Permafrost
National Research Council of Canada. Division of Building Research

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20386584
Technical Translation (National Research Council of Canada); no. NRC-TT-2006, 1981

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

TECHNICAL TRANSLATION
TRADUCTION TECHNIQUE 2006

PERMAFROST

Research Institute of Glaciology,
Cryopedology and Desert Research,
Academia Sinica, Lanchou, China,
1975

Canada Institute for Scientific and Technical Information

Institut canadien de l'information scientifique et technique

Ottawa, Canada
K1A 0S2

PREFACE

The People's Republic of China has about 22 per cent of its territory underlain by permafrost, making it third in area after Canada and the Soviet Union. Like the other countries of the northern circumpolar region, China is confronted by engineering problems in coping with permafrost during development of its northern and mountainous areas. Since 1975 when the first contact was made with Chinese permafrost workers, the Division of Building Research has endeavoured to keep abreast of Chinese developments in this field through the literature and by continuing these contacts.

This book is the first known general text on permafrost in China describing both scientific and engineering aspects in this country.

The Division is most grateful and wishes to express its sincere thanks to the Secretary of State Department who translated the book and to Dr. R.J.E. Brown of the Division of Building Research who checked the translation.

Ottawa
February 1981

C.B. Crawford,
Director.

TABLE OF CONTENTS

Page

Page

CHAPTER ONE

PERMAFROST PHENOMENA

In general, any type of ground which is at a temperature below $0^{o}C$ and contains ice is referred to as frozen ground. Ground which freezes in the winter and completely thaws in the summer is said to be seasonally frozen; that which freezes in the winter and does not thaw for one or two years is referred to as biennially frozen; and ground which remains in a frozen state for three or more years is called perennially frozen, or permafrost.

Since the surface layer in permafrost regions thaws in the summer and refreezes in the winter, it consists of seasonally frozen ground. This active surface layer can be further subdivided into two types depending upon its relationship to the underlying permafrost: 1) seasonally frozen layer - a layer which thaws in the summer but, on refreezing in the winter, does not come into contact with the permafrost table, because the soil beneath it is in a thawed state, or for some other reason; or 2) seasonally thawed layer - a layer which thaws in the summer but has complete contact with the underlying permafrost when it refreezes in the winter (Fig. 1).

Permafrost makes up approximately 26% of the total land area in the world.

The freezing and thawing of groundwater in permafrost regions gives rise to a series of strange and highly unique phenomena. These so-called permafrost phenomena pose a serious threat to the stability and safety of buildings and other structures in these areas.

I. Permafrost Phenomena Associated With Freezing

A. Pingos

In permafrost areas sudden spouts of water sometimes appear spontaneously over large tracts of frozen ground and are then followed by spontaneous explosions. The eruption of these so-called "water volcanoes" has been witnessed on occasion. At the northern foot of a mountain in the Tanglha Range there were elliptical mounds, about 1 m high and 2 - 3 m in diameter, which had radiating fissures at their summits. One year, on a day in August, a column of water about 2 cm in diameter suddenly shot out from the summit of one of these mounds, reaching a height of about 1 m. Then, 4 or 5 minutes later, the mound suddenly exploded with a thunderous clap, clumps of frozen soil and rock being thrown in all directions. Some of these clumps were as much as half a metre in diameter, and pieces of rock 10 cm across were blown 7 m into the air and 70 m away. After the explosion large volumes of water poured out of the remainder of the mound along with numerous air bubbles. Several hours passed before this activity began to subside, revealing a pit that had been formed where the mound had exploded. This pit was not very large. In the next few days, at distances ranging from 7 to 32 m from this pit, three more of these "water volcanoes" erupted one after the other, presenting a magnificent spectacle. These "water volcanoes" are unique types of pingos, referred to simply as explosive pingos.

Pingos generally are thrust up in the coldest months (Jan.-Feb.) of the year. The ordinary type of pingo completely disappears in the summer thaw and is thus called a seasonal pingo. It is formed when the ground freezes downward in the winter, compressing the space available for groundwater* and putting it

---

* Translator's note: Literally, "shrinking the excess water cross section." This apparently refers to a reduction in the total pore volume.

under pressure. During the freezing process, moreover, pore water migrates to the freezing plane[1], thus forming segregated ice. It is well known that volume increases as water turns into ice; this transformation, in other words, produces considerable lifting force. As the freezing extends downward through the ground, the lifting force of the ice layer and the hydrostatic pressure of the confined water increase, until their combined force exceeds the strength of the overlying layer of soil. At this point the ground surface will heave, forming a pingo.

Figure 2 gives a schematic diagram of a pingo that was formed in the northeast.** This pingo was 26 m long, 12 m wide and 2.7 m high, and had a fissured summit. Underneath the green surface layer of moss and lichen was a black peaty layer, and below this was a sparkling layer of ice which formed an arched shell. At the bottom of the cavity formed by this arch, crystal clear water flowed very, very slowly, and the glitter of the ice and water was so dazzling that it seemed to come from some mythical world.

This kind of seasonal pingo can be found throughout many types of land in permafrost regions - river floodland, marshland, benchland, slow mountain slopes and piedmont belts. Outwardly pingos are elliptical and mound shaped, and on the surface horizontal and vertical intersecting cracks appear. They range in diameter from a few metres to several dozen metres and in height from several dozen centimetres to two or three metres. Finally, they can be found solitary or clustered in groups. When the pingo arises under a stand of trees, the trees directly on top of the pingo will "stagger like drunkards", forming a so-called "drunken forest".

---

1) For a discussion of this phenomenon, see Chap. 2, Sec. 3.

** Translator's note: Usually refers to the area formerly known as Manchuria.

When the air temperature rises quickly in the thawing season, the upper frozen part of the pingo will thaw rapidly and lose its strength. When, concurrent with this, the internal stresses become sufficiently large, the pingo may spout forth water and become explosive as described above.

On the Tibetan plateau there also can be seen a perennial type of pingo which is formed by a supply of water originating below the permafrost layer.* These pingos far exceed seasonal pingos in scale; not only are they larger, but, as the name implies, they last throughout the year. The perennial pingo shown in Plate 1 occurs at the mouth of a channel opening onto an alluvial fan at a gap in the Kunlun mountains**; abruptly rising some 20 m above the surrounding plain, this pingo is 40 - 50 m long and more than 20 m wide. Covering its surface is a layer of clayey soil about 1.2 m thick, below which is an arch- or dome-shaped layer of pure ice. This dome of ice forms a cavity within which water flows throughout the year. After this pingo was artificially exploded open, smaller pingos, along with icings***, were observed to form every year at its centre (Plate 2).

A type of spring pingo also can be formed under the influence of human activities. In a certain area in the north-east one year in April, during the thawing season, a railway roadbed began to steadily expand and rise up. By the middle of May it had risen 1.2 m in some places, leaving the two tracks

---

* Translator's note: The footnote which appears at this point in the original text merely explains a Chinese term for Chinese readers.

** Translator's note: An inference; literally, "at Kunlun mountain gap-flood fan-apron-channel mouth".

*** Translator's note: Literally, "ice vertebra". From subsequent uses of the term this would appear to mean icings and not ice wedges.

at different heights, the difference ranging from 70 to 100 mm. Ground heaving such as this can be dangerous to railways and to other vehicular traffic. Digging down through the section which had risen, investigators found segregated ice 1 m below the surface of the roadbed. Water flowed out when the depth of excavation reached 1.35 m. Two minutes later there was a sudden thunderclap-like noise, and a column of water about 0.7 m in diameter spurted up, to a height of about 0.6 or 0.7 m above the ground surface. This column promptly began to sputter, giving a fireworks-like display, and water rushed turbulently out of the excavated hole and flooded the surrounding area (Plate 3). At the same time a roadbed in the vicinity of this heave suddenly sank. A half hour later the water column fell, and after an hour the ground had more or less returned to its previous level, the mound sinking back 1.2 m. The railroad tracks, meanwhile, had dropped down 710 mm.

The formation of this type of spring icing is related to the construction of railroad embankments. Generally speaking, embankments act to maintain the temperature of the underlying ground, thus serving to reduce the depth of thaw in the spring. Moreover, the loads and vibrations repeatedly conveyed by passing trains act to compress the underlying soil, thus impeding the drainage of suprapermafrost water. In the winter the ground surface begins to freeze, and this process subjects the suprapermafrost water to increasing pressure as the frost extends downward. Because of the strength of the overlying ground, which has already frozen, the hydrostatic pressure of the confined water cannot force the ground upward. However, when the surface thaws the following spring, the strength of the upper layer of ground diminishes to the point where the pressure exerted by the trapped water becomes sufficient to cause the ground to heave. This forms a spring icing (Fig. 3). Excavation of the upper layer of this feature created a weak spot in the case discussed, allowing the confined water to break through and rush out, leading to the deformation of the roadbed.

B. Icings

In permafrost areas one can sometimes see, even from very great distances, an immaculate, dazzling body of ice occupying a riverbed, floodland, benchland, the borderland around a piedmont alluvial fan, or an intermountainous depression. Such a body of ice is called an icing.

Icings differ in size and in shape. Some are only 1 - 2 m in diameter, while others can be as much as 1 - 2 km. Some are ellipitical and mound-shaped, while others are elongated and shaped like a bugle or trumpet (Plates 4 and 5). Sometimes icings occur alone, other times in groups.

Icings can be classified into two basic types according to the source of supply of their water - i.e., river icings or spring icings. In the winter, after the upper layer of a river freezes, the water underneath has less space to flow and is consequently subjected to increasing pressure. As the upper frozen layer becomes thicker, the hydrostatic pressure below rises, eventually reaching the point where the water breaks through a weak area of the ice and overflows. Freezing of the overflowing water creates a river icing. River icings usually are distributed on floodlands and riverbeds. Spring icings are formed in a similar manner when groundwater under pressure overflows and subsequently freezes. Most spring icings occur on the land bordering piedmont alluvial fans, on the base of mountain slopes, in depressions, etc.

The vast majority of icings last only one year. They develop mainly from January to April each year, ceasing to grow sometime around the last week of April. At this time cracks and channels begin to appear in the surface (Plate 6) of the ice, which then gradually comes to pieces, completely disappearing around August or September.

A point worth noticing here is that the majority of icings which occur along railways or near other engineering or construction works, arise only after the work has been undertaken. This is because, in many cases, the engineering or construction work disturbs the channels through which groundwater moves, and proper measures are not taken to ensure adequate drainage of the area. For example, when soil is excavated to build up a roadbed, it sometimes happens that the digging will destroy vadose passages, with the result that groundwater will flow out over the soil surface near the excavation. This water freezes with the coming of winter to form an icing, and as new water comes out of the ground and freezes the body of ice expands, gradually spreading over the road surface in some cases and creating a hazard. Moreover, if the flow of groundwater is blocked by the cutting of a railroad subgrade, the water may flow up and freeze to the tracks themselves, sometimes even submerging them under ice.

Icings pose a grave danger to all types of structures. Sometimes the growth of an icing will cause a railroad bed to rise several centimetres, or even on occasion two to three metres; this can seriously disrupt communications. A section of the railroad passing through the Great Khingan Range runs just below a gently sloping hill luxuriantly covered with tall, water-logged grass. Below the railway tracks on the other side is a river. After the ground surface freezes in winter, the water which ordinarily would be flowing freely on the surface passes underground (enroute to the river), only to be obstructed in the vicinity of the railway tracks. The trapped water then builds up pressure. When the hydrostatic pressure reaches a certain point, the water suddenly bursts through the overlying frozen soil and shoots out over the surface, sometimes reaching a height of as much as 2 m. The fissure resulting from the water's breakthrough will gradually freeze over as the air temperature falls and as the hydrostatic pressure of the remaining water diminishes. After more time passes, however, the hydrostatic pressure of the water beneath the frozen surface will again increase and there will eventually be another sudden eruption. This cycle repeats itself throughout the winter, with large volumes of groundwater being shot up to the frozen surface. This water itself freezes to form icings, which spread over the surrounding area. One such icing covered as much as 500 m of track. Icings can rise anywhere from 20 to 200 mm in one 24-hour period. In just one winter a low embankment originally 0.5 m high became completely covered with ice.

C. Rock Streams in Cold Regions

When people describe their encounters with bitterly cold conditions, they often use the expression "ice as cutting as a knife, frost as cutting as a sword". In fact, however, ice and frost are even "sharper" than knives and swords, since they are able to split hard rock and reduce it to fragments.

Everyone knows that exposed bedrock is composed of different minerals. Because different minerals have different coefficients of expansion, they expand and contract at different rates as the temperature rises or falls. This process produces unequal internal stresses within a body of rock, leading to fractures. After water from rain and snow seeps into these fractures and subsequently freezes, a tremendous expansive force is generated owing to the expansion of volume that accompanies freezing. An expansive force of such magnitude is sufficient to enlarge the fractures in any rock, no matter how hard, and this enlargement in turn permits even larger volumes of water to run in. Repeated cycles of freezing and expanding force the fractures in the rock to lengthen and widen more and more, eventually splitting the rock into large numbers of fragments. The detritus produced by this weathering process in cold regions is transported by gravity and flowing water, and ends up accumulating in different landforms at different locations. A field of detritus appearing on a mountain top is called a "rock sea" (or felsenmeer) (Plate 7); one appearing on a mountain slope or in a mountain furrow is called a "rock stream" or "stone river", provided that it has the elongated shape of a stream or river (Plate 8); one appearing at the base of a mountain or at the mouth of a channel is called a "rock waste cone" if it is fan- or cone-shaped.

When a mass of rock fragments moves down a mountain slope, construction and engineering works are often seriously endangered. In the Great Khingan Range there is a weathered mountain about 100 m high, 200 m wide, and having a 30 - 40° slope covered with trees, moss and lichen. This mountain was judged to be stable, so construction of a railway was approved and earth was excavated in the area. However, the assumption that the mountain was stable turned out to be erroneous, as an entire felsenmeer at its summit came sliding down during the construction work, necessitating a change in the course of the railway. Thus, when projects are still in the planning stage, sufficient heed must be given to the possible instability of rocks on mountains in cold regions.

D. The Effect of Frost Heaving on Buildings

When water contained in foundation soil freezes it expands in volume. When this happens and the total load of a building is insufficient to counteract the expansive force generated by the freezing of (the ice in) the foundation soil, the base of the building will then be pushed upward. The consequent unequal elevation of the base at the various sides of the building may then cause cracks to appear, or may even make the structure tilt or topple over.

In permafrost regions and in a number of other areas in our country which experience relatively deep penetration of seasonal frost, quite a few buildings are damaged every winter - because, first of all, they were built on sites which expand markedly when freezing sets in, and secondly, because effective countermeasures were not taken at the outset. The expansion of the ground underneath acts on the base of a building in an unequal manner, causing deformation - walls develop cracks, doors and windows go askew or lean out from the walls, brick or stone steps are raised up, and so on. Plate 9 shows the state of a building in one of these areas which was damaged by frost heaving of this sort. This force is the main cause of winter damage to houses and other buildings in areas with relatively deep seasonal freezing.

Frost heaving of railway roadbeds usually occurs when a shallow cut has been made in fine grained soil or when the embankment is low and built on grassy, water-logged marshland. These types of soil generally are sandy or clayey and they frequently have a high moisture content. When this moisture freezes the railroad tracks are very easily elevated to different heights, disrupting rail traffic.

As for the construction of bridges and pipelines in permafrost regions, it should be mentioned that wooden bridges are quite susceptible to damage by frost heaving; in fact this can be regarded as the primary type of frost damage to wooden bridges. Drainage pipes in these areas frequently become disjointed and jagged, and the end and wing walls are pushed outward and are cracked as a result of the freezing and expanding of the foundation soil. Figure 4 shows the cracks in the end and wing walls of a conduit in one of these areas.

II. Permafrost Phenomena Associated with Thawing

Various types of ground ice occur in permafrost.

In regions characterized by clayey soil, which has a relatively high water content, the upper portion of the permafrost generally contains a thick layer of ice, either formed purely of ice or consisting of ice admixed with detritus and lumps of soil. The thickness of this layer of ground ice varies widely, from 20 or 30 cm to 4 - 5 m. The upper part of this ice layer comes into contact with the seasonally thawed layer, while the lower part merges with the permafrost table. The ice generally is distributed either in a lens or in a layered form (Plate 10), and its extent is often suggested by the overall surface relief. Because this sort of thick ice layer is not far beneath the ground surface, it can very easily melt under the influence of natural or artificial factors. Melting of this ground ice can produce thaw flow*, solifluction and thaw settlement** among other phenomena characteristic of permafrost regions. These are all extremely dangerous for engineering and construction works.

A. Thaw Flow

On the slope of Fenghuoshan, a mountain on the Tibetan plateau, workers once excavated dirt and left a single small pit. In just a few months time this pit had changed into a large furrow several dozen metres long. After three years this furrow had grown even longer and wider, and had extended all the way to the mountain top, leaving the mountain "utterly ragged and broken down", as the saying goes. The old proverb "the hole of an ant can destroy a mighty dike" must indeed be true. This kind of phenomenon is known as thaw flow. How is it produced?

---

* Translator's note: Literally, "thaw-slip-collapse".

** Translator's note: Literally, "heat-thaw-subsidence".

After the excavation was finished, subsoil ice was left exposed along the walls of the small pit. This ice melted when the thawing season arrived, causing the upper soil and grass cover to lose its support and collapse under its own weight. This material fell down the slope (of the pit), covering the layer of ice which had lain exposed but at the same time newly exposing the subsoil ice in the area just above the pit. The cycle then repeated itself, producing a new collapse, new exposure and so on, extending upwards until a more general collapse resulted (Plate 11). Since these thaw flow slides occur step-by-step, a terraced type of surface is often left behind. Moreover, the collapsing proceeds mainly from bottom to top, with only slight lateral development, and this means that the debris strewn down the slope has a tongue- or winnow-shaped outline.

When a retrogressive thaw flow slide of this sort occurs on a slope having a relatively thick layer of ground ice, it may well be attributable to the effect of human activities (e.g., engineering work or excavation of soil). Or it may be the result of natural causes (e.g. fluvial erosion of the slope). Muddy material from the thaw slide often will flow down and cover the surface of a road, block culverts, accelerate the softening and subsidence of a roadbed, etc. Thaw flow thus frequently affects communications.

B. Solifluction

The structure of fine grained soil on gentle slopes is destroyed by freezing and thawing action. As this type of ground thaws, moreover, the water that is released is unable to infiltrate downwards owing to the underlying layer of frozen ground. As a consequence the surface soil on such slopes becomes saturated and can turn to sludge, which, under the influence of gravity, will slide over the frozen layer and work its way down the slope. This phenomenon is called solifluction.

Two types of solifluction can be distinguished, one involving the surface layer and the other, deeper layers. Surface solifluction occurs in the upper portion of the thawed layer. It is widely distributed, but occurs on a comparatively small scale. Finally, this type of flow is relatively fast. Deep-layer solifluction, meanwhile, usually occurs on gentle slopes ($<10^{\circ}$) which do not drain well. A layer of underground ice or permafrost serves as a slip plane. Flows of this type can be several hundred metres long and several dozen metres wide, and they can give the soil surface a staircase-like appearance. Flow in these cases is slow and not easily observed.

The dangers posed by solifluction do not arise as quickly as those associated with icings or pingos, nor are they as serious. Although solifluction does not pose an immediate threat, it can destroy buildings and other construction works with the passage of time. For example, solifluction on a mountain in one area, working slowly but irresistibly over a three-year period, pushed railroad tracks 18 m down the slope.

C. Thaw Settlement

The depth of seasonal thaw increases when the temperature of the surface soil is raised as a result of natural (e.g. warm weather) or artificial (e.g. cutting trees, burning wood to heat houses, etc.) factors. This downward extension of thawing means that the ground ice or permafrost partially melts, causing the overlying soil to settle because of its own weight or because of external loads. Such a phenomenon is called thaw settlement.

Thaw settlement that occurs under natural conditions often will be manifested as a hollow, a lake basin bog, a staircase-like relief, etc.

Human activities very often are the cause of thaw settlement. In permafrost regions almost every construction project - railroads, roads, buildings, bridges, pipes, etc. - can give rise to such settlement when proper countermeasures are not taken, and this negligence can lead to deformation or destruction of the completed structures. Experience has shown that settlement caused by melting of ground ice is a major threat to all types of construction works in permafrost areas.

A so-called thaw basin (Fig. 5) usually develops under heated houses or other buildings. As the soil within this basin thaws it will subside and be compressed, under its own weight as well as the weight of the building above, and this subsidence frequently leaves the foundation uneven. When the unevenness passes a certain point the building will be affected, eaves twisting every which way, doors and windows going askew, walls being cracked, etc. In severe cases the building itself will tilt and may eventually topple over and become totally unusable.

In permafrost regions the main cause of damage to railway roadbeds is thaw settlement. Three types of settlement can be distinguished:

Compression Settlement

Mainly occurs in marchland or areas of tall grass where water accumulates.

Because tall grass, peat and so on are readily compressed, the weight of embankments and the vibrations and loads of passing vehicular traffic will eventually make the soil more compact, leading to subsidence of the roadbed. This subsidence may amount to as much as 45 - 70% of the thickness of the entire peat layer. This type of settlement often stabilizes during the construction period, or after a year or two of operation of the completed road, etc.

Gradual Settlement Over the Years

This type of settlement occurs in areas with underground ice.

Removal of the grass cover or peat layer during construction, or the accumulation of water on top of a completed road embankment and its subsequent infiltration downward, can cause ground ice to slowly but steadily thaw, and this in turn can cause the roadbed to gradually subside year by year. For example, in one area water accumulating on an embankment 1.8 m high caused ground ice to melt, and this thawing led to an average annual decline of 500 - 600 mm in the embankment, the amount of subsidence reaching 1000 mm in rainy years. Subsidence of this type makes road maintenance work very troublesome.

Sudden Settlement

Sometimes roads are built over clayey, ice-rich soil. When this ice melts the soil reaches a supersaturated state, and it may almost entirely lose its bearing capacity. In addition, when the depth of thaw is unequal on the two sides of the embankment, a slanting, frozen slip plane is formed beneath the roadbed. Under these conditions the vibrations and loads resulting from passing traffic may force the supersaturated clayey soil to be squeezed out along the frozen slip plane, so that a sudden slump will occur in an embankment that had been gradually subsiding during a warm period. Sudden settlement often will cause vehicles to lose the road and have accidents.

In the Great Khingan Range subsidence of embankments is due in the majority of cases to melting of a thick layer of ground ice. There can be no question that thaw settlement is a major cause of damage to railroads in permafrost regions.

Generally the buttresses of bridges are buried fairly deep; furthermore, they are cold structures. Settlement, therefore, seldom affects the span of a bridge. However, when piping is laid in the northeast, where ground ice abounds, the permafrost table may drop if the ground is excavated improperly. Melting of the ground ice can then cause the pipes to subside. Because the foundations supporting the ends of pipes are buried relatively deep, the ends will sink less than the middle section. This results in pipes sagging in the middle (Fig. 6) and leaking from the bottom.

Water pipes can become disjointed because of unequal subsidence, or may even be cracked apart. Thus settlement can damage them in much the same way as frost heaving. The difference is that one occurs in regions characterized by ground ice and the other in areas with fine grained soil having a relatively large water content.

III. Commonly Observed Types of Frost Damage in Buildings and Engineering Works

A. Water Entering Heated Buildings

Heated buildings maintain above zero (^{o}C) temperatures year-round so that some of the ground underneath them remains in a thawed state year-round, too. This thawed ground is shaped like a basin (Fig. 7). When groundwater is present in the soil above the frozen layer, it is able to flow freely in the summer; however, once winter comes, the ground surface all around the building freezes up, and this compresses and confines the water in the soil. At this time only the ground beneath the building is still in a thawed state and is relatively pervious. The hydrostatic pressure of the groundwater increases as the frost extends downwards, and eventually the point arrives when the pressure exerted by the confined water exceeds the resistance of the building's foundation soil. At this point water will burst through the floor of the building and flood the rooms, leaving those in the building no choice but to dig a hole or pit indoors to hold the water, day and night scooping it up in pails or buckets and taking it outdoors. In some cases as much as 48 buckets of water will need to be removed each day, and this is a great inconvenience.

B. Bar-Shaped Foundations and Inward Curving of Outer Walls of Buildings

In winter, when the ground surrounding a building freezes up, pressure will be exerted horizontally against the building's foundation soil, pushing it inwards. Since the soil beneath the building will still be in a thawed state, its strength will be far less than the inward pressure of the freezing and expanding soil surrounding it. As a result the foundation soil will be pushed inwards from all sides when its strength is no longer sufficient to resist those pressures. This type of deformation of the foundation inevitably leads to concave bending of the outer walls of the building above.

C. Frost Boils

Frost boils can occur in seasonally frozen regions for a variety of reasons. One major cause is the wintertime accumulation of water in fine grained soil under roads (i.e. the migration of water up toward the frozen surface). This water turns to ice. During the winter the road surface, freezing and expanding slightly, will frequently develop cracks, but this in itself will not affect traffic. However, when spring arrives and the roadbed begins to thaw, the accumulated ice also melts and, owing to the inferior drainage capacity of fine grained soil, the roadbed will reach a saturated or supersaturated condition and its bearing capacity will be sharply diminished. At this point the weight from the repeated passing of vehicles will cause the road surface to change. If light vehicles are on the road the pavement will simply become soft, restricting the speed of traffic, but heavier vehicles will cause the soil beneath the road to be pushed out onto the surface, covering the road with mud. Vehicles can become mired in the mud, bringing traffic virtually to a halt.

Frost boils similar to the types described above can occur on roads in permafrost regions, too. They can be due to the causes cited above or to other factors. Take, for instance, a road passing through a region with abundant ground ice. If for some reason the depth of thaw increases one year, the ground under the road may become saturated with water when the ice melts, and the repeated pressure exerted by traffic on the road can cause a deep frost boil to form.

IV. Stopping up of Drainage Pipes and Water Pipes

A drainage pipe often will become blocked with ice when it is conveying spring water from a slope above it, particularly if the flow is slight. Under these conditions the onset of winter will mean that water which has not yet discharged from the pipe will freeze inside it. This layer of ice will gradually become thicker, eventually stopping up the drainage pipe. Moreover, since water expands in volume when it freezes, drainage pipes stopped up with ice are frequently cracked open.

The temperature of groundwater is very low in permafrost regions. Water flowing through a water pipe in winter constantly loses heat to the cold pipe wall. When the temperature of the water falls below $0^{\circ}C$, the pipe will become lined with ice. If the ice on the pipe wall grows thicker it may obstruct the flow of water, eventually stopping up the water pipe altogether and possibly cracking it open. The result, of course, is an interruption of water supply.

All of the various permafrost or frozen ground phenomena outlined above pose threats to engineering and construction works, but, (as Chairman Mao has written), "Under certain conditions, good results can be obtained from bad things, and bad things can also be obtained from good things." In their struggles against all these kinds of frost damage over many years, the broad masses of workers, peasants and soldiers have gained considerable experience in turning these misfortunes to advantage.

For example, icings and pingos are indeed dangerous to buildings and engineering works. Nevertheless, they can serve as excellent indications of where supplies of water may be found in frozen ground regions characterized by a dearth of water sources. Pingos and icings are very easy to spot in winter, and below these it is usually possible to find groundwater. When warmer weather arrives frost mounds and icings disappear, but their activities leave behind traces of their presence. After a mound disappears, for instance, a "druken forest" created by it does not disappear. Sparsely spaced, dwarfishly small or even withered plants can indicate that an area was covered with a sheet of ice; some icings, furthermore, leave white markings on the bark of trees, etc. All of these signs can be put to use to help find water. Pingos, which do not disappear even in warm weather, can serve as reliable indicators of water sources. In March, 1958, an icing was discovered in a certain area in the Great Khingan Range. Trees were found caught in a layer of ice 3 - 4 m thick, and no vegetation at all was growing in a belt 50 - 100 m wide and about 200 m long. From this icing it was discovered that spring water was rising to the ground surface along a fissure. As much as 650 tons of spring water per day was found to issue from this crack, even in dry periods. This water was of a very high quality, suitable for drinking or for industrial use. Also in the Great Khingan Range a pingo formed by artesian water was discovered near a town. This mound was 90 cm high and had water issuing from its fissured summit, spurting about 10 cm into the air. Investigation revealed that over 400 tons of water per day issued from this source. This high-quality, soft water has already become a major supply source for this town.

In addition, the considerable strength of frozen ground can be utilized to build roads on marshland. The low temperature of frozen ground can be utilized to construct natural refrigerators within the soil itself, and low-temperature laboratories can also be built in this way. The impermeability or poor permeability of frozen ground can be used to construct dams or intercepting drains in the winter. The excellent bonding properties resulting from the freezing of groundwater can be utilized to establish wells in areas of shifting sand. The strength produced by the freezing of a building's foundation to underlying frozen ground can be utilized to support the weight of buildings; building foundations, furthermore, can be placed right in the permafrost layer itself and the strength produced by the freezing of a building's foundation to permafrost can be used to combat the effects of the heaving pressure within the seasonally frozen layer. In short, there is really no reason to fear permafrost. So long as we thoroughly understand the laws governing its behaviour, we can control it and prevent the damage it would otherwise cause; and we can even turn it to advantage.

CHAPTER TWO

THE DISTRIBUTION AND FORMATION OF FROZEN GROUND

1. The Distribution of Frozen Ground in China

Before introducing the distribution of frozen ground in China, we will mention the two parameters that determine the distribution of frozen ground: the temperature and the thickness of the frozen ground layer.

As we all know, the temperature of the atmosphere within a year varies from month to month. Similarly, the temperature of a frozen ground layer above a certain depth also varies from month to month. We now define the yearly ground temperature differential as half the range of change of the ground temperature within a year. In Figure 8, A_1 and A_2 represent the depth where the respective yearly ground temperature differentials are Z_1 and Z_2. The yearly ground temperature differential is greatest in value at the ground surface, and decreases as the depth increases, until at a certain depth its value becomes zero.

The depth at which the annual ground temperature fluctuation is zero is termed the depth of zero annual amplitude. (Depth h_2 where b is in the figure.) One can safely say that the ground temperature below this depth does not vary within the year. In the Greater Khingan Mountain region, the depth of zero annual amplitude is usually between 15 and 20 m, while in the Chinghai-Tibet plateau it is usually between 10 and 15 m.

The value of the ground temperature at the depth of zero annual amplitude is called the average annual ground temperature; t_{ep} · t_{ep} is negative in the region of perennially frozen ground. The lower the value of t_{ep}, the greater the thickness of the perennially frozen ground, and an increase of t_{ep} indicates degradation of the perennially frozen ground while a decrease indicates aggradation. The value of t_{ep} is positive in non-permafrost regions.

In a permafrost region, there is a depth below the ground surface where the highest value of the ground temperature is zero. (This is shown in the figure as depth h_1 at point a.) The ground above that depth thaws in the summer and freezes in the winter, hence is a seasonally thawed layer. The ground below that depth remains frozen all year round, hence is perennially frozen. Therefore we term this depth as the bottom of the seasonally thawed layer or the upper limit of the perennially frozen ground. The depth h_1 is then the thickness of the seasonally thawed layer, or the depth of the upper limit of the perennially frozen ground.

The value of the ground temperature in the lower part of the permafrost layer is zero degrees (for example, at depth h_3 at point c). This depth is called the lower limit of the perennially frozen ground, above which is the permafrost and below which is thawed ground.

The distance between the upper limit and the lower limit of the perennially frozen ground is its thickness (as H in the figure).

In the permafrost region there may be areas without frozen ground. The latter is called the thawed region and it consists of two types: one in which the thawed ground starts from the ground surface and goes right through the whole frozen ground layer, this is called the thoroughly thawed region; and the other is thawed ground but does not penetrate the frozen layer, such that there is frozen ground below the thawed ground, this is called the nonthoroughly thawed layer. Usually a thoroughly thawed region is formed under the beds of big rivers, lakes, near hot springs and under big heated buildings, while nonthoroughly thawed regions are formed under beds of small rivers, some beaches along the rivers, and under ordinary sized heated buildings.

In China, perennially frozen ground is distributed in the northeastern part, north of the Greater Khingan Mountain and north of the Lesser Khingan Mountain, in the Chinghai-Tibet Plateau, as well as in the western high mountains such as Tienshan, Altai Mountain region (see Figure 9). The total area of permafrost in China is about 18.5 to 19 million square kilometres, about 19 to 20% of her territory. The distribution of the perennially frozen ground is governed by latitude horizontally, and by altitude vertically.

The highest latitude of permafrost in China is in the northeastern region. Here the winter is 8 months long while the summer is very short, with the presence of dense forests. All these contribute to advantageous conditions for the existence of permafrost. From the northern part of this region southwards, the distribution of permafrost changes from continuous to island type distribution. In the very northern part of the Greater Khingan Mountain, apart from the Ergune River, the Heilungkiang and the beds of their branches, some of the river beaches, and the exposing regions of hot springs (these are thawed regions), the basic distribution of permafrost is continuous. Further south we have the southeastern tip of the permafrost of the Europe-Asia Mainland, this is a transition region between perennially frozen ground and non-perennially frozen ground where the occurrences of permafrost are scattered among the thawed regions like islands; thus it is an island type distribution in this area. The majority of these permafrost areas are found under tatao* grass or the bog muck stratum in marsh land area, while a smaller number occur in the lowland moors in the furrow valleys not in the direction of the sun. The latter type bears the characteristics that their surface area is usually not too big, has high ground temperatures, small thickness and is usually unstable. Further south we have the seasonally frozen layer that has not gone completely through the thaw stage found in marsh land or bog muck developed regions or residual of the regressed perennially frozen ground. This type of frozen ground is usually buried more deeply below the earth surface and is not in contact with the seasonally frozen ground. Table 1 lists the thickness and temperature of permafrost in some regions of northeastern China. It can be seen from Table 1 that the thickness of the frozen ground decreases from the northern region to the southern region while the average annual ground temperature increases in the same direction.

In the mid-latitude areas of the world, apart from present day glaciers or the scattered permafrost islands found at the summits of high mountains where it is snowbound all year round, there is generally no perennially frozen ground of any significance. However, in the western part of China, not only is there permafrost coexisting with glaciers and perennial snow accumulation (such as the perennially frozen ground at Tienshan, Chilien Shan, and Altai Shan), there are also large areas of continuous permafrost on the Chinghai-Tibet Plateau between the Himalaya Mountains and Kunlun Mountains. Why are there large areas of perennially

---

* Translator's note: Phonetic translation only. Literally: tower head grass.

frozen ground at mid-latitude on the Chinghai-Tibet Plateau? This is because the general altitude of the Chinghai-Tibet Plateau is 4,000 m above sea level or more; hence the temperature here is much lower than other mid-latitude areas. The frozen period of the ground surface in this region is as long as seven to eight months (from September of each year to April or May of the following year). Even in the warm season, there is temporary freezing of the ground surface at night. An example is in the Kunlun Mountains (approximately 4,700 m elevation), we have observed that even in the warmest month of July, the highest temperature in the day is 17.6°C, while the lowest temperature at night is only -8°C. Thus, apart from the fact that there are thawed regions in the exposed zone of hot springs and beneath the large rivers, on the plateau the permafrost occurs in large areas and is continuous. On the other hand, although Golmud is not quite 100 km north of the Kunlun Mountains, since its altitude is only 2,800 m, there is no perennially frozen ground. It can therefore be deduced that the existence of the permafrost on the plateau is governed mainly by the local altitude. Thus, the perennially frozen ground has a definite vertical distribution.

The lower limit of the distribution of permafrost can now be defined as the line that joins the altitudes where the perennially frozen ground first appears. Table 2 lists the values of the lower limit of permafrost in the western part of China. It can be seen from Table 2 that, as the latitude decreases, the lower limit of permafrost increases. This demonstrates that the distribution of permafrost on a plateau, besides being governed by altitude, is also affected by the latitude of its location. Corresponding to this is the fact that, as the latitude and the altitude increase, the average annual ground temperature decreases; hence the thickness of the permafrost increases (see Table 3). In the Chinghai-Tibet Plateau, there is usually a decrease of $1^{o}C$ in the average annual ground temperature of the frozen layer as the altitude increases by 100 to 150 m. A similar decrease of $1^{o}C$ in the average annual ground temperature is observed as one goes northward 100 to 200 km. The decrease in the average annual ground temperature is accompanied by a corresponding increase in the thickness of the frozen ground.

The area of distribution of seasonally frozen ground far exceeds that of perennially frozen ground. Of these the region of distribution of the seasonally thawed layers is the same as that of the perennially frozen ground. Apart from being distributed in discontinuous permafrost areas and the thawed areas of permafrost regions, these seasonally frozen layers occur widely where there is no permafrost.

In the practical aspects of engineering, the depth of the foundations of buildings for industrial or domestic purposes is generally greater than 0.5 m. Thus basing ourselves on practical engineering requirements, we have drawn isopleths of thickness of 0.5 m for the seasonally frozen layer on the diagram of the distribution of frozen ground. It may be seen from this diagram that, in the temperature zone of China, the depth of the seasonally frozen layer is usually greater than 0.5 m.

2. The Formation of Perennially Frozen Ground

On the earth's surface there are complex processes of heat exchange, namely; radiation, convection and conduction.

The earth's surface absorbs the sun's radiation and at the same time it continues to impart heat energy to the atmosphere through radiation. The atmosphere, in turn, imparts part of its absorbed heat energy back to the earth's surface through radiation.

Apart from exchange through radiation, there are also heat adjustments between the ground surface and the atmosphere in the vertical direction via heat expended by evaporation from the ground, the latent heat of condensation associated with the release of moisture from the atmosphere, as well as turbulent currents which exchange heat in the vertical direction. Simultaneously there is a strong exchange of heat in the horizontal direction through the atmospheric circulating currents and the ocean currents.

In addition to the above, there is also heat flow from the interior of the earth to the ground surface via the method of conduction.

Although the heat exchange processes at the ground surface are very complex, the net result is either heat absorption or heat loss at the ground surface.

During the cold half of the year, the ground surface gives off heat so that the ground gradually cools. Generally speaking, when the ground temperature decreases to below zero, the water in the ground freezes and the ground becomes frozen ground. If, at that particular location, the amount of heat absorbed by the ground surface within a year is greater than the amount of heat dissipated, then in the warm half of the year the frozen ground formed during the cold half of the year will thaw completely so that seasonally frozen ground results. On the other hand, if at that location the amount of heat absorbed in a year is less than the amount of heat dissipated, then the frozen ground formed during the cold half of the year will not thaw completely but leaves a residual part. If, over a long period of time, the condition under which the yearly dissipated heat is greater than the amount of heat absorbed is maintained, then, as the years go by, a permafrost layer of considerable thickness will be formed.

Generally speaking, most of the permafrost is formed after deposition and is frozen from the top downwards. This type of frozen ground is termed epigenetic frozen ground. However, in the regions of accumulation, such as alluvial plains, developing deltas and diluvial fans, dried up lakes and marsh lands, occasionally one may find freezing in the deposition process, and hence the freezing of the permafrost from lower regions upwards. This type of permafrost is called syngenetic. Glacier ice buried in drift is the same as syngenetic ice. In the middle of a solifluction area at Fenghuo Shan on the Chinghai-Tibet Plateau, there was observed a rise in the permafrost table due to mud flows, resulting in an increase in the thickness of the frozen ground from the lower part upwards. In the natural environment one often observes a mixed frozen ground layer consisting of isogenetic frozen layer and syngenetic frozen layer. An example of this is that of the lower layer of the perennially frozen ground being isogenetic while the upper layer is syngenetic. This condition is called a multigenetic frozen layer.

Because there has been little research done on the formation of permafrost in China, at the present it is still difficult to determine its origin. However, based on the existing information, it is possible to make a general analysis on the origin of permafrost in China. Existing data indicate that the thickest permafrost in China may reach 100 to 200 m. "Three feet of ice cannot be formed in just one cold day", as a Chinese saying goes. It is therefore evident that such thick frozen ground cannot be the product of one or several years; its formation must date back to many, many years ago.

It is known that there were several large scale glacier movements during the Quaternary. During the glacial age the climate was cold. Very thick layers of frozen ground were formed at the edge of the land with glacial movement, provided there were suitable geological and geographical conditions.

It is now understood that there were glacier movements on the Chinghai-Tibet Plateau and in the Greater Khingan Mountain in the Quaternary. Thus, very thick frozen ground layers were already formed at that time. Starting from roughly 17,000 years before now, earth's weather became warmer and the glaciers withdrew. The time span from then until the present is termed the postglacial period. The change of the weather during the postglacial period is shown in Figure 10. The figure illustrates that, about five thousand years ago, there was a high temperature period. During that period the frozen ground in the Chinghai-Tibet Plateau and in the northeastern part of China either partially or completely thawed. About 2,500 to 3,000 years ago, the weather again became cold and wet and continued for a period of about 2,000 years (The Little Ice Age). At this time, the residual frozen ground from the thawing at the high temperature period continued to thicken and is preserved to this day.

During the past one hundred years, there was a tendency for the climate of the world to become warmer, thus causing some regression of the perennially frozen ground in certain areas. One example is the southern boundary of the perennially frozen ground in northeastern China. Due to the warming of the climate, the ground ice melted under natural conditions, thus bringing about the creation of thaw lakes, thaw settlements, etc. The southern boundary of permafrost also moved northward; some of the permafrost at the southern boundary disappeared naturally over a period of several years or decades. All this demonstrates that many permafrost areas in northeastern China degraded because of the change towards a warmer climate.

We should be aware of the fact, however, that the perennially frozen ground is not the product of just one factor; the climate. One example is in the Chinghai-Tibet Plateau; there are numerous thaw basins related to the melting of the ground ice, while on the other hand, we see examples of the increase in thickness of the permafrost in mud flow accumulations. Another example is in the northeastern part of China; under identical climatic conditions, there is permafrost in some areas but not in others, or in some other instances permafrost exists beside areas with no permafrost. All this means that the existence of the permafrost is not caused by only one factor. The climate is also related to other factors such as geology and geography. Perennially frozen ground is therefore a product of the combined factors of climate, geology and geography.

3. The Relationship between Frozen Ground and the Local Conditions

There is a very close relationship between the dissipation or absorption of heat by the ground and the change in weather. Thus, the change in climate is a very important factor governing the formation and development of frozen ground. Moreover, the factors of radiation, aerial circulation, geology and geography (latitude, altitude, distribution of land and water, ocean currents, landform, etc.), are interrelated, one factor influencing the other and together they control the change in climate.

Radiation from the sun is the fundamental motive force behind the change in climate. The aerial circulation accounts for the difference of climate at various locations. The geological and geographical factors, however, may modify the effects of the radiation factor and the forms of the aerial circulation. Thus, the geological and geographical factors are also important factors in the type of climate observed.

The distribution of radiation energy from the sun is mainly determined by latitude, while the aerial circulation is mainly caused by the difference of heat energy from the sun at different latitudes. Thus, latitude is the most important of the geological and geographical factors to affect the climate. Thus, the climatic regions are drawn according to latitude. The effect of altitude on climate is even more pronounced than the effect of latitude; therefore in the high mountain regions one may sometimes observe a range of vegetations over a range of altitude, varying from dense, thick tropical forests at the bottom of the mountain to land covered with glaciers, without as much as a stalk of grass for its vegetation at the mountain summit. However, the higher the altitude, the smaller the ground surface area; this decreases the effect of altitude on climate. The distribution of land and water also has a very significant effect on the temperature differentials. It follows that besides the possibility of dividing the globe into climatic regions, it is also possible to subdivide each climatic region into continental climatic regions and oceanic climatic regions.

The geological, geographical factors over a vast region (latitude, altitude, distribution of land and sea, etc.) are the important factors to influence the climate. Regionally geological and geographical factors (medium size landforms, large areas of vegetations, etc.) may, within the bounds of the same climatic region, produce small climatic differences to form the so-called regional climate, while the regional geological and geographical factors (small landforms, characteristics of vegetations, special features of the land surface, and snow coverage, etc.) may influence the atmosphere from the ground surface to two metres above it, to form the so-called microclimate.

Since the geological and geographical factors are important factors influencing the climate, and at the same time they also control the heat conduction process of the ground, it follows that they are important factors in determining the formation and development of frozen ground. This is why we say that frozen ground is the joint product of the climatic, geological and geographical factors.

We have already seen from the distribution of frozen ground in China that its distribution temperature and thickness, mainly follow the rules of latitude and altitude. In a region of fixed latitude and altitude, formation and type of frozen ground are determined by the regional geological and geographical conditions.

In the following sections the effect of geological and geographical conditions on the distribution of permafrost and its temperature and thickness are discussed.

A. Ground and Water

The effect of latitude and altitude may be combined as the effect of temperature. Temperature is the external condition for the formation of frozen ground, while the internal conditions for the formation of frozen ground are the nature of the ground and its water content. In his article "On contradiction", Chairman Mao discussed the metaphysical world outlook, "They search in an over-simplied way outside a thing for the causes of its development, and they deny the theory of materialist dialectics which holds that development arises from the contradictions inside a thing. Consequently they can explain neither the qualitative diversity of things, nor the phenomenon of one quality changing into another."

*Thus if we want to discuss the existence of the thousands of facies of the frozen ground within the same region, we have first to study the internal causes, namely; ground and water.

Frozen ground differs from other types of ground in that it is "frozen". This "frozen" condition is caused by the freezing of the water within the ground. Thus the freezing of the groundwater constitutes the special feature of the frozen ground, and this freezing has characteristics different from the freezing of ordinary water. We have to understand these characteristics before we can have the correct interpretation on the many complex facies of the frozen ground. These characteristics are: the existence of unfrozen water within the frozen ground, supercooling of the groundwater, the change of heat properties after freezing, and the movement of the water, etc.

(a) Unfrozen water

Although the ground is "frozen", there still exists some unfrozen water, which remains in a liquid state under conditions of negative temperature and certain pressure. Why is the unfrozen water not frozen at negative temperatures?. The answer to the above question is the effect of the interaction of ground and water at negative temperatures.

First, let us examine the structure and nature of a water molecule. The chemical representation of a water molecule is H_2O, meaning that it is made up of two

---

*Translator's note: All appropriate translations of the quotations of Chairman Mao are taken from the "Selected works of Mao Tse-Tung", published by the Foreign Language Press, 1965.

hydrogen atoms and one oxygen atom. The nuclei of these three atoms make up an isosceles triangle, with an apex angle of 105^{o} (see Figure 11). The oxygen nucleus occupies the apex of this triangle while the two hydrogen nuclei occupy the ends of the base of the triangle. The electrons they carry (eight for the oxygen nucleus and two each for the hydrogen atoms) are rearranged in a new manner when the water molecule is formed, and each moves in its neighbourhood according to some fixed rules. Since the oxygen nucleus differs from the hydrogen nuclei, in particular the number of electrical charges carried by the nuclei is different, it follows that the interactions between the electrons and various nuclei are different. The net result is that the electron has a much higher probability of spending its time closer to the oxygen nucleus than to a hydrogen nucleus. Thus, the distribution of an electron in a water molecule does not follow an even pattern, but spends more time at the oxygen end of the molecule and less time at the hydrogen end of the molecule. Although the electrical charge of the water molecule as a whole is neutral, the oxygen end of the molecule appears negatively charged while the hydrogen end of the molecule appears positively charged. This type of molecule with positive charge at one end of the molecule and negative charge at the other end of the molecule is called a dipolar molecule.

Let us now examine the ground particles. The surface of the ground particles are made up of free radicals or ions. These free radicals or ions bear electrostatic attracting forces; thus, an electrostatic attracting force field is formed in the region of the ground particle surface. The water molecule, being a dipolar body, is therefore attracted by the electrostatic attracting force. Thus, when water is in contact with the ground particle, it will interact with the electrostatic force. The result of this interaction is the loss of the freedom of movement of the water molecules close to the surface of the ground particles, so that these water molecules are orderly and closely aligned. As Figure 12 shows, the closer to the ground particle surface, the stronger the strength of the electrostatic attracting field, resulting in a layer of high density water tightly attached to the ground particle surface. This water is called strongly bonded water. As we go further away from the ground particle surface, the weaker the electrostatic attracting force becomes, and the greater the freedom of movement of the water molecules. Thus, the water molecules there are looser, less orderly, and only weakly oriented. This is the weakly bonded water. Further away, although the water molecules are still under the influence of the electrostatic attracting field; they are more significantly influenced by gravitation, and form the so-called capillary water. At a distance even further away, the water molecules are no longer under the influence of the electrostatic attracting force and are subjected only to the gravitational field, thus forming the so-called gravitational water. Gravitational water is the same as the ordinary, liquid-state water.

As mentioned above, the strongly bonded water, the weakly bonded water, and the capillary water are all under the influence of the attractive forces of the molecules at the ground particle surface. To freeze these types of water, besides the necessity of overcoming the molecular attraction of the ordinary liquid-state water, it is also necessary to overcome the attracting forces exerted by the ground particle surface on these water molecules. All these lower the freezing point of these types of water and it is no longer $0^{\circ}C$ as for ordinary water. The closer the water molecules to the ground particle surface, the stronger the attracting force to which they are being subjected, and therefore the lower their freezing point. Thus, the strongly bonded water remains unfrozen at -78°C, while the weakly bonded water would freeze completely only at -20 to -30°C. The freezing point of the capillary water is also slightly less than 0°C. Thus, even at negative temperatures, there is still a part of the water that remains unfrozen in the frozen ground; this is, of course, the so-called unfrozen water.

The formation of unfrozen water is, moreover, related to the nature and the amount of salt dissolved in water. We all know, in our daily life, that the freezing point of salty water is lower than that of plain water, and that the more concentrated the salt solution, the lower is its freezing point. This characteristic is also present in solutions of other salts. Thus if there are any salts in the groundwater, it would be beneficial to the formation of unfrozen water. This phenomenon is particularly prominent in salty ground.

Pressure also plays a part in the formation of unfrozen water. The melting temperature of ice may be changed by pressure. Under normal pressure (one atmosphere), the melting temperature of ice is 0°C. However, if the pressure increases, ice can melt at temperatures several degrees below zero. When the pressure is 100 times the atmospheric pressure, ice melts at -0.9°C; when the pressure is 1,500 times the atmospheric pressure, ice melts at -14.1°C.

Within the frozen ground, the contact surface between the ground particles is very small. Thus, even when the external load is not heavy, there still exists a very large stress at the contact surface of the ground particles. This stress causes the ice at the contact places between the ground particles to melt at negative temperatures, thus forming unfrozen water.

In practice we have also discovered that the amount of unfrozen water is related to the coarseness or fineness of the ground particles. The finer the ground particle size, the greater the amount of unfrozen water. Now what is the reason behind this?

As we have mentioned above, the surface of the ground particles has the ability to attract other types of molecules. We term this energy the surface energy.

The amount of surface energy of the ground body is related to the ground particle size. When the volumes are identical, the smaller the grain size, the larger the surface area, thus the larger the surface energy.

The fact that for particles of the same volume, the smaller grain size, the larger the total surface area may be illustrated in Figure 13.

Figure 13 shows the division of a cube in which the length of each side equals 1 cm into eight small cubes in which the length of each side equals 0.5 cm. The volume of the system remains unchanged in the division process. Now, the surface area of the large cube equals six times the surface area of one face, hence it is 6 cm^2. The surface area of one new small cube equals six times 0.5 cm times 0.5 cm, in other words 1.5 cm^2. It is therefore evident that after the division, the volume of the cube remains unchanged, but the total surface area has increased two-fold.

Calculations would demonstrate that when the diameter of the ground particle is 1 mm, the total surface area of the ground particles in 1 cm^3 of ground is approximately 60 cm^2; if the diameter of the ground particles is 0.001 mm the total surface area of the ground particles in

1 cm^3 of ground is approximately 6 million cm^2. Thus the total surface area of the ground body made up of small size particles far exceeds that of the ground body made up of large size particles. It follows that the surface energy is far greater in the case of fine grained particles.

The value of the ground particle surface energy is also related to the mineral and chemical constituents of the ground particles. Under natural conditions, the surface energy of the minerals that form small size particles (such as montmorillonite*, kaolinite) is usually greater than the surface energy of the minerals that form large size particles (e.g. quartz). Thus it may be said that, in general, the smaller the particle size, the greater the surface energy.

Since the surface energy of the smaller sized particles is greater than that of the larger sized particles, the smaller size particles can exert a stronger influence on the water molecules, and the amount of unfrozen water formed therefore greater.

Let W_H, the content of unfrozen water, be the index of the abundance of unfrozen water within the frozen ground. In other words, at a fixed negative temperature, W_H is the ratio of the weight of unfrozen water within the frozen ground (g_H) to the weight of dry ground (g_C).

$$W_H = g_H/g_C$$

The indices to indicate the ice content in frozen ground are the ice content in weight, the ice content in volume, and the relative ice content.

---

* Translator's note: Phonetic translation only.

The ice content in weight is the ratio of the weight of ice in the ground to the weight of dry ground. The content of ice in volume is the ratio of the volume of ice to the volume of frozen ground. Both indices may be expressed in percent.

In practice the index relative ice content is more often used. The relative ice content (i_O) is the ratio of the weight of ice (g_{Π}) to the total weight of water (g_B equals the weight of the unfrozen water, plus the weight of ice) within the frozen ground, expressed in percent

$$i_O = g_{\Pi}/g_B$$

The relationship between the relative ice content and the unfrozen water content in frozen ground may be expressed by the following:

$$W_H = W(1 - i_O)$$

where W is the water content of the frozen ground in weight, expressed in percent

$$W = \frac{g_{\Pi} + g_H}{g_c}$$

When the temperature is at 0^oC, all the gravitational water freezes. At this time the unfrozen water content is equal to the sum of the bonded water content and the capillary water content. If the water content is increased the increased part can only be gravitational water which will have to freeze, while the unfrozen water content remains as the sum of the bonded water content and the capillary water content. Thus at a fixed temperature, the unfrozen water content is independent of the water content.

We may therefore conclude from the above that, for a certain kind of ground, its unfrozen water content is determined by the temperature only, and is independent of the water content of the ground.

Since $W_H = W(1 - i_O)$, $i_O = 1 - W_H/W$, for a fixed kind of ground, W_H is a constant at a fixed temperature. Thus as W increases, i_O also increases. From this we may conclude that, at a fixed negative temperature, the relative ice content is directly proportional to the groundwater content.

The relationship between the unfrozen water content and temperature may be obtained from experiments (see Figure 14). Each type of ground has its own relationship curves between unfrozen water content and temperature. This also confirms the above conclusion that for a fixed type of ground, the unfrozen water content is determined only by the temperature, and is independent of the total water content in the ground. Thus the phase change of water at the time of freezing or thawing of a fixed type of ground may be represented by the relationship between its unfrozen water content and temperature.

It may be seen from Figure 14 that, for clayey ground, the change of the unfrozen water content from $0^{\circ}C$ to $-3^{\circ}C$ is very large. This temperature range is called the strong phase transformation region. From $-3.0^{\circ}C$ to -7 or $-9^{\circ}C$, the change of the unfrozen water content is comparatively smaller; this is the medium phase transformation region. At temperatures lower than -7 to $-9^{\circ}C$, the unfrozen water content changes hardly at all; this is the weak phase transformation region.

The existence of unfrozen water within the frozen ground exerts an exceedingly large influence on the properties of the frozen ground. For example, at the same negative temperature and with the same water content, the strength of the frozen gravel soil is greater than the strength of frozen clay. This is because at a certain negative temperature, almost all the water within the gravel soil freezes into ice, and thus make the soil particles strongly adhere to one another. However, at the same negative temperature and with the same water content, there is still a significant quantity of unfrozen water within clay; and thus the extent of adherence of the ground particles by the ice is weak, resulting in a lowering of strength of the frozen clay. Under various negative temperatures, the unfrozen water content of clay may be 5 to 10% of the total water content. As we all know, it requires about 0.4 to 0.5 cal of heat to lower the temperature of 1 g of frozen ground by $1^{o}C$, while it takes 80 cal to convert 1 g of water into ice. This poses a difference of 160-fold. Thus the presence of unfrozen water in the frozen ground influences the heat properties of the ground to a very great extent.

(b) Supercooling of groundwater

As we all know, water freezes at $0^{o}C$. However, we have also observed the following phenomenon: in a closed vessel, pure water may remain unfrozen even at temperatures many degrees below zero. As soon as the cover of the vessel is removed, or even with the cover on, when the vessel is vigourously shaken, the water almost immediately crystallizes into ice and this crystallization occurs throughout the entire amount of water present.

What is the reason behind this?

The reason is that for water to crystallize, there must be some crystal nuclei in the water. These crystal nuclei may be ice crystals, or dust, or other mechanical inclusions. Of these the ice crystals are the most effective nuclei in the process of crystallization. Since both the vessel and the water are pure, they are void of crystal nuclei, and thus the water remains non-crystallized even at temperatures below $0^{o}C$. This is then the phenomenon of supercooling. When we remove the cover of the vessel, dust from the atmosphere falls into the water and becomes crystal nuclei, thus causing the immediate crystallization of the supercooled water.

Now how does vigourous shaking of the vessel cause the supercooled water to crystallize? This is because the vessel is not completely filled with water. Somewhere on the vessel wall, above the water level, there is a certain amount of frost crystals. When the vessel is vigorously shaken, some of these frost crystals fall into the supercooled water and at once become crystal nuclei, thus causing the immediate crystallization of water into ice.

The supercooling of water is related to the degree of cooling. When the water is placed in a medium temperature in the neighbourhood of $0^{o}C$, it may be supercooled to the temperature of its surrounding medium, and this supercooling state may last a long time without crystallization. If the degree of cooling is great, then one does not observe an extended period of supercooling.

The supercooling of water is also related to the volume of the water. The smaller the volume, the less the chance of formation of crystal nuclei and the greater the extent of supercooling. An example is the ability of one experimenter to supercool a drop of water to as low as $-72^{o}C$ without crystallization.

There are some common properties between the supercooling of groundwater and the supercooling of pure water, at the same time there are properties unique to the supercooling of groundwater. These characteristic properties are:

Under natural conditions the freezing of the ground starts at the very top layer. The needle crystal bodies of ice can then penetrate into the lower lying still unfrozen ground layers. The existence of these icy crystals excludes the possibility of supercooling of the underlying ground layer. Thus the phenomenon of supercooling is usually found only at the very top layer of ground, and never at the lower layers.

There is a large quantity of small particles in the ground to act as crystal nuclei. Therefore, the supercooling of groundwater is not as stable as the supercooling of pure water in a vessel.

The attracting forces of the ground particles towards the water molecules enable the supercooling of those water molecules subjected to such forces. Thus, if the water content of the ground decreases to the maximum molecular water content, the phenomenon of supercooling becomes very distinct.

Experiments show that the curves of freezing or thawing of the groundwater are the same regardless of the type of ground. These curves may be divided into five sections (see Figure 15).

It can be seen from the figure that as soon as the supercooled groundwater starts to crystallize, due to the release of the latent heat of crystallization of ice, the local temperature of the ground rises rapidly, until it stabilizes at a certain temperature. At this time the freezing of the water between the ground particles occurs.

We define this maximum, most stable temperature (0_3 in Figure 15) as the onset of freezing temperature.

The onset of freezing temperature of the ground is determined by the water content of the ground and its particle size. It is also determined by the concentration of the aqueous solution.

When the groundwater content approaches the maximum molecular water content, since the water molecules are subjected to the attracting forces of the ground surface molecules, it leads to a lowering of the onset of freezing temperature. The smaller the water content, the lower the onset of freezing temperature (see Figure 16). By the same token, the smaller the ground particle size, the greater the surface energy, and therefore the lower the onset of freezing temperature. If there is salt in the water, the higher the salt concentration the lower would be the onset of freezing temperature.

When the water content is very large and the water starts to move towards the frozen surface, a large quantity of heat is released due to the phase transformation of a large quantity of water. This large quantity of heat slows down the cooling of the underlying ground layers so that the ground there stays at $0^{o}C$ at a relatively longer period. This is the so-called "zero curtain".

(c) Change of heat properties after the ground is frozen

There are many differences between the heat properties of frozen ground and thawed ground. The differences between heat properties of ground in the process of freezing or thawing and frozen ground or thawed ground are even greater. All these differences are the result of the different characteristics of the groundwater at various phases.

The specific heat of liquid state water is 1 cal/g deg. In the solid state, the specific heat of ice is 0.5 cal/g deg, which is only one-half the value of the specific heat of the liquid state. The coefficient of heat conductivity of water in the liquid state is 0.5 kcal/m h deg, while the coefficient of heat conductivity of ice at $0^{o}C$ is 1.935 kcal/m h deg, approximately four times that of water. Thus, generally speaking, the capacity of heat conduction in the frozen state is greater than the capacity of heat conduction in the liquid state for the same type of ground.

During freezing (thawing), the water (ice) has to release (absorb) 80 cal/g of heat. This accounts for the very substantial differences between the heat conduction processes in ground with phase transformation and the heat conduction processes in ground without phase transformation.

In the following we introduce the difference of the various thermal indices for frozen ground and thawed ground.

1. Specific heat (C) is the amount of heat required to change the ground body temperature by $1^{o}C$. Its unit is cal/g deg or kal/kg deg.

Experiments demonstrate that the specific heat of a certain type of ground is based on the weighted average of its various constituents (both the content and the specific heat of the gaseous phase in a ground body are small, hence both can be neglected). Thus the specific heats of thawed ground and frozen ground are, respectively,

$$C_T = \frac{C_{CK} + WC_B}{1 + W}$$

$$C_M = \frac{C_{CK} + (W - W_H)C_{\Pi} + W_H C_B}{1 + W}$$

where C_T, C_M are the specific heat of thawed ground and frozen ground, W is the water content in weight, expressed in decimals, W_H is the amount of unfrozen water, expressed in decimals, and C_{CK}, C_B, C_{Π} are the specific heats of the mineral skeleton, water and ice, respectively.

In our calculations we can usually use the following values: the specific heat of water is 1 cal/g deg, the specific heat of ice is 0.5 cal/g deg, and the specific heat of the mineral skeleton as follows: at positive temperatures the specific heat of the general mineral skeleton is 0.20 kcal/kg deg, for organic clay it is 0.24 kcal/kg deg; at negative temperatures the specific heat of sand is 0.17 kcal/kg deg, and that of subclay is 0.19 kcal/kg deg, while the specific heat of the carbonaceous subclay is 0.20 kcal/kg deg.

2. Volumetric heat capacity (C_V) is the amount of heat required to change the temperature of 1 m^3 of ground by 1^oC. Its unit is either in cal/cm^3 deg or in $kcal/m^3$ deg.

The volumetric heat capacity of ground may be calculated according to the following formula:

$$C_{VT} = C_T\gamma$$

$$C_{VM} = C_M\gamma$$

where C_{VT}, C_{VM} are the volumetric heat capacity of thawed ground and frozen ground, respectively

γ is the volumetric weight of moist ground, in g/cm^3

$$\gamma = \gamma_{CK}(1 + W)$$

where γ_{CK} is the volumetric weight of the mineral skeleton (dry volumetric weight), in g/cm^3.

In practice the formulae used in calculations are:

$$C_{VT} = (C_{CK} + WC_B)\gamma_{CK}$$

$$C_{VM} = [C_{CK} + (W - W_H)C + W_HC_B]\gamma_{CK}$$

The volumetric heat capacity of the ground is an index reflecting the ability of the ground to hold heat. From Figure 17 it may be seen that the volumetric heat capacity of both frozen ground and thawed ground increases linearly with the increase of water content or the increase of dry volumetric weight. However, the rate of increase of C_V for frozen ground is slower than the rate of increase of C_V for thawed ground. This is obviously due to the smaller specific heat of ice compared to the specific heat of water.

3. The coefficient of heat conductivity is (λ). When the temperature gradient is 1 (a decrease of $1^{\circ}C$ in temperature over unit length), the amount of heat passing through a unit surface area in unit time is termed the coefficient of heat conductivity. Its unit is cal/cm s deg or kcal/m h deg. It is an index to reflect the rate of heat conduction of the ground mass.

It may be seen from Table 5 that there is a large difference between the coefficients of heat conductivity of the 3 basic constituents of thawed ground. When water is added to dry soil, the resulting coefficient of heat conductivity is greater than the coefficient of heat conductivity of dry soil or that of water by a significant amount. For example, the coefficient of heat conductivity of saturated soil is one to three times the coefficient of heat conductivity of water. The coefficient of heat conductivity of soil in the dry state is between that of water and air. Thus, it is evident that the conductivity properties of the ground depend to a great extent, on the conditions of the ground, that is, the relationship between the three basic constituents. Of these factors, the change in water content plays the most important part in affecting the conductivity properties of the ground.

As for frozen ground, since its water has changed into ice and the conductive ability of ice is about 4 times that of water, it follows that the heat properties of frozen ground differ significantly from the heat properties of thawed ground (see Table 6). This type of change may be represented by B (equals λ_M/λ_T), which is the ratio of the coefficient of heat conductivity of the ground in the frozen state (λ_M) to the coefficient of heat conductivity of the ground in the thawed state (λ_T).

The value of B reflects the change of coefficient of heat conductivity of the ground due to phase changes. When the value of B is less than one, it means that the coefficient of heat conductivity of the ground decreases upon freezing. When B equals 1 it means that the coefficient of heat conductivity of the ground remains unchanged upon freezing; when B is greater than one it means that the coefficient of heat conductivity of the ground increases upon freezing. The greater the value of B, the greater the difference between the heat properties of frozen ground and thawed ground. The values of B follow the following rules:

For ground of a certain constitution and moisture content, the value of B is determined by the density of the ground (volumetric weight). When the density of the ground decreases, the pore spaces in the soil increase. The proportion of heat conducted by the air increases, resulting in a small change of the coefficient of heat conductivity of the ground due to phase change. Thus the value of B is small.

For a given moisture content, the value of B is determined by the fineness or coarseness of the soil particles. The finer the particles, the larger the unfrozen water content, and therefore the smaller the amount of water participating in the phase change; thus, the smaller the change in the coefficient of heat conductivity. So, for a fixed moisture content, the value of B is greater for coarse grained soil than for fine grained soil.

For the same type of soil, the value of B is determined by the ice content.

Let us first examine the relationship between the values of B and the moisture content for soil with fine particles. By using the following approximate, simplified diagram (Figure 18), it may assist us to achieve a better understanding of the quantitative aspect of this relationship.

In Figure 18:

W_e is the natural moisture,

W_{MM} is the maximum molecular moisture content (the moisture content of the ground where there is a maximum amount of strongly bonded water and a maximum amount of weakly bonded water),

W_n is the saturated moisture content, i.e. the moisture content when the soil pores are completely filled with water,

W_H is the unfrozen water content.

It may be seen from the figure that when the moisture content is small (slightly greater than the unfrozen water content W_H), because of the small quantity of ice crystals formed, the effect of the increase of coefficient of heat conductivity of the frozen ground is not yet prominent. At the same time, there is destruction of the membrane water by the formation of the ice crystals, leading to a change of the heat contact between the soil particles, which in turn leads to the predominant effect of the lowering of the heat conductivity properties of the frozen ground.

The net result is therefore a lowering of the ability of heat conduction of the frozen ground when compared to the ability of heat conduction of thawed ground. In other words, $\lambda_M/\lambda_T = B$ is less than 1. When the moisture content increases, the quantity of ice crystals formed also increases; thus, a greater amount of heat is conducted by the ice, resulting in an increase of heat conductivity properties of the ground. The value of B therefore increases. When the moisture content reaches a certain fixed value the value of B = 1. In a non-strong phase change region, this value of moisture content may be taken as that moisture content value at which no more unfrozen water freezes. This value is approximately equal to the maximum molecular moisture content (W_{MM})[1]; in a strong phase change region, because there is still a relatively large quantity of unfrozen water undergoing phase change. W_H is a varying quantity, and so this value of moisture content may be taken as, approximately $W_H + 10$. As the moisture content increases, there is an increasing amount of ice in the frozen ground, and a greater effect exerted by the ice on raising the heat conducting properties of the frozen ground. The value of λ_M continuously increases, so that the value of B also increases proportionally in a linear fashion. When the soil is saturated the rate of increase of λ_T becomes smaller while λ_M still continues to increase. The value of B therefore keeps increasing.

---

1) Experiments show that the water content in the region $\lambda_M/\lambda_T < 1$, for organic clay is 40 to 50%, for subclay it is 14 to 18%, for crushed stone subclay is 6 to 8% (the value of λ_M/λ_T for sand of medium coarseness is always greater than 1).

The relationships shown in Figure 18 may be expressed in formulae:

In a strong phase change region

$$B = \frac{a(W_e - W_H - 10)}{W_n - W_H - 10}$$ (not applicable when $W_e < W_H + 10$)

In a non-strong phase change region

$$B = 1 + \frac{a(W_e - W_{MM})}{W_n - W_{MM}}$$

For sandy ground

$$B = 1 + \frac{a(W_e - 10)}{W_n - 10}$$

In the formula the value of a is determined by the constitution and type of soil while at the same time it increases as the density increases. For clayey soil a = 0.1 to 0.2, while for sandy soil a = 0.5 to 0.8.

4. Coefficient of temperature conductivity (K) is an index to reflect the rate of change of temperature during an unstable heat process. Its unit is cm^2/s or m^2/h.

$$K = \frac{\lambda}{c\lambda} \ cm^2/s$$

The meanings of the symbols in the formula is the same as above.

Figures 19 and 20 show, respectively, the relationship between the coefficient of temperature conductivity of thawed ground and frozen ground, and moisture content. The coefficient of temperature conductivity of thawed ground at first increases as the moisture content increases. When the moisture content approaches the maximum molecular water content (for organic clay it is approximately 110 to 130%; for subclay it is approximately 14 to 17%; for medium sand mixed with gravel it is 5 to 7%), the temperature coefficient also reaches its maximum value. Then as the moisture content continues to increase, the coefficient of temperature conductivity decreases and gradually approaches a stable value. For frozen ground, the coefficient of temperature conductivity at first increases as the ice content increases, the rate of increase being approximately the same as that of thawed ground; it then further increases as the ice content increases until after a certain ice content, the rate of increase of the coefficient of temperature conductivity slows down.

It may be seen from Figures 21 and 22 that the coefficient of temperature conductivity of both frozen and thawed ground increases linearly as the dry volumetric weight increases.

After we understand the characteristics of the unfrozen water mentioned above, let us now examine the reasons behind the existence of the thousands of facies of frozen ground within the same region.

For example, under other identical conditions, with a fixed water content, the rate and depth of freezing exceeds the rate and depth of thaw for the same type of ground. Why is this so?

Moisture and soil play an important part in this case. As we have mentioned above, under normal conditions the coefficient of heat conductivity of frozen ground is greater than the coefficient of heat conductivity of thawed ground, while the heat capacity of frozen ground is smaller than the heat capacity of thawed ground. This is to say, for the same type of ground, the rate and depth of freezing are greater than the rate and depth of thaw. This is particularly true of the seasonally thawed layer, as it is unidirectional thawing (from the ground surface downwards) but with bi-directional freezing (both from the ground surface downwards and from the permafrost table upwards), this kind of difference is even more prominent.

Another example is in northeast China. Here we often discover that under identical climate conditions, there is permafrost in some areas while only seasonally frozen ground layers exist at other locations; or at some places there may even be perennially frozen and seasonally frozen layers existing side by side. What is the reason for this?

The leading effects here are still exerted by the properties of the ground and its moisture content. We know that the smaller the soil particles, the greater the surface energy, and the greater the moisture holding capacity. Thus, in the natural world, generally speaking, the moisture content of fine granular ground is greater than the moisture content of coarse granular ground. The larger the moisture content, the greater the ratio λ_M/λ_T. This is to say that the amount of heat loss by that particular ground layer in winter is also greater. For an extremely moist bog muck and clay, λ_M/λ_T is greater than 1.5, while for a bedrock with very low moisture content, λ_M/λ_T is less than 1.0. Therefore, under identical climatic conditions, the amount of heat lost by the fine grained soil in winter is large, and permafrost will form; sandy pebbles with very low moisture content would only lose a small amount of heat in winter resulting probably in the formation of only a seasonally frozen layer. Or, in the case of permafrost degradation, the perennially frozen ground in coarse grained soil with low moisture content would first completely degrade to become seasonally frozen ground, while the permafrost in the moist fine grained soil would degrade relatively more slowly and some would persist. This is one way of finding permafrost and seasonally frozen ground beside each other.

For similar reasons and because of the strong influence of the latent heat of water, the depth of seasonal thaw or freezing for moist, fine grained soil is less than the depth of seasonal thaw or freezing of coarse grained soil which has a lower moisture content. This phenomenon is true for both permafrost and seasonally frozen ground. An example of this is in northeast China; the depth of seasonal thaw in a permafrost area differs with the type of ground. For bog muck the depth of thaw is 0.5 to 1.2 m; for subclay it is 1.5 to 2.2 m; for clay with sandy gravel or crushed stone it is 1.8 to 2.6 m, while for sandy gravel it is 2.5 to 3.5 m. Correspondingly, the average annual ground temperature of the moist, fine grained soil is lower than the average annual temperature of the coarse grained soil with low moisture content. From the presently available data, it is evident that the various types of ground may lead to a difference of 1 to 2^{o}C in the average annual ground temperature in the Chinghai-Tibet Plateau (see Table 7).

However, all contradictions under certain conditions may turn to their opposite directions. There are phenomena opposite to what is observed when the moisture content is the same. This is because the finer the particle size, the larger its unfrozen water content, and the smaller the change in heat conductivity properties during freezing. Thus when the moisture content is identical, the value of λ_M/λ_T for fine grained soil is smaller than that for coarse grained soil. Therefore, the depth and rate of freezing or thawing are smaller for coarse grained soil than for fine grained soil, and the average annual ground temperature of coarse grained soil is also lower than that of fine grained soil.

Let us cite another example. Near the southern boundary of the permafrost region in northeast China, there still exists occasionally perennially frozen ground at depth even when the average annual temperature at the ground surface has become positive. What then is the reason behind this?

Here the important action is still that of moisture content and the type of ground. The areas where this phenomenon occurs usually have fine grained soils with extremely high moisture contents. The vegetation is usually hydrophilic such as tatao grass, and bog muck is also widespread. We know that there are changes in the thermal physical properties as the wet ground freezes. Thus the balance of the heat input and output of a seasonally frozen (thawed) layer can only be established when the average annual ground temperature at the ground surface (t_{II}) is not the same as the average annual ground temperature at the base (t_h) of that layer. When the moisture content is very small, $\lambda_M/\lambda_T < 1$; in this case the average annual ground temperature at the ground surface is lower than the average annual ground temperature at the base, or $t_{II} < t_h$. When the moisture content increases to a certain value, $\lambda_M/\lambda_T = 1$, and in this case $t_{II} = t_h$. When the moisture content continues to increase $\lambda_M/\lambda_T > 1$, here $t_{II} > t_h$. The greater the moisture content the greater the difference between these two temperatures; at times this difference may reach as high as $3^{o}C$. Therefore, if the average annual temperature at the ground surface is positive but approaches zero, for ground with high moisture content, the average annual ground temperature at the base of the seasonally frozen ground may be negative. It follows that a thin frozen ground layer may exist below. This may be a newly formed permafrost layer, or it may be an unthawed seasonally frozen layer left behind from the previous year.

The fineness or coarseness of the soil particles determines the permeability of the ground. The permeability of coarse grained soil is better. Thus, when the summer rain brings with it large quantities of heat to permeate into the ground, it leads to an increase in thickness of the seasonally thawed layer, and a decrease of thickness of the frozen ground; the ground temperature therefore correspondingly increases. In northeast China, the summer temperatures are rather high, and 70 to 90% of the annual rainfall falls in the summer. Thus, the influence of this permeating action on frozen ground layers is very prominent.

The quantity of salt in the groundwater determines the onset of freezing temperature of the ground, which in turn influences the thickness of the frozen ground layer. As the amount of salt in the water increases, the onset of freezing temperature of the ground decreases, thus leading to a decrease in thickness of the frozen ground layer under identical ground temperature conditions.

Chairman Mao taught us "In order to understand the development of a thing, we should study it internally and its relations with other things". The actions of the ground and water are interrelated to and mutually influence the actions of other geological and geographical factors. Therefore, in the following, let us further examine the actions of other geological and geographical factors.

B. Vegetation

Vegetation is like a blanket covering the ground surface, and like a blanket, it has the effect of preserving heat. If there is permafrost below, vegetation would also serve to protect it. Vegetation can decrease the annual temperature differential at the ground surface, and decrease the amount of heat entering the ground; thus, it has the action of decreasing the temperature.

In summer, when solar radiation is high, the plants are also growing and prospering and they can shield and reflect the direct radiation. In an open area, the radiation is 1.5 cal/cm^2 min. compared with only 0.01 cal/cm^2 min. in dense forest. This type of action is particularly prominent in the Greater Khingan Mountain Range where the forests are so dense that the leaves and branches of the trees seem to cover the sky. The forest of Betula alba, a member of Larix leptolepis, in the northern part of the Greater Khingan Mountain Range, is capable of decreasing the annual temperature differential at the ground surface by 4 to 5^{o}C.

The root system of a plant is capable of retaining water. Some plants such as bryophyta have an amazing ability to absorb water. 100 g of dry bryophyta can absorb as much as 400 to 1,500 g of water, while the tips of its root can absorb 5,000 g of water. The plants also have to release water in their growing process: at night the surface energies of the plants can condense the water vapour in the atmosphere. A walk on the grass in the morning would show us the strings of pearls of morning dew covering the leaf surface, ... this type of relationship between plants and water is very significant. We know that the specific heat of water is rather high. In summer when we feel the burning sensation of the ground surface, we can still feel fairly cool in water. This is because the specific heat of water is high, it can absorb a considerable quantity of heat without raising its temperature too much. Evaporation of water requires a large amount of heat energy, associated with a high amount of latent heat. The plants also have to absorb energy from the sun to carry out photosynthesis which enable the plants to grow. These characteristics of the plant therefore greatly decrease the temperature differential at the ground surface, and effectively cut down the amount of heat entering the ground. This decreases the depth of seasonal thaw. When the depth of seasonal thaw in other regions reaches 3 to 4 m, the depth of thaw of the area covered with more than 20 cm of bryophyta is less than 0.5 m.

In plateau areas grass coverage can decrease the yearly temperature differential by 4 to 5°C. On the first terrace of the Duosuo River in the Muli region of Chilien Mountain, the depth of seasonal thaw of ground with vegetation coverage is 1.7 m, while the depth of seasonal thaw of ground without vegetation coverage is greater than 2 m.

Our observed data illustrate (Figure 23) that, upon removal of the grass coverage, the depth of seasonal thaw increases by 0.4 m.

It can be seen from the above discussion that the temperature lowering action of the vegetation coverage is very prominent. During exploitation of the forest resources, the removal of the vegetation coverage often increases the depth of seasonal thaw, leading to the melting of the ground ice and hence the regression of the permafrost. This leads to all kinds of thawing phenomena, endangering the safety of engineering construction.

When the ground surface becomes marshy, it accumulates a large quantity of water. In the marshy region of the Great Khingan Mountain Range, there is an abundant growth of tatao grass and bryophyta, with several centimetres to 2 or 3 metres of bog muck below. It is therefore usual for permafrost to develop under marshy land. Moreover, there was a development of ground ice layers, leading to a minimum depth of seasonal thaw. The average annual temperature of the ground layer is 1.0 to 1.5°C lower than that of non-marshy land.

C. Topography

Topography determines the position of the heat exchange interface between the ground layers. Thus the depth to the permafrost table in the Chinghai-Tibet Plateau varies according to the undulations of the landform. When other conditions are the same, the depth to the permafrost table in the mountain ridge area is less than in low, depressed areas. This is because, in winter, apart from the heat exchange by the ground layers in the mountain ridge area in a vertical direction, there is also heat exchange with the two lateral mountain slopes. In the low, depressed area, however, in winter there is heat exchange in one direction only; thus there is little heat loss, and the average annual ground temperature is higher than that of the mountain ridge area, and so the depth to the permafrost table is greater. However, we often observe the opposite situation in practice. In other words, the depth of the permafrost table in a mountain ridge area is greater than that in a low, depressed area. Why is this so? This is because everything is interrelated to and mutually influences other things in its surroundings. Of course at the low, depressed area there is only one direction for the heat exchange process, but because of the participation of other geological and geographical factors in the heat exchange process of the ground, the whole process becomes entangled and complex. For example, in the low depressed area, the ground is usually more fine grained thus leading to a large water content. In some areas the land becomes marshy and accumulates water, resulting in dense vegetation growth. Although there is heat exchange in two directions in the mountain ridge, because it usually consists of exposed bedrock, the effect of other geological and geographical factors exceeds the effect of the topography. Thus the depth to the permafrost table in the mountain ridge area is less than in the low, depressed areas.

As was mentioned before, the air temperature and the average annual ground temperature decrease as the altitude increases. However, there are exceptions at the watershed area of the Greater Khingan Mountain where the gorges are deep and mountain slopes steep. The air temperature and ground temperature of the watershed region in winter are higher than that in the gorges and valleys. When the water content of the ground layer is less than 15 to 20%, the ground temperature at the watershed region is higher than the temperature in the gorges by 1 to 2^{o}C. The difference may become as high as 2 to 2.5^{o}C if the ground surface is marshy. This is the result of a combined effect of the cold winter air in the gorge or valley becoming stagnant forming a temperature inversion, of the development of bog muck and clayey soil so that the ground surface becomes marshy, of the shielding of the sun by the mountain slopes on both sides, and of the relatively small amount of snow cover, etc.

The influence of topography is often manifested in the influence of degree of slope gradient and aspect. The quantity of radiation from the sun onto the ground surface is related to aspect and degree of slope. Generally speaking, under identical conditions, the ground temperature of a south facing slope is higher than the ground temperature of a north facing slope, and the ground temperature of a west facing slope is higher than that of an east facing slope. Moreover, the influence of aspect on ground temperature and thickness of the frozen ground layer increases as the slope increases. When the slope is between 20 and 30 degrees, this type of effect becomes very prominent. An example is the slopes on the two sides of the Chinghai-Tibet Highway at Xidatan, the south facing one being steep and the north facing one gentle. The ground temperatures at the same depth of the two slopes differ by 2 to 3°C, the lower limit of the perennially frozen ground on the north facing slope is 100 m lower than the lower limit at the south facing slope, and the thickness of the seasonally frozen layer is also less by 1.5 m. Another example is on the third and fourth terraces on a north facing slope of the upper part of the Heilungkiang River. The land there has a forest cover approaching 80%, the average annual ground temperature is 0 to 0.5°C, and permafrost 30 to 50 m thick has developed. The terrace on the south facing slope has a coverage of only 10 to 20% of pine trees, the average annual ground temperature is 2.7°C, and there is no permafrost. Thus, the ground temperature on a south facing slope may differ from that on a north facing slope by as much as 2.5 to 3°C.

In the Greater Khingan Mountain region, the main difference between the ground surface conditions on the south facing and north facing slopes is manifested in the longer hours of sunshine on the south facing slope than on the north facing slope; thus, the time of snow accumulation is shorter on the south facing slope, weathering is more advanced and groundwater movement is more active. Icings and pingos appear mainly at the foot of the south facing slope. Herbal plants prosper on the south facing slopes while woody plants are the chief vegetation on the north facing slopes.

For the east-west facing slopes of 20 to 30 deg slope at the upper region of the Heilungkiang River, the annual yearly ground temperature of the granite in the east facing slope is 0 to -1°C, while that in the west facing slope is 1°C. Similarly, the average annual ground temperature of the northeast facing slope is lower than that of the south-west facing slope by 1.5 to 2°C.

Chairman Mao has taught us "In approaching a problem a Marxist should see the whole as well as the parts." Thus not only do we realize the difference resulting from the various quantities of radiation energy from the sun due to the direction and gradient of the slope, we should also acknowledge the composite effect of other factors. When the slope is gentle, the important factors of ground temperature are usually not aspect, but the nature of the ground and water. For example, the following conditions occur in the Greater Khingan Mountain: permafrost occurs on the south facing slope where the ground surface is marshy and the topsoil is composed of moist clay; there is no permafrost on the north facing slope which is composed of coarse debris materials with good permeability and where the average annual ground temperature is positive. If we only considered the fact that the south facing slope receives more solar radiations than the northern slope, then we would arrive at the wrong conclusion.

The influence of aspect on the seasonally thawed layer far exceeds its influence on the seasonally frozen layer. That is to say, the depth of seasonal thaw on the south facing slope far exceeds that on the north facing slope, while the depth of seasonal freezing on the south facing slope does not differ too much from that on the north facing slope. The reasons behind this may be explained with a diagram. When other conditions are identical, the relationship between the depth of seasonal freeze (thaw) (Z), the average annual ground temperature (t), and the annual ground temperature differential may be illustrated in Figure 24. As shown in the figure, the abscissa represents the average annual ground temperature; the average annual ground temperature of a seasonally frozen layer is positive; thus it is to the right of $0^{\circ}C$, the average annual ground temperature of a seasonally thawed layer is negative; thus it is to the left of $0^{\circ}C$. The ordinate represents depth; the curves are the lines joining the annual ground temperature fluctuations at various depths.

It can be seen from the figure that in the seasonally frozen layer, for a given fluctuation A_1, when the average annual ground temperature is t_1 the depth of the seasonal frost is h_1; when the average annual ground temperature is t_2 the depth of seasonal freezing is h_2. $t_1 < t_2$ and $h_1 > h_2$. Thus, for a seasonally frozen layer, for a given fluctuation, the higher the average annual ground temperature the smaller the depth of seasonal frost. The reverse is true for a seasonally thawed layer; for a given fluctuation, the higher the average annual ground temperature, the greater the depth of seasonal thaw.

Similarly it may be seen from the figure that for a given average annual ground temperature, the greater the fluctuation the greater the depth. This is true for both seasonal freezing and seasonal thawing.

We know that due to the influence of snow cover in winter, the ground temperatures on both the north and south facing slopes are of approximately the same value, while in summer, the south facing slope receives more sunshine in the day, and hence a greater amount of heat. Therefore, not only does the south facing slope have a higher average annual ground temperature than the north facing slope, it also has a larger annual ground temperature fluctuation.

Now let us examine Figure 25. Due to the high value of the average annual ground temperature and the greater value of the annual ground temperature fluctuation on the south facing slope, the depth of seasonal thaw (h_3) is therefore much greater than the depth of seasonal thaw (h_4) on the north facing slope. As for the seasonally frozen layer, the fact that the annual ground temperature fluctuation is greater on the south facing slope than that on the north facing slope is one factor to increase the depth of its seasonal freezing, while the fact that the average yearly temperature* is higher on the south facing slope than on the north facing slope, is another factor to decrease the depth of seasonal freezing. These two factors acting in opposite directions cancel each other, with the net result that there is little difference between the depth of seasonal freezing on the south facing slope (h_1) and the depth of seasonal freezing on the north facing slope (h_2).

D. Snow Cover

There are three main effects of snow coverage:

(1) Snow is a poor conductor of heat, it hinders the exchange of heat between the ground surface and the atmosphere; it serves as an insulator.

(2) The rate of reflection of solar radiation from snow (40 to 85%) far exceeds that of the ground surface (15 to 20%) and the vegetation cover (20 to 25%), so that part of the solar heat does not reach the ground surface; hence snow has a cooling effect.

(3) The melting of snow requires a large amount of heat, and so this action has a cooling effect.

These three effects are working in contradiction with each other. Thus, the total effect of snow cover has to be determined by the effect placed in the leading position under certain concrete conditions. The effect of snow cover, therefore, varies under different conditions of thickness, density and time of formation of the snow cover.

In winter, snow cover hinders the dissipation of heat from the ground surface to the atmosphere and its insulating effect is therefore manifested in the preservation of heat at the

---

* Translator's note: The word ground is probably missing. It makes more sense to read average annual ground temperature.

ground surface. Thus, in winter, the ground temperature at places with snow cover is higher than that at places without snow cover. In summer time, however, snow cover greatly hinders the absorption of heat by the ground surface from the atmosphere. Its insulating effect is then manifested in the cooling of the ground surface, which is opposite to the first mentioned effect.

When the snow cover reaches a certain thickness in the winter, its insulating effect becomes predominant and the snow cover becomes heat preserving (see Table 8). When its thickness reaches a certain value, the amount of heat required for the melting of the snow becomes the predominant factor in summer, and snow cover then serves as a coolant of the ground layers.

As the density of the snow cover increases, its heat conductivity also increases; thus its effect as a heat insulator decreases.

In the permafrost region in northeast China, the snowfall in winter forms a snow cover of 10 to 20 cm thickness. On the watershed and high terrace lands, there is also drifting due to wind, and occasionally snow accumulation may reach as much as 0.5 m high or more. When the snow cover is 10 cm thick, the annual atmospheric temperature differential is 48^{o}C, and the average annual ground temperature in the ground with snow cover is 1.5 to 2^{o}C higher than that without snow. When the snow cover is 20 cm thick, the difference is as much as 2.7 to 3.2^{o}C. Thus, the effect of snow cover is very significant.

In the Chinghai-Tibet Plateau, the quantity of precipitation between May and September is 90% of the annual total, mostly in the form of snow, hail, and occasionally, rain. Thus, the main effect of the snow cover on the plateau is to lower the temperature. However, the snow cover on the plateau is thin, it is discontinuous, and the period of existence is short. Therefore, its effect is not very significant.

E. Rivers, Lakes

River water holds a large quantity of heat, and has the effect of raising the temperature of the neighbouring ground. The extent of this effect depends on the quantity and rate of flow, and water temperature and the rate of flow.

For large rivers, the beds are devoid of permafrost (for example, the Heilungkiang River in northeastern China, the Tuotuo River on the Chinghai-Tibet Plateau). In winter, the surface of the Heilungkiang River is frozen, and the ice is 1.5 to 2 m thick. The average annual ground temperature at the bottom of the river is still 2 to 3^{O}C, and there is no frozen ground 100 m below the riverbed. In September, 1965, the ground temperature at 20 m below the centre of the riverbed of the Tuotuo River was found to be 2.5^{O}C. Below beds of other rivers such as the Gun River, Keyi River, there was no permafrost. On the banks of the large rivers and on low terraces near large rivers there is also no permafrost.

For small rivers, however, there is often permafrost under the beds. It is usually buried deeper in the ground. For example, 7 m below the beds of Tuli River in the Greater Khingan Mountain there is perennially frozen ground, and the same is true 4 m below the riverbed of the Niuer River. There is also permafrost below sections of the beds of small rivers such as the Telichalk* River, the Chormayi* River, and the Beilu* River in the middle of the plateau.

---

* Translator's note: Phonetic translation only.

The influence of river flow on the thickness and the rate of development of the seasonally thawed layer in the riverbed far exceeds its influence on the thickness and the rate of development of the seasonally thawed layer in the banks (Table 9).

The density of water is greatest at $4^{\circ}C$; thus, at the bottom of fresh water lakes there is always a layer of water at $4^{\circ}C$, this has a warming effect on the underlying frozen layer. The extent of influence of fresh water lakes on frozen ground layer is dependent on their surface area and their depth. The larger the surface area and the greater the depth, the more significant the influence. It has been calculated that when the length and width of the lake is greater than the thickness of the frozen ground, and when the lake water is rather deep, the thawed region at the bottom of the lake would penetrate the entire frozen ground layer.

The lakes on the plateau are usually salty, the concentration of the minerals may reach as high as 6,000 to 8,000 mg/l. There is usually a layer of low temperature salt solution at the bottom of this kind of lake and this has a cooling effect on the ground layers below.

F. Groundwater

Groundwater is widely distributed above the permafrost region. This water exerts a great influence on the thermal physical properties of the ground. Moreover, because its recharge is from rain seeping downwards from the ground surface, it brings with it heat which flows along the permafrost table; hence the depth and rate of seasonal thaw is increased. For example in the Togmegla region, due to the water above the frozen layer at the bottom of the mountain slope, the thickness of the seasonally thawed layer is 0.5 m greater than in the general region. However, when the water above the frozen layer becomes stagnant and forms a marsh, a decrease in-ground temperature occurs.

Due to the large quantity of water in the alluvial layers, and the fact that it always acts with the ground surface water, the effect of a rise in temperature exerted by this water on the ground layers is also prominent. For example, the average annual ground temperature of the Heilungkiang riverbed near Leku Ho Village in northeastern China is 2^{o}C, while the average annual temperature of the ground surface at the river bank is only -1 to -2^{o}C.

The water below the permafrost also exerts a very strong influence on it. This is particularly true of the hot springs along the tectonoclastic zone. This water usually penetrates the entire permafrost zone to form a thawed region. The water temperature of the hot springs along the rift at the foot of the Tanglha Mountain reaches as high as 40 to 72^{o}C all year round, leading to the disappearance of the permafrost.

G. Human Activities

Under the great guidance of Chairman Mao who said "To uphold revolution, to improve on production, to improve on work, and to improve on military provisions", there are rapid developments of the socialist revolution and socialist construction in the permafrost region. We are now in the process of developing and exploiting forest and mineral resources in this region. In the process of construction, the harvesting of timber, removal of grass cover, draining of standing water, drying the ground surface, building of reservoirs and canals, siphoning of groundwater, and construction of industrial and domestic structures all lead to an elevation of the ground temperature and therefore a degradation of the permafrost.

In particular, the construction of heated buildings such as heating plants, heated workshops, brick and tile factories and the construction of reservoirs all exert a very strong influence on the permafrost; they can make all the permafrost disappear within a short period. These occurrences are often found in the Greater Khingan Mountain region. Generally speaking, because human activities are more concentrated in cities than rural areas, the depth of seasonal thaw is greater and the depth of seasonal freezing is less in the former.

To summarize the above, there are many complex factors influencing the thickness and temperature of the frozen ground. As Chairman Mao taught us "If in any process there is a number of contradictions, one of them must be the principal contradiction playing the leading and decisive role, while the rest occupy a secondary and subordinate position. Therefore, in studying any complex process in which there are two or more contradictions, we must devote every effort to find its principal contradiction. Once this principal contradiction is grasped, all problems can be readily solved." Of the many factors and contradictions mentioned above, the absorption and dissipation of heat by the ground layers are the principal contradictions. Latitude, altitude, topography, vegetation coverage, soil water, snow cover, ground surface water, groundwater, etc. all exert an influence, the net result of which is the dissipation or absorption of heat by the ground layers. If the dissipation of heat becomes the principal role of the contradiction, the ground temperature of the frozen ground decreases, the thickness of the frozen ground increases and permafrost develops. On the other hand, if the absorption of heat becomes the principal role of the contradiction, the ground temperature rises, the thickness of the permafrost decreases, and it degrades. Thus, this pair of contradictions, the dissipation and the absorption of heat, play the leading and the decisive role, while the many other varied factors and contradictions all play a subordinate role.

"In this world, things are complicated and are decided by many factors, we should look at problems from different aspects, not just from one." For the sake of easy description, we have listed and introduced the action of each factor one by one. However, in the natural environment, these factors are interrelated and interdependent. For example, the constituents of the soil usually determine its permeability and water content, and consequently influence the movement of the groundwater and vegetation growth. Thus, we have to look at a problem dialectically to grasp the rules of the movement of a thing.

Chairman Mao also taught us "'Have a head for figures.' That is to say, we must attend to the quantitative aspect of a situation or problem and make a basic quantitative analysis. Every quality manifests itself in a certain quantity, and without quantity there can be no quality." Change in quantity can lead to change in quality. For example, when the thickness of the snow cover or the depth of standing water on the ground surface is small, each has the effect of lowering the ground temperature. However, when its quantity exceeds a certain value, it exhibits an opposite effect, i.e. to increase the ground temperature. Thus, we should have a concrete analysis for a concrete condition, to achieve the ideal "have a head for figures". Only this method of analysis is scientific.

4. <u>Groundwater in the Permafrost Region</u>

Groundwater in the permafrost region is the main factor responsible for damage to the various engineering constructions. At the same time, however, it is of vital importance to the industrial and domestic water supply in the permafrost region.

Our working people in China have long since had a deep understanding of groundwater in the permafrost region through practical experience. There are three types of groundwater in this region: suprapermafrost water (that is, water above the permafrost), intrapermafrost water (water within the permafrost), and subpermafrost water (water below the permafrost).

A. Water Above the Permafrost (Suprapermafrost Water)

This water is in the seasonally thawed layer, and the permafrost table forms the bottom boundary surface; it has a free water surface. Since this water is near the ground surface, it is easily influenced by climatic changes and hence not very stable. In winter the upper part of the water freezes and the unfrozen water below is under pressure.

The floating water that is in contact with the frozen ground is in a solid state towards the end of winter and the beginning of spring. For floating water that is not in contact with the frozen layer, part of it remains in a liquid state throughout the year.

Water above the frozen layer is mainly replenished by rain. The recharge region is the same as the distribution region. Occasionally, it is also replenished from water below the permafrost which rises through thawed zones. The degree of mineralization of this type of water is usually rather low, and it can be used as a source of water supply. However, this use in winter is limited, since its quantity is not large and it is subjected to seasonal changes. Some water above the permafrost near rivers and lakes occurs in greater quantities. For example, on the first terrace of the Gunha, Iltuliho in northeastern China, not only is the thickness of the water-containing layer more significant, but there is a water supply throughout the year. Thus, it is a good water source.

B. Water Within the Permafrost (Intrapermafrost Water)

Occasionally there are intercalated thawed layers in the permafrost. The water found there is called thaw water within the frozen layers. At Sidaogu, Fuma Xian, northeastern China there are sheet-like frozen layers separated by intercalating thawed layers. The local working inhabitants termed them "checkers". They say: "There is intrapermafrost water coming out of the checkers."

Since water within the permafrost is completely surrounded by ground layers of negative temperature. It can only maintain its liquid state by constant movement. Water within the permafrost may connect to the water above it or to the water below through a thawed region, and receives its replenishment there. When the water within the permafrost is replenished by the subpermafrost water, it reflects some of the properties of the latter water. The same is true if the recharge is from the water above the frozen layers.

C. Water Below the Permafrost (Subpermafrost Water)

This type of water is below the permafrost and is usually under pressure. It has a positive temperature, which rises as the depth of the water increases.

This layer of water is the greatest threat to mining in the permafrost region. However, due to its abundant quantity, its stable state, good healthy conditions, it is also a reliable source of water supply.

There is water below the permafrost over wide areas in the Greater Khingan Mountain and the Chinghai-Tibet Plateau region. Along the rifts of the Greater Khingan Mountain, the subpermafrost water comes to the surface in springs.

The degree of mineralization of this water is between 200 to 300 mg/l, the water temperature ranges from 0.8 to 4°C. In the Chinghai-Tibet Plateau area, the subpermafrost appear as springs along the tectonoclastic zones. In the region between the Kunlun Mountain and the Tanghla Mountain, the degree of mineralization of the water below the frozen layer is between 2,000 to 7,800 mg/l, and the water temperature is between 0 to 7°C, mostly between 1 to 4°C. In the region north of the Kunlun Mountain and south of the Tanghla Mountain, the degree of mineralization of the water below the frozen layers is lower, 320 to 803 mg/l. In the region of the Tanghla Mountain, the temperature of the hot springs may reach 40 to 70°C.

CHAPTER THREE

EFFECTS OF PERMAFROST ON BUILDINGS

The deformation or damage to construction caused by freezing and thawing of water in the foundation soil is referred to as frost damage. It can be caused either by freezing of water in the soil or by melting of the groundwater or both: that is, by the repeated freezing and melting of water in the soil. In addition, further damage of construction works can be caused by the loss of strength of the foundation soils when they thaw.

I. Damage to Construction Works by Frost Heaving

When the water in the foundation soil freezes a bonding action (or freezing potential) results, joining the frozen soil firmly to the foundation. The water in the soil increases in volume as it turns into ice. When this type of volume expansion is sufficient to cause relative displacement between the grain particles, frost heaving occurs and, subsequently, severe frost heaving potential is produced. This is conveyed to the construction works through the freezing potential between the basal surface of the foundation and the lateral faces of the foundation. When the weight of the building and the added bonding force is insufficient to resist the frost heaving potential, the building is lifted upwards. When the foundation soil freezes water will move towards the freezing plane; a phenomenon called water migration. Because of this, the portion that has been frozen, greatly increases in water content, and so does the magnitude of frost heaving. As a result, the building is lifted up even more. Furthermore, since the foundation soil is often heterogeneous and also because the degree of freezing in the frozen soil at various parts of the foundation soil beneath is different, the movement is always uneven resulting in uneven deformation results. As soon as this type of differential movement exceeds the permissible values, the construction is damaged. This type of damage is the main one in the seasonally frozen regions. It is also one of the main reasons for damage to construction in the permafrost region.

Does the freezing of groundwater in all situations cause damage to construction through frost heaving, and does it cause damage to the same degree? The answers are no. Whether or not frost heaving will cause damage to construction, and if so, to what extent, is determined by water migration and frost heaving during freezing of the soil. These actions are related to the overall conditions of the soil such as temperature, water content and forces acting at a particular place at a point of time. In the following, we will discuss the effects of factors such as the soil, temperature, water and pressure on rate of water migration as well as the magnitude of frost heaving, freezing potential and frost heaving potential.

A. Water Migration and Frost Heaving

If we observe the changes in distribution of water content in the soil before and after freezing, we will discover that, after freezing, the water content increases in the upper part of the soil but decreases in the lower part (see Figure 26). That is to say, during freezing, water migrates upward.

Research has proven that when the soil freezes under certain conditions, the water in the lower part moves to the freezing plane, a phenomenon called water migration.

How does water migration occur? Theories explaining it are many. Some think that it is caused by the water head pressure differential. Some think that it is caused by capillary potential, and still others think that it is caused by electro chemical potential differential. There are many complex and varied theories. In the following, we will only focus on the "hypothesis of film water migration" which at present is generally considered as the principal cause.

As previously discussed, water and soil interact to form bound water, which is also called film water or hydraulic film. In the soil, the spaces between soil particles are small. The soil particles may even be in contact with each other. Hence, the hydraulic film of two adjacent soil particles joins together to form a common film (Figure 27). When the upper part of the soil body freezes, ice crystals form. In this formation process, part of the water content is drawn from the hydraulic film of the soil particle a which is close to the freezing surface, resulting in the thinning of the hydraulic film. At this time, if there is a grain particle c in the common hydraulic film, it will be pulled by the force exerted by the grain particle a and particle b. Since the water membrane of the grain particle a has been thinned, the distance between the water molecules and the soil particle a will be smaller than the soil particle b. Hence, the pulling force exerted on the water molecule c by the soil particle a is greater than that by the soil particle b. In other words, the force exerted on the water molecule c is not in equilibrium. The direction of the resultant force points to the soil particle c. Therefore, the water molecule moves upward, that is, migrates towards the soil particle a. Because of this, the water molecule in the thick membrane always will continuously migrate towards the thin membrane until a state of equal thickness between the two adjacent hydraulic films is reached. In the freezing process, the expanding ice crystal continuously draws water away from the adjacent hydraulic film, resulting in the thinning of the latter. The water molecule in the adjacent thick membrane also flows continuously to fill up the thin membrane. Thus, during freezing, this continuous migration process causes the migration of water towards the freezing surface of the lower part of the soil.

Water migration is the main physical-mechanical process in frozen soil. We know that when water freezes its volume increases by 9%. The action of water migration gathers relatively more water content. When it freezes, it causes drastic frost heaving in the soil, and when it thaws, it causes drastic depression. Therefore, water migration is the most important factor in causing frost damage to construction works.

One of the main results of water migration is the aggregation of ice which separates the soil particles from the ice layer to form an ice bedded layer, but, the formation of the ice-bedded layer is determined by certain conditions which are:

1. Soil Condition

Water migration and the aggregation of ice frequently occur in fine grain particles and, in particular, water migration is most severe and its heaving nature is strongest in silty slightly clayey and silty slightly sandy soils. This is because the grains of these types of soil are very small in size. They have enough surface energy with which they can facilitate water migration in large quantities. At the same time, even though the voids in this type of soil are very small, they are not so small that they will offer great resistance to the migrating flow from the bottom soil layer to the freezing surface. On the contrary, even though clayey soil has sufficient surface energy, because of the small size of the voids, great resistance to the migration flow results and, thus, its frost heaving property is less than silty slightly clayey and silty slightly sandy soils.

Coarse grained soils, especially sand and gravel, because of their coarse surfaces and small surface energy, do not produce water migration during freezing. Their water content only freezes at the original location or moves downward by gravity. After freezing, the water content even decreases in the upper part but increases in the lower part (Figure 28). If the water can flow out freely from the sand during freezing, its volume in reality does not expand and, thus, it does not have a frost heaving property. To use the properties of these soils, we can excavate the frost heaving soil surrounding the foundation and replace it with gravels in order to prevent frost heaving.

2. Water Condition

Let us first do a rough computation. Suppose there is a 1-metre-thick soil layer which has a relatively high water content, making up 30% of the total volume. After freezing the volume increases by 9%. Now the entire soil layer undergoes frost heaving and its uplifted height is 100 cm x 30% x 9% = 2.7 cm. That is to say, even in high water bearing soil the frost heaving magnitude after freezing is only several centimetres at most, but we discovered that the extent of severe frost heaving in natural environment may exceed 2.7 cm. Apparently, this severe frost heaving is produced by the supply of additional water from outside. Experience also shows that the severe frost heaving zone is often very close to the groundwater table. The external supply of water mainly comes from groundwater.

In this way, we can distinguish two types of frost heaving: one is called the open type frost heaving which, in the process of freezing, receives an external supply of water and the other is called the closed type frost heaving which receives no external supply of water in the process of freezing.

The open type frost heaving quite often forms a very thick ice layer (the type of ice formed by water migration is called segregated ice) and results in severe frost heaving.

The ice layer formed by the closed type frost heaving is relatively thin and the frost heaving is relatively small. Inside the seasonally thawed layer of the closed type heaving, water migration produces a definite pattern in the redistribution of water (Figure 29). In the freezing process, the water content inside the seasonally thawed layer migrates towards the upper and the lower freezing surfaces (the freezing surface of the surface layer and the uppermost control surface of the permafrost). Hence, it forms a rich water bearing belt at the upper and lower ends, whereas the soil layer which freezes last forms a weak water bearing belt. By making use of these special characteristics we can ascertain the position of the uppermost control limit of the permafrost based on the distribution curve of the water content.

Now, let us again look at the relationship between frost heaving and water content. Let us assume that the freezing depth of a certain soil layer is Δh and the corresponding frost heave is Δh_i. Here, the frost heaving of the unit freezing depth is referred to as the frost heaving depth or frost heaving rate of the soil layer, which is expressed by η_i

$$\eta_i = \frac{\Delta h_i}{h_i}$$

Figure 30 shows the relation curve between the frost heaving rate η of the slightly clayey soil and the water content W. The curve shows that when the water content is below a certain value, the frost heaving rate is zero. Numerous experiments have proven that only when the water content of the soil exceeds a certain limit value will it exhibit frost heaving. This limit value is called the initial frost heaving water content of that soil and is indicated by W_o. Under normal circumstances, the initial frost heaving water content of the clayey soil is roughly greater than its plastic water content or slightly greater than its prefreezing water content. What accounts for this phenomenon is that at a given negative temperature when the water content of the soil is equal to the prefreezing water content at the same temperature, the water in the soil does not freeze. When the water content is roughly greater than the prefreezing water content, the portion of the water content which is greater than the prefreezing water will freeze and expand in volume, but, because of the small amount of water content there are more free spaces - voids in the soil. These crevices allow the ice crystals to grow freely and this does not allow the creation of the relative displacement between soil particles needed for frost heaving. On the contrary, at this time, the soil contracts because of cold and, thus, a cooling contraction phenomenon results. Therefore, we should distinguish between two concepts: frost heaving of water in the soil and frost heaving of soil. Only when the water content in the soil exceeds the initial frost heaving water content of that soil will the frost heaving of water in the soil cause frost heaving.

The initial frost heaving water content varies with the nature of the soil. Under normal conditions, its value increases with the increase in the silt clayey grain (<0.05u) content of the soil and decreases with the increase in the size of the soil particle; that is, it is mainly controlled by porosity. Table 10 tabulates several typical initial frost heaving water content values.

Let us look at Figure 30 again. When the water content of the soil is greater than the initial W_o and smaller than a certain water content w_b, along with an increase in water content, the rate of frost heaving will rapidly increase. The relationship between η and W is approximately linear, that is,

$$\eta = C(W - W_o)$$

In the above equation, C is a ratio constant.

When the water content is greater than W_b, the frost heaving rate gradually slows down with an increase in the water content, and is always smaller than the frost heaving rate (η水$=9\%$)* of the water, but in the open system, because of the external supply of water, its frost heaving rate can exceed 9%.

3. Temperature Condition

When the temperature gradient of the soil is very great as a result of great cooling intensity, the freezing surface of the surface layer rapidly moves downward. The water in the soil freezes at its original location because it cannot migrate quickly enough from the underlying layer to the freezing surface. Ice formed under this type of condition is generally distributed through the voids or at the contact points of the grain particles. Those ice bodies which are not visible to the human eye are the complete-body-structured frozen ground[1], and those visible to the human eye are the group-granular-structured frozen ground. Generally speaking, there is no conspicuous frost heaving in the formation of this type of frozen ground.

---

* Translator's note: the equation reads: $\eta_{water} = 9\%$

Note 1: The structure of the frozen ground refers to the shape, size, relative arrangement and linking relationship of the various parts of the frozen ground.

If the cooling strength is small, the downward migration of the freezing surface is slow and it will even remain at a certain level for a long period of time because of the blockage of latent heat. At this time, after the migrating flow of the underlying layer overcomes the resistance along its route, it still has enough time to reach the freezing surface and form an ice layer. When there is a supply of additional water, then, the longer the freezing surface remains, the thicker the ice layer formed. In these circumstances, the ice layer often exhibits a bed-shaped or lens-shaped intercalation with grain particles (the interbedded layer of grain particles often exhibit a complete-body-structure and sometimes exhibit a bedded structure) to form bedded structured frozen ground. When the bedded ice produced by freezing combines with the veinlet ice to become reticular, then, reticular frozen ground results. In the formation of the frozen ground in these two types of structure, the soil shows distinct frost heaving.

The frost heaving in the soil caused by water migration has a certain pattern as the depth changes. As shown in Figure 32, in the permafrost regions, the maximum frost heaving rate occurs at the freezing depth of approximately one-third beneath the ground surface. The maximum frost heave occurs in the ground surface layer. The part of the soil body with frost heaving magnitude ranging from 75 - 90% is called the principal frost heaving region. The principal frost heaving region is mainly distributed within the range of the freezing depth two-thirds below the earth surface. Within the confines of the remaining one-third of the freezing depth, the freezing heaving magnitude is very small. Frost heaving only appears in the upper part of the frozen ground.

B. Freezing Potential

When the water of the foundation soil freezes, agglutination force results and it eventually bonds the soil to the foundation. This type of bonding force is called the freezing potential.

The freezing potential between the soil and the foundation only manifests itself when there is an external loading action and, also, the direction of its action is always opposite to that of the external loading action. This property of the freezing potential is similar to that of the frictional force of the thawing soil. It can exert the following actions on the stability of the foundation.

1. During the period when the seasonally thawed layer refreezes, the lateral surface of the foundation in the seasonally thawed layer is subjected to the action of the upward tangential frost heaving potential σ_τ. At this time, τ_i, which is subsequently produced along the lateral surface of the foundation in the permafrost and which is in the direction opposite to the tangential frost heaving potential counteracts σ_τ. In these circumstances, the freezing potential exerts consolidation action to counteract frost heaving (Figure 33).

2. When the seasonally thawed layer is in the process of thawing, its foundation undergoes a downward movement because of loading and gravity. At this time, the upward freezing potential subsequently produced along the lateral surface of the foundation in the permafrost, exerts a load carrying action in order to counteract depression.

Based on the numerous laboratory experiments we have discovered that the magnitude of the freezing potential is related to a series of factors. These factors are:

1. Temperature

When the water content is constant, the relationship between the freezing potential and temperature is as shown in Figure 35. When the water content of the soil is greater than the prefreezing water content and its temperature is lower than the initial freezing temperature, ice will appear in the soil. Whenever there is ice, freezing potential results. Within the range of the strong and medium phase change regions, the freezing potential rapidly increases with the lowering of the temperature, and their relationship is almost linear. Within the range of the weak phase change regions, the increase in freezing potential becomes relatively slow. The reason is that the size of the freezing potential is related to the bonding force between the ice crystals and the foundation. It is also related to the quantity of ice crystals participating in bonding. On the one hand, within the range of the strong and medium phase change regions, along with the decrease in the temperature, the activity property of the hydrogen ion in the ice crystal decreases. As the structure of the ice crystals becomes tighter, the bonding force becomes greater. On the other hand, within the range of the strong and medium phase change regions, while the temperature decreases there is still a large amount of prefrozen water turning into ice, and consequently the quantity of ice crystals participating in bonding increases. The results of these two factors acting concurrently is to relatively speed up the increase in freezing potential as the temperature decreases. However, in the weak phase change regions, the quantity of the prefrozen water content which can become ice as the temperature decreases already is small. Thus, any increase in the freezing potential totally depends upon reducing the activity property of the hydrogen ion in the ice crystal. Therefore, in the weak phase change regions, along with the lowering of the temperature, the increase in the freezing potential accordingly slows down.

2. Water Content

At a given negative temperature, the relationship between the freezing potential and water content is shown in Figure 36.

From the figure, we can see that a given negative temperature, freezing potential results when the water content is greater than the prefrozen water content at the same temperature. Freezing potential increases as the water content decreases. When the water content reaches a certain critical value, the freezing potential also reaches a certain critical value, the freezing potential also reaches its maximum value. After the water content exceeds the critical value, the freezing potential decreases as the water content continuously increases, and it eventually approaches a constant value -- the ultimate freezing potential. This is because, when the water content increases, the amount of ice crystals participating in bonding increases. Consequently, the colloidal area between the soil and foundation also increases and so does the freezing potential. When the water content reaches the critical value, the crevices in the soil layer are completely filled with the ice crystals. The colloidal areas between the foundation and the frozen ground reaches the maximum and, the freezing potential also accordingly reaches its maximum value. We know that, because of the surface tension between the grain particles after the water in the soil freezes, the activity property of the hydrogen ion is less than the hydrogen ion of the pure ice at the same temperature. That is to say, its bonding force is greater than that of pure ice. After the water content exceeds the critical value, as the water content continuously increases, the quantity of ice crystals participating in bonding already reaches the maximum value and, thus, it does not increase further, but at the same time, the ice layer between the grain particles and the foundation becomes thicker and thicker that is to say, the distance between the ice layer and the grain particles becomes greater and greater. The activity potential of the hydrogen ion in the ice crystals also gradually increases, reducing the magnitude of the bonding force. Accordingly, the freezing potential also reduces until the ice crystals are not subjected to the surface tension of the grain particles and until it eventually becomes closer to the freezing potential of pure ice.

3. Grain Particle Components

When the water content and the temperature are the same, the freezing potential of the coarse grain particles is greater than that of the fine grain particles, but, under natural conditions, the water content of the fine grain particles is generally greater than that of the coarse grain particles and, thus, their freezing potential increases accordingly. With regard to soils of the same category, even though their components are different, their freezing potential is basically the same. Among coarse grain particles the freezing potential of sand is the greatest and, therefore, sandy soil is the most ideal fill material. It has the highest freezing potential and it also can prevent the formation of the ice interbedded layer in the vicinity of the foundation. It is also easy to irrigate.

4. Length of External Action

We know that by increasing the pressure we can lower the melting point of ice and thereby cause it to melt at a negative temperature. Under long term external loading action, the ice in the frozen ground will continue to melt. It also moves from high pressure to low pressure. Thus, when the deformation limit is at a stable value, the stress of the frozen ground accordingly decreases as time elapses, and stress relaxation results. When the stress is constant, deformation continuously increases with time, and creep is produced in the frozen ground. This property of the frozen ground is called the rheological property.

Because of this special rheological property, there is a close relationship between the magnitude of the freezing potential and the added load rate during experimentation. The greater the added load rate, the greater the freezing potential obtained from testing and the closer it is to the instantaneous value (Figure 37). The high speed freezing potential which, within 1 - 2 seconds, causes relative displacement between the experimental apparatus and the freezing soil is referred to as the instantaneous value. The freezing potential obtained during the added load at the standard speed is called the ultimate value and the test value of the lengthy loading action is referred to as the long term freezing potential.

What has practical significance to engineering construction, is the long term freezing potential but it is difficult to ascertain and, therefore, we generally employ the ultimate freezing power in our calculations.

5. Properties of the Foundation Materials

Even with the same soils and under the same conditions, the freezing potential between different materials will be different. This is solely a result of the coarseness of the surface of the material. The actions caused by the coarseness of the material are listed below:

a. If the surface of the material is very coarse its surface area will be large and, consequently, its bonding will be great and its freezing will increase accordingly.

b. The high coarseness of the surface of the material easily permits intrusion between the frozen ground and the foundation. Therefore, in order to produce relative displacement between the foundation and the frozen ground, it is necessary not only to overcome the bonding force produced between the grain particles and foundation, but also to overcome the shear resistance in the ice in part of the frozen ground.

Hence, if we increase the surface roughness of the various types of foundation, which are buried in the permafrost, we can increase the freezing potential and, accordingly, decrease foundation movement.

Table 11 lists the long term freezing potential value of the surface of the frozen ground, concrete, and wooden foundations. They can serve as a reference.

C. Frost Heaving Potential

When the ground is heaving because of freezing, frost heaving potential results. Two types of frost heaving potential can be distinguished according to the directions of the frost heaving potential acting upon the foundation surface, the normal frost heaving potential σ which is perpendicular to the foundation base, and the tangential frost heaving potential τ which is along the lateral base (Figure 38).

When the direction of the warm current interacts with the lateral surface of the foundation, because of the dissymmetry of the potential, normal frost heaving potential σ_- results. σ_- acts upon the outer wall of the foundation of the heat construction work; it often causes concave curved deformation.

The normal frost heaving potential acting upon the base of the foundation is generally very great, reaching from the strength of several kgs to more than 10 kgs per square centimetre. Some are even so great that common construction works usually cannot withstand them and, therefore, they should be avoided.

In practice, it is difficult to avoid the normal frost heaving potential acting upon the lateral base of the foundation. The only thing that can be done is to put into practice certain measures to reduce their frequency of occurrence, because the tangential frost heaving potential acts upon the lateral base by means of the freezing potential between the frozen ground and the foundation, the magnitude of the tangential frost heaving potential is thus closely related to the freezing potential.

Figure 39 shows indoor test data and also indicates the relationship between the long term frost heaving potential, the tangential frost heaving potential and the water content of the clay in the warm water region. From the figure, we can see that the relation of the freezing potential and water content, and the relation of the tangential frost potential and water content are similar. The strength of both increases as the water content increases until the latter reaches a certain critical value and its strength reaches the maximum value. After the water content exceeds this critical value, its strength decreases as the water content continuously increases. Finally, it approaches a fixed value -- the freezing potential and the tangential frost heaving potential of ice, but the nature of these two types of potentials is different. The freezing potential results from the bonding force of ice whereas the frost heaving potential results from the volume expansion of ice. Hence, we can still see a clear difference between these two types of potentials in Figure 39. As shown in the figure, when the water content of the experimental clay is greater than the prefrozen water content (at -7^{o}C the prefrozen water content is 9%), ice crystals appear in the soil and freezing potential results. When the water content is 9 - 12%, the quantity of ice crystals gradually increases. The increase in the collodial area results in an increase in freezing potential, but, within the range of the water content, there are still relatively large voids for the ice crystals to grow freely. Thus, no frost heaving occurs as a result of relative displacement between grain particles, and no freezing potential manifests itself. Only when the water content is greater than 21% (roughly equivalent to the initial frost heaving water content), then the freezing of water in the soil frost heaving results, and tangential frost heaving potential is produced. Therefore, freezing potential must come before and also must be greater than the tangential frost heaving potential.

If we compare the relationship between the freezing potential and the tangential frost potential at the negative temperature, we will further discover their common and individual properties. From Figure 40, the frost heaving potential and the tangential frost potential increase as the temperature decreases. The value of the freezing potential still increases even if the temperature is below -50^{o}C, whereas, the tangential frost heaving potential already tends to be stable at -9^{o}C. From this we can further see the differences in the basic natures of the freezing potential and the tangential frost heaving potential. The magnitude of the freezing potential is determined not only by the activity property of the hydrogen ion in the ice crystal. The magnitude of the tangential frost heaving potential, however, is determined by the quantity of ice crystals in the soil. After the temperature becomes lower than the strong and medium phase change regions, the prefrozen water content which can become ice in the soil becomes very small. Thus, in this temperature zone, the soil usually does not heave and the tangential frost heaving potential tends to be stable, but at this time, as the temperature decreases the activity potential of the hydrogen ion gradually decreases and the freezing potential subsequently increases.

Similar to the case of freezing potential, the relationship between the tangential frost heaving potential and the roughness of the material surface of the foundation is the same. That is to say, the coarser the material surface, the greater the tangential frost heaving potential.

II. Thaw Settlement Damage to Construction Work

There are many forms of ice with varied structure in the frozen ground. After thawing, the volume of these ice bodies decreases, causing a definite amount of settlement in the soil because of their own weight. After the ice has turned into water, the water, through the action of gravity and the action of external loading will gradually be expelled through the voids, and this further causes the soil to collapse and subside. The fine grained frozen ground with high ice content frequently turns into slurry after thawing and, consequently, loses its load carrying potential. Through the action of its gravity and external loading, it frequently is expelled from the two sides of the base of the foundation, creating large scale settlement. Because the properties of the foundation soil and the ice content in a construction site are heterogeneous, and their thaw depth is different, the settlement in different parts of a construction site will not be uniform.

Frozen ground with different structures will result in different compression and settlement features after thawing. The texture of the complete-body-structured frozen ground shows little change after thawing. Therefore, its physical mechanical property shows little change as compared to before freezing, but saturated or supersaturated complete body structured fine sand and silt sand frequently loose their load carrying potential after thawing. As for bedded and reticular structured frozen ground, if there are ice layers or ice blocks in them, after thawing, there will be a great change in their structure. Furthermore, their load carrying potential is often very low or even nonexistent.

In the following, we will look at the conditions after the soil thaws from a fixed quantity point of view.

It has generally been accepted that soil compressibility is caused by a decrease in the volume of the voids. Therefore, if we understand the ratio value of the voids under different pressures, we can still find the compressibility of the soil.

Through the compression experiment of the non-lateral expansion, we obtained the relation curve between the crevices ratio e and the external pressure P, that is, the so-called compression curve, as shown in Figure 41. It is a curved line, but if a short portion of it is used, it can almost be treated as a straight line. For instance, if the void ratio is e_1, when the soil begins to receive pressure P_1 and when the pressure increases to P_2, its void ratio is e_2. When the changed value of the pressure $\Delta P = P_2 - P_1$ is not too high, its curve can almost be treated as a straight line. At this time, its gradient is

$$a = \frac{e_1 - e_2}{P_2 - P_1} = \frac{e_1 - e_2}{\Delta P} .$$

"a" is called the compression coefficient and can be used to reflect the magnitude of the compressibility.

With the compression curve e - P, it is easy to find the amount of settlement in the soil when the pressure increases from P_1 to P_2. If we assume that the volume of the grain is 1 and the volume of the crevice is e, then, the ratio between the grain volume and the total soil volume is $\frac{1}{1 + e}$, and the void volume is $\frac{e}{1 + e}$. If the height of the soil is h_1 at pressure P_1, the void ratio is e_1 and the cross-sectional area of the soil is F (because of the lateral limit expansion, thus, F = constant), then the volume of the grain particles should be $\frac{h_1F}{1 + e_1}$. Similarly, when the Pressure is P_2, the grain volume is $\frac{h_2F}{1 + e_1}$. Since the volume of the grain particle does not change, the following equation is obtained

$$\frac{h_1F}{1 + e_1} = \frac{h_2F}{1 + e_2}$$

thus,

$$h_2 = h_1 \frac{1 + e_2}{1 + e_1}$$

therefore, magnitude of settlement:

$$S = h_1 - h_2 = h_1 \left(1 - \frac{1 + e_2}{1 + e_1}\right) = h_1 \frac{e_1 - e_2}{1 + e_1}$$

or

$$S = h_1 \frac{a\Delta P}{1 + e_1}$$

If we let $a_o = \frac{a}{1 + e_1}$ be the volume compression coefficient and let H and P represent the original height of the soil h, and the pressure added value ΔP respectively, we will get:

$$S = a_o PH$$

Figure 42 is the variation curve of the crevice which in the course of frost thawing changes with the external pressure P. "a" is the compression curve during thawing. When the load is added to the frozen ground at negative temperature, it undergoes a compression process, and yet, the change in voids is not great. If the frozen ground starts thawing after the temperature changes from negative to positive, or more accurately, when the temperature of the ground reaches the thawing temperature (generally speaking, we can take 0^oC as the thawing temperature for coarse grains such as sandy gravels, etc.; for fine grains we can take -0.1 to -0.3^oC) the frozen ground will thaw continuously At this time, even though the external pressure P does not increase, the crevice ratio will rapidly change with the thawing of the frozen ground. After the frozen ground layer completely thaws and the external pressure is added, the compression curve of the ordinary thawing soil can be obtained.

If we first let the frozen ground thaw and then apply external pressure, then, the relationship between changes in the void ratio and the external pressure is as shown in Figure 42b. When the external pressure P = 0 (a large number of experiments have proven that it should be when the external pressure P is very small or close to 0), because the volume of the frozen ground decreases after the ice turns into water, the void ratio has already undergone changes under its own weight, that is,

$$\Delta e_{p \to o} = A$$

"A" is the thaw settlement coefficient. When the external pressure is increased to P, the compression process is the same as ordinary thawing soil

$$\Delta e_p = P \cdot tg\beta = aP$$

$a = tg\beta$ is the compression coefficient.

Therefore, the total variation in the void ratio during the compression process of thawing frozen ground is

$$\Delta e = \Delta e_{p \to o} + \Delta e_p = A + aP$$

and the depression magnitude of the frozen ground during thawing compression is

$$S = h_1 \frac{\Delta e}{1 + e_1} = h_1 \frac{A}{1 + e_1} + h_1 \frac{aP}{1 + e_1}$$

If we let $A_o = \frac{A}{1 + e_i}$ be the thaw settlement coefficient of the volume, $a_o = \frac{a}{1 + e_i}$ be the compression coefficient of the volume and let the original height h_1 be H, then, we have

$$S = A_o H + a_o PH$$

It is noteworthy that in ordinary thawing ground, P is the added pressure, but, in computing the thawing compression for frozen ground, P ought to be the total acting force of that particular layer, that is, including the weight of the ground and the added pressure. If we separate the added pressure from the weight of the ground, we have

$$S = A_o H + a_o PH + a_o \frac{\nu}{2} H^2$$

In the above equation, P - added pressure

$\frac{\nu H^2}{2}$ - weight of ground

ν - soil unit weight

The above discussion concerns the conditions of a homogeneous thin soil layer. However, the natural foundation soil frequently is composed of varying kinds of soil layers, and each of them differs in their thawing compressibility. Even in the case of homogeneous soil, because the weight and the added pressure of the soil vary according to the depth, so does its thawing compressibility. Hence, in computing the settlement magnitude, we should, according to the actual situation, divide the foundation soil into many thin layers. By adding up the settlement magnitude of each layer we will get the total settlement magnitude of the foundation S.

$$S = \sum_{i-1}^{n} S_i = \sum_{i-1}^{n} A_{oi} h_i + \sum_{i-1}^{n} a_{oi} P_i h_i + \sum_{i-1}^{n} a_{oi} q_i h_i$$

In the above equation, $\sum_{i=1}^{n} S_i$ - from S_i, S_2, S_3... to the required total settlement at the n layer

P_i, q_i - are respectively the mean added pressure and mean weight pressure of the thin layers in the central portion of the bottom part of the foundation

Then, how do we determine the depth of the compressed layer? Usually, in computing the deformation of the foundation of the frozen ground, we use the so-called concept of "force maintaining layer" which limits the depth of the compressed layer to the value at which the added stress is equal to or less than 0.1 - 0.2 times the weight of the foundation soil. Any depth above this is called the "force maintaining layer", but, the thawing compressibility of the frozen foundation soil differs from the "force maintaining layer". First of all, thaw settlement is directly related to the thawing depth. At the same time, after the frozen ground thaws, another new compression consolidation action occurs. Therefore, in practical work, the computation of the depth of the compression deformation caused by the gradual thawing of the foundation soil should be confined to the depth of stable thawing (stable thawing boundary surface).

Since the compressibility of frozen ground is much less than that of thawing ground, in computing the added stress of the foundation soil, the permafrost beneath the stable thawing boundary surface can be almost virtually regarded as the incompressible layer (except for frozen ground ice in ice content with soil temperature near $0^{\circ}C$). The vertical stress at the intersectional point N between the boundary surface and the axis of the foundation can be computed with the following equation

$$\sigma_N = KP$$

In the above equation,
- K - the coefficient of stress, can be obtained in Table 13 based on h/b and a/b
- h - the distance from the bottom of the foundation to the stable thawing boundary surface
- b - half the width of the foundation
- a - half the length of the foundation
- P - the average external pressure in the foundation soil at the bottom portion of the foundation

In order to simplify the computation, we further assume the added stress coefficient K beneath the axis of the foundation to be in linear distribution. The discrepancies in the nature of the soil and the structure of the frozen ground should be taken into consideration when dividing the soil into thin layers.

In the following, we will give an example of computing the thawing compression magnitude:

Example: A certain bar-shaped foundation, its buried depth D = 1.8 m. The stable thawing depth of the foundation is 5.1 m. Its geological profile is shown in Figure 43. Its foundation width 2b = 1.0 m, and the average external pressure

$p = 1.5 \text{ kg/cm}^2$. What is the ultimate thawing compression magnitude at point 0 at the outer wall of the construction work?

Calculate the weight stress of the foundation soil at the marked height at the bottom of the foundation:

$$\sigma_c = 1.75 \text{ ton/m}^3 \times 1.8 \text{ m} = 3.15 \text{ ton/m}^2$$
$$= 0.32 \text{ kg/cm}^2$$

Hence, the added pressure of the foundation base is

$$\sigma_o = p - \sigma_c = 1.50 - 0.32 = 1.18 \text{ (kg/cm}^2\text{)}$$

The ratio value between h (distance from the base of the foundation to the thawing boundary surface) and b (half the width of the foundation) is

$$\frac{h}{b} = \frac{3.3 \text{ m}}{0.5 \text{ m}} = 6.6$$

From Table 13, we see that the coefficient of stress at point N at the thawing boundary surface is

$$K_N = 0.281$$

Thus, we get

$$\sigma_N = K_N \cdot \sigma_o = 1.18 \times 0.281 - 0.33 \text{ (kg/cm}^2\text{)}$$

According to linear interpolation, we get

$$\sigma_{Z-3.5} = 0.74 \text{ kg/cm}^2$$

The weight stress of the soil is q

$$q_{Z=3.5} = 0.32 \text{ kg/cm}^2 + 1.7 \text{ m}$$
$$= 0.61 \text{ kg /cm}^2$$

$$q_{Z=5.1} = 0.61\text{kg/cm}^2 + 1.8 \text{ ton/m}^3 \times 1.6 \text{ m}$$
$$= 0.90 \text{ kg/cm}^2$$

Therefore, if the thawing compression layers are divided into two:

first layer: 1.8 - 3.5 m, $h_1 = 1.7$ m

mean added stress: $\bar{\sigma}_1 = \frac{1.18 + 0.74}{2} = 0.96 \text{ (kg/cm}^2\text{)}$

mean weight stress: $\bar{q}_i = \frac{0.32 + 0.61}{2} = 0.47 \text{ (kg/cm}^2\text{)}$

mean stress: $\bar{\sigma} + \bar{q}_i = 1.43 \text{ kg/cm}^2$

thawing compression magnitude:

$$S_1 = 0.055 \times 170 \text{ cm} + 0.025 \text{ cm}^2\text{/kg} \times 1.43 \text{ kg/cm}^2 \times 170 \text{ cm} = 15.4 \text{ cm}$$

second layer: 3.5 - 5.1 m, $h_2 = 1.6$ m

mean added stress: $\bar{\sigma}_2 = \frac{0.74 + 0.32}{2} = 0.53 \text{ (kg/cm}^2\text{)}$

mean weight stress: $\bar{q}_2 = \frac{0.61 + 0.90}{2} = 0.75 \text{ (kg/cm}^2\text{)}$

mean stress: $\bar{\sigma}_2 + \bar{q}_2 = 1.28 \text{ kg/cm}^2$

thawing compression magnitude:

$$S_2 = 0.002 \times 160 \text{ cm} + 0.011 \text{ cm}^2/\text{kg} \times 1.28 \text{ kg/cm}^2 \times 160 \text{ cm} = 2.5 \text{ cm}$$

And the total settlement magnitude is:

$$S = S_1 + S_2 = 15.4 + 2.5 = 17.9 \text{ (cm)}$$

A large amount of test data show that, in various types of frozen soils, there is a close relationship between their thaw settlement coefficient A_o and a_o, and the physical index such as the dry unit weight and water content, etc. Figure 44 shows the relation curve between A_o of sandy gravels at the Kiliang Hill of Quinghai Province and the dry unit weight ν_{CK}. In ordinary thawing regions, sandy gravels are always good natural foundation soil, but not the frozen sandy gravels. Because sandy gravels for a long period of time have undergone freezing, their grain particles are separated by ice coatings. When thawing occurs, severe sinking also occurs, as shown in Figure 44. When its dry unit weight approaches or exceeds 2.0 g/cm^3, the value of A_o is less than 1%. If its dry unit weight is less than 1.85 g/cm^3, then, its thaw settlement coefficient rapidly increases.

Figures 45 and 46 respectively show (1) the relation curve between the ice thaw settlement coefficient A_o and the dry unit weight, and the water content; and (2) the relation curve between the compression coefficient a_o and the dry unit weight. We can see that when the dry unit weight of the natural frozen mild clay approaches or is greater than 1.4 g/cm^3, A_o approaches zero. As the dry unit weight decreases, the structure of the soil loosens, and hence, A_o continuously increases. When the dry unit weight is greater than 1.0 g/cm^3 A_o and ν_{CK} are in linear relation

$$A_o = K_{(\nu_o - \nu)}$$

In the above equation, K - ratio coefficient

ν_o - initial thawing depression

In addition, the thaw settlement coefficient A_o is also related to the water content of the soil. When the water content is less than 60%, both of them can be expressed by the linear relation

$$A_o = K'(W-W_o)$$

In the above equation, K' - ratio constant

W_o - the initial settlement water content, close to or slightly greater than the plastic limit water content

When the water content continuously increases, a large quantity of grain particles are separated by the ice crystals and therefore, its settlement increases during thawing.

If the dry unit weight of the clay is raised, the void ratio will be reduced and its corresponding compression coefficient a_o will be lowered (Figure 46).

It should be pointed out that when there are changes in the mineral composition, grain particle composition, and especially in the organic content of the soil, the relationship between A_o and a_o, and their dry unit weight and the water content will change subsequently. The relation curve can be obtained through various tests in various areas. In regions where tests cannot be carried out, we can rely on simple physical indexes (dry unit weight, water content). From the curve we can obtain A_o and a_o and we can also estimate the thaw settlement magnitude of the foundation soil of the construction work.

III. Thermal Process in the Foundation Soil

In the above, we have introduced the effects caused by frost heaving and thaw settlement in the foundation soil in construction works. Then, under what conditions does the foundation soil thaw, and to what depth? Under what conditions will the foundation soil freeze and to what depth? And, also, under what conditions will the foundation soil be in the repeated freeze-thaw state, and to what depth? All these are closely related to the thermal conditions of the construction works. The construction works built by industry and ordinary citizens are of many categories and are different in structure. Depending on the thermal conditions, these can be grouped into two large categories: namely, heated and unheated, or they can be called warm-structured substances and cold-structured substances. Because the thermal conditions in the structured substances are different, the thermal processes in the foundation soil also vary.

A. Heated Construction Works

In seasonally frozen regions, when the ground freezes in the winter, the foundation soil along the outer wall of the construction works also refreezes. The average value of the maximum freezing depth Z_o, which was obtained over a period of years of testing at the time when there was no snow or grass cover is referred to as the standard freezing depth. The ratio $Z/Z_o = m_t$ between the freezing depth Z and standard freezing depth Z_o at the foundation soil along the outer wall is referred to as the coefficient of influence of the heated condition upon the freezing depth. In situations without test data, the standard freezing depth can be computed from the meteorological conditions of the local area by using the following equation

$$Z_o = 0.28 \sqrt{\Sigma Tm + 7} - 0.5$$

In the above equation, ΣTm - is the total sum of the monthly negative temperature (mean temperature of 10 years duration)

The coefficient of influence on freezing depth m_1 of the foundation soil along the outer wall of heated construction works can be found in the following table (Table 14).

After the construction works on the permafrost are subjected to heat, the permafrost in the foundation soil will continuously thaw and gradually form a stable thawing basin, but in the foundation soil beneath the outer wall, because of the direct influence of seasonal freezing and thawing, refreezing occurs when the ground freezes. Generally speaking, there is little refreezing beneath the south wall, but the foundation soil beneath the east, west and north walls partly refreezes or even totally and solidly freezes, forming a single body with the underlying permafrost.

Despite the many computation methods as yet, no satisfactory solutions have been found to determine the thaw basin of the foundation soil of a heated building in the permafrost regions. Some of them are experimental in nature and are limited to local application, and, thus, cannot be used universally. In the following, one of the computation methods of «СНиП II-Б, 6—66» is introduced. It can be used to determine the maximum freezing depth of the building centre and the peripheral area (start computing from the design height-index of the indoor horizontal ground).

Let the signs represent the following meanings:

B	-	house width, metres
L	-	house length, metres
t_n	-	indoor annual temperature $^{\circ}C$
t_O	-	soil temperature 10 metres below ground surface (close to the average annual ground temperature), $^{\circ}C$.
λ_r, λ_M	-	are respectively the coefficients of heat conductivity in Kcal/m.h.$^{\circ}C$ which can be found in Tables 15-18
R	-	heat resistance of the floor surface inside the building. For ordinary buildings we can use

$$R = 1 - 1.5\, m^2 \cdot h \cdot {}^{\circ}C/Kal$$

$$a = \frac{\lambda_r R}{B} \qquad \beta = \frac{-\lambda_M \cdot t_O}{\lambda_r t_n}$$

The maximum thaw depth H^o_{max} and the maximum thaw depth H_{max} at the centre of the building can be determined through the following equations,

$$H^o_{max} = K \times \xi_o \times B \qquad H_{max} = K \times \xi \times B$$

In the above equations, K - coefficient, can be found in Table 19

ξ_o, ξ - coefficients, can be found in the Figures 48a and b respectively

Related data for the thawing basin in the foundation soil in a heated building can be accumulated throughout the year at the observation station. They can also be determined by actual survey of the buildings which can be used for a certain number of years. In places where conditions permit, hydraulic power and electric power can also be used to determine the thaw basin. Figure 49 shows zero isotherms in the foundation soil of a heated building at Chiliang Hill in Chinghai Province. The average annual temperature of that area is -5.8 C.

Based on an analysis of the materials obtained over the years, the average annual temperature of that building is about 15^{o}C. The maximum freezing depth of the foundation soil of the building at the centre is 5 - 6 metres. The maximum freezing depth beneath the outer wall on the north side is about 2.5 metres. The soil here freezes completely in the winter. The soil along the outer wall beneath the south side is in a thawed state almost throughout the year. Its maximum freezing depth is about 5 metres. The maximum freezing depth beneath the outer walls of the east and west sides is about 3 metres and the soil partly or completely freezes in the winter.

Through actual survey and by combining the available computation methods, the railway Ministry proposed "to stabilize the maximum freezing depth value when the heat source is high up in the sky". This is tabulated in Table 20 and can be used as a reference in practical usage.

Judging from the presently available data obtained from observation and surveys, in ordinary heated buildings in the permafrost regions at Chiliang Hill of Chinghai Highland, the ratio of the maximum freezing depth of the foundation soil beneath the outer wall of the heated building and the maximum freezing depth of the foundation soil beneath the centre of the building are: 0.5 - 0.75 for the east and west walls, 0.75 - 0.9 for the south wall and 0.4 - 0.6 for the north wall.

If the elevated heated buildings with ventilated basements are properly managed, the position of the permafrost table in the foundation soil will not change very much. It may even rise slightly, which may be sufficient to maintain the foundation soil in the freezing state.

B. Unheated Buildings

Because the foundation soil of the buildings in seasonally frozen regions can avoid the direct radiation of the sun, the total reception of heat decreases and, therefore, the refreezing depth in winter is greater than that in the natural state. Hence, for buildings which are not subjected to heat or not often subjected to heat in winter or which cannot be properly used except with prefreezing (including the foundation in winter) we can use m = 1.1. For embankment construction in seasonally frozen regions, because of the heat preservation of the overlying layer, the freezing depth of the natural foundation soil beneath the road foundation accordingly decreases. The degree of decrease varies with the heat retaining properties of the embankment.

The situation in permafrost regions differs from that of the above. When building an embankment in a severely cold region, if properly managed, the embankment can exert the heat retaining action on the underlying layer. It can gradually raise the permafrost table and form a frozen core in the embankment (Figure 50). In the winter, the entire embankment will completely freeze.

Hence, in seasonally frozen ground or permafrost regions, after a building is constructed, because of the differences in thermal conditions, various types of freeze-thaw cyclical processes will appear in the foundation soil. Concurrent with these processes, the foundation soil may undergo frost heaving, thaw settlement and repeated freezing and thawing, all of which will have various effects on the construction works.

IV. The Load Carrying Potential of Foundation Soils in Frozen Ground

Similar to other normal regions, in order to construct a building on frozen ground, the permissible load carrying potential first must be obtained. We not only have to guarantee the strength of the foundation soil, but also at the same time we have to consider whether the building can be used when the settlement is caused by the permissible load carrying potential, that is, by its own action.

If we assume that the permissible load carrying potential is [p], the external load pressure p acting upon the foundation soil must satisfy $p \leqslant [p]$.

At present, there are several principal methods to ascertain the permissible load carrying potential of the foundation soil.

A. Using the Construction Experience of Nearby Regions

If various types of construction works were built in the vicinity at different times, observing the operating conditions of them and the real pressure acting on the base of the foundations is the most reliable means of determining the permissible load carrying potential [p] of the foundation soil.

B. Based on the Data obtained from Field Experiments

In areas where no previous examples can be followed, carrying out loading experiments or standard intrusion experiments at the actual construction site to ascertain the ultimate load limit of the foundation soil is absolutely necessary for building important engineering construction works. From this, we can also obtain the magnitude of elasticity and the compression coefficient of the foundation soil in the remote area, but, to test the relation between the magnitude of settlement beneath the load carrying plane and the pressure is not the same as carrying out this procedure below the foundation soil. The discrepancies between them should be noted.

C. To Determine by Rules

The basic load carrying potential of the foundation soil for the permafrost was prepared and listed in Table 21 in the railway "bridge letter" of China. This was done according to various soil conditions and the highest average monthly temperature at the bottom of the foundation. This table can be used in the design of bridges, and as reference by other departments. However, the special characteristics of the constructions works must be taken into consideration, and the table should not be rigidly applied. With the accumulation of more construction experience, the rules will be continuously supplemented and improved.

D. To Compute by Theoretical Equations

Here, we will briefly introduce the theories of the plastic load and ultimate load limit as well as the semi-experimental equation of the foundation soil.

1. Plastic Load p_a

The load which can cause the foundation soil along the two margins at the base of the foundation to reach equilibrium[1] is referred to as the plastic load. Here, we will introduce the following computation method to obtain p_a, that is, when under the strip loading conditions at which the width is b, and the buried depth is h, and only the soil along the two marginal sides of the base of the foundation has reached ultimate limit equilibrium.

Note 1: Under the action of the added pressure, if the shear stress of the foundation soil is smaller than the shear strength, the soil will be in equilibrium and also in a stable state. If the stress is just equal to the shear strength, we can say that, in this condition, the soil is in the ultimate limit equilibrium state. At this time, an increase in a small amount of external force will upset the stability of the soil.

Assume

- p - bar-shaped load strength of the foundation
- γ - soil unit weight
- h - buried depth of foundation
- γh - weight of soil above buried foundation
- Z - vertical distance from any point N away from base of foundation

At this time, when subjected to the bar-shaped distributed load action $(p - \gamma h)$, the stress of the random point N (with an addition of the weight of the soil) on Figure 51 can be approximated by the mechanical elasticity

$$\left.\begin{matrix}\sigma_1 \\ \sigma_2\end{matrix}\right\} = \frac{(p - \gamma h)}{\pi} - (2\beta \pm \sin 2\beta) + \gamma(h+Z)$$

When ultimate limit equilibrium occurs along the two margins at the base of the foundation, it can be treated as the ideal elasticity body. Its maximum shear force ought to be a constant and it is also equal to the long term bonding when subjected to lengthy loading action that is

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = c_{\text{ДЛ}}$$

Comparing the above two equations, we get

$$\frac{\sigma_1 - \sigma_2}{2} = \frac{(p_a - \gamma h)}{\pi} \sin 2\beta = c_{\text{ДЛ}}$$

$$\therefore (p_a - \gamma h) = \frac{c_{\text{ДЛ}}\pi}{\sin 2\beta}$$

When $\sin 2\beta = 1$, we get the minimum external load strength, at this time

$$p_a = \pi c_{АЛ} + \gamma h$$

Under the action of p_a mentioned above, the various points confined to the margins of the foundation soil reach the ultimate equilibrium, but other points are still in the elastic stage. In this way, it will not cause severe settlement in the foundation soil, nor will it cause the foundation soil to collapse. Therefore, in the past, the plastic load has been suggested to be used as the permissible load potential of the foundation soil.

2. Ultimate Limit Load

Under the action of the load, the entire foundation soil enters into the ultimate limit equilibrium state. At this time, it can be treated as the ideal elastic body. In 1922, it was applied to frozen ground. If we only consider the bonding force of the frozen ground, the ultimate limit load at the two dimensional surfaces are

$$p_k = (2 + \pi) c_{АЛ} + \gamma h$$

or

$$p_k = 5.14 c_{АЛ} + \gamma h$$

Spatially, the ultimate limit load for pressure reception at the base of the square is

$$p_k' = 5.71 c_{\text{дл}} + \gamma h$$

When using the p_k as the load potential of the foundation soil, it must be divided by the safety coefficient K which usually takes the value K = 1.5 - 2.

In using the equation, we must know the bonding c of the frozen ground. Experiments show that the shearing strength τ of the frozen ground is composed of both the bonding force c and the internal frictional angle Φ, and furthermore, their relationship with the normal pressure follows Coulomb's Law (Figure 52)

$$\tau = c + tg\ \Phi$$

The bonding force of frozen ground is much greater than that of thawed ground, and it also rapidly increases with the lowering of temperature. Figure 53 shows the situation under which the long term bonding force of frozen clay changes according to the negative temperature. Within the confines of the testing temperature both of them are almost in linear relation, that is

$$c_o = c_o + a|0|$$

In the above equation, c_o - bonding force at 0^oC

$|0|$ - absolute value of soil at negative temperatures

a - ratio constant

c_o - bonding force when temperature equals 0

The internal frictional angle Φ also increases with lowering of the temperature (as shown in Figure 52), but when the temperature of the soil approaches $0^{o}C$, the internal friction angle of the frozen ground is actually equal to that of thawed ground. However, the bonding force of frozen ground is much greater than that of thawed ground. At this time, the shear stress caused by the bonding force of frozen ground is several times greater than that caused by the internal friction angle. Therefore, the effect of the internal friction angle may be ignored in computation. In addition, the shear strength of frozen ground can also be raised when the water content increases.

Besides the abovementioned, the shear strength of the frozen ground, because of rheological properties, changes with the acting time exerted by the load (or increased load rate) (Figure 54). In practical engineering construction practice, especially in construction on fine grained foundation soil with high ice content at a temperature of $0^{o}C$, attention must be paid to the effects of the rheological properties of the frozen ground. For this reason, the persistent strength index is employed in computation.

Because the bonding force dominates the shear strength in the frozen ground, the frozen ground (especially fine grained soil) can be treated as an ideal plastic body. In this way, the bonding force c can be computed by pushing a rigid sphere against the surface of the frozen soil (Figure 55)

$$c = 0.18 \frac{P}{\pi DS}$$

In the above equation, P - load added on the sphere
D - diameter of sphere
S - depth of sphere pressed into soil. Its value changes with time

When the testing time is long enough, that is, when $t \to \infty$, we get S_∞. By using this, the persistent agglutination force $C_{дл}$ can be calculated. In engineering computation, when the value of $C_{дл}$ is obtained by using the rigid sphere method, the action of the internal friction angle Φ has already been taken into consideration.

Generally speaking, the load carrying potential of frozen ground is always easily satisfied. The only thing is that when a saturated soil layer has a temperature close to $0^{O}C$, because of its strong rheological properties, the resulting weakness of the foundation soil may cause deformation damage to the construction work.

* * *

There are many types of damage caused by frost to construction works in frozen ground. They can be grouped into four main factors: temperature, soil, water and force.

Factors such as house heating, solar radiation, wind, damaged vegetation cover, discharge of snow cover, etc. can eventually be reduced to the raising or lowering of the temperature. The soil factor includes such elements as grain size composition, mineral and chemical composition, etc. and eventually they can be reduced to the magnitude of the surface potential of the grain, but, in practical usage, the coarseness or fineness of the grain can be used to indicate their magnitude. The water factor includes the amount of water present in various states and also the composition of the water basin and water content, principally the latter. The force factor includes the magnitude of the external load and its properties (persistent, instantaneous and vibrating, etc.) and is expressed in the magnitude of the force under normal conditions. These four factors all exist in the process of frost damage to any construction work. Even with factors such as soil, water and a given pressure, if the temperature is higher than the initial freezing temperature, freezing will not occur. Also, in course grained soil which is well drained, even with factors such as temperature, pressure and water, frost heaving or thaw settlement may not occur. Also, even when the necessary temperature, pressure and soil factors are present, without water, frost heaving and thaw settlement will not occur. Similarly, even with the necessary temperature, water and soil conditions for causing frost heaving, if the weight of the construction work can resist the freezing potential, frost damage will not occur. Therefore, the raising and lowering of the temperature, the coarseness or fineness of the grains, water content and the magnitude of the force are the four basic contradictory factors in the process of frost damage.

Among these four key factors, changes in temperature and pressure are caused by changes in external conditions and therefore, they are the external factors, whereas soil and water are the internal factors. "In dialectic materialism, the external factors are the prerequisites for change whereas the internal factors are the bases for change. The external factors function through the internal factors."

Among these four factors, what needs to be emphasized is the water factor.

Water is a good solvent. It is an indispensible medium in carrying out various kinds of chemical reactions. The physical-chemical reactions in frozen ground cannot do without water.

Water has a large latent heat of crystallization. After it freezes, its thermal property drastically changes. This controls the complicated thermal conductivity process in frozen ground.

After water freezes, its strength increases drastically. After ice melts its load carrying potential approaches zero. These special characteristics of water mean that frozen ground has a high load carrying potential, but the load carrying potential of thawing ground is much lower.

Frost heaving and thaw settlement of soil is caused by the freezing and melting of the water. That is, the rheological properties of the ice causes stress relaxation and creep of the frozen ground.

When we say frozen ground, we do not mean that the grain particles are frozen, but that water particles freeze in the soil. What produces frozen ground is that the water in it becomes ice and only the dry soil at a negative temperature can be termed "cold soil". Because there is no freezing and thawing in this type of soil, therefore it changes very little under positive and negative temperature. Basically, it is very different from frozen ground. In other words, the freezing and thawing of soil constitute the basic difference between frozen ground and other types of soil.

Without the freezing and melting of water in soil, frost damage to construction works would not occur. Therefore, we can say that the basic contradictions in the course of frost damage is the freezing and melting of water in the soil.

CHAPTER FOUR

PREVENTION AND SOLUTION OF FROST DAMAGE TO BUILDINGS

"Marxist's philosophy holds that the most important problem does not lie in understanding the laws of the objective world and thus being able to explain it, but in applying the knowledge of these laws actively to change the world."* Through discussions in the last chapter we have gained preliminary understanding of the classification and occurrence of frost damage. Now, let us further introduce methods for the prevention and solution of frost damage to buildings. To prevent and solve frost problems, we must plase emphasis on "Prevention", i.e., do our best to avoid, eliminate, or alleviate to the greatest extent any occurrence of frost damage during the early stages of construction, on the basis of objective rules being fully controlled. Then, if any frost damage does occur due to the limitation of human knowledge or changes in external conditions, actions can be taken immediately to cope with it.

Past experience indicates that the best way to deal with frost problems at the source is to have the permafrost engineering geological exploration done well, the selection of sites of buildings and routes of roads made properly, and the construction principles set up correctly before starting construction. Doing work seriously at this stage will enable us to achieve maximum results with little effort. Frost heaving and thaw settlement are the commonest and most frequent phenomena among all frost actions. Frost damage caused by the repeated cyclic action of freezing and thawing

---

* Translator's note: A quotation from Chairman Mao.

are also commonly observed. Since their features vary, separate corresponding measures should be taken to deal with them, based individually on the cause of formation and the affecting factors.

The case of loss of stability of a building due to insufficient foundation strength occurs mainly at the ice rich permafrost table at high temperature (soil temperature approaching $0^{o}C$). This phenomena can be avoided if the determination of the basic bearing power of the foundation is made accurately during exploration, and the prescribed construction principles are strictly observed during service of the building so that the temperature at the foundation can be maintained below the designated value.

I. Proper Site (Route) Selection and Permafrost Engineering Geological Exploration

Many an engineering practice has indicated that in order to maintain the stability of various construction structures, particularly that of large, heated buildings or building groups in a permafrost region, good construction foundations must be selected at first. As to the construction of roads, especially railroads, route selection is of the most importance prior to construction.

To achieve a proper site (route) selection, it is necessary to conduct an engineering geological exploration to determine the practical engineering geological conditions of the permafrost and to classify the possible construction space into good and bad areas to facilitate general planning and logical layout.

On classification of construction areas or foundation soils, the Chinese "Design Specifications of Industrial and Civil Building Foundations" divides the frost heaving susceptibility of foundation soils into four classes based on differences in soil property, moisture content, and groundwater conditions (Table 22). The classification applies to the seasonally frozen (thawing) layer. As to permafrost, the classification varies with the buildings concerned, both in standard and in method. We classify permafrost, based on the dissimilarity in soil property and water (ice) content, into four classes as listed in Table 23 by the susceptibility of post-thaw settlement. If both the frost heaving and thaw settlement susceptibilities of the seasonally frozen soils and those of the permafrost at the site of the foundation are classified accurately during exploration, a logical selection of sites of buildings and routes of road can be worked out during the design stage, and preventive and corrective measures can be taken as necessary according to the characteristics of the soils concerned.

Generally speaking, buildings, particularly heated ones, should be built as much as practically possible on bedrock, on the residual layer of thin weathering horizons or on layers composed mostly of gravels and debris. Sandy (cobblestone), alluvial terrace areas, where both frost heaving and settlement tendencies are little, is also good for construction purposes. For the design of heated buildings in such areas, principles governing construction in non-permafrost regions of non-thawing foundations soils are generally applicable.

It is advisable to avoid construction in areas of ice rich fine grained soils or ice rich pebbly soils, as excessive settlement will occur after thawing. In case such a construction is necessary, the design must be based on the principle that its foundation can be maintained in the frozen state or can be thawed and excavated beforehand in accordance with the actual conditions of the permafrost (temperature, thickness, ice content, etc., of the frozen soil).

In addition to the above, considerations must be made on a source of daily water supply and facilities for discharging accumulated surface water and industrial sewers.

Excavation should be reduced to a minimum in the permafrost region where a route (particularly a railroad) passes. Avoid low-filling, shallow digging and zero cross section. In hilly areas, it is most appropriate to pass the route on the upper part of a gentle slope, rather higher and, as much as possible, on the sunnier part of it. If the route is to extend along the valley of a large river, it is best to have it built on the high terrace land and the thawed floodplain. It is a general principle to detour a route to avoid special geologically unfavourable areas. However, when detouring is not feasible, the following principle may be followed: Passing by means of embankments along the upper edge of the area, where thick ground ice occurs, or on the lower side away from thaw flow slides. In areas where groundwater develops, consideration should be given to possibilities of occurrence of any icings or pingos resulting from the change in water regime and geological conditions due to roadbed construction. Besides, route considerations should take into account the engineering geological requirements of building groups, large bridge sites, long tunnels, and large supporting structures. In addition to calculating the water flow level for the under bridge space on a river in which water keeps flowing all year round, attention must be paid to the accumulated height of river icings and other icings.

Large and medium bridges should be situated in the thawed floodplain as much as practically possible. In a permafrost region, it is best to select sites where the riverbed is narrowest in the bedrock and cobblestone areas and to avoid sites where icings and pingos of large sizes may occur. Generally, sites of culverts should be selected for the most logical route proposal. However, in adverse geological areas where larger pingos, icings, and thaw flow slides are present, an appropriate deviation of the route, based on not affecting the direction of the route, is advisable to effect an improvement in the construction and operational conditions of the culverts.

II. Proper Selection of Construction Principles

"Qualitatively different contradictions can only be resolved by qualitatively different methods."* China is vast in area, containing regions of highly varying natural conditions. In order to fulfill the hope of achieving greater, faster, better and more economical results, construction principles must be chosen properly in accordance with local practical features.

At the present, there are four design principles pertaining to buildings in permafrost regions: (1) Maintaining the foundation soil in a frozen state; (2) Considering gradual thawing of the foundation soil; (3) Thawing the foundation soil prior to construction, or removing the original, natural foundation soil and replacing it with backfill; and (4) Designing without regard to the frozen soil.

---

* Translator's note: A quotation from Chairman Mao.

The principle of maintaining the foundation soil in the frozen state applies to areas with thicker permafrost (>15-20 m), lower annual average temperature, limited building heating temperature, and limited size. This principle can be considered for use in the northwestern part of the Great Khingan Range and in the hinterland in the Chinghai-Tibet Plateau. Though the construction with this principle will be costlier, stability of buildings can be maintained for a long period of time.

The principle of considering gradual thawing of the foundation soils (i.e. a principle which enables structures of the foundation and buildings to withstand uneven settlement of the foundation soil during thawing) is useful under conditions where the temperature of frozen soils are unstable, the buildings release considerable quantities of heat, and the settlement of the foundation soil after thawing is limited. Therefore, it is mainly used for foundations in coarse grained frozen soils such as frozen sandy pebbles and cobblestones.

The preconstruction thawing method or the method of removing and replacing foundation soil prior to construction, is useful only when the ice rich permafrost is not thick (3-5 m, or more), the temperature is high and unstable and the settlement of the foundation is excessive after thawing. To obtain a dependable foundation base at depth considerations should be made to include further artificial reinforcement of the soil upon thawing. This method is applicable to areas where permafrost borders the seasonally frozen soil; it is not only costly but also time consuming. However, it ensures stability of the foundation once it is applied.

As to layers of rigid rocks with fissures not fully developed and of drier, coarse grained soil, the design can be made on a non-frozen basis, even though they are in the frozen state, i.e., disregarding the existence of frozen soils.

III. Prevention and Solution of Frost Heaving

As stated above, frost susceptibility and frost intensity of foundation soils are mainly determined by: (1) Properties of the soil itself; (2) Moisture contents; (3) External coldness condition; and (4) External loading pressure. They are the so-called four major factors: soil, water, temperature, and force. In preventive and combatting practices, the main contradictions should be grasped according to the actual local conditions so that appropriate remedies can be made. The following are methods commonly used to prevent and combat frost heaving:

A. Replacement of Base and Lateral Foundation Soils

If the local soils are susceptible or strongly susceptible to frost heaving (such as clean sandy pebbles, sandy cobblestones, and medium or coarse sands), this is a reliable method to prevent the building foundation from frost deformation, as has been widely used in engineering practice. For example, in northern Heilungkiang Province, the base and lateral soils of building foundations are always removed and replaced with layers of coarse and medium sand (Figure 56) with good frost heaving prevention results. The thickness of the sand is 0.8 - 1.5 m for the base and 0.2 - 0.5 m for the side of the foundation.

In the railroad constructions, it is also common to replace the original soils with sandy cobble (pebble) fills. As shown in Figure 57a, the thickness of the replacement is determined by the depth of freezing (thawing). If the lower part of the layer to be replaced belongs to a water confining layer, it is necessary to add a compacted clay water confining layer 0.2 - 0.3 m in thickness on the surface of the sandy pebble layer to keep water from seeping into the foundation base. A sandy layer is also effective in preventing frost boils on highways. Figure 57b illustrates a structural diagram of a sandy subgrade and conduit drains of a highway. In seasonally frozen areas, the commonly accepted thickness of a highway subgrade is 20 - 30 cm for coarse sand and 30 - 40 cm for medium sand, subject to appropriate adjustments according to actual conditions. Besides, limestone has been used widely in China as base course material in road constructions. Experience proves that limestone exhibits a high degree of water stability, strength, and effectiveness in frost boil prevention.

B. Drainage and Water Confining Layer

As we know, apparent frost heaving occurs only when the moisture content in the soil exceeds the initial frost heaving moisture content. Therefore, draining the accumulated surface water and keeping it and groundwater from penetrating into the foundation soil is one of the basic methods for preventing foundation soils from frost heaving.

At places with groups of buildings, the installation of drainage structures, sewers and surface water should be worked out following an integrated plan. If the surface and groundwater in the area are relatively abundant, the addition of interceptor ditches and drains on slopes above the structures should be considered. In railroad and highway engineering, quite a few methods and types of drainage are available for excess water prevention and discharge purpose, e.g., elevated water interceptor ditches, side ditches, and catch basins for preventing surface water from accumulating, and water developing wells, and water catch pits of different types for lowering the groundwater table. If a route is located in an ice rich permafrost area, water prevention and discharge drainage structures should be built a certain distance away from the route; reinforcement and seepage prevention from the drainage should be considered; and adequate longitudinal slope of the drainage should be assured.

Drains with a vertebral shaped outlet are recommended for areas where groundwater appears throughout the year. The course of the outlet is a vertebral shaped discharge rock body insulated with grass pads and peat horizons to allow the water to flow out of the ground along a rock layer free from quick freezing. The size of the vertebral shaped body must be determined by the amount of outflow of spring water. In winter, the insulated vertebral shaped outlet, an invention of Chinese railroad workers and technicians, has proved to be considerably efficient.

A water confining layer functions identically to water drainage, except that the former separates groundwater from the foundation soil which would otherwise be affected. Figure 58 shows a confining layer for a highway roadbed in an area with a relatively high groundwater table. It consists of a coarse sand, gravel or detritus horizon to keep the groundwater from rising to the roadbed through capillarity. A thickness of 15 - 20 cm may be required for the general purpose. To preclude the lowering in effectiveness of the confining layer due to clogging, an anti-filtration horizon may be laid above and beneath it. The confining layer may also be filled with waterproof asphalt products 3 - 5 cm in thickness. In this case, antifiltration horizons are no longer needed. In seasonally frozen areas, a clinker layer is often laid on a railroad, acting as both insulation and capillary water confinement, although the insulating and confining effectiveness diminishes gradually after long use.

C. Elevation of Foundation Base

This method is widely used in highway and railroad constructions. Embankments are elevated to such a height that there is adequate thickness of soil on the roadbed in a dry state and free from any capillary effect from groundwater or surface water. Elevated roadbeds are more commonly seen in flat areas where the groundwater table is high and surface water discharge is difficult. The minimum height of an elevation fill for an ordinary highway, H, may be determined this way:

$$H = h_1 + h_c$$

where h_1 - Thickness of dry layer a roadbed must have. It can be determined by the road surface strength and stability required. 60 cm is usually the accepted value.

h_c - Height of capillary rise, varying with type and compactness of soil (Table 24).

The elevated roadbed functions as insulation, and reduces the depth of freezing (thawing) as well. This brings about a new depth of freezing (thawing) from the roadbed, higher than the one before elevation. It may alleviate or even eliminate frost heaving, and avoid thaw settlement of the roadbed.

D. Logical Selection of Foundation Depth

The depth of a foundation must satisfy the requirements of strength and stability a structure needs from the foundation on which it rests. It can be determined based on the class of building, years of service, mechanical property of foundation soil, groundwater table, and depth of freezing (or thawing).

In order to eliminate the effect of frost heaving of the foundation soils on foundation stability, building construction codes usually require that foundations be laid 0.2 - 0.3 m below the depth of freezing. However, a great deal of experimental data in recent years indicate that the frost heaving intensity (frost heaving rate) is not evenly distributed within the whole depth of freezing. Frost heaving basically disappears below two-thirds of the maximum depth of freezing. The depth above that is called the effective frost heaving region or the primary frost heaving zone. Examples: In the city of Harbin where the maximum depth of freezing is 1.8 m, little frost heaving occurs at the depth of 1.0 m and frost heaving is virtually non-existent below 1.2 m. In Ch'angch'un where the depth of freezing is 1.5 - 1.6 m, few building foundations laid below 1.2 m have been found damaged by frost heaving where the water table is not high. Therefore, in seasonally frozen areas the depth of a foundation for an ordinary building can satisfy the foundation strength and stability requirements if it is greater than the depth of the effective frost heaving zone. In view of the above, the Chinese "Design Specifications of Industrial and Civil Building Foundations" requires the minimum foundation laying depth in seasonally frozen areas to be:

(1) Free from any consideration of the effect of depth of freezing for Class I frost susceptible soils.

(2) Determined by the following formulas for Class II, III, and IV frost-susceptible soils:

$$D_{min} = Z_o \cdot m_t - h_d$$

where D_{min} - Minimum foundation laying depth (m)

h_d - Thickness of residual permafrost layer (m); determined from Figure 59 for Classes II and III soils, and at $h_d = 0$ for Class IV soils.

Z_o - Standard depth of freezing (m)

m_t - Coefficient of effect of heating on depth of freezing (Table 14)

However, it has to be clarified that laying a foundation below the effective frost heaving zone can eliminate the stress from freezing only at the foundation base. The sides of the foundation which pass through the main frost zone still need to be protected from frost deformation by replacement with a non-frost susceptible fill, or by application of bituminous mats on the foundation sides.

Unheated buildings (or cold foundations) in permafrost regions may be treated in a similar way as mentioned above. Since there always exists freezing stress at the permafrost table in which the foundation is laid, a static equilibrium reached between this stress and the freezing stress of the upper layer can also be used for the determination of the depth of pile foundations which are laid more deeply (Figure 60).

Assume P - External load on the pile foundation

h_1 - Depth of the effective frost zone, approximately $h_1 = 2/3\ H$, H is the depth of freezing

h_2 - Depth of foundation below permafrost table

τ_1 - Mean frost shear stress of soil acting on the foundation (refer Table 12)

τ_2 - Mean long period freezing stress of permafrost acting on the foundation; (refer Table 11)

a, b, or r - The dimensions and radius, respectively, of rectangular cross section and cylindrical pile of the foundation.

For a foundation of rectangular cross section conditions for the static equilibrium are:

$$P - \tau_1 \cdot h_1 \cdot 2(a+b) + \tau_2 \cdot h_2 \cdot 2(a+b) = 0$$

We obtain
$$h_2 = \frac{2\tau_1 \cdot h_1 (a+b) - P}{2\tau_2 (a+b)}$$

While for a cylindrical pile, the condition is

$$P - \tau_1 \cdot h_1 \cdot 2\pi \cdot r + \tau_2 \cdot h_2 \cdot 2\pi \cdot r = 0$$

We obtain
$$h_2' = \frac{2\pi \cdot r \cdot h_1 \cdot \tau_1 - P}{2\pi \cdot r \cdot \tau_2}$$

When the depth of the foundation in permafrost exceeds h_2 (or h_2'), the mechanical stability of buildings on the foundation under frost can be guaranteed.

E. Use of Frost Resistant Types of Foundations

Appropriate changes in types of foundation to achieve frost resistant results is one of the important ways to prevent and combat frost damage. Figure 61 shows expanded types of foundations quite commonly seen in seasonally frozen and permafrost regions, where (a) illustrates a concrete pier type foundation expanded gradually with depth; (b) an expanded reinforced concrete pillar foundation; and (c) an explosion expanded short pile widely used in the vast seasonally frozen regions, and gradually introduced into permafrost regions in China. Due to its freedom from seasonal restrictions and exemption from heavy earthwork, the use of explosion expanded piles increases daily. The feature of all the above types is characterized by their self-anchoring action by which the freezing shear stresses are offset and, thus, frost deformation is prevented.

The future of pile foundation is most promising because it requires minimum earthwork, allows mechanized construction techniques, and lengthens the construction season. Due to its deep insertion into the permafrost and tight bonding with the frozen soil, it can stop frost heaving of the foundation while taking the load of a large building. Regarding the question of the appropriate depth to which the pile should be installed into the permafrost, a determination can be made by calculations using the formulas given in the preceeding section. In order to improve the anchoring effectiveness of a foundation, the surface roughness of the part to be buried in the permafrost may be increased, or anchoring devices may be added.

F. Insulation and Chemical Measures

Provision of an insulating layer on the surface of a foundation is one of the important methods for preventing frost heaving. The physical basis for this lies in the decrease in the depth of freezing and the amount of frost heaving as a result of the increased thickness of the insulating layer. Thus, the depth of the foundation or thickness of backfill can be reduced appropriately, and building frost deformation can be prevented. In northeast China, clinker is used as a replacement fill material on roadbeds for railroads and urban roads to eliminate frost damage and frost boils. It provides anti-capillary as well as insulating effects with noticeable results. In Norway in Europe, prefabricated peaty insulating blocks are added to the roadbed base of railroads, achieving excellent results against frost heaving. Peaty blocks have a high water holding capability. It releases large amounts of latent heat when its water content undergoes freezing, greatly hindering percolation as well. In the area surrounding Tach'ing Oil Field, paraffin clinker, a waste from oil refining, is used to fill the space beneath the drainage around buildings. The depth of freezing is obviously reduced due to the excellent insulating performance of the paraffin clinker, and hence excessive frost deformation of building foundations is prevented.

The essence of chemical methods are: First, addition of soluble salts to lower the freezing point of water in the soil to reduce or limit the frost susceptibility of the soil at a certain climatic condition, thus totally or partially preventing frost deformation of the soil from occurring. Second, the addition of chemical reagents to increase the hydrophobicity of the soil to avoid totally or partially water transport phenomena during freezing and thus greatly reducing the frost heaving intensity. For instance, in some railroad station areas in northern China where frost heave occurs due to poor drainage, sodium chloride has been added to the foundation soil to increase its salinity, in order to lower the freezing point and keep the frost deformation within a tolerable range so that the railroad can maintain normal operation. In many seasonally frozen areas, the use of hydrophobic matters, such as bituminous mats, has achieved good results in combatting frost heaving, although its durability is still a problem pending further research and the cost is high. With the development in science and technology, chemical anti-frost heave methods will surely be developed and applied.

IV. Prevention and Solution of Thaw Settlement

The basic reason for settlement in permafrost regions is the melting and compression of ice crystals, ice particles, ice lenses, or "sandwiched" ice contained in the permafrost, due to heat and load of the buildings. The heat here includes that from buildings heated throughout the year, that stored in the water surrounding the buildings, and that due to the destroyed equilibrium of natural surface heat resulting from engineering activities during construction. In order to prevent buildings from settling, action should therefore be taken on four aspects: Soil quality, heat, external pressure, and water. Some methods commonly used for preventing and combatting settlement are stated below.

A. Replacement of Foundation Soil

This is to remove ice rich soil and replace it with thawed backfill, in compacted layers. This method is widely employed in the construction of buildings, roads, bridges, and culverts.

When a railroad is to pass through a warm temperature, low thickness, ice rich area in the form of cuts, low embankments, or zero profile, it is common practice to remove the ice-rich frozen soil and replace it with a fill of as much coarse grained soil as practically available locally. Figure 62 illustrates the cross section of a fill for a low embankment less than 0.5 m in height in an ice-rich area. The thickness h of the fill must be greater than the calculated thickness of the insulating layer to maintain the ice rich permafrost under the foundation in a frozen state throughout the year. A backfilled roadbed must satisfy such requirements as strength, water confinement, and freedom from frost. Any homogeneous coarse grained soil, or homogeneous fine grained soil, the water content of which is lower than one half the sum of the plastic limit and liquid limit, can be used as fill material. Similar requirements apply to fills of subgrade for cuts and culvert foundations.

B. Insulation

The basis of this method is the use of materials or soils of higher insulating capability to isolate heat sources so as to allow little heat to enter the ice rich permafrost table and, thus, to maintain the foundation in a frozen state.

Figure 63 shows a heated building of the elevated floor type. The vents under the floor allow most of the heat released through the floor to escape by air convection without entering into the foundation soil. Moreover, the permafrost table under the building floor will not lower but, on the contrary, will often rise because of a lack of direct sunshine throughout the year. This type of building, apparently excellent in keeping the foundation soil in the frozen state, needs higher construction investment, has colder floor temperatures particularly for daily living purpose, and requires more care and attention. For instance, vents should be widely open in winter and closed in summer; human activities around the building, which may effect thawing of the foundation soil (e.g., accumulation of water, destruction of the ground surface, addition of heat energy, etc.), should be completely avoided. Otherwise, the expected results can never be achieved.

High fill foundations good for dwelling purposes have been promoted for use in recent years. Their cost is generally low if local soils are used, but they provide better living condition. The thickness of fill must be enough to ensure that heat from the thaw basin of the building will not reach the ice rich soil layers. Since the foundation projects above the original ground surface (Figure 64) with a large heat dissipation area, much of the heat from a heated building will be given up through the sides of the embankment, leaving only that at the bottom to penetrate into the original soil layers. Therefore, the depth of thaw in a high fill foundation is smaller than that of an ordinary foundation. The height of fill can be reduced, and insulation efficiency improved, if air ducts or rock-laid insulated drains are buried beforehand in the high fill foundations.

In railroad construction in permafrost regions, insulation is one of the main methods to protect roadbeds from thaw settlement. Figure 65 shows the cross section of an insulated embankment, measuring more than 2 m in height, with insulation at the base and insulated protective shoulders on both sides. These shoulders can be filled up with local materials such as clay with gravel. The surface should be covered with a peaty layer 0.5 m in thickness. Generally, the top measures 2 m in width and 1 m in height. Experience has proved that if the surface water is handled properly, the ground surface around the embankment is kept free from any destruction. If a good construction season is selected, the permafrost table beneath the embankment will certainly rise, making railroad operation more normal. For an ordinary road, methods of insulation are not necessarily as complicated. Generally, an embankment 1 m in height is enough to maintain the ice rich permafrost at the foundation base.

Recently, elevated and insulated aqueducts have been in use. This can also keep heat containing pipeflows away from the ice rich permafrost and ensure that foundations of the elevated aqueducts are firmly anchored in the permafrost table.

C. Discharge of Accumulated Water

The confluence of surface runoff from water accumulation along the upper slope of the route in summer produces a large quantity of heat which may cause continuous melting of ground ice and, in turn, settlement of the roadbed to a great extent for many years. Hence whether the insulated embankment can achieve the anticipated results or not is determined, to a great degree, by how effectively its drainage facilities perform. Drainage of accumulated water is not only necessary for preventing and combatting frost heaving but is also effective against settlement in ice rich areas.

By the same token, it appears to be of particular importance to install drainage and sewerage systematically for any industrial complex and dwelling district in permafrost regions. They are of absolute necessity if the stability of buildings is to be ensured.

D. Construction Season

Experience indicates that construction works such as excavation of foundation pits, and cut slopes is best started in winter if the foundation base and sides are to be maintained in the frozen state. Late fall and early winter when the weather turns cold and the depth of seasonal thaw reaches a maximum value is particularly favourable for excavation work in ice rich areas.

In recent years, the development in engineering of explosion-expanded short-pile foundations in China has been remarkable. The method has been gradually under promotion for application in permafrost regions. The explosion expanded, short pile foundation work is free from any seasonal restriction. Experiments have been started on drilled, prefabricated piles the future promotion of which is promising in areas where mechanical equipment is available. Presently, in road and bridge constructions, drilling by percussion and rotary drills, fixing walls with mud, and making concrete piles for piers by on-site casting are universally used, and have proved to be relatively successful in permafrost regions.

E. Foundation Laying Depth

The depths referred to here are mainly for heated buildings in permafrost regions. As mentioned before, a thaw basin will form under each foundation and the depth of thaw of every side of the building foundation varies with the direction it faces and the difference in its direction toward the wind. Therefore, the foundation depth should be properly chosen through calculation on foundation settlement during thaw compression. Table 25 lists "Values of Allowable Foundation

Deformation of Buildings" stipulated in the Chinese "Design Specifications for Industrial and Civil Building Foundations". When calculations indicate that laying a foundation in the thaw basin fails to meet the building deformation stability requirement, the foundation must be laid in the permafrost table beneath the thaw basin. Now, it is not only the permafrost at the base of the foundation that bears the load, but the freezing strength between the permafrost on the sides of the foundation and the foundation material participates also in the load-bearing (as shown in Figure 66).

Assume P - External force acting on the foundation

h_1, h_2 - Foundation laying depths in thawed area and in permafrost, respectively

τ - Mean freezing strength between permafrost table and foundation material (using long term freezing strength)

(σ) - Allowable load bearing capacity of the foundation base soil (refer Table 17)

a, b, or r - Respective measurements and radius of rectangular and circular foundation cross sections

Soil horizons within the depth of the thaw basin compact and settle due to gravity upon thawing (until a stable depth of thaw is reached), causing a downward pulling force on the foundation. This pulling force is negligible when the rate of settlement is very small. Thus, according to conditions of static equilibrium, we obtain for a rectangular cross section:

$$P - h_2[2(a + b)]\cdot\tau - ab[\sigma] = 0$$

$$h_2 = \frac{P - ab[\sigma]}{2(a + b)\tau}$$

For a circular cross section:

$$P - h_2 2\pi r\tau - \pi r^2[\sigma] = 0$$

$$h_2 = \frac{P - \pi r^2[\sigma]}{2\pi r\tau}$$

In other words, the load-bearing capacity and stability requirement can be satisfied when the foundation depth is

$$H > h_1 + h_2.$$

V. Methods of Prevention and Solution to Frost Damage Commonly Used in Structures

A. Concave Deformation of Buildings

This is caused by normal frost heave stress σ_- acting on the sides of a foundation. Similar to combatting ordinary frost heave, the effective method is to remove the soil from the sides, replace it with non-frost susceptible soil and drain the accumulated water. The rigidity of the foundation will be increased with very good results as well. Figure 67 shows a bending moment diagram after the foundation has been installed with partition walls. The foundation beams can be considered approximately to be rigid on a plane. When the length of a single span decreases, the bending moment will be proportional to the square of the reduction in length, i.e., when the length is ½ that of the original, the bending moment becomes ¼ the original, and the curvature (deflection) will be 1/8 the original. This indicates a very good effect of installing laterally partitional walls with prevention of concave bending of a foundation and its outer walls.

B. Damage in Roadbeds by Icings and Pingos

If a roadbed passes through areas with icings and pingos, efforts should be made to intercept and drain the water from the higher side and the surrounding areas of the roadbed. In addition to strengthening the general purpose drainage such as intercepting ditches, catchpits, etc. and deepening elevated ditches, side ditches, and insulated conduits, ice preventing dikes may be added. The dikes can intercept surface water in summer and prevent the route from being covered by runoff accumulated ice in winter. The height of the dike can be determined by the thickness of winter runoff accumulated ice. Furthermore, as previously mentioned, an insulated, vertebrae-shaped water outlet is effective for discharging water in the permafrost region in winter.

C. Ice Filling of Conduits

The following methods are available to prevent and solve ice filling of conduits:

Heating method: This is to raise, by heating, the temperature of the water source to a certain value so that the waterflow can maintain an above-zero temperature throughout the entire course. The method is widely used in China as well as in foreign countries. In industrial and mining districts, heat from industrial waste water and waste gases is utilized to heat the water supply line through tubing installed parallel with the water supply line. This may lower the cost drastically. Besides, the water supply line can be buried in the same trench with heating pipelines.

Heat radiated from the heating pipelines can prevent the freezing of the water line.

Empty pipeline method: Essentially, the pipeline is buried shallow and water is allowed to flow only at predetermined times, allowing the pipeline to empty itself after use. Since there is no water to stay inside the pipeline, freezing and ice filling will not occur. This method can be used for pipelines laid in a generally sloping area. It is not appropriate, however, for water supply systems for large industrial and mining enterprises.

In addition, having insulation materials (peat, asbestos ropes, fibreglass, etc.) wrapped around pipelines may achieve prevention of ice filling as well. The method is widely employed for all pipelines whether they are elevated, exposed, or buried. The insulation materials must be moisture resistant. It is costlier to use light insulation materials such as asbestos ropes and fibreglass but they last longer.

In seasonally frozen regions with limited depth of freezing, water supply lines, if buried below the maximum depth of freezing, will be free from any frost damage.

D. Sliding Collapse of Cut Slopes

To avoid sliding collapse of side slopes, permafrost may be replaced as shown in Figure 68, though the thickness must be adequate to maintain the ice rich soil layers of the cut slope in a frozen state. When replacing with coarse grained soil a water confining layer, 0.3 - 0.4 m in thickness, should be laid; when fine grained soil is used, a 0.3 - 0.4 m thick layer of gravels, coarse grained soil, or clinkers should be laid on top.

Another appropriate measure is to install structural headwalls on the cut slopes to protect the slope edges (Figure 69). Generally, the cross section of a headwall may be of the gravity type, of the smallest cross-sectional area found in headwalls for use in non-permafrost regions, but the foundation of the headwall must be laid on a dependable base. In designing a headwall, the pressure of the soil behind the headwall can be obtained only by calculating the pressure of the seasonally thawed layer of the soil behind the headwall. When no replacement with insulating fill behind the wall is considered, frost heaving stress must be taken into consideration. When no insulation behind the headwall is considered, the distance between the rear side of the headwall to the excavation surface will not necessarily be greater than the depth of seasonal thaw, as long as it is enough to meet the construction requirement. However, the space behind the headwall must be backfilled and compacted with emphasis laid on lateral drainage. On top of the cut, retaining dikes should be built and, if the water collecting area is large, elevated ditches should be added.

Headwalls are generally good for protection up to 3 - 6 m in height. It is not economical to use headwalls for protection below 3 m. In such a case, the insulation method may be applied. For protection above 6 m, a method combining the insulation and the structural headwall methods may be used (Figure 70).

Table 1. Thickness and temperature of permafrost in northeastern China

Location	Latitude	Altitude (m)	Average annual air temperature (^{o}C)	Average air temperature differential (^{o}C)	Average annual ground temperature (^{o}C)	Thickness of permafrost (m)
Leku Ho	53°20'	800	-5.0	52.5	-2.0 to -2.5	50 to 100
Gun Ho	50°41'	979.8	-5.2	46.8	-1.6	
Yake Ho	49°24'	667	-2.8	46.4	-0.5	3 to 23

Table 2. The lower limit of permafrost distribution in western China

Region	Altitude of lower limit of permafrost (m)
Altai Shan	1200 to 1800
Tien Shan	2700 to 2800
Chilien Shan	3500 to 3800
Northern slope of Kunlun Shan	4200 to 4300
Chinghai-Tibet Highway	4400 to 4600
Southern slope of Tanglha	4700 to 4900
Northern slope of Himalaya Mountains	5000
Huanduan Shan	5200 to 5800

Table 3. Thickness and temperature of permafrost in some regions of the Chinghai-Tibet Plateau

Location	Latitude	Altitude (m)	Average annual air temperature (°C)	Average air temperature differential (°C)	Average annual ground temperature (°C)	Thickness of permafrost (m)
Togmegla	32°49'	4950	-5.2	25.3	-1.7 to -2.4	70 to 80
Fenghua Shan	34°27'	4700	-4.9	24.1	-3.4 to -4.0	120
Mouth of Kunlun Shan	35°30'	4780	-5.7	24.3	-3.0 to -5.0	150 to 190
Chilien Shan Muri	38°15'	4000	-5.5	24.2	-0.6 to -2.3	30 to 95

Table 4. The onset of ground freezing temperatures

Type of ground	Sample location	Content of readily soluble salt (mg/100g)	Water content %	Dry weight per volume (g/cm^3)	Onset of freezing temperature (^oC)
Grass covered humus soil	Muli		246.2	0.32	-0.024
Yellow subclay mixed with broken stones	Muli		20.7	1.64	-0.047
Blackish grey powdery subclay	Muli		62.0	0.96	-0.047
Humic subclay	Muli		31.2	1.40	-0.187
Yellowish green subclay	Togmegla	0.1157	26.5	1.53	-0.2 to -0.32

Table 5. The coefficient of heat conductivity of air, water and several types of typical thawed ground

Name	λ, in cal/cm s deg			
Air	0.00005			
Water	Liquid state	0.0014	Solid state	0.0054
Bog muck	Saturated state	0.0011	Dry state	0.00027
Clay		0.0021		0.00033
Sandy clay		0.0032		0.00045
Fine sand		0.0039		0.00045
Coarse sand		0.0041		0.00047

Table 6. The coefficients of heat conductivity of several types of soil in the Reshui-Chinghai region

Type of ground		Crushed stony ground	Clay	Organic
Water content, %		15.0	30.0	90.0
Volumetric weight, g/cm^3		1.9	1.5	0.7
Coefficient of heat conductivity, kcal/m h deg	Thawed	1.68	1.39	0.89
	Frozen	2.18	2.11	1.37

Table 7. Influence of type of ground on average annual ground temperature

Location	Subclay	Sandy gravel
Mouth of the Kunlun Mountain	-4 to -5	-3 to -4
Fenghuo Mountain	-3.5 to -4	-1.5 to -3.5
Muli	-1.9	-0.6 (bedrock)

Table 8. The effect of heat preservation of snow cover of a certain thickness*

Location of observation	Thickness of snow cover (cm)	Temperature at snow surface (°C)	Temperature under the snow (°C)
In shrubs	21	-28	-13
Under tatao grass	20	-23	- 8

* According to data observed by Jinlin in northeast China on December 31, 1958

Table 9. The influence of rivers on the depth of thaw in the Togmegla region*

Location	Togmegla River	Erdao River
River bed	1.7 to 2.0 m	1.74 m
River bank	0.61 to 0.75 m	0.96 m

* Based on the data taken on September, 1963 and June, 1964.

Table 10. Water content of initial frost heaving of several typical soils

A	*B* (W_p)	*C* %	*D* %	*E* (c)	*F* %
G	21.0	86.17	81.47	0.77	22.0
H	9.3	40.16	31.12		9.5
I		9.49	7.98		7.5
J		8.35			10.0
K		2.0			9.0

A : Soil type

B : Plastic limit water content

C : Water content of grains with radius < 0.1μ

D : Water content of grains with radius < 0.05μ

E : Crevice ratio corresponding to W_O

F : Initial frost heaving water content

G : Clayey soil

H : Sandy soil

I : Calculiform gravel

J : Medium sand

K : Coarse sand

Table 11. Persistent freezing potential (ton/m^2) of freezing ground as well as concrete and wooden foundation surfaces

A	*B*						
	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0	-4.0
C	6	9	12	15	18	22	28
D	8	13	17	21	25	29	38
E	7	11	15	19	23	27	35

A : Names of soil

B : Highest mean monthly temperature (°C) of the soil layer

C : Clay, clayey soil, sandy soil

D : Sandy soil

E : Debris, pebbly soil

Explanations:

1. The numerical values in the table above are applicable to common concrete and wooden construction materials.
2. For frozen ground which does not undergo thaw settlement the numerical values listed in the table should be lowered 10-20% depending on the water content. The freezing potential (that is, the value obtained according to the friction force of the thawing ground) of the dry soil is not to be taken into consideration because it does not exert any bonding force towards the foundation soil.

3. The freezing potential is not to be taken into consideration if the temperature of clayey soil is above $-0.3^{o}C$; if the temperature of sandy soil is above $-0.2^{o}C$; or if the temperature of pebbly soil is above $-0.1^{o}C$ (that is, to obtain the value of the frictional force of the thawing ground). When the soil temperature is between $-0.5^{o}C$ and those of the above mentioned, the interpolation method is to be used to ascertain its value.

4. The numerical values in the above table may be lowered by 30% for metal foundations which have not been previously treated.

5. The numerical values tabulated in the table above are not suitable for frozen ground with salt content greater than 0.5%.

Table 12. Tangential frost heaving potential (ton/m^2) exerted upon concrete and wooden foundation surfaces during freezing

<table>
<tr><td rowspan="2">A</td><td>D</td><td>$I_L \le 0$</td><td>$0 < I_L \le 0.5$</td><td>$0.5 < I_L \le 1$</td><td>$I_L > 1$</td></tr>
<tr><td>E</td><td><5.0</td><td>5.0-10.0</td><td>10.0-15.0</td><td>15.0-25.0</td></tr>
<tr><td>B</td><td>F W_o (%)</td><td>$W_o \le 12$</td><td colspan="2">$12 < W_o \le 18$</td><td>$W_o > 18$</td></tr>
<tr><td>C</td><td>G</td><td><4.0</td><td colspan="2">4.0-8.0</td><td>8.0-16.0</td></tr>
</table>

A : Clayey soil

B : Sandy soil

C : Debris, pebbly soil

D : Liquid limit of the soil

E : Tangential frost heaving potential

F : Total water content

G : Tangential frost heaving potential

Explanations:

1. The conditions suitable for using the numerical values in the above table are:

   a. various types of construction works with very high water content

   b. when the foundation basically does not allow deformation

2. When the tangential frost heaving potential exerted on the foundation by the surface water during freezing is 15 - 20 ton/m^2.

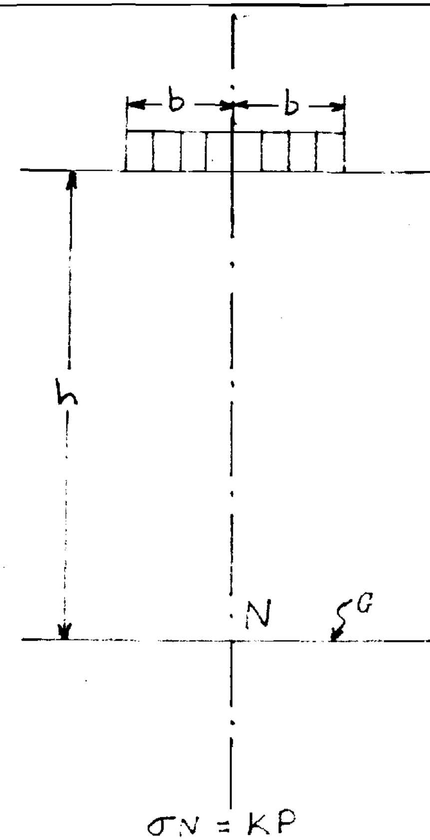
3. Use the higher numerical values from the table for silty clayey soil and sandy soil which have more than 15% silt-clay content.

4. Since there is a close relationship between the tangential frost heaving potential and the soil properties, freezing conditions as well as the hydrogeologic conditions, it is best to use the actual test data from various locations.

5. $I_L = \frac{W-W_p}{I_p}$, $I_p = W_L - W_p$

   In the above equation: W_L - liquid limit
   W_p - plastic limit
   I_p - plastic index

Table 13. Vertical stress coefficient K at point N (which also coincidentally falls on the axis of the foundation) on the stable thawing boundary surface

h/b	*A* *B*	*C* $\frac{a}{b} = 1$	$\frac{a}{b} = 2$	$\frac{a}{b} = 3$	$\frac{a}{b} = 4$	*D* *E* $\frac{a}{b} = \infty$	*F*
0	1.000	1.000	1.000	1.000	1.000	1.000	
0.25	1.009	1.009	1.009	1.009	1.009	1.009	
0.50	1.064	1.053	1.033	1.033	1.033	1.033	
0.75	1.072	1.082	1.059	1.059	1.059	1.059	
1.00	0.965	1.027	1.039	1.026	1.025	1.025	
1.5	0.684	0.762	0.912	0.911	0.902	0.902	
2.0	0.473	0.541	0.717	0.769	0.761	0.761	
2.5	0.335	0.395	0.593	0.651	0.636	0.636	
3.0	0.249	0.298	0.474	0.549	0.560	0.560	
4	0.148	0.186	0.314	0.392	0.439	0.439	
5	0.098	0.125	0.222	0.287	0.359	0.359	
7	0.051	0.065	0.113	0.170	0.262	0.262	
10	0.025	0.032	0.064	0.093	0.181	0.185	
20	0.006	0.008	0.016	0.024	0.068	0.086	
50	0.001	0.001	0.003	0.005	0.014	0.037	
∞	0	0	0	0	0	0	

A : Spherical

B : Radius

C : Rectangular (length 2a, width 2b)

D : Strip

E : That is

F : Figure

G : Stable thawing boundary surface

Table 14. m_t values of heated buildings

A	*B*	*C*
D	0.7	0.85
E	0.8	0.95

A : Floor surface structure

B : Central section of outer wall

C : Corners of outer wall

D : Floor surface built directly over the ground

E : Floor surface built directly over the dragon bone

Table 15. Conductivity coefficient of barilla clayey soil (with 50% barilla content)

A *B*	*C* %	*D* *E*	
ν_{CK}	W	λ_T	λ_M
0.4	10	0.10	0.07
	30	0.17	0.13
	50	0.24	0.24
	70	0.32	0.40
	90	0.40	0.58
	110	0.48	0.78
	130	0.55	0.96
0.5	10	0.14	0.09
	30	0.23	0.19
	50	0.33	0.34
	70	0.43	0.55
	90	0.54	0.81
	110	0.65	1.08
	130	0.76	1.35
0.6	10	0.17	0.12
	30	0.29	0.25
	50	0.43	0.46
	70	0.57	0.74
	90	0.72	1.07
	110	0.85	1.43
	130	0.99	1.75
0.7	10	0.21	0.15
	30	0.36	0.33
	50	0.54	0.60
	70	0.71	0.96
	90	0.89	1.37
	110	1.07	1.82
	130	1.24	2.18
0.8	10	0.25	0.18
	30	0.44	0.40
	50	0.65	0.75
	70	0.87	1.18
	90	1.08	1.69
	110	1.30	2.23
	130	1.50	2.69

Table 16. Conductivity coefficient of clayey soil

A *B*	*C* %	*D* *E*	
ν_{CK}	W	λ_T	λ_M
1.2	5	0.29	0.28
	10	0.48	0.45
	15	0.65	0.65
	20	0.76	0.89
	25	0.80	1.16
	30	0.88	1.42
	35	0.96	1.62
	40	1.07	1.81
1.3	5	0.34	0.33
	10	0.56	0.53
	15	0.79	0.76
	20	0.89	1.03
	25	0.94	1.35
	30	1.01	1.64
	35	1.10	1.88
1.4	5	0.40	0.39
	10	0.63	0.62
	15	0.93	0.88
	20	1.05	1.18
	25	1.09	1.56
	30	1.20	1.89
	35	1.32	2.15
1.5	5	0.45	0.44
	10	0.78	0.72
	15	1.08	1.01
	20	1.23	1.36
	25	1.26	1.77
	30	1.39	2.11

0.9	10 30 50 70 90 110 130	0.30 0.52 0.77 1.02 1.29 1.54 1.88	0.22 0.50 0.91 1.44 2.05 2.67 3.17

A : Dry unit weight

B : ton/m^2

C : Water content (weight)

D : Conductivity coefficient

E : Kcal/m.h.^{o}C

Table 17. Conductivity coefficient of clayey soil (with 50% debris)

A *B*	*C* %	*D* *E*	
ν_{CK}	W	λ_T	λ_M
1.2	3	0.26	0.23
	7	0.38	0.38
	10	0.48	0.54
	13	0.59	0.73
	15	0.65	0.88
	17	0.67	0.98
1.4	3	0.37	0.34
	7	0.55	0.56
	10	0.72	0.77
	13	0.88	1.01
	15	0.98	1.17
	17	1.02	1.28
1.6	3	0.51	0.47
	7	0.77	0.76
	10	0.99	1.03
	13	1.23	1.33
	15	1.35	1.50
	17	1.42	1.62
1.8	3	0.67	0.62
	7	1.02	1.01
	10	1.30	1.35
	13	1.61	1.70
	15	1.78	1.88

A : Dry unit weight

B : ton/m^2

C : Water content (weight)

D : Conductivity coefficient

E : $Kcal/m.h.^oC$

1.6	5	0.53	0.51
	10	0.87	0.83
	15	1.25	1.15
	20	1.39	1.54
	25	1.42	2.02
	30	1.58	2.38

A : Dry unit weight

B : ton/m^2

C : Water content (weight)

D : Conductivity coefficient

E : $Kcal/m.h.^{o}C$

Table 18. Conductivity coefficient of medium coarse sand (with 10-20% gravel)

A *B*	*C* %	*D* *E*	
ν_{CK}	W	λ_T	λ_M
1.4	2 6 10 14 18	0.38 0.86 1.04 1.14 1.21	0.42 0.98 1.23 1.44 1.60
1.5	2 6 10 14 18	0.45 0.98 1.16 1.28 1.35	0.51 1.14 1.38 1.61 1.79
1.6	2 6 10 14 18	0.55 1.14 1.32 1.45 1.50	0.63 1.38 1.60 1.85 2.03
1.7	2 6 10 14 18	0.69 1.32 1.50 1.64 1.72	0.81 1.65 1.90 2.14 2.32
1.8	2 6 10 14	0.86 1.53 1.71 1.85	1.03 1.96 2.25 2.46

A : Dry unit weight

B : ton/m^2

C : Water content (weight)

D : Conductivity coefficient

E : Kcal/m.h.^oC

Table 19. Values of coefficient K

$\frac{L}{B}$	*A*				
	β=0.2	0.4	0.8	1.2	2.0
1	0.45	0.56	0.63	0.66	0.70
2	0.62	0.74	0.84	0.86	0.88
3	0.72	0.84	0.91	0.93	0.96
4	1.00	1.00	1.00	1.00	1.00

A : Values of K under following conditions

Table 20. The maximum thaw depth values H of stable thaw basin when heat source comes from air

H: *A* / *B* / *C* / *D*	5.6		7.2		9.0	
	J	*K*	*J*	*K*	*J*	*K*
E	7.8	5.7	8.6	6.3	9.4	6.9
F	7.2	5.3	7.9	5.8	8.7	6.4
G	10.0	7.3	11.0	8.0	12.1	8.8
H	6.5	4.8	7.2	5.3	7.9	5.8
I	8.4	6.2	9.3	6.8	10.1	7.5

A : Height of building (m)

B : Metre

C : Type of soil

D : Name of building

E : Hotel, sleeping room, apartment

F : Office, worker's house, residence, dormitory

G : Bathroom

H : Kitchen, dining hall

I : Sick room

J : Coarse grained soil

K : Fine grained soil

Explanations:

1. The H values in the above table are for the conditions in which the ratio between the length and the width of the house is L/B 5. When L/B = 1 the H value should be multiplied by the coefficient 0.8. When L/3 is equivalent to the values between 1 - 5, the interpolation method is to be used.
2. The H values in the above table are tabulated when the natural upper limit is 2.4 metres. When the natural upper limit is not equivalent to this value, the difference should be accordingly added or subtracted.

Table 21. Basic load carrying potential of foundation soil in frozen ground

A	*B*	*C*				
		-0.5	-1.0	-1.5	-2.0	-3.5
1	*D*	80	95	110	125	165
2	*E*	60	75	90	105	145
3	*F*	45	55	65	75	100
4	*G*	40	45	55	65	85
5	*H*	35	40	45	50	65
6	*I*	25	30	35	40	55

A : Order

B : Name of soil

C : Maximum average monthly soil temperature (°C) along the basal surface of the foundation

D : Rubble-stone soil

E : Gravel soil, gravel sand, coarse sand, medium sand

F : Fine sand, silt sand

G : Mild sandy soil

H : Mild clayey soil, clayey soil

I : When Nos. 1-5 (that is D-H) are highly susceptible to thaw settlement

Explanations:

1. When the foundation soil of Nos. 1 - 5 (that is: D - H) can be subjected to thaw settlement, the values listed in the above table are to be lowered by 20%.
2. The load carrying potential of the water bearing ice layer should be determined through experimentation. The load carrying potential is not to be taken into consideration.
3. When the frozen ground which is highly susceptible to thaw settlement and water bearing ice layer are used as foundations, a layer of sand no less than 20 - 30 cm thick should be laid along the basal surface of the foundation.
4. The numerical values listed in the table above are not suitable for frozen soil with salt content greater than 0.5%.

Table 22. Classification of Foundation Soils by Frost Heaving Susceptibility*

Soil	Natural Water Content W%	Min. dist. ground-water to depth of freezing	Class
Stony soils Gravelly soils (containing ≤30% clayey soil by weight) Gravelly sand; coarse sand; medium sand; fine sand (containing >85% by wt. sand grains larger than 0.1 mm in size)	Not considered	Not considered	I
Fine sand (containing ≤85% by weight sand grains bigger than 0.1 mm in size) Silt	$W<14$	>1.5	I
		≤1.5	II
	$14 \le W < 18$	>1.5	
		≤1.5	III
	$W \ge 18$	>1.5	
		≤1.5	IV
Clayey soils	$W \le W_P$	>2.0	I
		≤2.0	II
	$W_P+5 \ge W > W_P$	>2.0	
		≤2.0	III
	$W_P+9 \ge W > W_P+5$	>2.0	
		≤2.0	IV
	$W > W_P+9$	Not considered	

* 1. Frost heave susceptibility of foundation soils should be based on the lower soils within the depth of freezing. If the foundation depth is less than the lower soil depth, redetermine the foundation depth with susceptibility of the upper soil.
2. When gravelly soils contain 30% by wt. clayey soils, determine with the susceptibility of the clayey soils.
3. Minimum distance from groundwater table to depth of freezing means the distance between the highest water table during freezing (or the highest annual water table) and ground surface, and that between the lowest water table (or the lowest annual water table) and the standard depth of freezing. The lesser of the two values obtained is used for the determination of the frost susceptibility of soils.
4. Frost-heaving classes I, II, III, and IV represent respectively no frost heaving, weak frost heaving, frost heaving, and strong frost heaving.
5. W_P - Water content at plastic limit.

Table 23. Classification of Permafrost Foundation Soils by Thaw Settlement*

Soil	Total Water in Permafrost W%	Class
Gravelly cobble type soils (silt content $\leq 15\%$); Gravelly sand: Coarse and medium sand	$W<10$	I
	$W\geq 10$	II
Gravelly and cobbly loam; Coarse sand; Medium sand (silt content $>15\%$)	$W<12$	I
	$12\leq W<18$	II
	$18\leq W<24$	III
	$W\geq 24$	IV
Silt; Fine sand	$W<14$	I
	$14\leq W<21$	II
	$21\leq W<28$	III
	$W\geq 28$	IV
Clayey soils	$W<W_P$	I
	$W_P\leq W<W_P+7$	II
	$W_P+7\leq W<W_P+15$	III
	$W_P+15\leq W<W_P+35$	IV
Soil containing ice layer	$W\geq W_P$**$+35$	IV

* Thaw settlement classes I, II, III, and IV represent no thaw settlement, weak thaw settlement, thaw settlement, and strong thaw settlement, respectively, of soils.

** Initial thaw settlement water content is used instead of W_p for coarse soils

Table 24. Critical Capillary Rise Height of Soils (m)

Soil	Compacted Soil With Nearly Optimum Water Content	Wind Desiccated, Compacted Soil	Ordinary Uncompacted Soil
Sandy soil	0.10	0.20	0.20 - 0.60
Loam	0.20	0.30	0.30 - 0.60
Silt	0.50	1.00 - 1.20	0.80 - 1.50
Clayey Soil	0.40	0.80	1.50 - 2.00
Clay	0.40	0.80	1.50 - 2.00

Table 25. Values of Allowable Foundation Deformations of Buildings

Deformation Characteristics	Foundation Soils	
	Classes I, II	Class III
Local tilt of brick, load bearing buildings	0.002	0.003
Settlement difference between 2 neighbouring foundation pillars of industrial and civil buildings		
(1) Steel and reinforced concrete framed buildings	0.002L	0.003L
(2) Side pillars to be filled between with brick walls	0.0007L	0.001L
(3) Buildings subject to no additional stress during uneven settlement of foundations	0.005L	0.005L
Pillar foundation settlement (cm) of level, framed buildings with pillar spacing equal to or greater than 6 m	12	20
Tilt of rails for bridge cranes		
Longitudinal	0.004	0.004
Lateral	0.003	0.003
Tilt of high-rise buildings		
$H \leq 20$	0.006 - 0.008	
$20 < H \leq 50$	0.005 - 0.006	
$50 < H \leq 100$	0.004 - 0.005	

Notes: (1) L - Distance between centres of two neighbouring foundation pillars (cm).
(2) H - Building height measured from outside ground surface (m).
(3) The respective load capacities of Classes I, II and III soils are: 20 ton/m$^2 \leq (R_1) <$ 30 ton/m^2, 130 ton/m$^2 \leq (R_2) <$ 20 ton/m^2, and 6 ton/m$^2 \leq (R_3) <$ 13 ton/m^2.

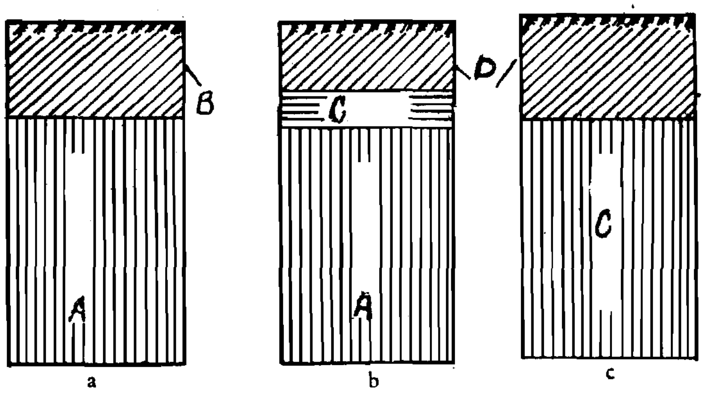


Figure 1   Seasonally Thawed and Seasonally Frozen Layers

a. Seasonally thawed layer

b. Seasonally frozen layer in permafrost region

c. Seasonally frozen layer in region of seasonally frozen ground

A. Permafrost

B. Seasonally thawed layer

C. Thawed soil

D. Seasonally frozen layer

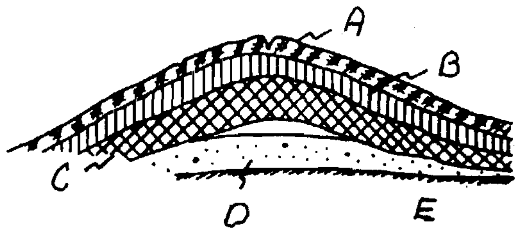


Figure 2   Schematic Profile of Pingo

A. Moss and lichen

B. Peat

C. Ice

D. Layer containing water

E. Frozen soil

Plate 1 Pingo

(Mound on highway, top of mound already artificially exploded open)

Plate 2 Thaw settlement of Small Secondary Pingo Inside Larger Pingo

(Picture shows residual depression)

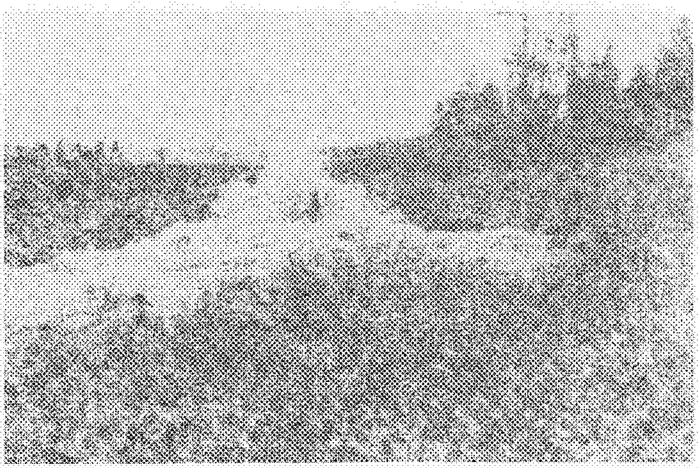


Plate 3 Water Gushing from Spring Icing Feature

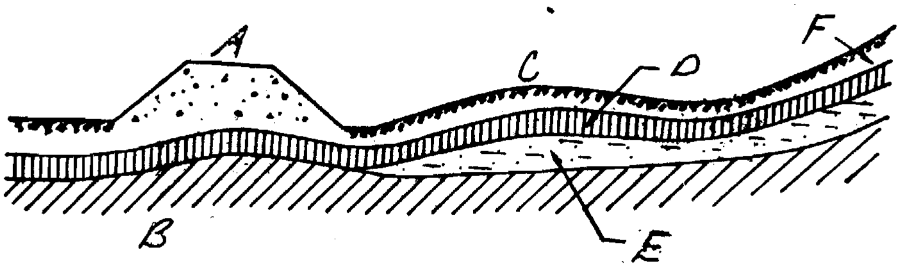


Figure 3 Sketch showing the formation of upheaved hill due to spring thawing.

A. Road bank

B. Stratum of old permafrost

C. Upheaved hill

D. Stratum of seasonal permafrost (not yet thawed)

E. Pressured, water-containing stratum

F. Stratum of thawed (softened) soil)

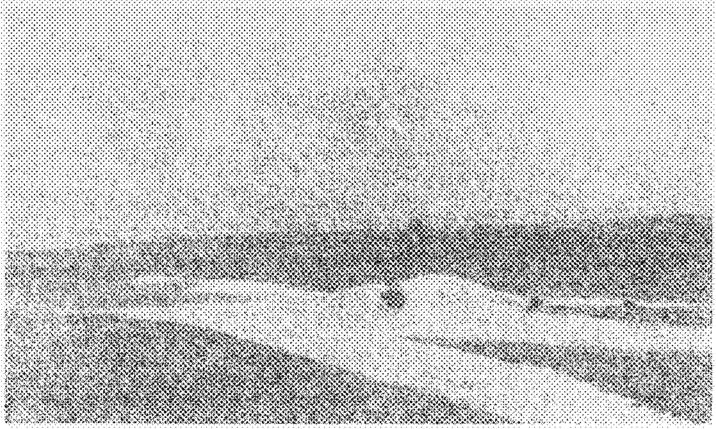


Plate 4 Elliptically-Shaped Icing on River Floodland (Fenghuoshan)

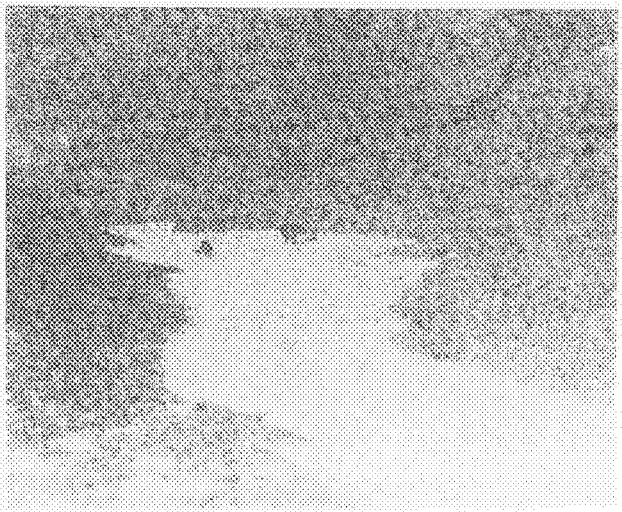


Plate 5 Elongated Icing in Intermontane Furrow (Hsitat'an)

Plate 6 Furrow Formed by Melted Icing (Fenghuoshan)

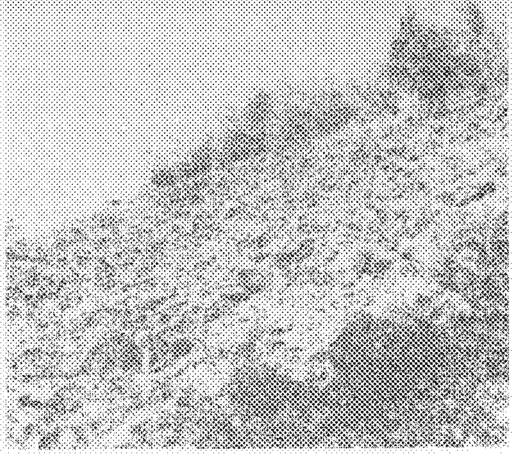


Plate 7 Felsenmeer at Summit of High Mountain (Great Khingan Range)

Plate 8 Rock Stream on Mountain Slope (Fenghuoshan)

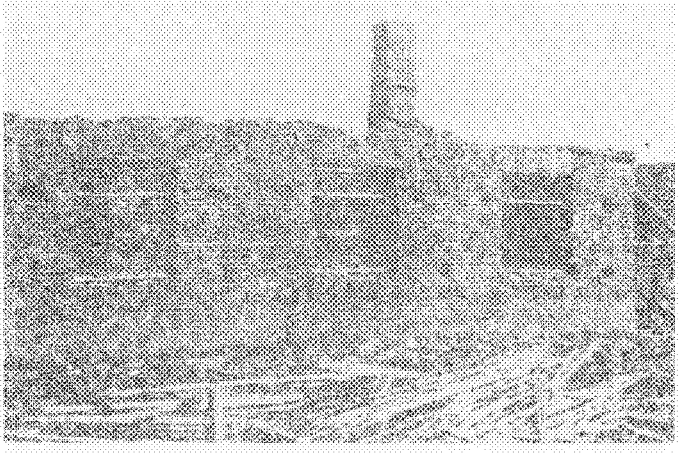


Plate 9 Building Damaged by Frost Heaving

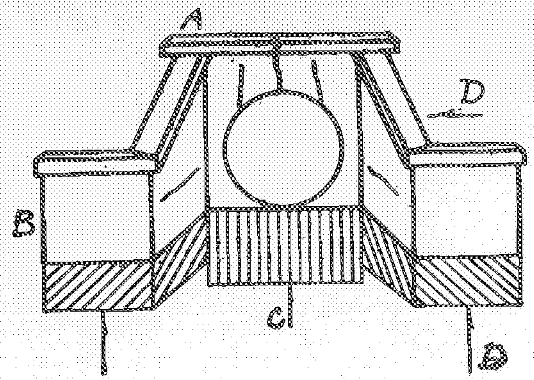


Figure 4   Cracks in End and Wing Walls of Conduit

A: Vertical cracks

B: Horizontal cracks

C: Normal lifting force at base of end wall

D: Normal lifting force at base of wing walls

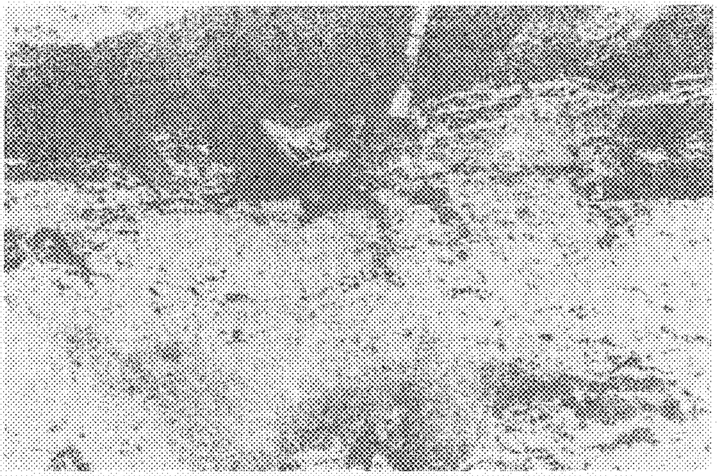


Plate 10   Interlaminated Ice and Marl

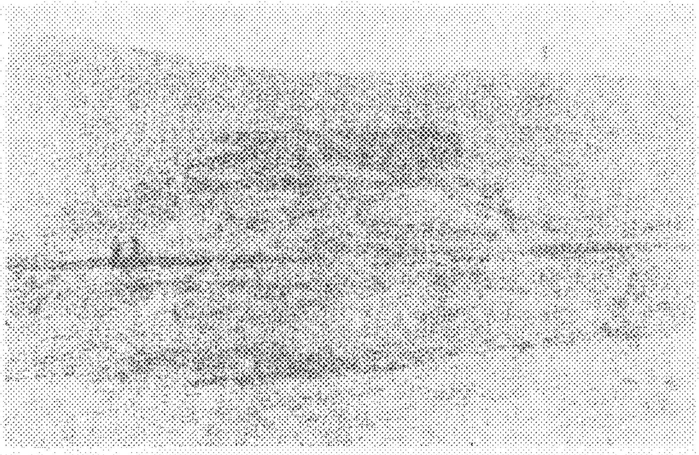


Plate 11   Thaw Flow (Fenghuoshan)

Plate 12 Natural Thaw Settlement (Fenghuoshan)

Plate 13 Thaw Settlement of Road Passing Through Area of Ice-Rich Soil (Great Khingan Range)

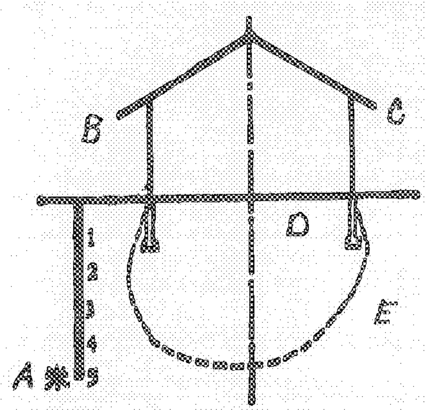


Figure 5 Cross Section of Thaw Basin Under Experimental Building after 3 Years of Use (Through Middle of Building)

A: Gauges

B: South

C: North

D: Thawed soil

E: Frozen ground

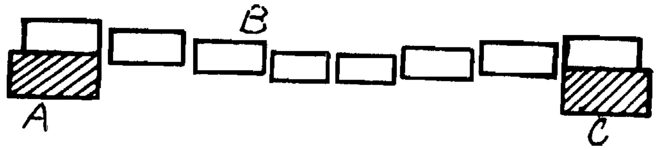


Figure 6 Schematic Diagram Showing Settlement of Pipe in Cohesive Soil*

A: Foundation at pipe inlet

B: Pipe in Cohesive soil

C: Foundation at pipe outlet

(*Literally, "mixed-congealed soil". The idea is that the soil holds together and is not loose and sandy. - Translator.)

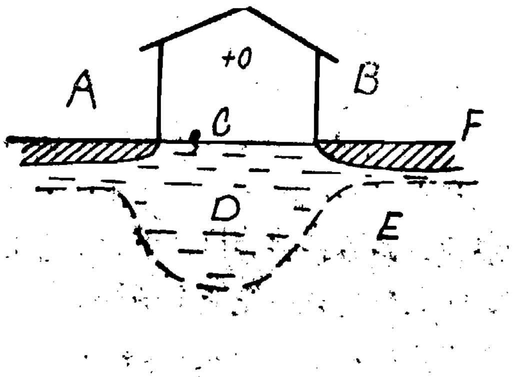


Figure 7 Schematic Diagram Showing Water Entering Heated Building

A: South

B: North

C: Water (place at which water enters)

D: Thaw basin

E: Permafrost

F: Frozen layer

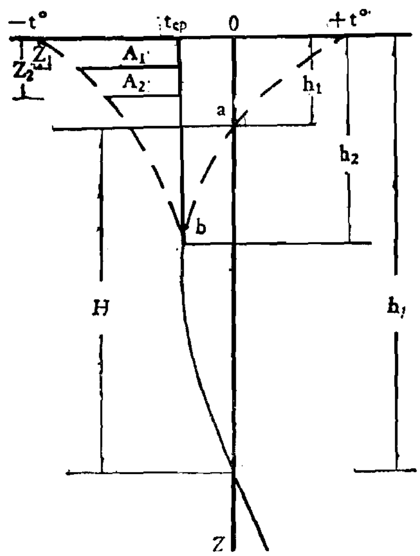
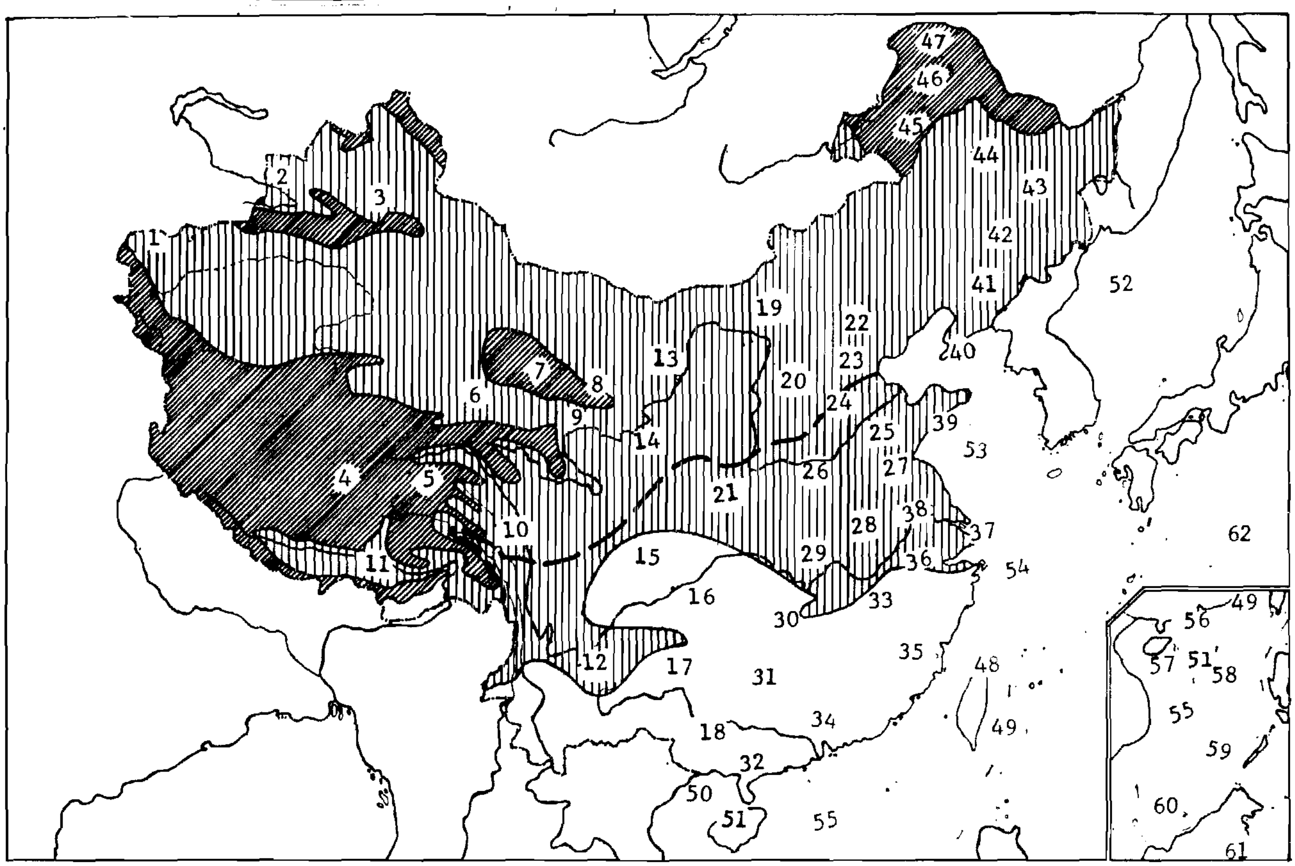


Figure 8 Diagram of the Temperature of a Cross-Section of Perennially Frozen Ground

Figure 9 Distribution of Frozen Ground in China



(hatched)	Perennially forzen ground region
(vertical lines)	Seasonally frozen ground region
(dashed line)	Isopleth of 0.5 m for seasonally frozen ground layers.

The boundary of China is based on the sixth edition of "The map of the People's Republic of China" published by the Map Publishers on December, 1971.

1. Kashi	13. Yinchuan	25. TSinan	37. Shanghai	49. Taiwan Island
2. Yining	14. Lanchow	26. Chengchow	38. Nanking	50. Beibowan
3. Urumchi	15. Chengtu	27. Hsuchow	39. Tsingtao	51. Japan Sea
4. Togmegla	16. Chungching	28. Hofei	40. Luda	52. Japan Sea
5. Wenchuan	17. Kweiyang	29. Wuhang	41. Shenyang	53. Yellow Sea
6. Golmud	18. Nanning	30. Changsha	42. Changchun	54. East China Sea
7. Muli	19. Huhehot	31. Kweilin	43. Harbin	55. South China Sea
8. Reshiu	20. Taiyuan	32. Chanchiang	44. Tsitsihar	56. Tungsha Islands
9. Xining	21. Hsi an	33. Nanchang	45. Yakeshi	57. Sisha Islands
10. Changdu	22. Peking	34. Kwangchow	46. Gunho	58. Chongsha Islands
				59. Nansha Islands
11. Lhasa	23. Tientsin	35. Fuchow	47. Moho	60. Tsangmoo Ennsha
12. Kunming	24. Shichiachong	36. Hangchow	48. Taipei	61. South China Sea Islands
				62. Pacific Ocean

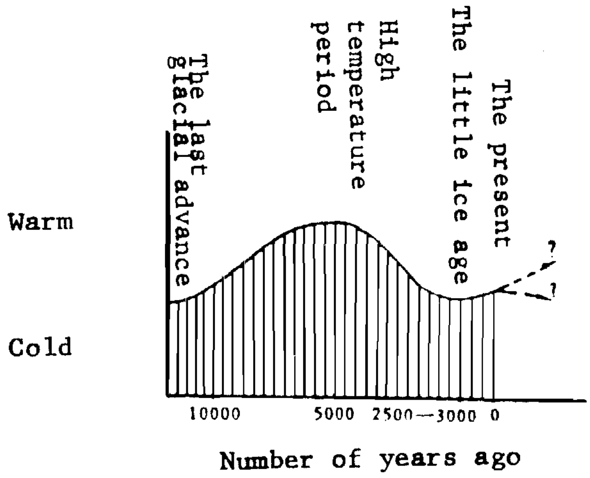


Figure 10 Diagram to illustrate the change in climate in the Post-Glacial period

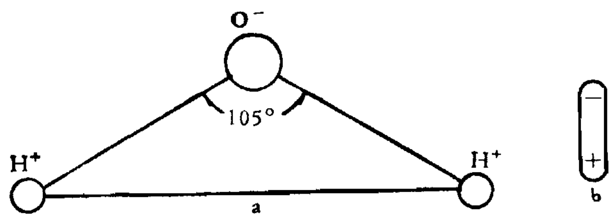


Figure 11 Structure of a water molecule

a. Structure of a water molecule b. Dipole

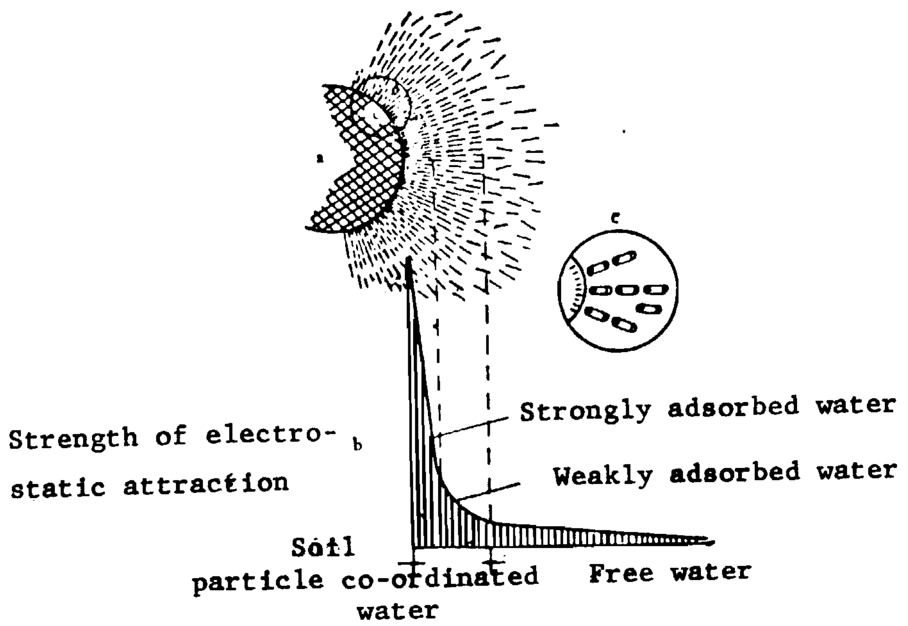


Figure 12 Diagram to illustrate the interactions between ground particles and water

a. Ground particles b. Change in electrostatic attraction field strength near the surface of the ground particles
c. The dipolar structure of a water molecule

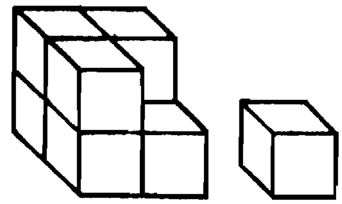


Figure 13 Increase in the surface area of a body as the number of division of the body increases

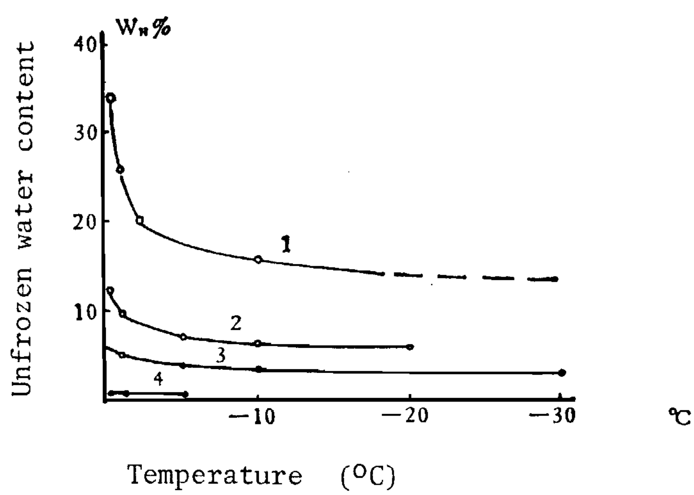


Figure 14 Curve showing the relationship between the un-frozen water content in frozen ground and temperature of the frozen ground.

1. clay 2. subclay 3. subsand 4. sand

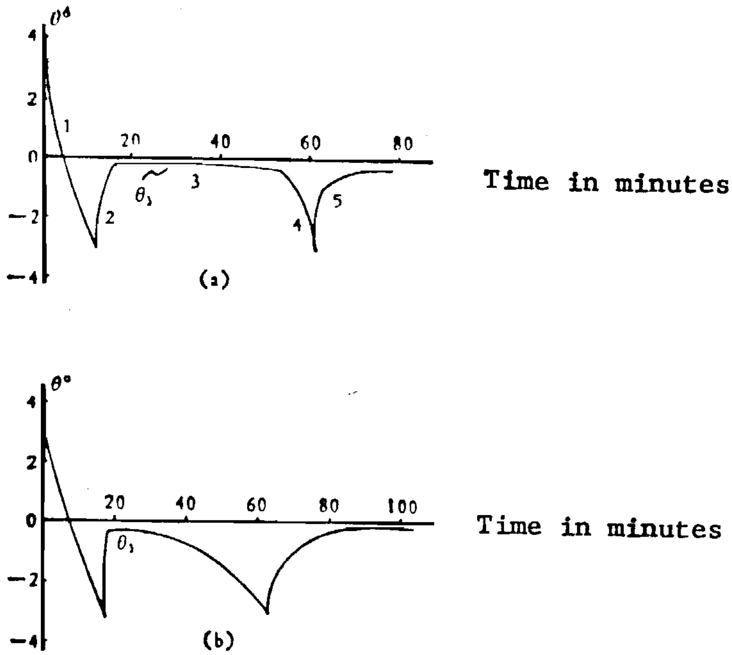


Figure 15 Curves of freezing and melting of groundwater

1. Cooling stage and supercooling stage
2. Sudden change in temperature stage
3. Crystallization of water stage
4. Continuous cooling of the frozen ground stage
5. Melting stage

(a) sandy ground (b) subclay

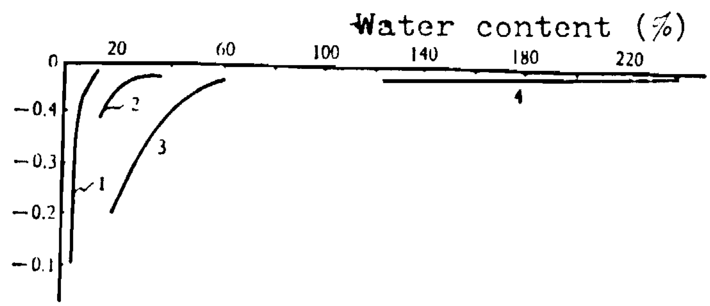


Figure 16 Curves showing the relationship between the onset of freezing temperature of several types of ground in the Muli Region

1. Yellow subclay mixed with stones
2. Yellow subclay
3. Greyish black powdery subclay
4. Grass covered humus soil

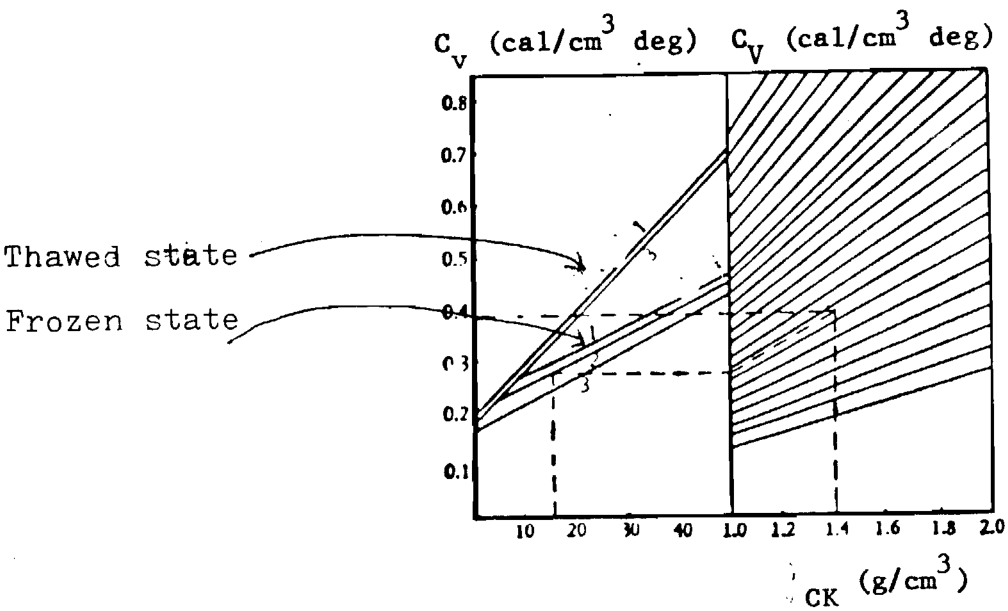


Figure 17 Relationship between volumetric heat capacity (C_V) * and water content (W) and dry volumetric weight (γ CK) of frozen ground and thawed ground

1. clay 2. subclay 3. sand

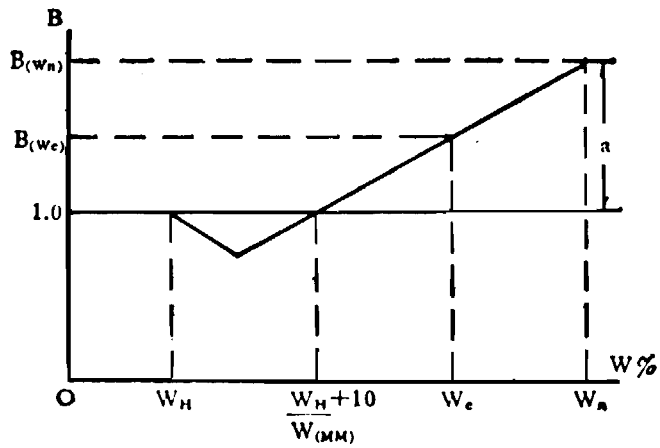
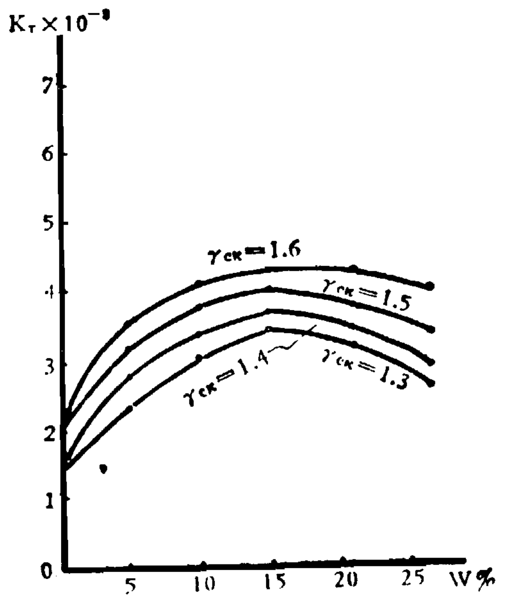
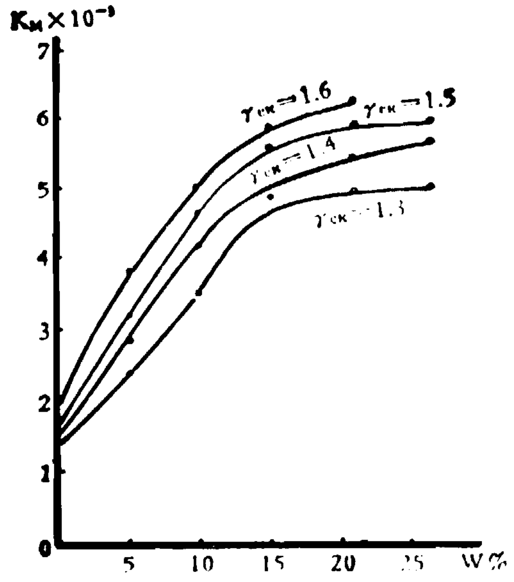


Figure 18 The relationship between $B = M/T$ and the water content for fine granular ground.

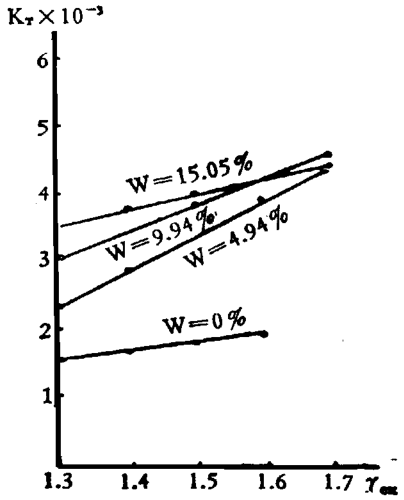


<u>Figure 19</u> Relationship between the coefficient of thermal conductivity and moisture content (W) of the thawed clay at Togmegla



<u>Figure 20</u> Relationship between the coefficient of thermal conductivity (K_M) and moisture content (W) of the frozen clay at Togmegla

Figure 21



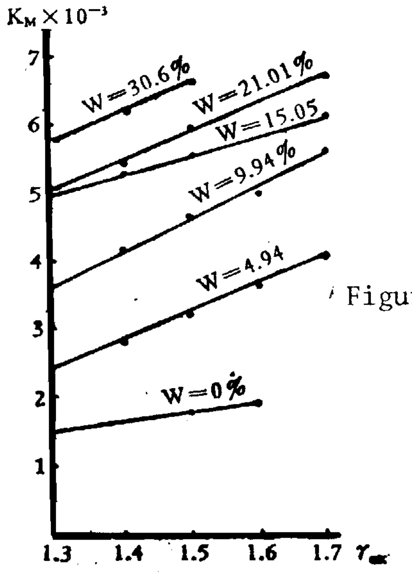


Figure 22

<u>Figure 21</u> Relationship between the coefficient of temperature conductivity (K_T) and dry volumetric weight (γ CK) of thawed clay at Togmegla

<u>Figure 22</u> Relationship between the coefficient of temperature conductivity (K_M) and dry volumetric weight (γ_{CK}) of frozen clay at Togmegla.

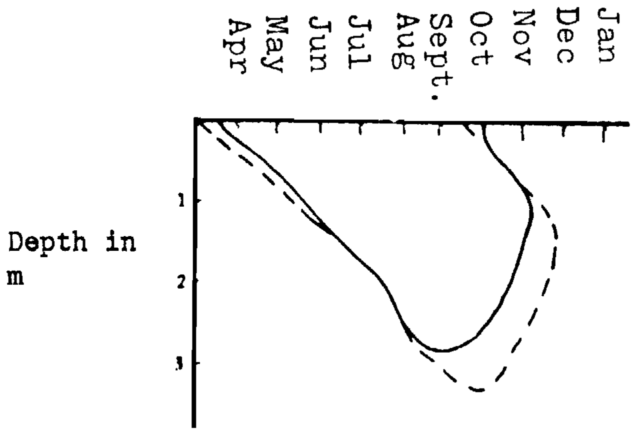


Figure 23 Diagram of the $0^{\circ}C$ Isopleth of the Ground Layer at Yakeshi

——— with vegetation coverage
--------- without vegetation coverage

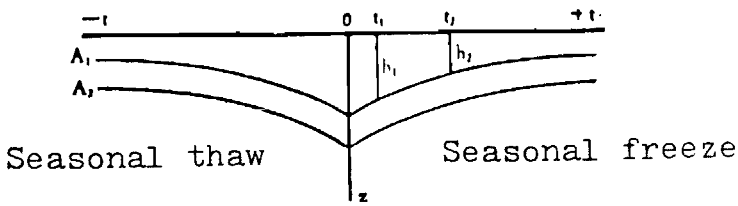


Figure 24 Diagram to Illustrate Relationship between Average Annual Ground Temperature, Annual Ground Temperature Differential and Depth of Seasonal Thaw*

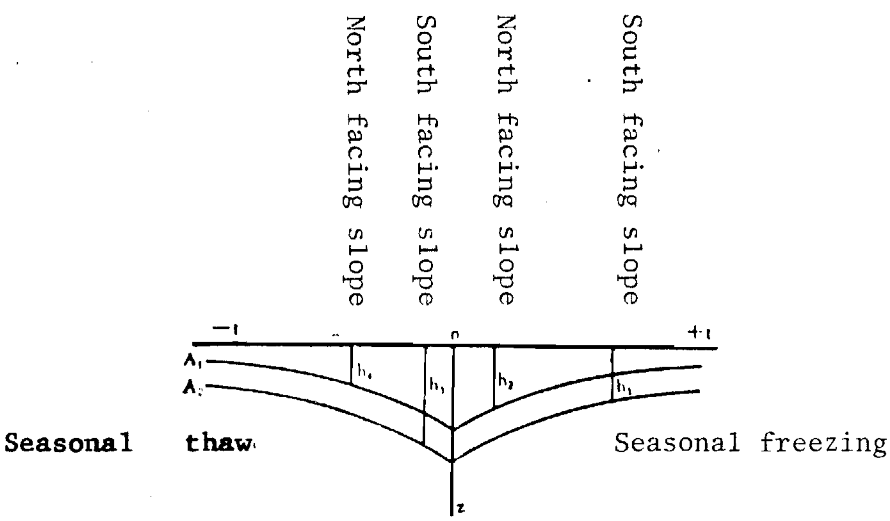


Figure 25 Diagram to Illustrate the Influence of Slope Direction on the Depth of Seasonal Freeze and Seasonal Thaw

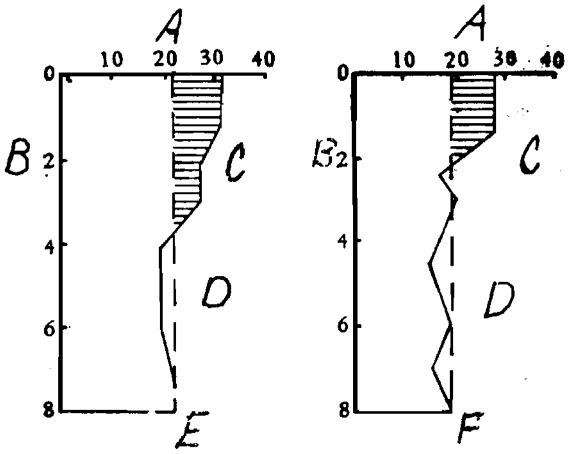


Figure 26 Water distribution before and after the soil freezes.

A. Water content (%)
B. Depth (cm)
C. After freezing
D. Before freezing
E. Silt sandy soil
F. Mild clayey soil

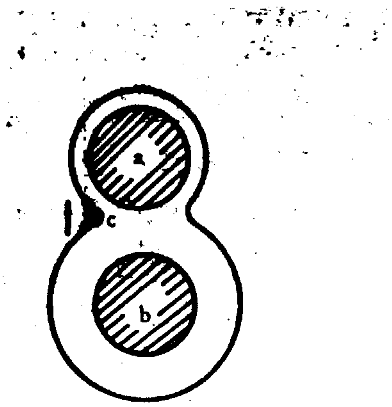


Figure 27 Film water migrates towards the film from the thick membrane.

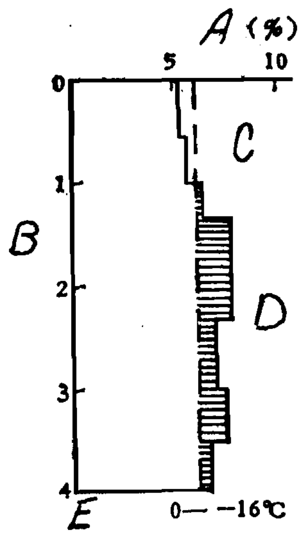


Figure 28 Redistribution of water content when sandy gravel freezes.

A. Water content
B. Depth (cm)
C. Before freezing
D. After freezing
E. Temperature

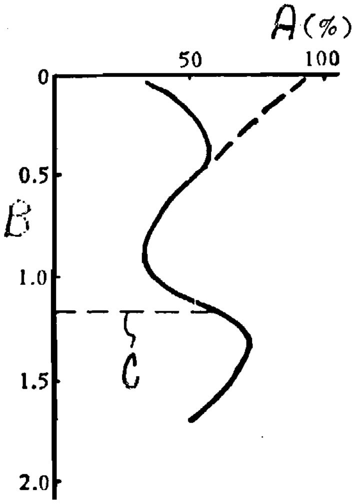


Figure 29 Schematic curve of water content distribution in the seasonally thawing layer (dotted lines show the marsh land)

A. Water content
B. Depth (m)
C. Permafrost table

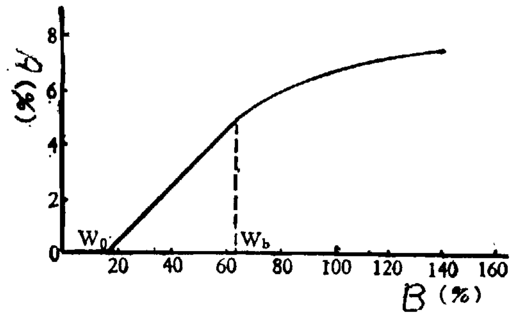


Figure 30 Relation between frost heaving rate and water content in a warm region (closed system)

A. Frost heaving rate
B. Water content

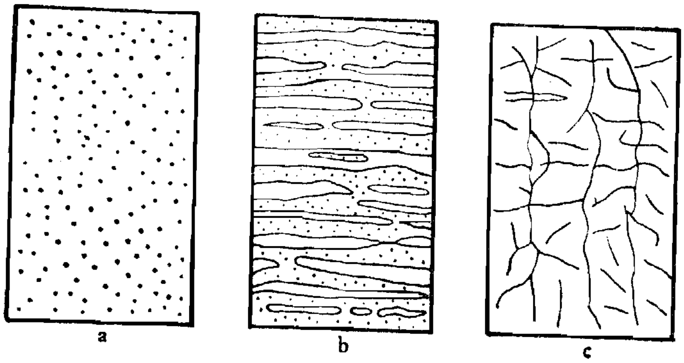


Figure 31 Three principal types of frozen ground structure
A. Granular
B. Bedded
C. Reticular

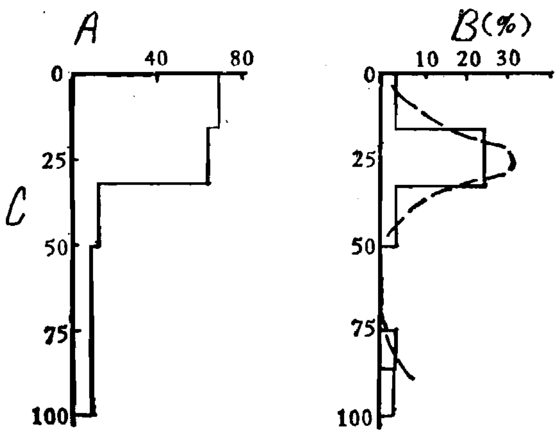


Figure 32 Frost heaving of soil according to changes in depth in permafrost regions

A. Total frost heaving magnitude (μ)
B. Frost heaving rate
C. Depth (cm)

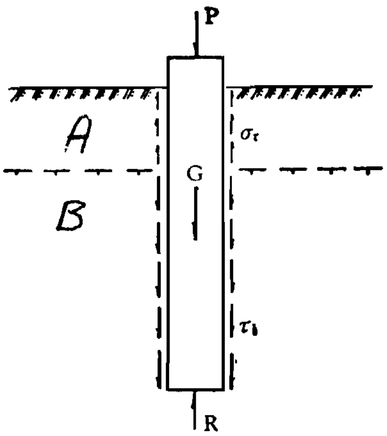


Figure 33 Consolidation action exerted upon foundation by the freezing potential

A. Seasonally thawing layer
B. Permafrost
P. Load
G.. Weight of foundation
R. Load carrying potential of the base of the foundation
σ_i. Tangential frost heaving potential
τ_i. Freezing potential

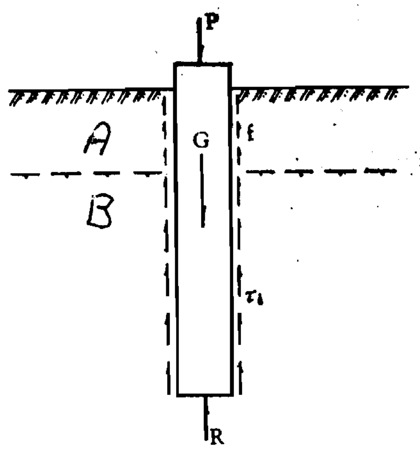


Figure 34 Load carrying potential exerted upon foundation by freezing potential

A. Seasonally thawing layer
B. Permafrost
F. Friction force

(Other symbols are the same as those in Figure 33)

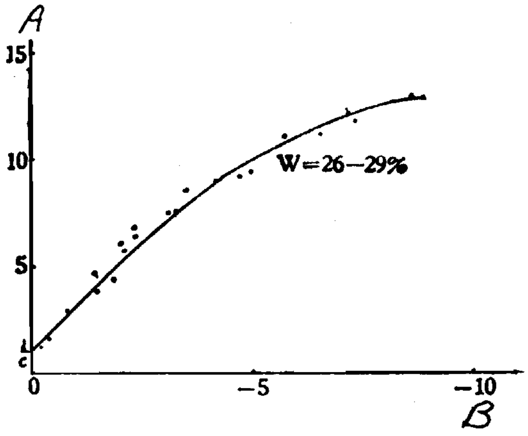


Figure 35 Relation between Freezing Potential of Frozen Clayey Soil and Temperature

A: kg/cm^2
B: Temperature $^{\circ}$C
C: Equivalent to the friction force of that particular soil at thawing state

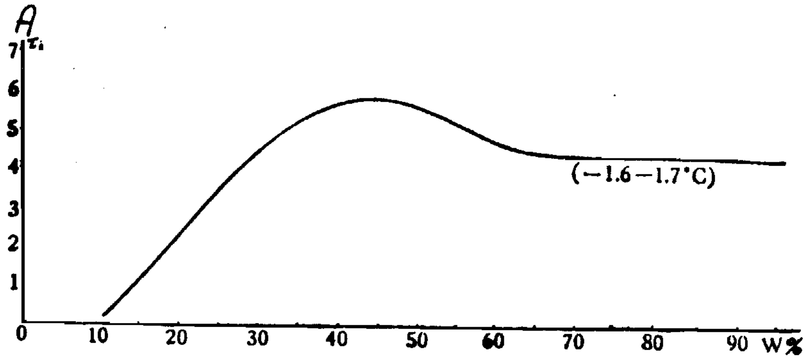


Figure 36 Relation between Freezing Potential (τi) of Clayey Soil and Water Content (W)

A: kg/cm^2

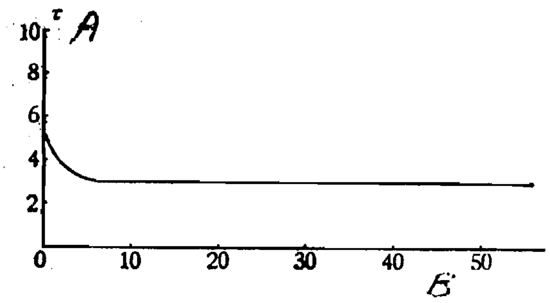


Figure 37 Relaxation Curve of Freezing Potential (τ) between Concrete and Sand

A: kg/cm^2
B: Time (h)

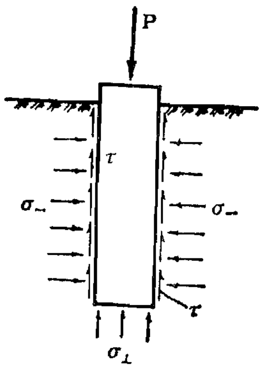


Figure 38 Various Types of Frost Heaving Potential

σ_+ : Normal frost heaving potential
γ : Tangential frost heaving potential
σ_- : Normal frost heaving potential along sides of foundation

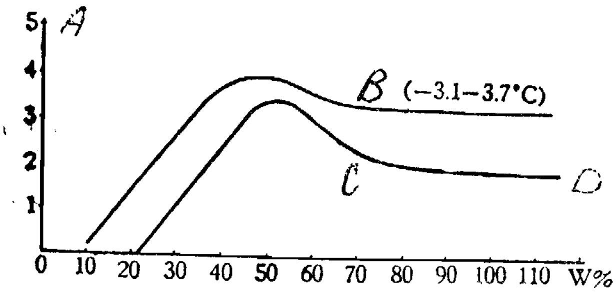


Figure 39 Relation of Persistent Freezing Potential and Tangential Frost Heaving Potential with Water Content of Warm Water Clayey Soil

A: kg/cm^2
B: Freezing potential
C: Frost heaving potential
D: Highest frost heaving potential

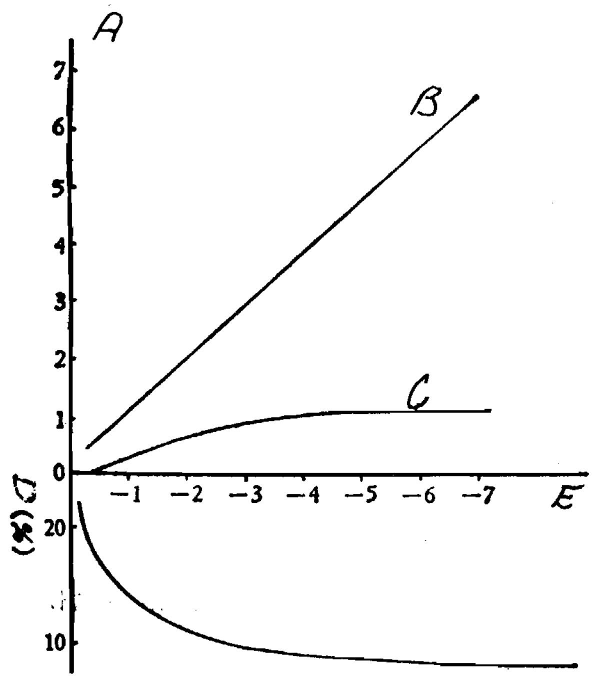


Figure 40 Relation of freezing potential, frost heaving potential and prefrozen water content (W_H) with temperature

A. kg/cm^2
B. Persistent freezing potential
C. Tangential freezing potential
D. Prefrozen water content
E. Temperature

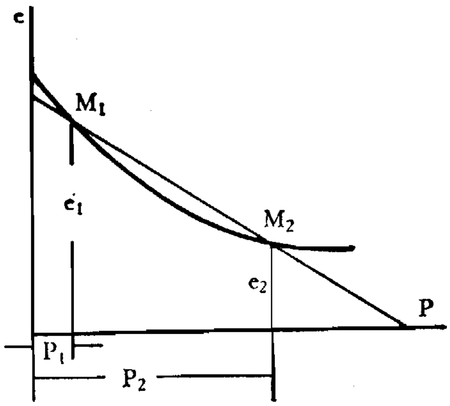


Figure 41 Compression curve during non-lateral heaving

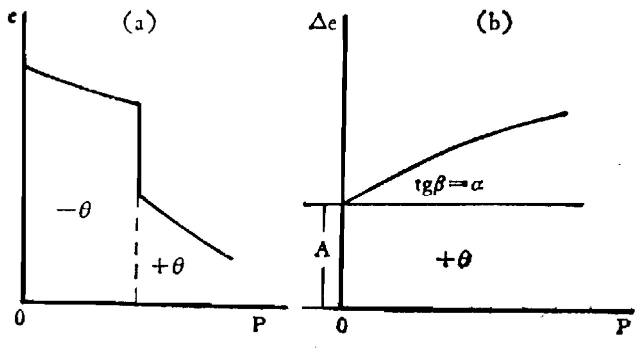


Figure 42 Change of void ratio during thawing of the frozen ground

A. Compression curve during thawing
B. Relation between change of void ration and the external pressure.

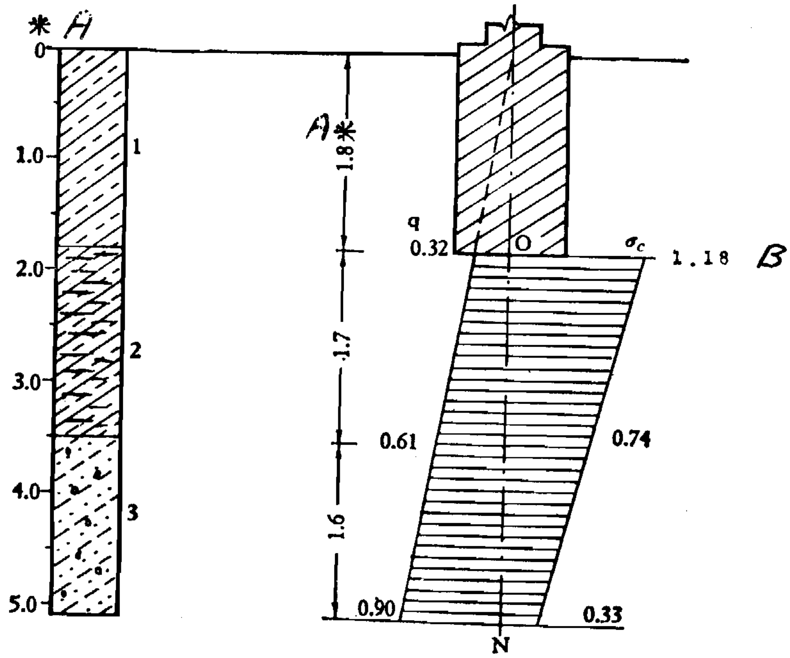


Figure 43 Computation Graph of the Final Thawing Compression Magnitude at the Centre Point of the Outer Wall of the Strip Foundation

A: Meter
B: kg/cm^2
1: Yellowish-brown clayey soil α = 1.75 ton/m^2
2: Frozen clayey soil exhibits thinly bedded frozen ground structure

α = 1.70 ton/m^2
W = 32.1%
A_0 = 0.055
α_0 = 0.025

3: Frozen mild sandy soil intercalated with a small amount of debris, exhibiting complete-bodied structure

α = 1.80 ton/m^2
W = 21%
A_0 = 0.002
α_0 = 0.011

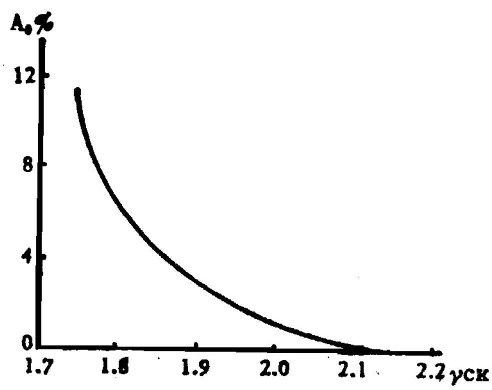


Figure 44 Relation between Thaw Settlement Coefficient (A_0) of Sandy Gravel Soil and Dry Unit Weight (γ_{ck}) in a Certain Region of Chiliang Hill in Chinghai Province

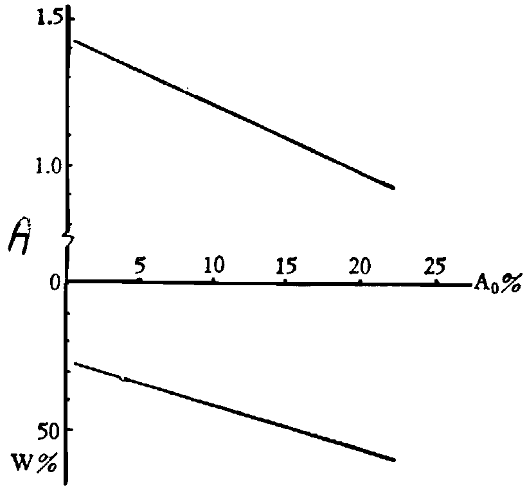


Figure 45 Relation of thaw settlement coefficient (A_0) with dry unit weight (γ_{ck}) and water content (W) of clayey soil in a certain region of Chiliang Hill

A. g/cm^2

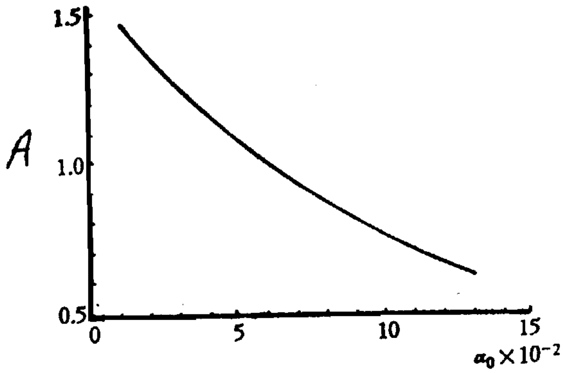


Figure 46 Relation between compression coefficient (α_0) and dry unit weight (γ_{ck}) of clayey soil in a certain region of Chiliang Hill

A. g/cm^2

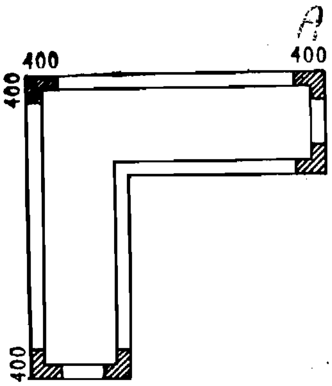


Figure 47 Schematic Diagram of central section of outer wall and corners (the shaded portions indicate the corners; the rest is the central section.)

A. cm

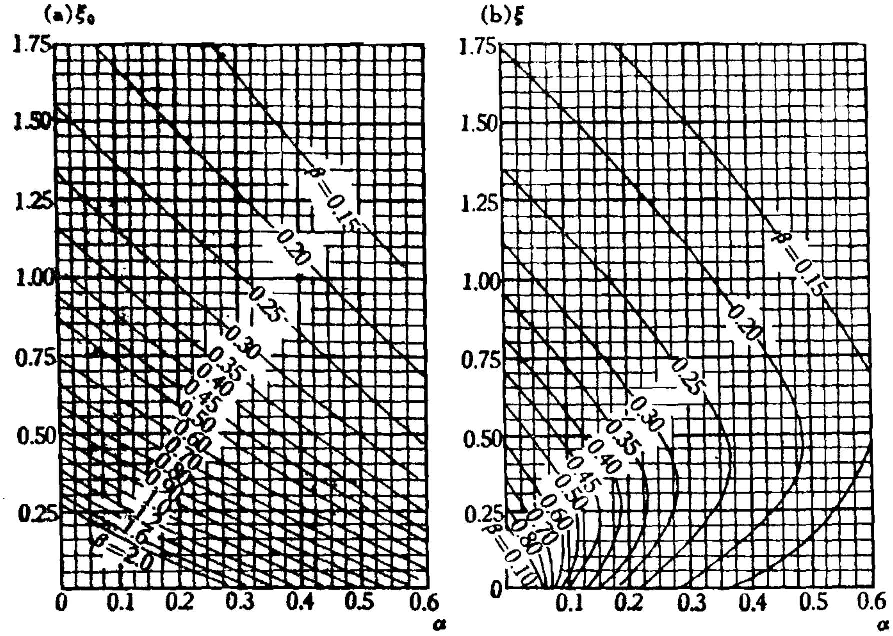


Figure 48 Nomograms for Computing ξ_0 and ξ

A: Nomograms for computing ξ_0
B: Nomograms for computing ξ
Table 16 and figure 48 are taken from CH_HП II-5 (standard designs of buildings on permafrost and foundation soils)

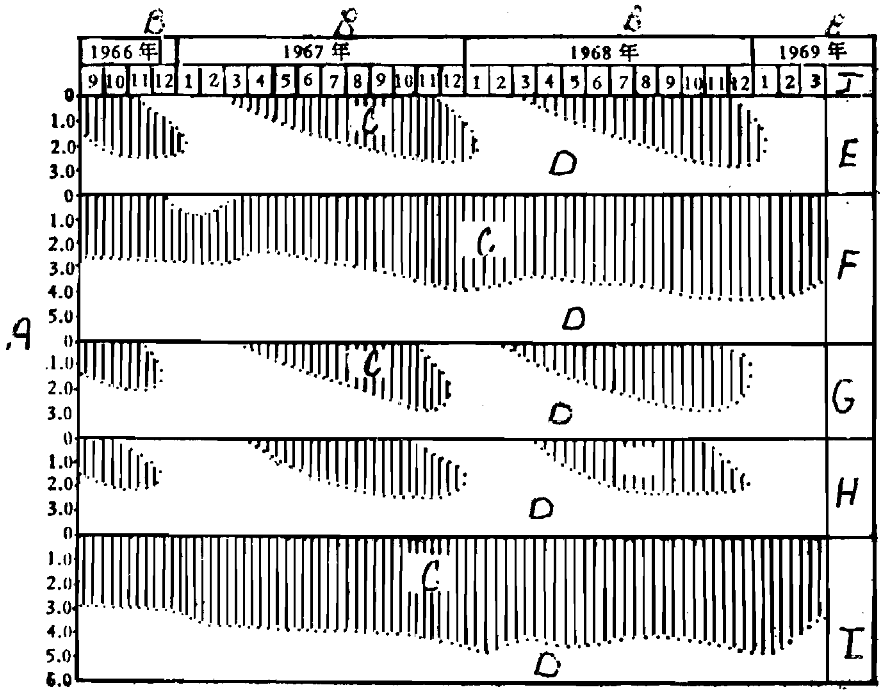


Figure 49 Zero Isotherms in Foundation Soil of a Heated Building in Muli of Chiliang Hill in Chihai Province

A: Depth (m)
B: Year
C: Thawed area
D: Frozen ground
E: Centre of east wall
F: Centre of south wall
G: Centre of west wall
H: Centre of foundation soil
I: Centre of building
J: One hundred unit

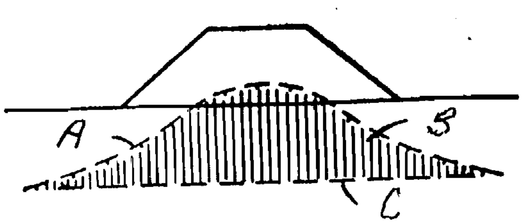


Figure 50 Freezing Core of Embankment

A: New upper limit
B: Core of frozen ground
C: Original upper limit

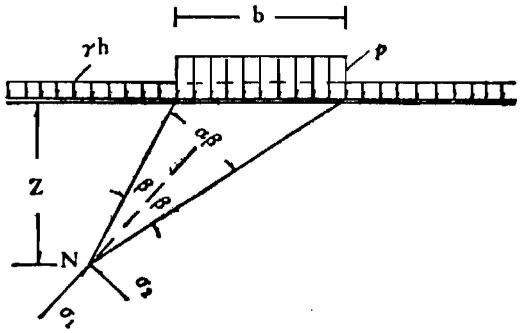


Figure 51 Computation of Critical Plastic Load

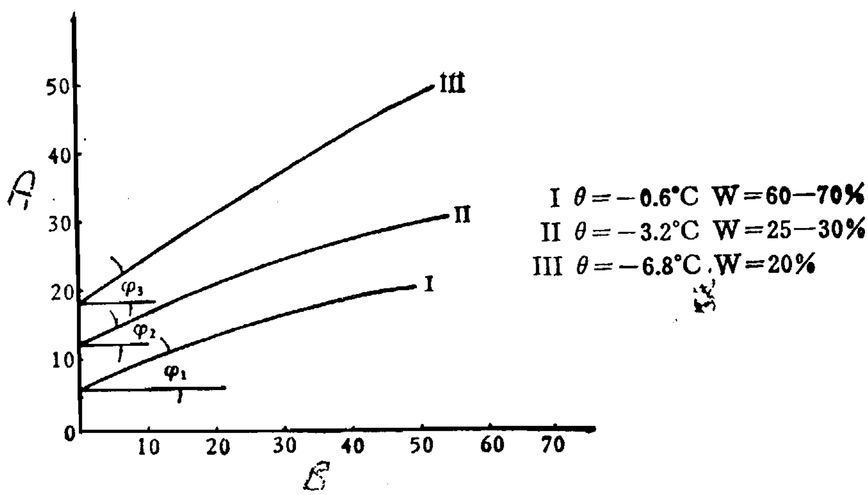


Figure 52 Relation between Shear Strength (instantaneous value) and Normal Pressure of Frozen Ground

A: Shear strength (kg/cm^2

B: Normal pressure (kg/cm^2)

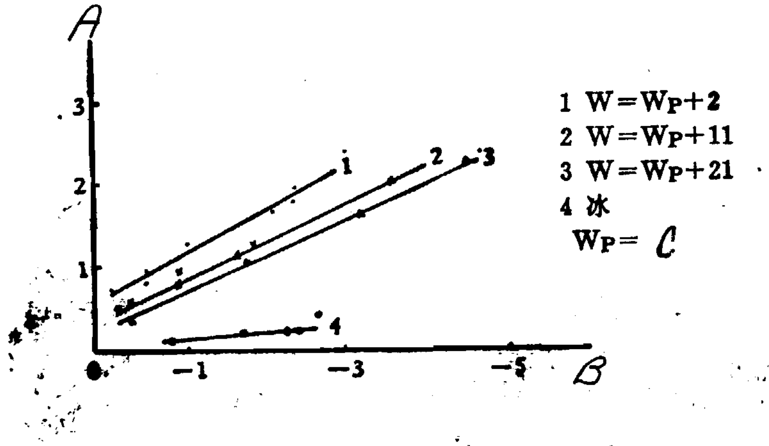


Figure 53 Relation between Persistent Bonding Force (c) and Negative Temperature of Clayey Soil in the Frozen Ground

A: kg/cm^2
B: Temperature
C: Plastic limit water content

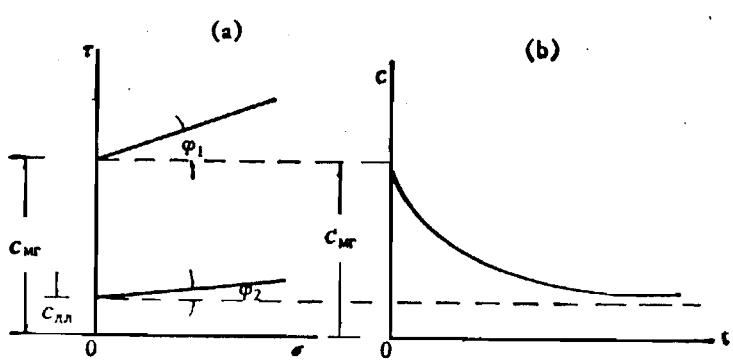


Figure 54 Transformation of Shear Strength with Time in Frozen Ground

C_{mr}: Instantaneous bonding force
$C_{\pi\pi}$: Persistent bonding force
A: Shear strength
B: Transformation of bonding force with time

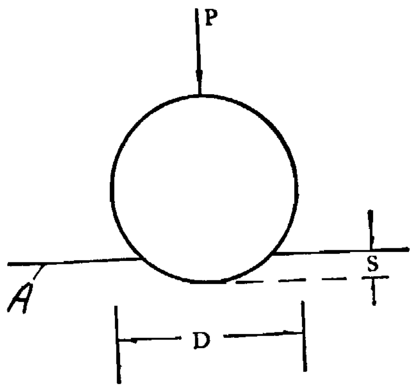


Figure 55 Computation of Bonding Force (c) by Rigid Sphere Model Test

A: Surface of test sample

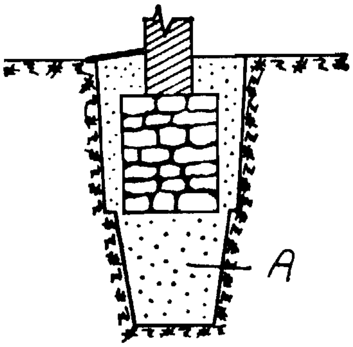


Figure 56 Sand Fill for Sides and Base of Building Foundations

A: Sand layer

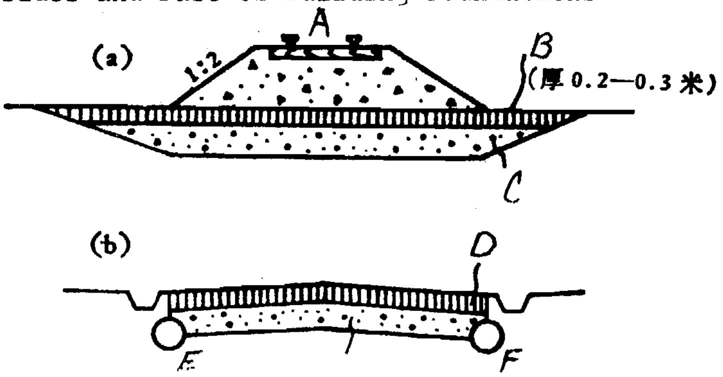


Figure 57 Sand Gravel Subgrade for Road Construction

(a): Railroad embankment
(b): Highway roadbed
A: Embankment
B: Water confining layer (0.2-0.3 m in thickness)
C: Replacement fill
D: Water confining layer
E: Replacement fill (sand, gravel in material)
F: Conduit

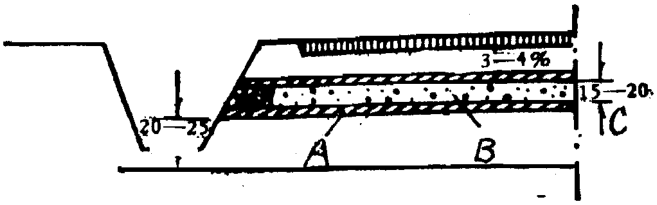


Figure 58 Structure of a Roadbed Water Confining Layer

A: Anti-filtration horizon
B: Water refining layer
C: cm

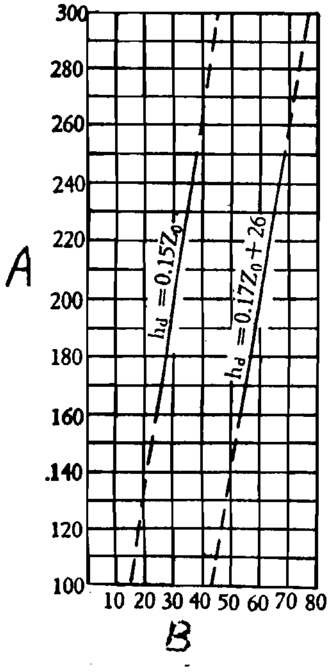


Figure 59 Thickness of Residual Permafrost Layer

A: Depth of freezing Z_0 (cm)
B: Thickness of residual permafrost layer h_d (cm)

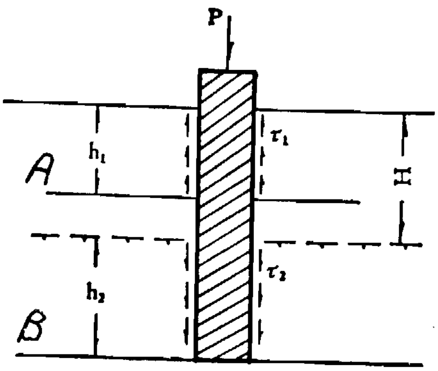


Figure 60 Calculation of Foundation Stability against Frost Heaving

A: Seasonally frozen soil
B: Permafrost

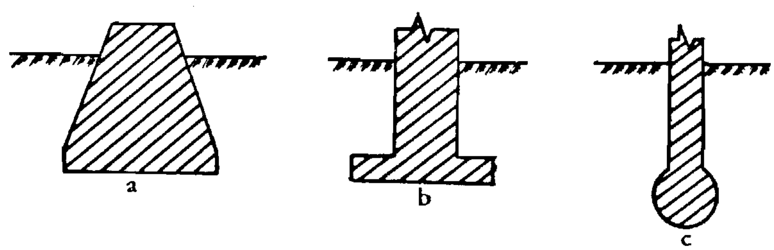


Figure 61 Expanded Types of Foundations Commonly seen in Permafrost Regions

A: Concrete pier type foundation
B: Reinforced concrete expanded columnar foundation
C: Explosion expanded short pile

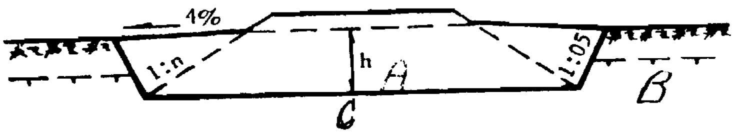


Figure 62 Schematic Diagram showing Cross Section of Fill for an Embankment 0.5 m in height

A: (Sand, gravel materials)
B: Permafrost table
C: Ice rich frozen soil

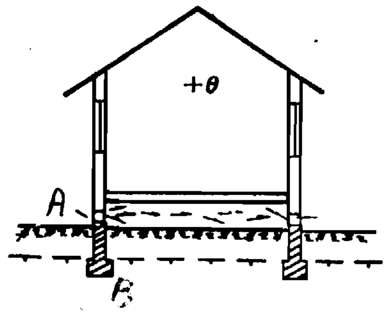


Figure 63 Schematic Diagram showing an Elevated Floor

A: Vent
B: Permafrost

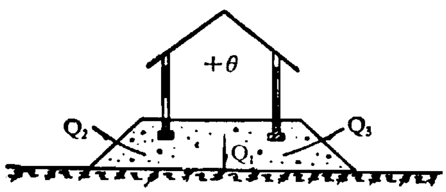


Figure 64 Heat Dissipation of a High Fill Foundation

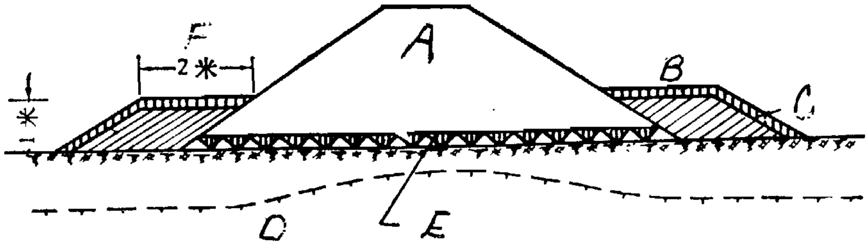


Figure 65 Cross Section of an Insulated Embankment

A: Clay and sandy gravel
B: Insulated protecting shoulder
C: Peaty layer
D: Upper limit of permafrost table
E: Insulation
F: m

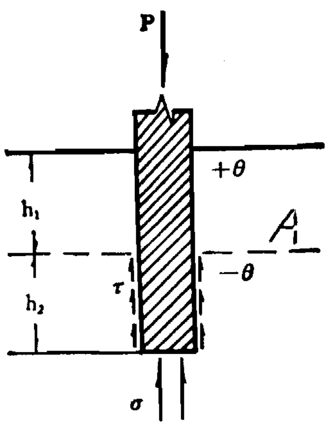


Figure 66 Calculation of Foundation Stability

A: Depth of thaw

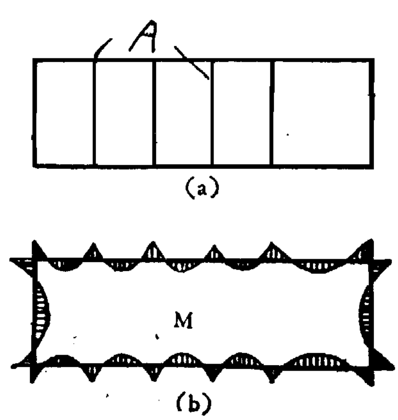


Figure 67 Bending Moment Diagram of Foundation with Partition Walls due to External Normal Frost Heave Stress

A: Partition walls

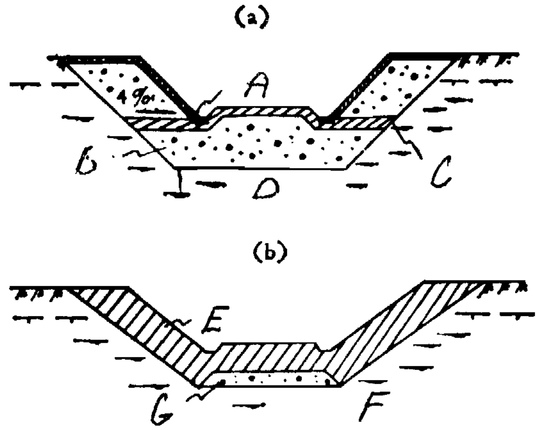


Figure 68 Replacement Fill for Railroad Cuts in Ice Rich Areas

(a): Coarse-grained soil
(b): Fine-grained soil
A: Drain orifice
B: Coarse-grained soil
C: Clay water confining layer
D: Ice rich soil layer
E: Fine-grained soil
F: Ice rich soil layer
G: Gravels

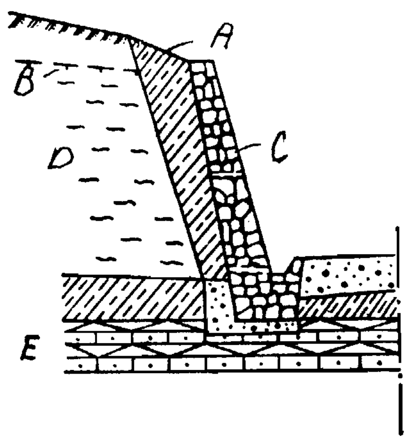


Figure 69 Structural Headwall

A: Local soil backfill
B: Upper limit of natural frozen soil
C: Headwall
D: Ground Ice
E: Bedrock

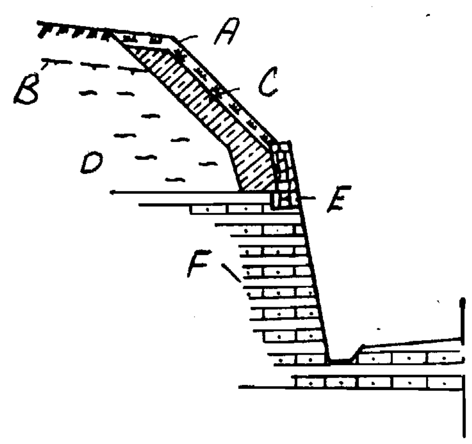


Figure 70 Method Combining Insulation Protecting Slope and Structural Headwall

A: Grass pad protecting slope
B: Upper limit of natural frozen soil
C: Local soil backfill
D: Ground ice
E: Headwall
F: Bedrock