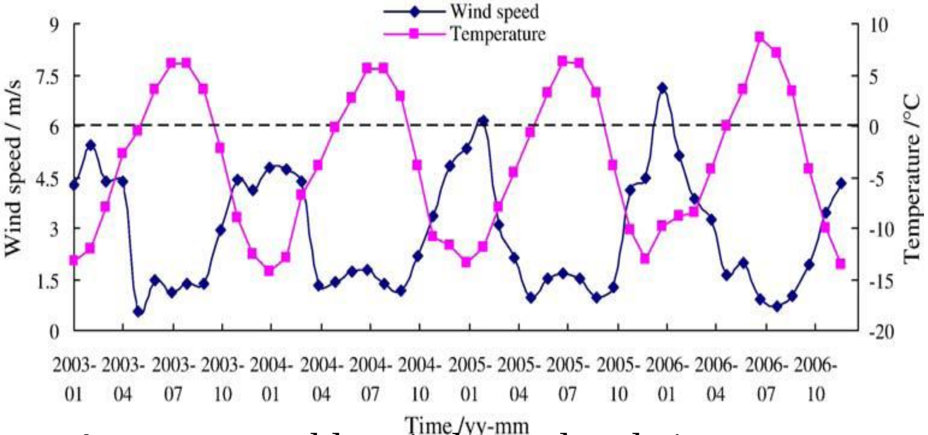
Inlets and outlets of the longitudinal culvert system, Beaver Creek experimental road site (Guy Doré,2010)

03 Qinghai-Tibet Railway

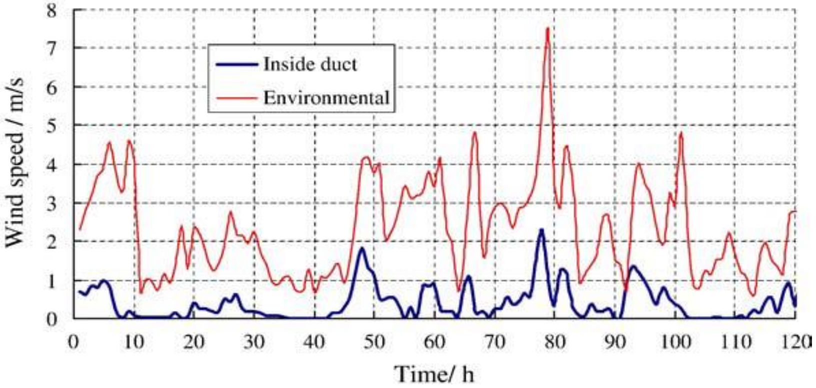
Controlling the heat convection

- Duct-ventilated embankment

Inlets and outlets of the longitudinal culvert system, Beaver Creek experimental road site (Guy Doré,2010)



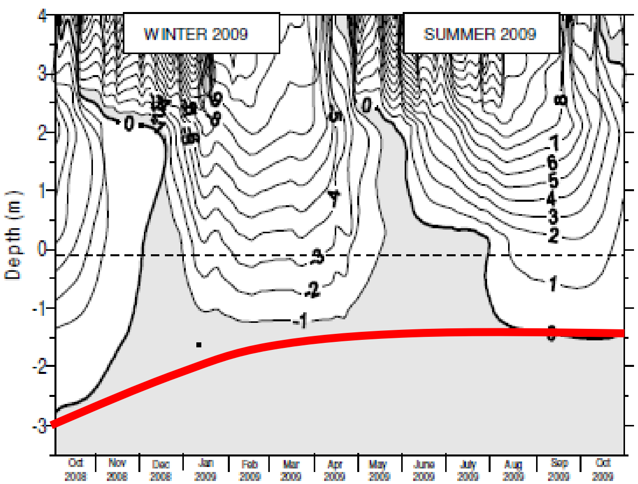
Average monthly wind speed and air temperature at a height of 2.2 m in the Beiluhe testing section.



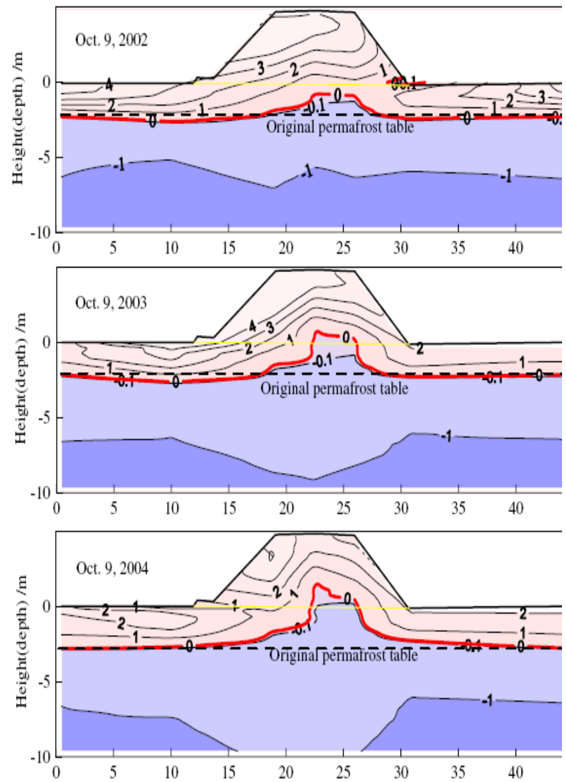
Wind speed monitored in and out duct

Controlling the heat convection

- Duct-ventilated embankment



Thermal regime of section 7, Beaver Creek experimental road site (Guy Doré,2010)



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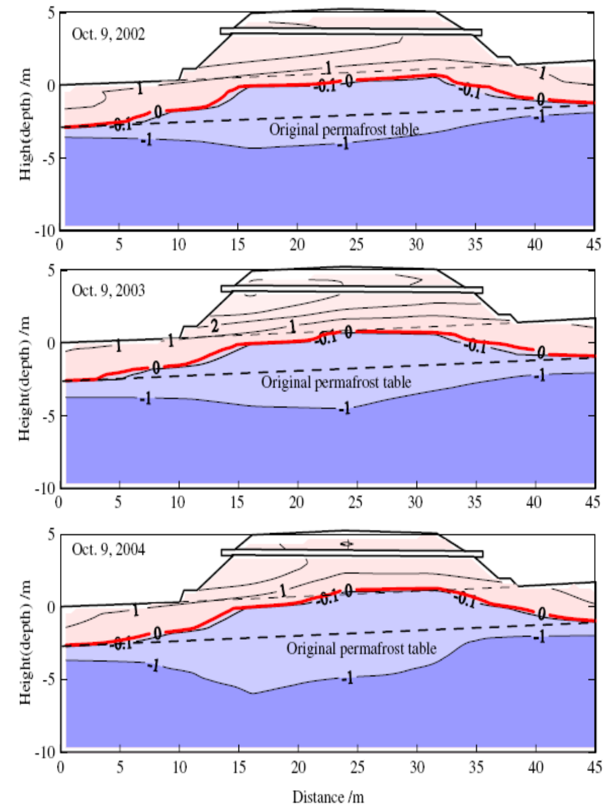
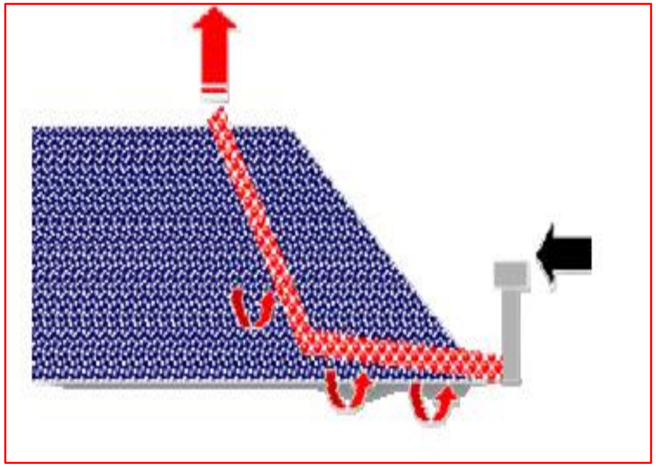


DVE

Controlling the heat convection

- Duct-ventilated embankment



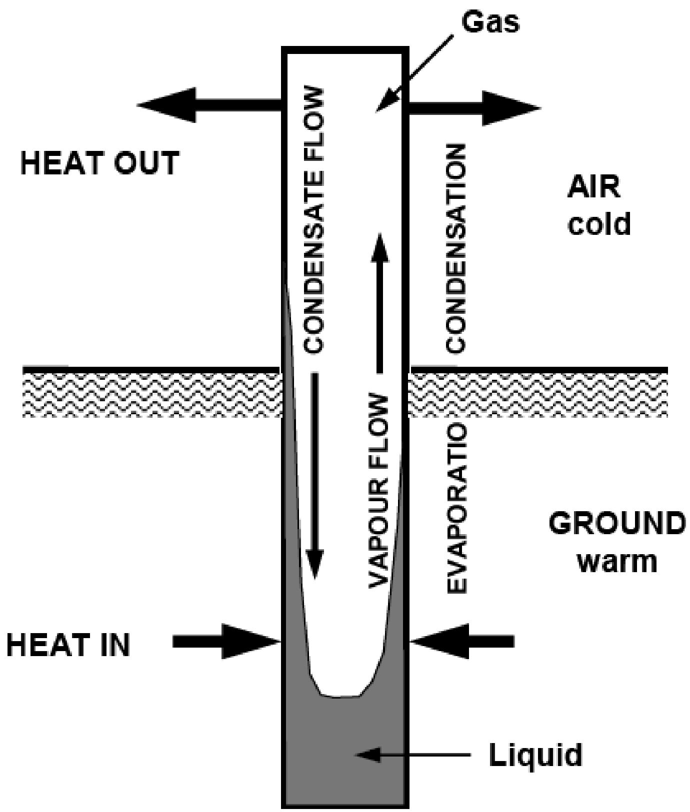


Heat drains structures at the Beaver Creek Test Site

Different configurations of ACE have been tested and monitored at experimental sites in Alaska and demonstrated its effectiveness for thermal stabilization of embankments built on thaw sensitive permafrost.

Controlling the thermal conductivity

- Thermosyphon

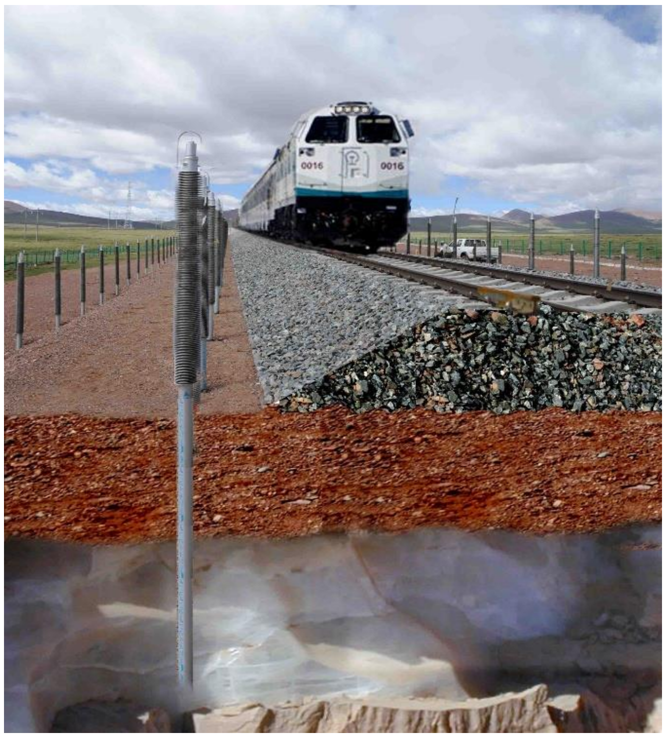


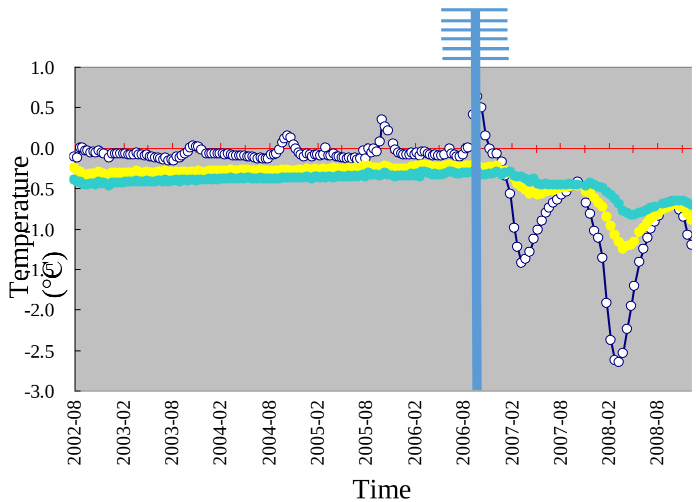
Working principle:

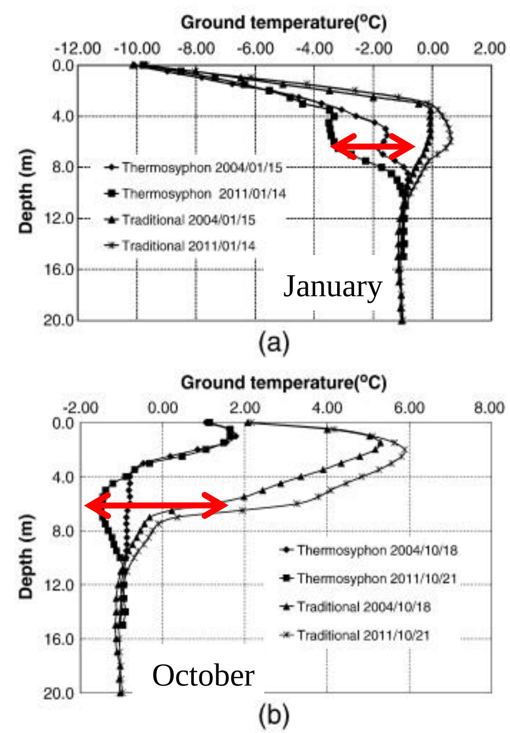
1. **Certain temperature difference between upper and lower parts in winter**;
2. **Ground temperature is relative higher than air temperature in winter. Working liquid becomes vapor and rises to the upper part. Then it condenses and flows down to the lower part, removing more heat into air**;
3. **This repeated process can cool the underlying permafrost**
4. **The thermosyphon is a effective device for heat conduction.**

Controlling the thermal conductivity

- Thermosyphon





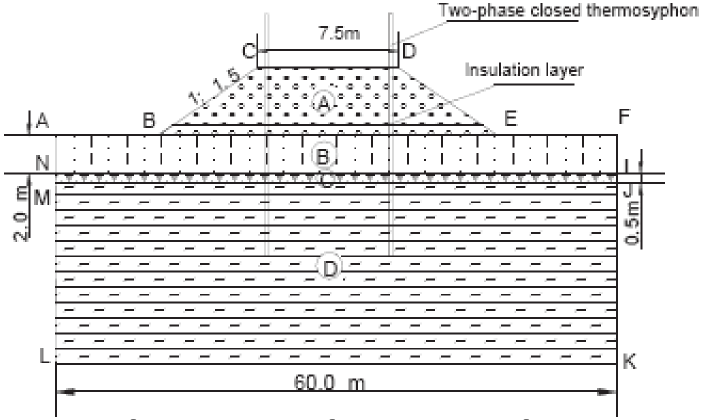


Thermosyphone embankment (Song et al., 2013)

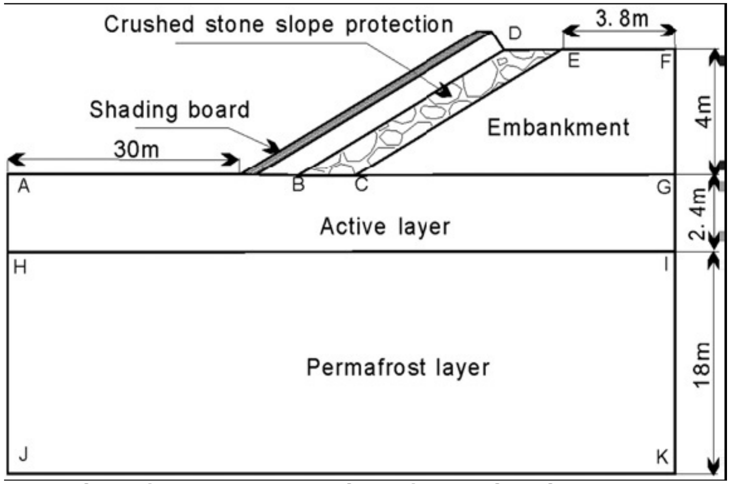
Comprehensively controlling

- Combined control measures

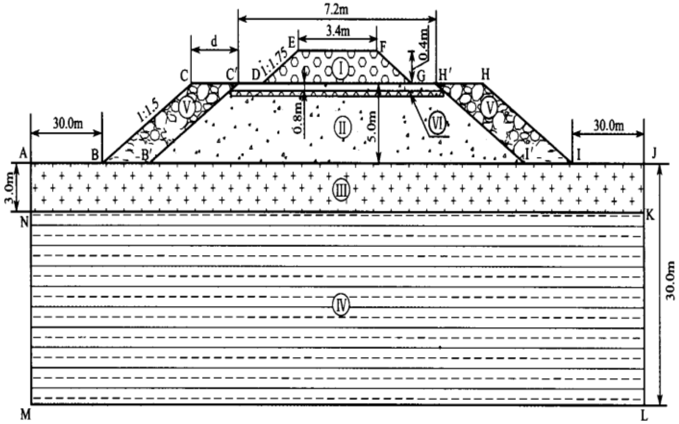
Dry bidge



Thermosyphon +insulation



Shading + crushed rock slope



crushed rock slope +insulation

03 Qinghai-Tibet Railway

Cautions

- Risk analysis- climate changes (1 ℃ /100a cost 0.5 trillion dollars for the QTR, for some embankments and culverts were changed into bridges) , permafrost condition, the randomness of design parameters;
- Environmental changes-weathering, wind-blown sand, snow covering…
- Start conditions for air convection embankment (ACE)-temperature difference (thickness of the cover soil layer and the crushed rock layer etc.), rock size, wind direction and speed…

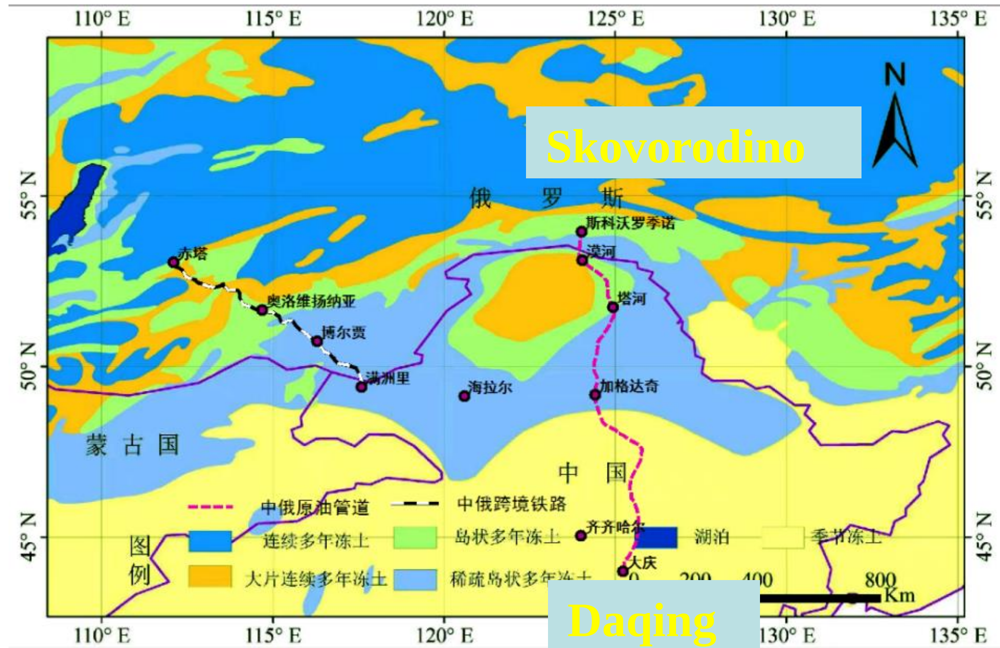
Contents

04 China-Russia Crude Oil Pipeline Engineering

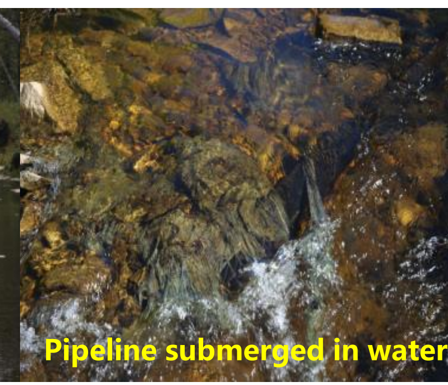
- The Russia-China Crude Oil pipeline (RCCOP) is important energy pipeline in the China-Mongolian-Russian Economic Corridor. It includes two lines, namely RCCOP I(operated in Jan. 2011) and RCCOP II(operated in Jan. 2018), both transporting the Siberian oil with an annual throughput of 30 million tons.

04 China-Russia Crude Oil Pipeline

- It is 1030 km long, passing through 518 km of permafrost and 512 km of seasonally frozen ground from Skovorodino, Russia, to Daqing, China
- Pipe diameter: 81.3cm；
- Burial depth: 1.6-2.0m
- ambient oil temperature



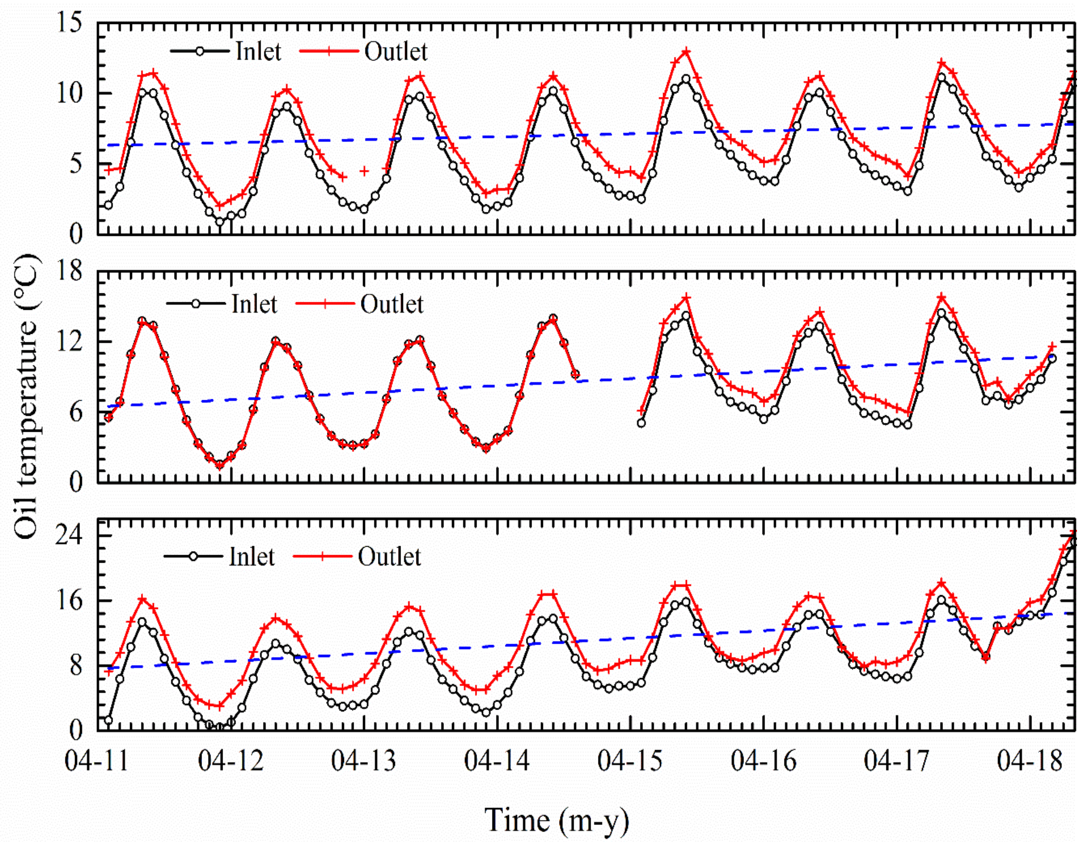
Pipeline frost and thaw problems



The pipeline faces serious threats from thawing of permafrost at the foundation and water accumulation in the trench.

Higher oil temperature

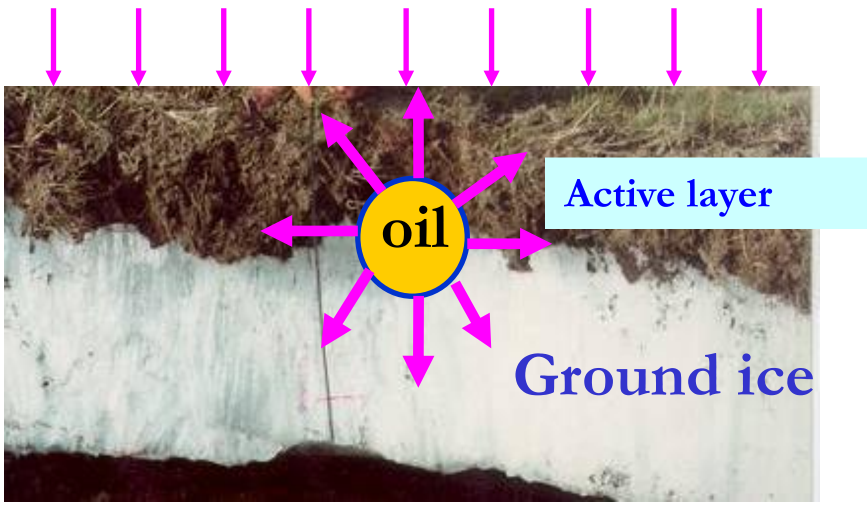
- The monthly average oil temperature ranged from 0.9 to 18.2°C， significantly higher than the expected value (-6 ~ +10°C)

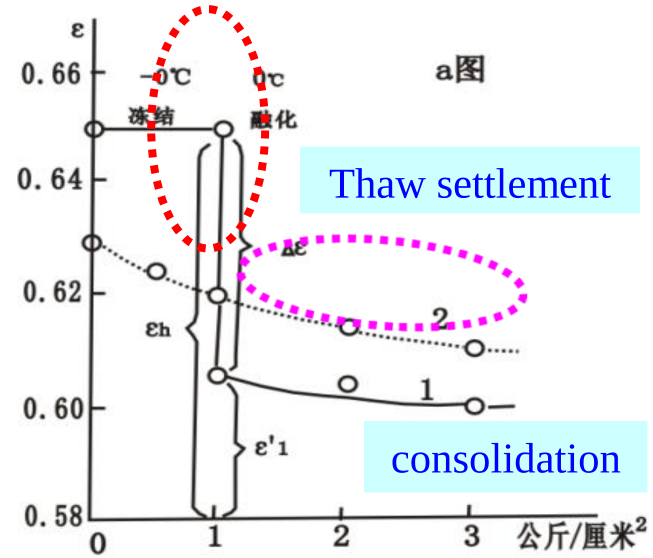


- Oil temperature increase by 1.3 to 2.4°C through pump station
- Oil temperature increased with time and decreased with distance

Oil temperatures recorded at three pump stations, namely Jiagedaqi, Ta'he and Mo'he during the period from 2011.5 to 2018.8

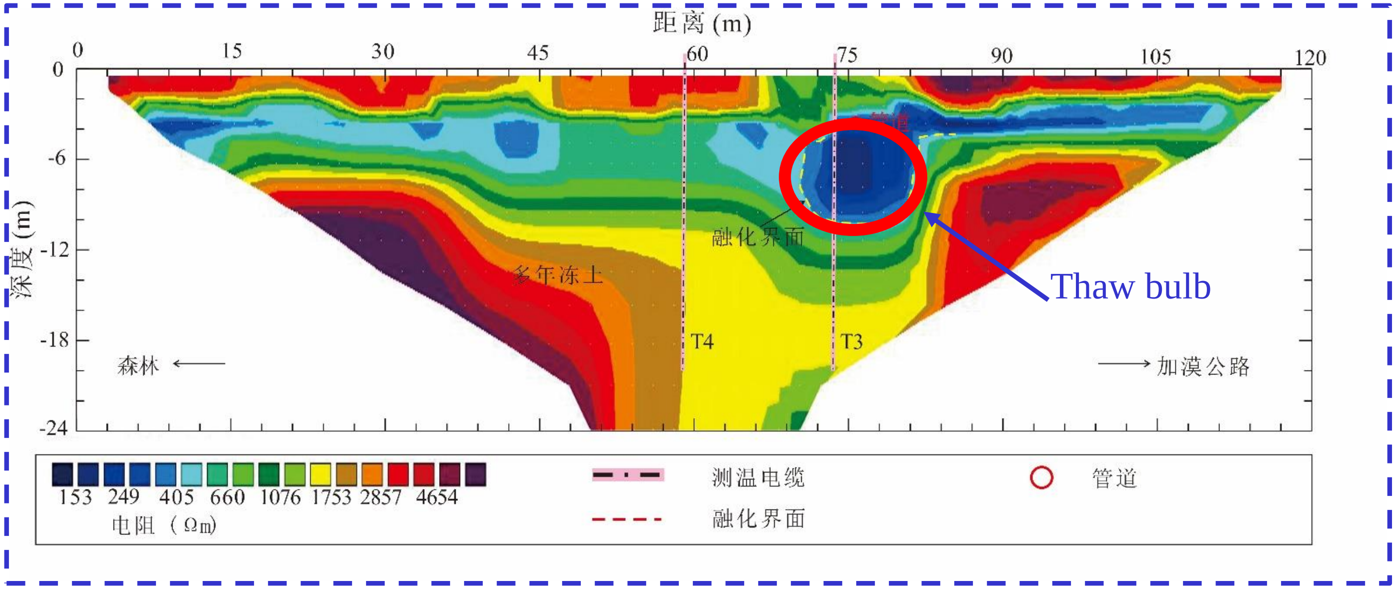
1. Thaw settlement

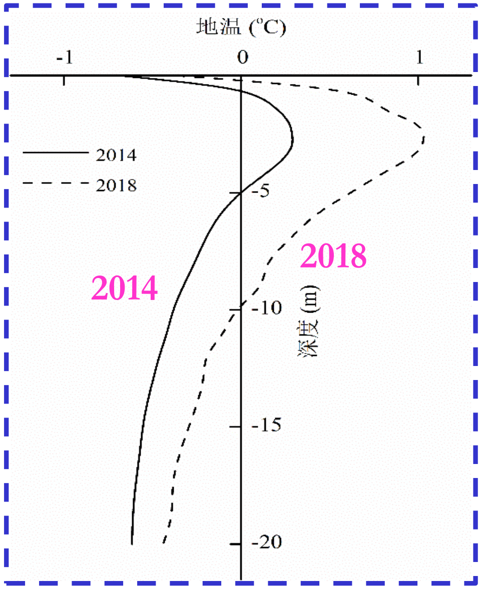




2. Thaw bulb around the pipeline

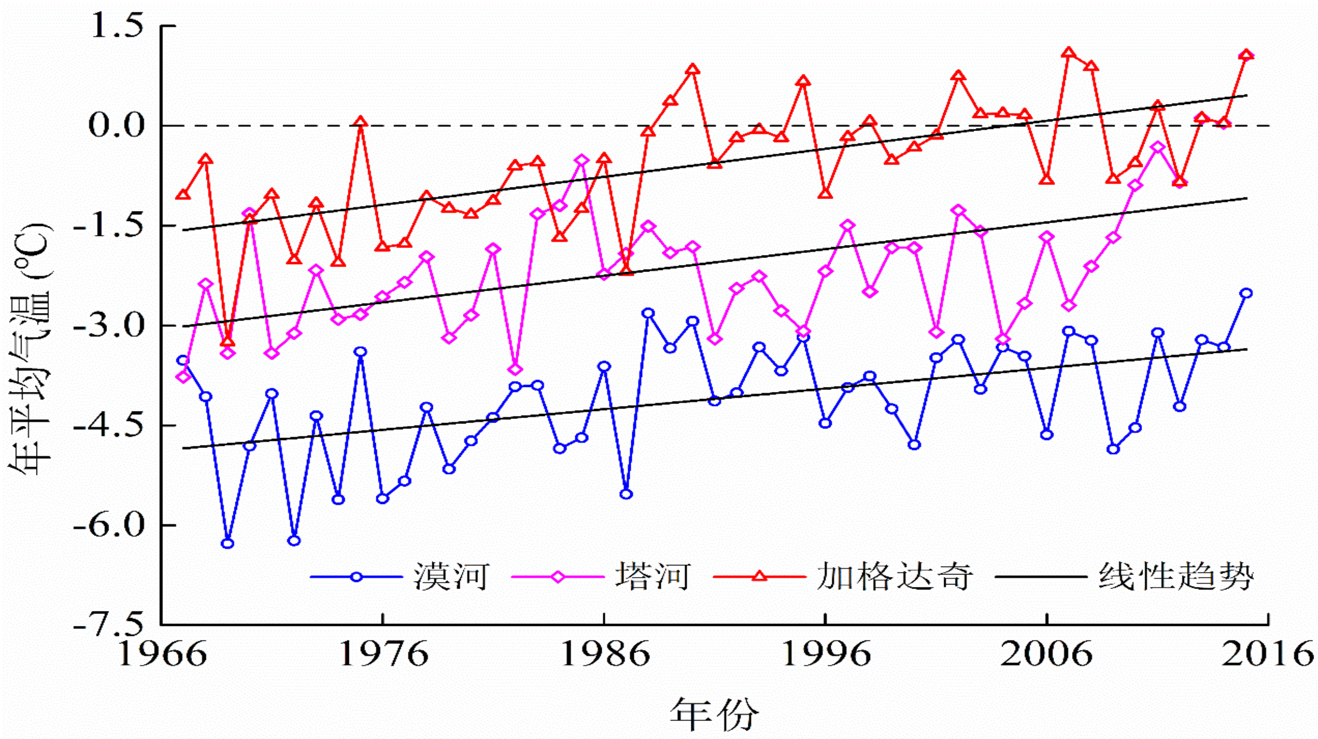
- The thaw bulb always exist throughout the year, gradually enlarging with time. For example, the bottom of thaw bulb increased from 4.9m in 2014 to 9.7m in 2018, at an increasing rate of 1.2m/a





3. Climate warming

- Climate warming accelerated the permafrost degradation along the oil pipeline, which is higher than the global average

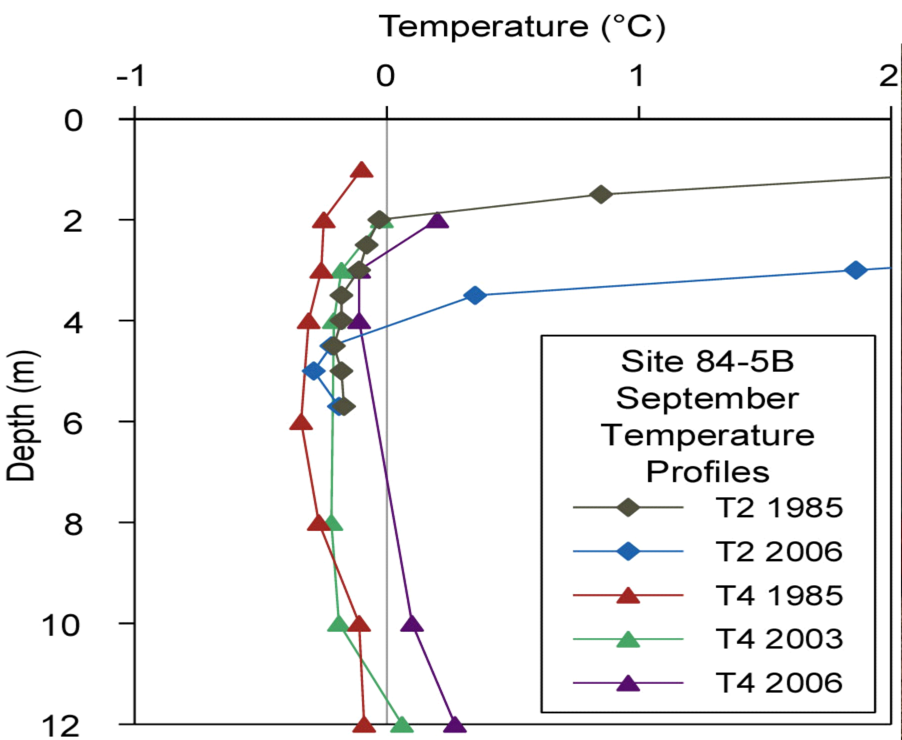


4. Deforesting

- Deforesting destroyed the energy balance on the ground surface， absorbing more solar energy and warming and thawing the underlying permafrost.

5. Wildfires

- Wildfires burns the vegetation and forest on the surface, warming the permafrost and accelerating its degradation.

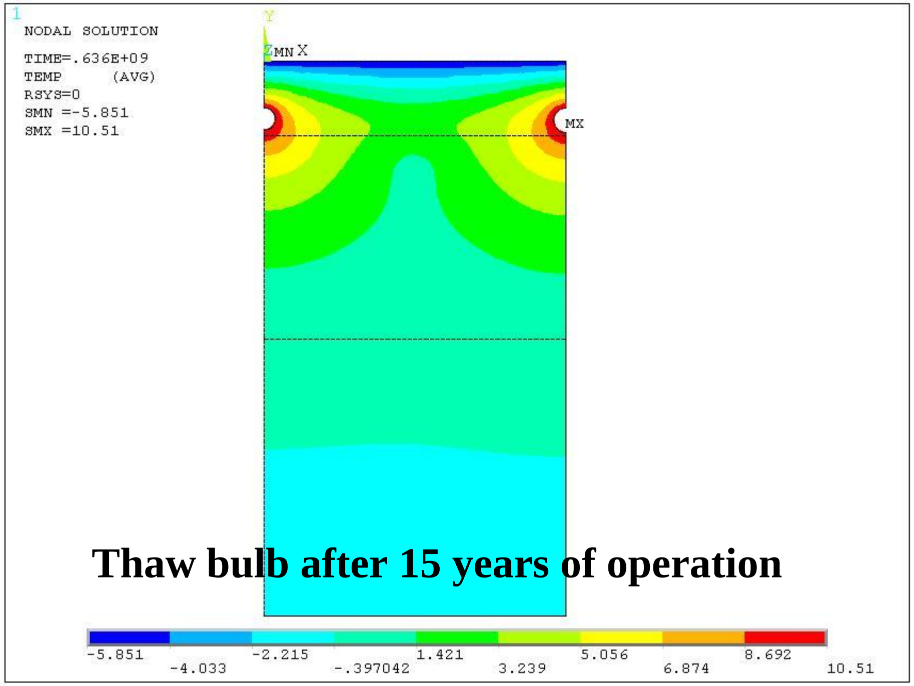


6. Excavating the trench

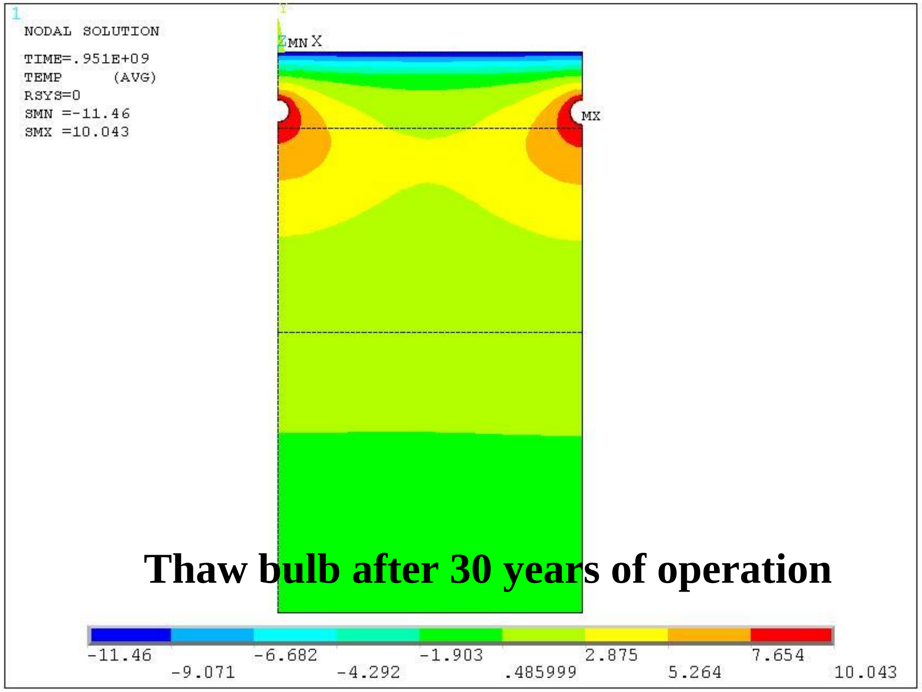
Digging a trench directly disturbed the permafrost and brought heat into permafrost. Accumulated water in the trench warms and thaws the permafrost.

7. Thermal effect between two pipelines

- The distance between two pipelines is always 10m, which is very close for the underlying permafrost, very sensitive to temperature. Two oil pipelines warm the permafrost together, making the permafrost degrading quickly.



Thaw bulb after 15 years of operation



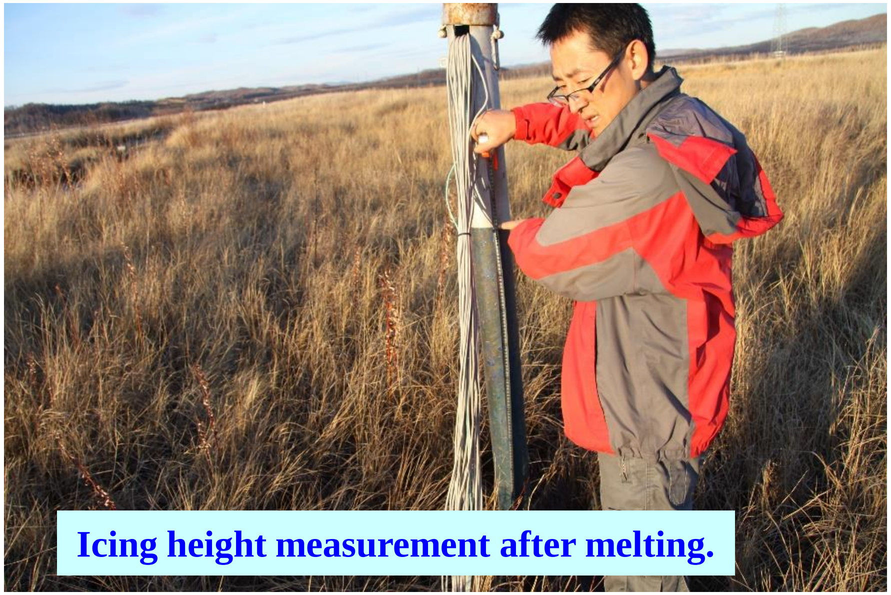
Thaw bulb after 30 years of operation

8. Icing

- Icing is widespread in winter along the pipeline, which always destroy the monitoring equipment. The pipeline is also at the risk of damage due to icing.

Spring icing above the pipeline

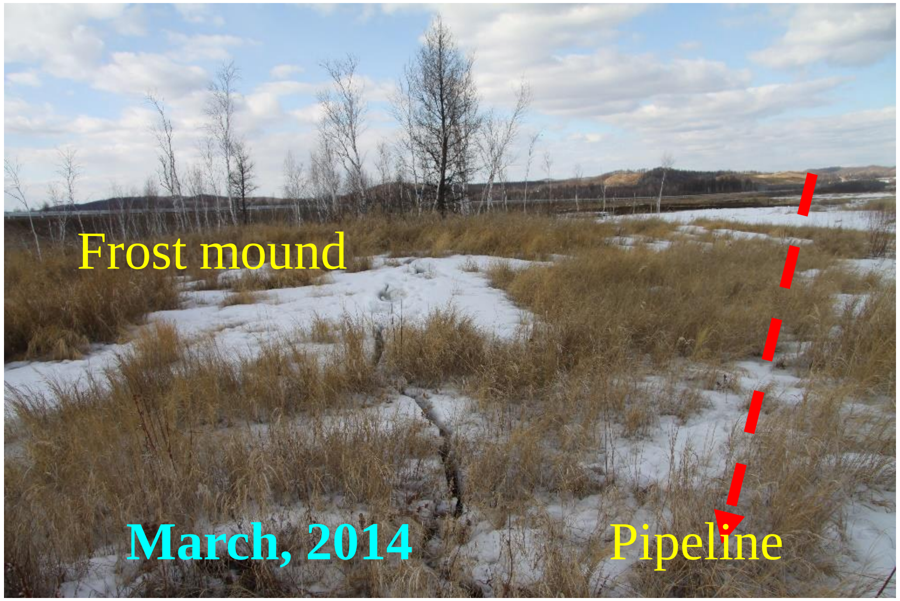
Icing damaged the monitoring system.

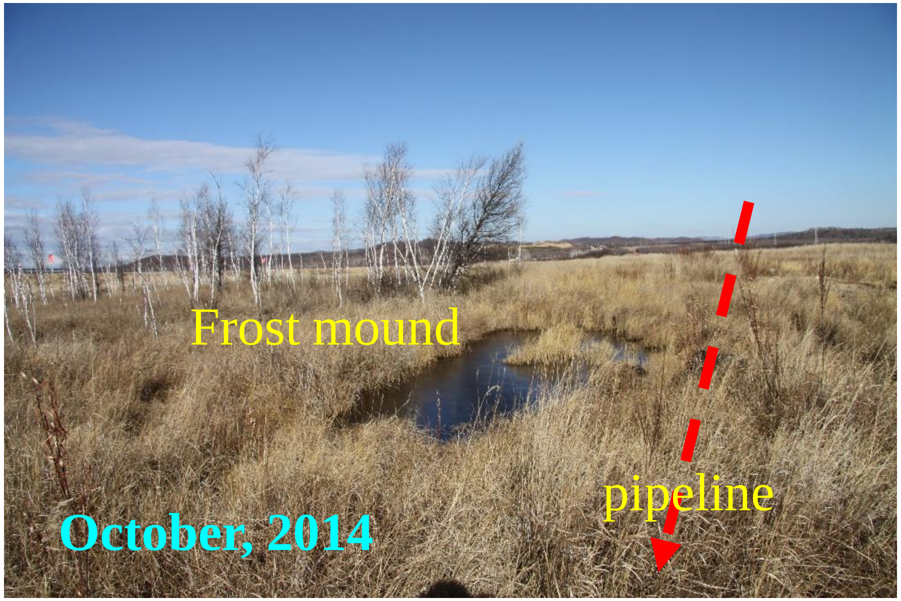


Icing height measurement after melting.

9. Frost mound

- Some frost mounds existed along the pipeline, which probably affect the pipeline.





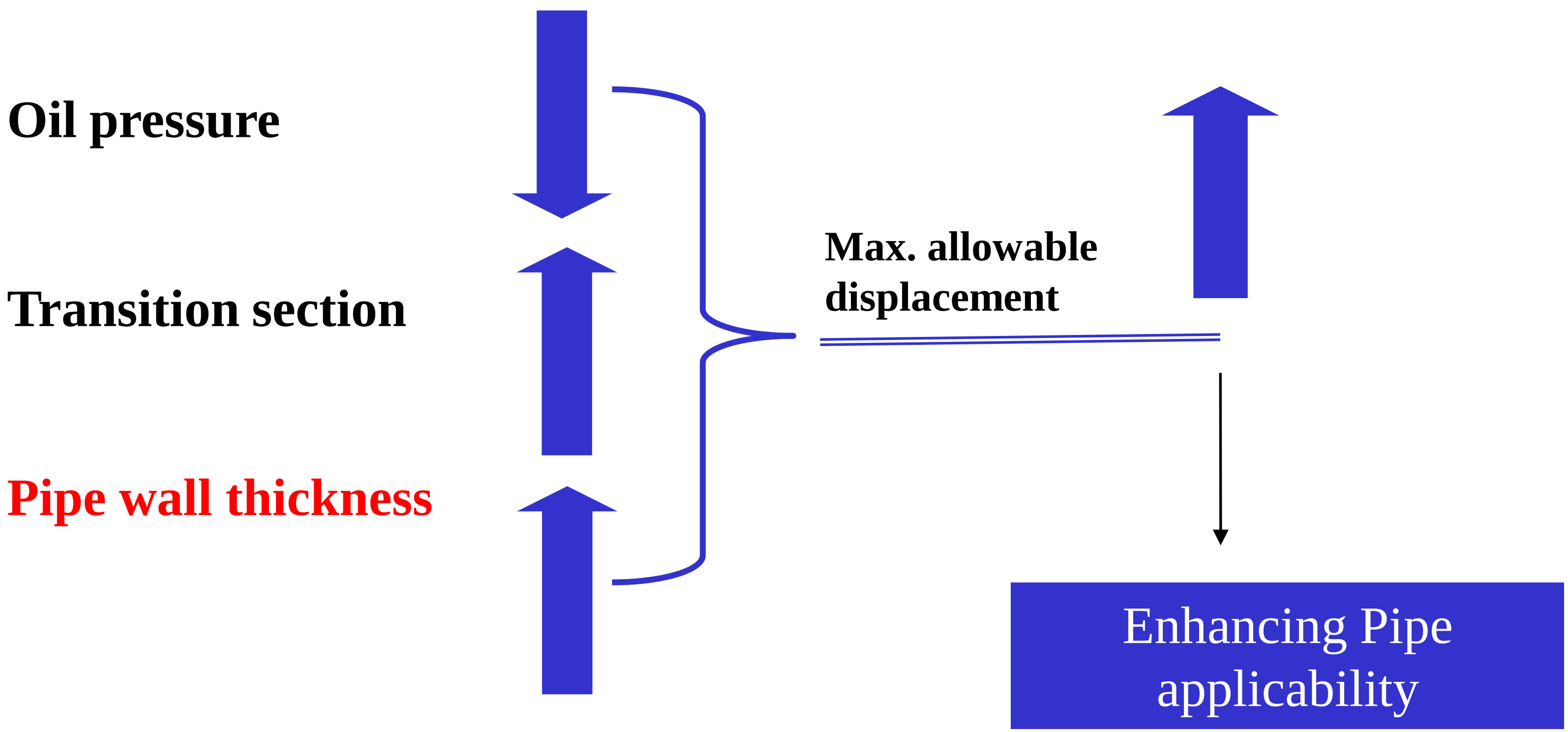
Objectives

- Improve the monitoring system including water, temperature and displacement measurements.
- Investigate the thermal state of underlying permafrost and formation process of frost hazards.
- Develop the new mitigative measures to prevent thaw settlement and study their cooling mechanisms
- Optimize the design parameters of new mitigative measures and apply them in field.

Mitigative measures of thaw settlement

- Pipe design: thickening pipe wall, lengthening the transition section
- Control of oil: cooling the oil, decreasing the oil pressure

Max. allowable displacement= F（oil pressure, length of transition section and pipe wall thickness）



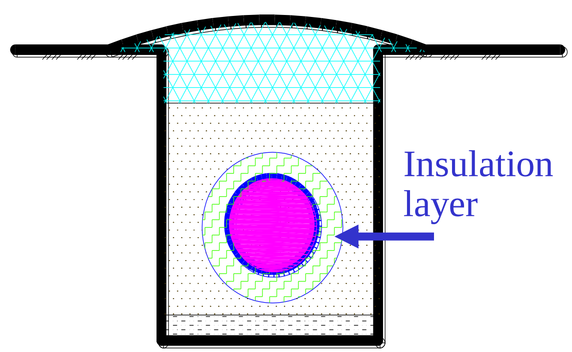
Mitigative measures of thaw settlement

- Mitigative measures adopted:

1） passive measure (pipe insulated by foam);

2） Positive measures (thermosyphon and air-ventilated pipe)

3） Combined measures (thermosyphon + sandbag, thermosyphon + insulation and displacement + insulation ）

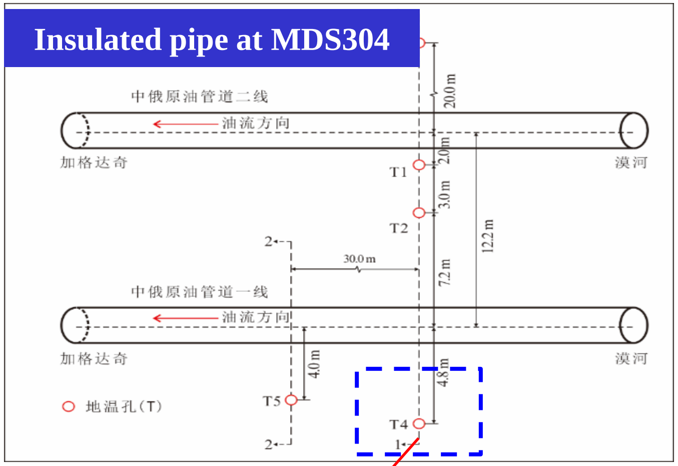


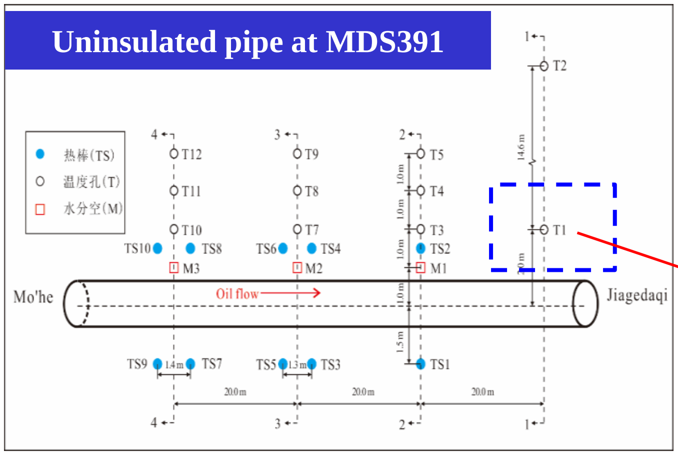
Thermosyphons

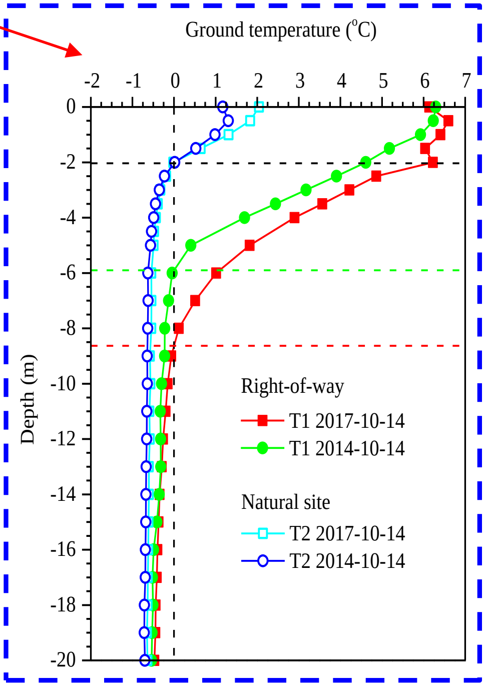
Air-ventilated pipe

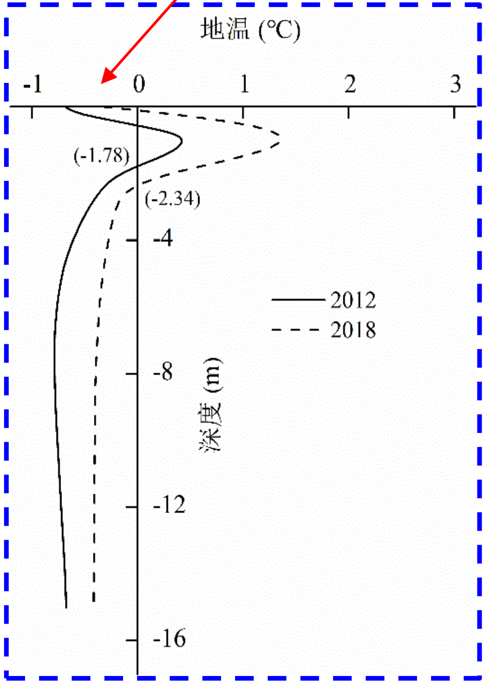
04 China-Russia Crude Oil Pipeline

Insulated pipe-----field tests







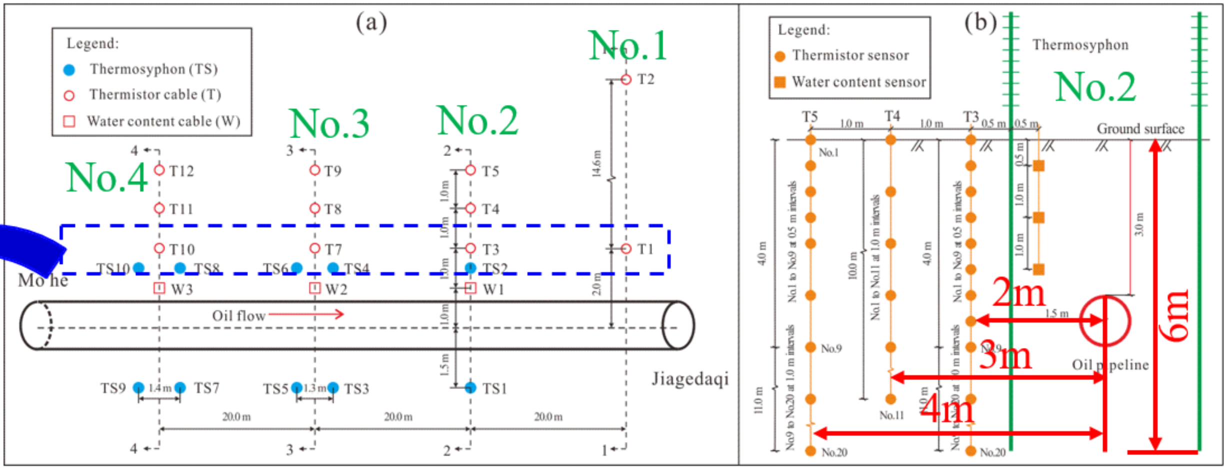


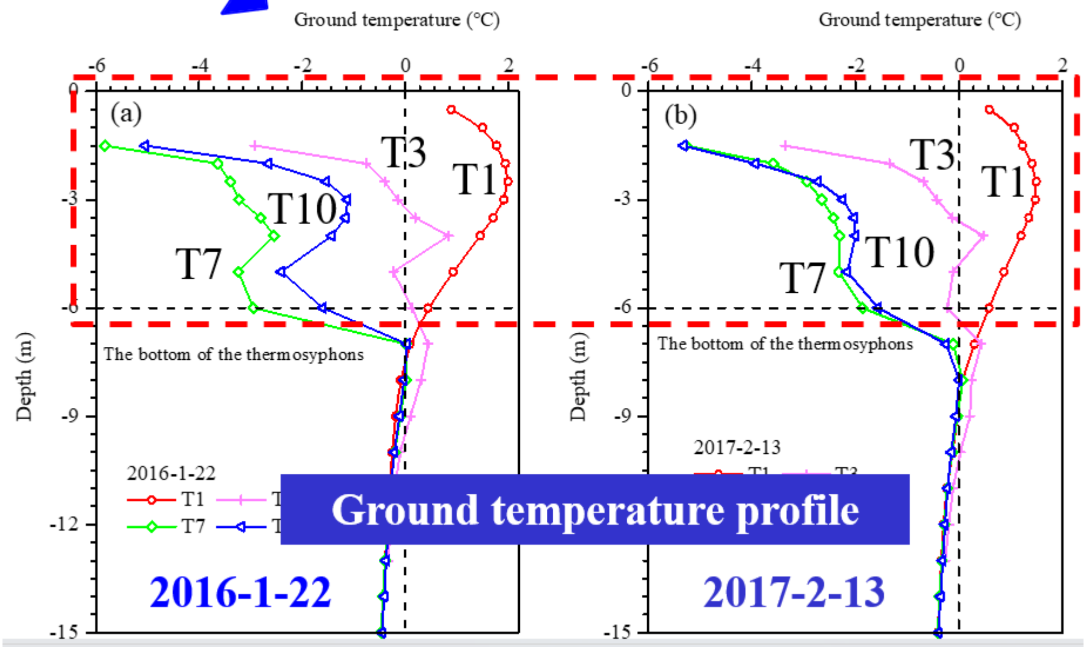
1) Insulated pipe: the permafrost table developed slowly, at an increasing rate of 0.093 m/a

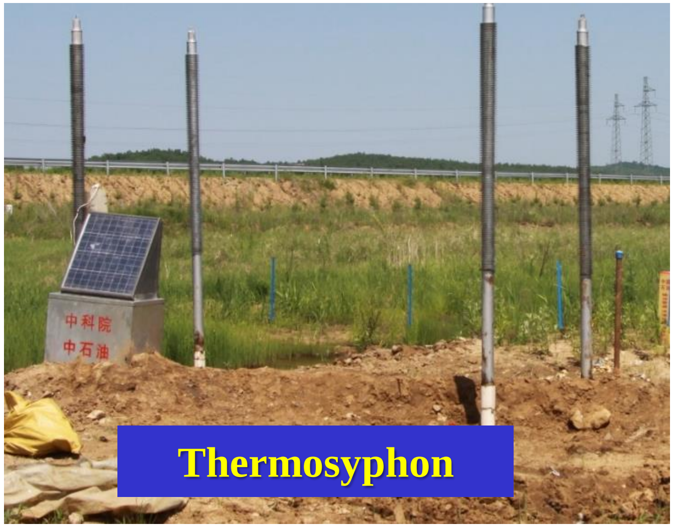
2) Uninsulated pipe: permafrost table deepened at a rate of 0.9 m/a

04 China-Russia Crude Oil Pipeline

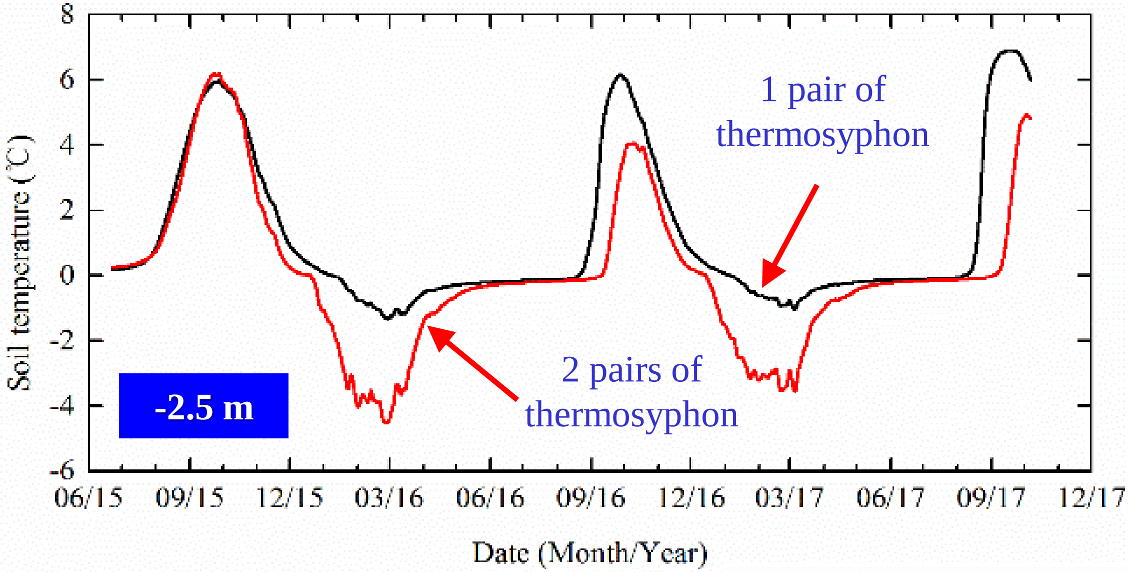
Thermosyphon------field measurements



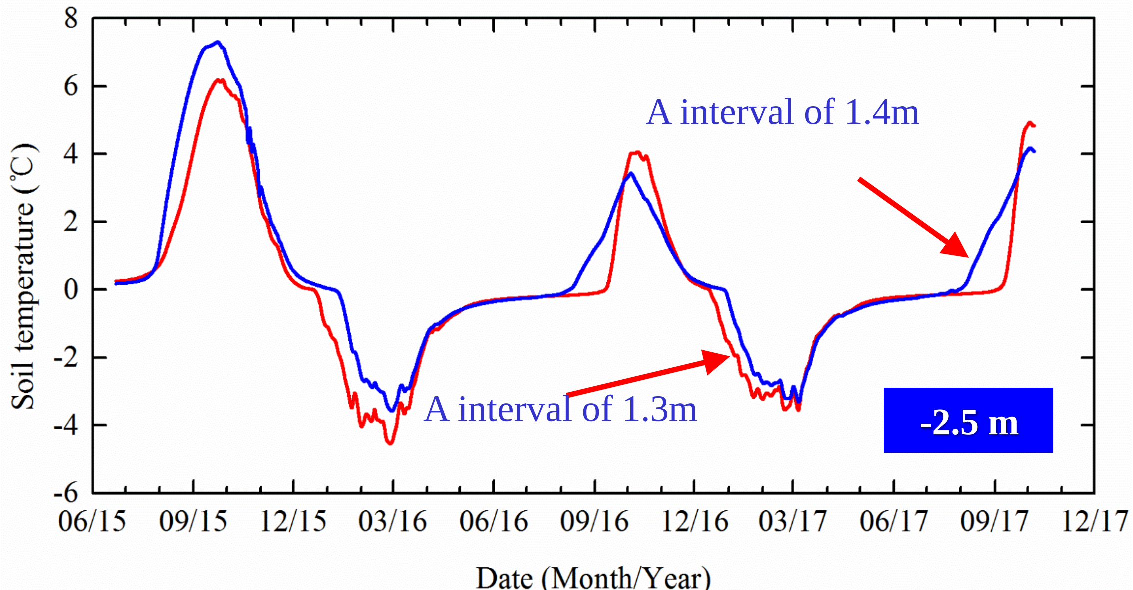




Thermosyphon------field measurements



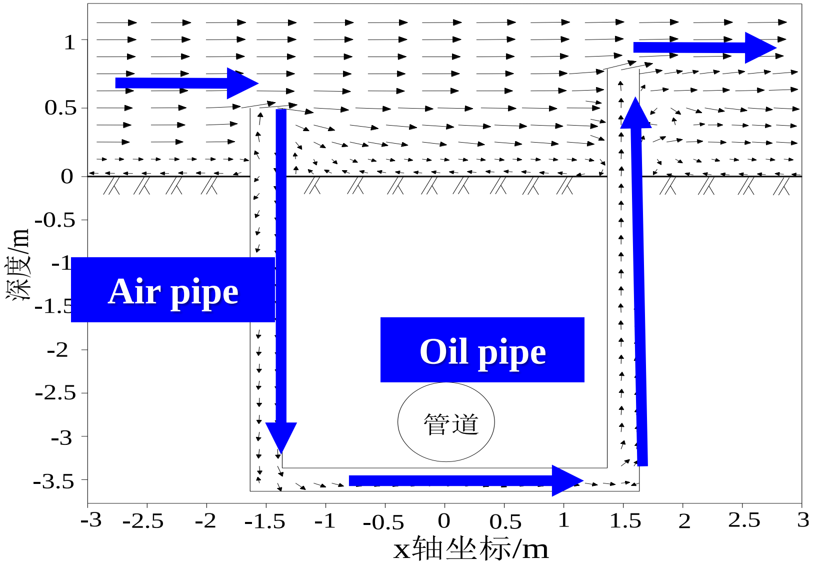
- Two pairs of thermosyphons have better cooling effect.



- The cooling effect depends on the number, interval and distance away form pipe center.
- It (thermosyphon) is a good mitigative measures.

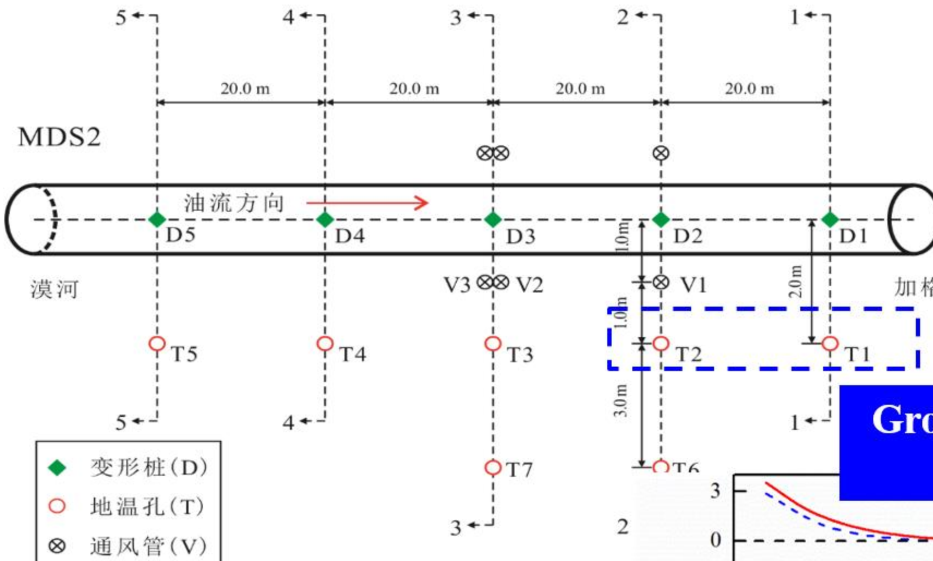
U-shaped air-ventilated pipes-----field test

Working principles: 1）Forced air convection in air pipe because of outer air flow. 2）Natural air convection just because of temperature difference between the upper and lower parts, without outer air flow.

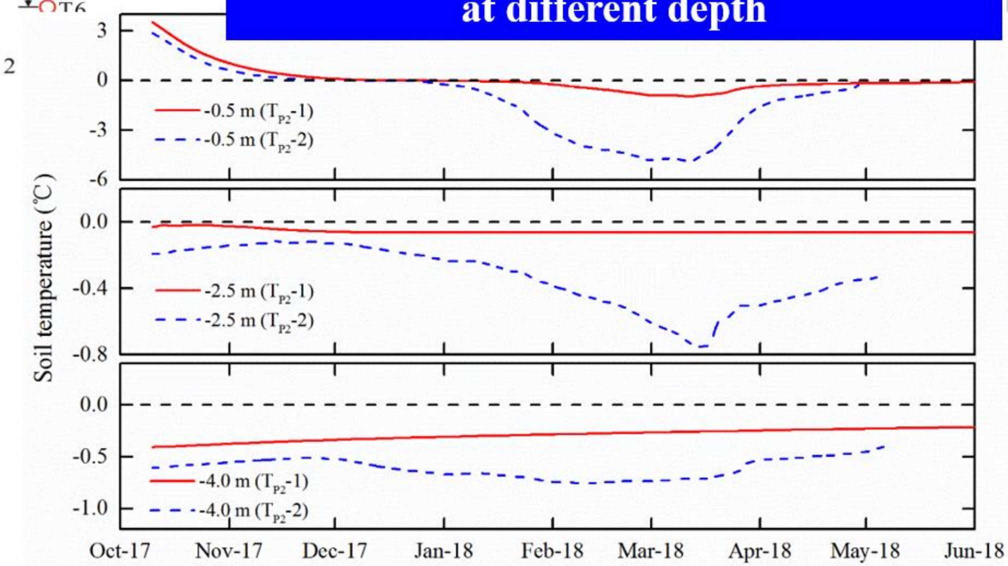


04 China-Russia Crude Oil Pipeline

Field measurements of ground temperature near the U-shaped air pipe

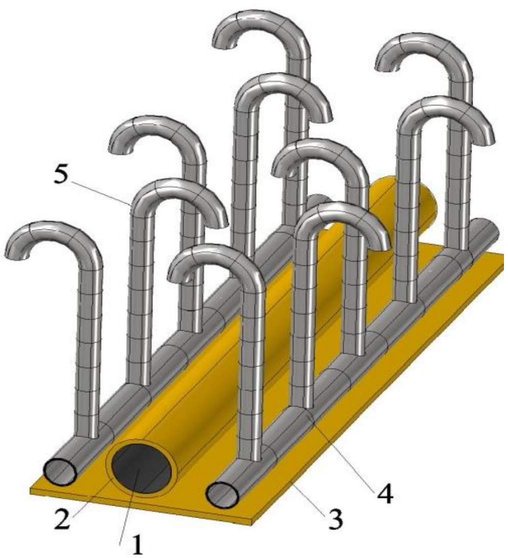


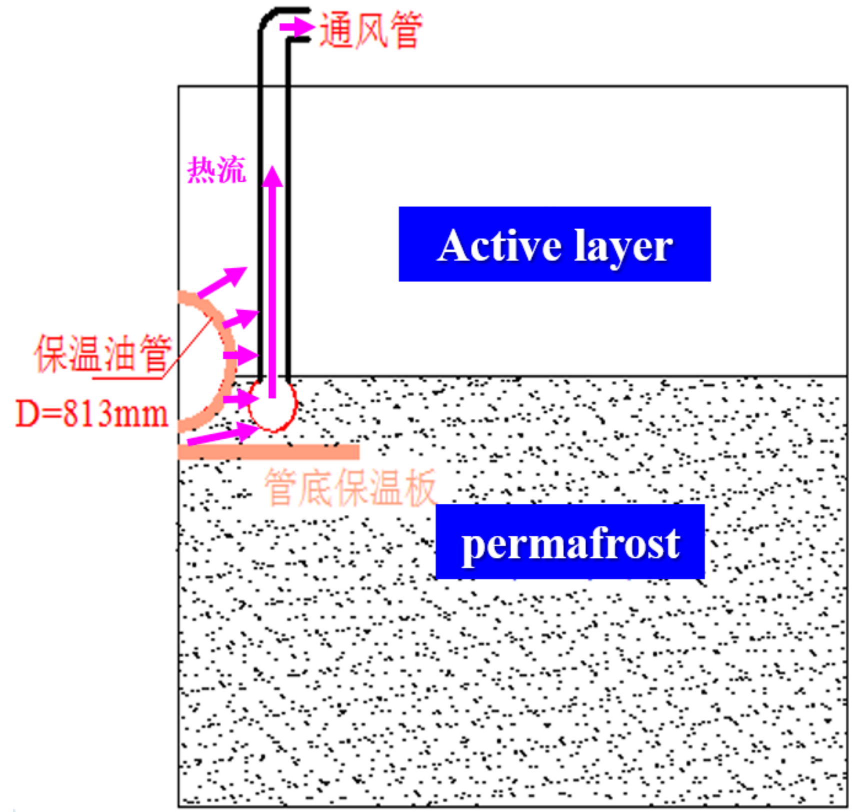
Ground temperature evolution with time at different depth



In winter, the ground temperature near air pipe is decreasing with time, showing the air ventilated pipe has certain cooling effect. Its cooling effectiveness needs long-term monitoring.

Longitudinal air-ventilated pipes----concept

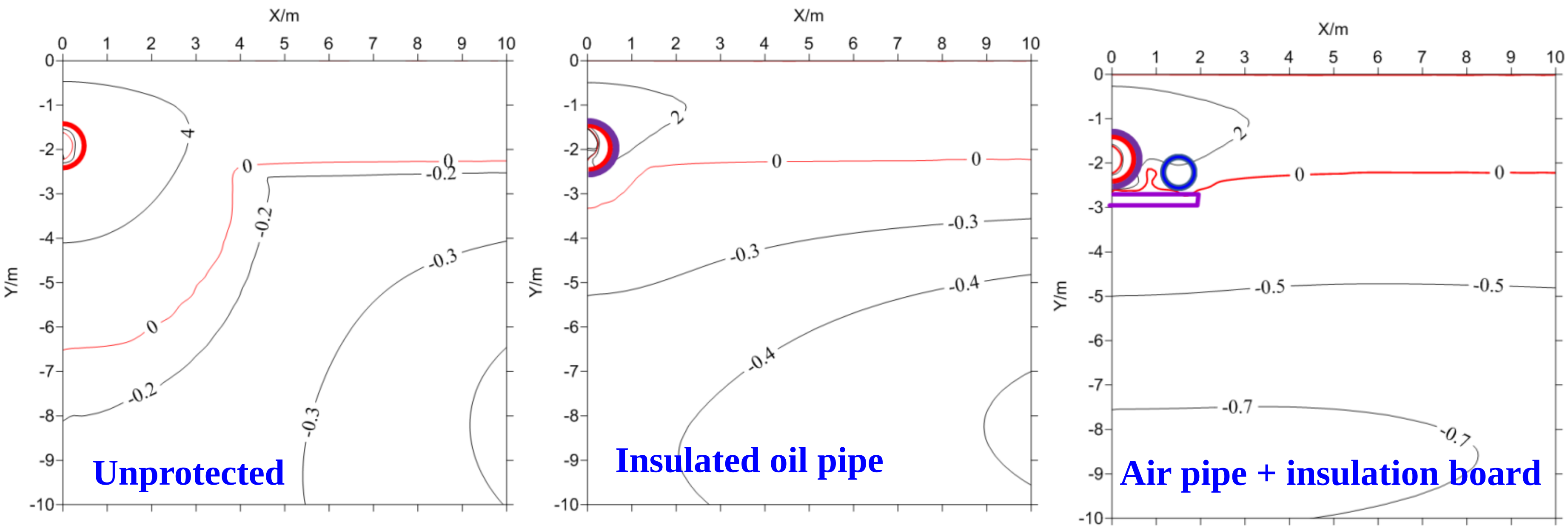




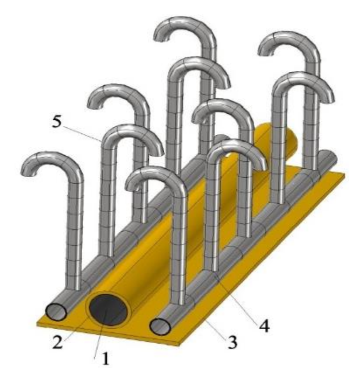
Ail flow in air pipe can remove the heat from the oil pipe in cold reason.

04 China-Russia Crude Oil Pipeline

Numerical results for the longitudinal air-ventilated pipe



- Insulation layer can reduce the heat entering into permafrost.
- The air-ventilated pipe can remove most of heat from the oil pipe



04 China-Russia Crude Oil Pipeline

Combination of thermosyphon and sandbag support----centrifuge model test

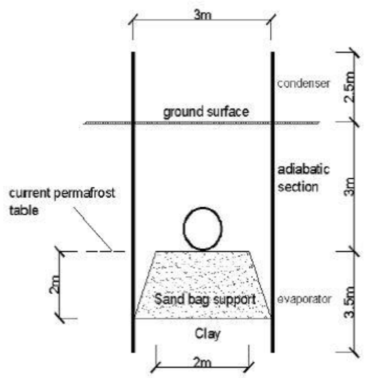


Figure 1. Cross section of the mitigation measure for thaw settlement

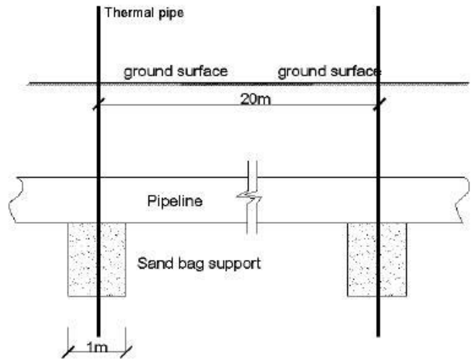
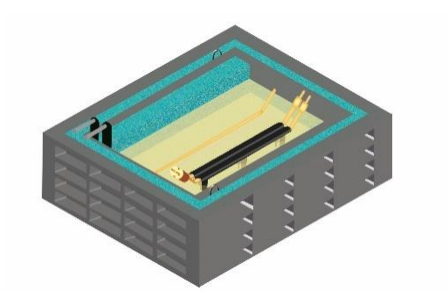
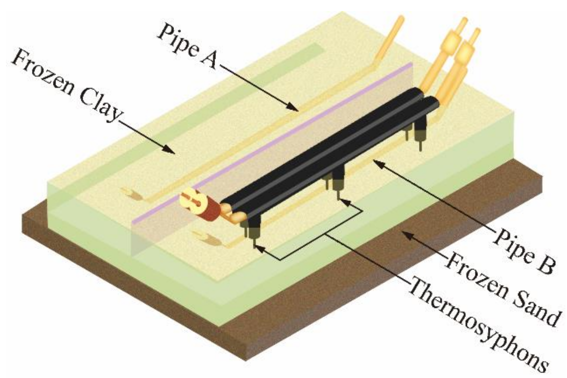


Figure 2. Longitudinal section of the mitigation measure for thaw settlement

Thermosyphon: cooling the surround permafrost

Sandbag: support the oil pipe.



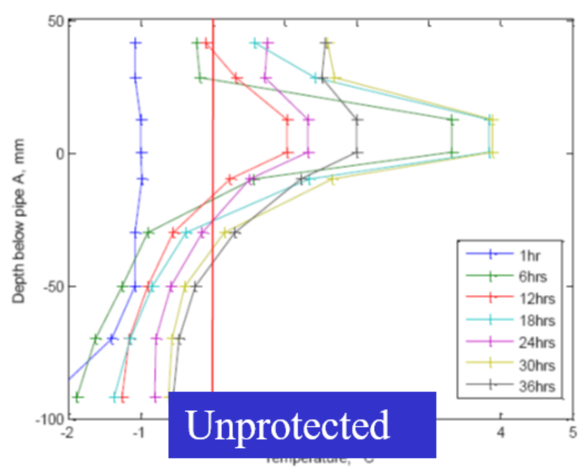


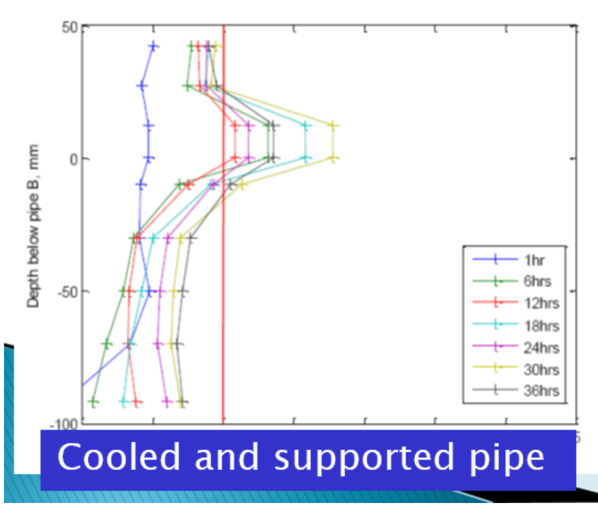
Centrifuge in C-Core in Canada

Scale law is 1:73

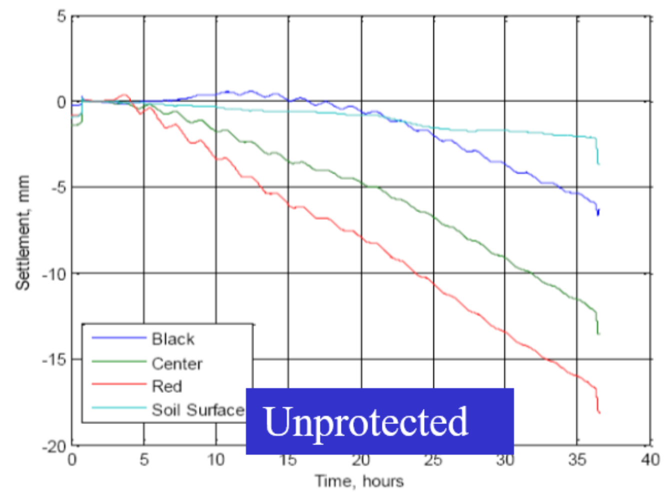
Results from centrifuge model test

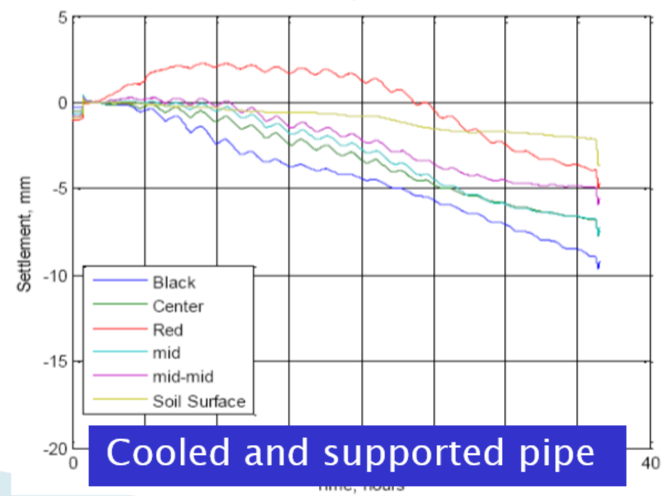
- Ground temperature profile



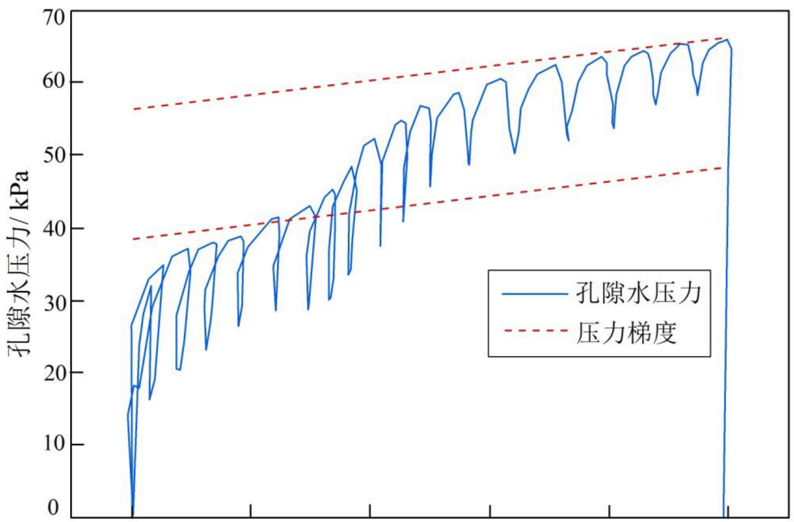


- Surface settlement

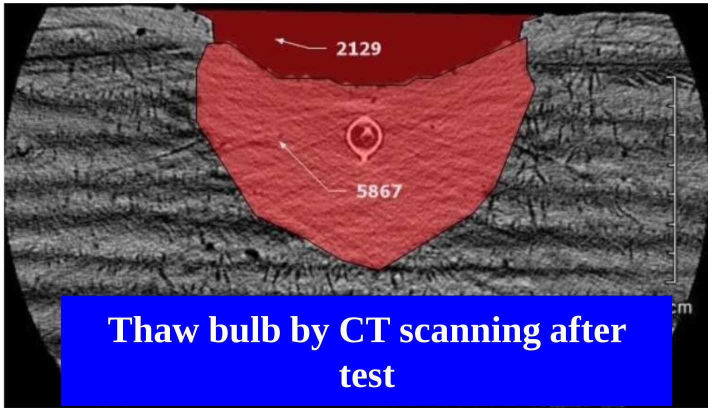




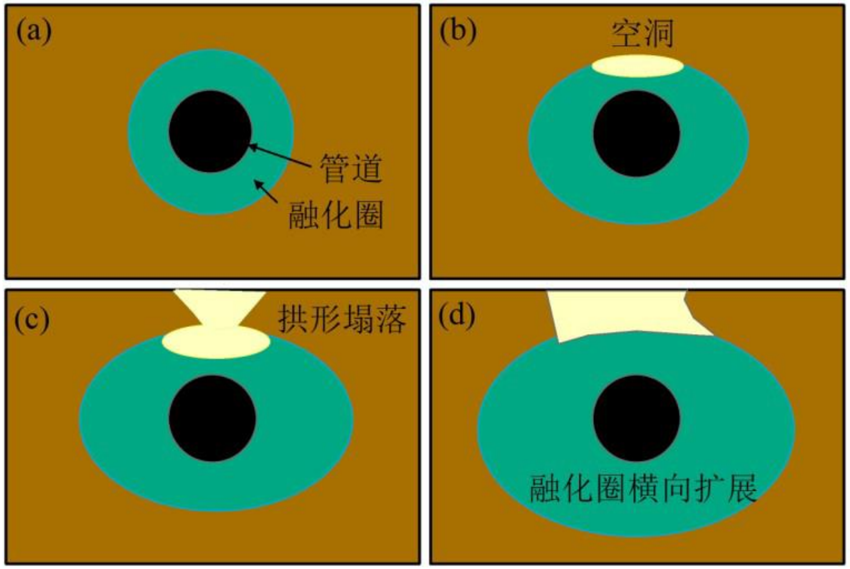
Results from centrifuge model test



Pore water pressure with freeze-thaw cycles



Thaw bulb by CT scanning after test



Schematic figure of thaw bulb development

Combination of Thermosyphon and sandbag can cool the permafrost and support the oil pipe, ensuing the safety of oil pipe

Thank You for attention!