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ROBINSKY E.I.
University of Toronto, Canada

MORA P.H.
Société Terre Armée, Canada

Reinforced earth in a freezing environment

La terre armée dans les pays froids

Plus de 40 ouvrages en terre armée ont été construits au Canada depuis 1970 et l'expérience acquise apporte une contribution importante à l'étude du comportement de la terre armée en pays froid. Le Canada peut être décomposé en trois régions climatiques: Climat tempéré à lóuest des rocheuses, climat froid à l'est et climat très froid au nord du 55° parallèle. Le présent exposé concerne essentiellement la seconde région qui est de loin la plus importante. Les effets du froid ont été classés en deux chapitres selon qu'il s'agit de l'action du froid à l'interieur de l'ouvrage ou à l'extérieur. Les conséquences des changements de volume dûs au gel ou des dilatations ou contractions différentielles dans les composants du matériau "Terre Armée" ont été analysées et la meilleure solution offerte pour les prévenir est d'utiliser des remblais ne contenant pas plus de 3% de grains fins passant au tamis N°200 en cas de granulométrie continue ou moins de 10% en cas de granulométrie uniforme. On a également essayé de définir les efforts extérieurs qui proviennent soit de masses de glace collées aux écailles, soit au contraire des bancs flottants qui poussent et frottent sur les parements sous l'effet des vents et des courants. D'une manière très générale on constate que les précautions et les formules empiriques que l'on utilise couramment pour tenir compte du froid sont applicables à la terre armée. Cette nouvelle technique présente en outre l'avantage d'éviter les déformations cumulatives qu'enregistrent les ouvrages de soutènement classiques sous l'effet des gels-dégels répétés des premières journées de printemps.

INTRODUCTION

Behaviour of Reinforced Earth (RE) has been reported extensively for structures built in moderate climates. As the use of this novel technique spreads even farther, the effects of severe winter conditions should be examined. One country where some experience has already been gained is Canada. Since 1971, forty structures have been commenced or completed. The most severe climatic effects encountered to date are associated with the sea wall at Mont St. Pierre, Québec. At this location the degree days of frost (Celsius) reach 1670 and tidal fluctuations combined with swell attain 6 m. In addition, extensive ice floes can deliver substantial blows to the structure.

Cold climate effects are extremely variable and complex, as witnessed by the numerous publications in recent years relating to cold regions, permafrost terrain, and ice-associated problems.

It is the intent of this paper to raise some questions associated with cold climate effects and to show that, for the most part, long-established criteria for the design of conventional structures in cold climates appear to be also adequate for RE design. A brief qualitative examination is made of the probable behaviour of RE in various freeze-thaw conditions. Where available, references to Canadian experience are given.

CLIMATIC CONDITIONS AND THEIR GENERAL EFFECTS

Overall, the Canadian climate is cold and severe. For most of the land only 40 percent of the days per year are frost free. Yet it is also a country of climatic contrast. The west coast climate represents a very small area of high precipitation and moderate winter temperatures which drop below freezing for only short periods of time. The east coast, and a belt stradling the St. Lawrence River through to the upper Great Lakes is considerably colder with average temperatures of +18°C for summers and −12°C for winters. Even more severe are the Cold Continental, Prairie and Mountain climates, representing more than one-half of the country, with average winter temperatures of −15°C to −20°C. Finally, north of aproximately the 55th parallel the very cold dry Arctic climate prevails.

To study the effects of cold weather conditions on RE behaviour in Canada, three climatic zones might be distinguished.

1. Moderate Zone. This zone comprises the west coast with its relatively moderate temperature. For this area the existing general specifications for RE apply.

2. Cold Zone. This zone includes the remaining country south of the permafrost regions, ie, south of approximately the 55th parallel, where winter termperatures range between $-5°C$ and $-20°C$. This is the zone to which this paper addresses itself.

3. Permafrost Zone. This zone comprises all land north of the 55th parallel -- the land of extreme winter temperatures and permafrost. The effects of permafrost are not discussed in this paper. However, it is expected that the behaviour of RE in a permafrost environment will soon have to be examined.

The application of RE in a cold climate should take into account several items additional to those considered in warmer climates. Inside the structure, differential thermal expansion and contraction of the structural elements and the possible resulting stresses should be examined. Ice formation, its expansion and the generated forces could play a major role in structures which contain a high water table. In addition, waterfront structures are faced with possible impact by floating ice sheets, weight at low tide of frozen ice masses adhering to the RE facing panels, and expansion of entrapped water within the structural elements. The effects of some of the above conditions can be analyzed qualitatively based on experience and the laws of physics. Others are rather complex and are perhaps better evaluated empirically by field instrumentation.

EFFECTS OF FROST WITHIN THE STRUCTURE

Preventing Frost Heave Action

The most important item in the design of any structure subjected to freezing and thawing temperatures is the prevention of damaging frost heave forces. These forces, created by water migration and expanding ice lenses, can be as high as 2700 kPa (400 psi).

Ice heave in highway construction is normally prevented by either one or a combination of several design features:

a. The ground water level is depressed by drainage systems to well below frost penetration depth in order to keep the zone of continuous capillary film below the freezing isotherm.

b. Frost susceptible material is replaced by free draining granular soil within frost-penetration depth, and/or,

c. Insulation is introduced below the pavement to prevent the penetration of frost.

In the construction of conventional retaining walls, the most practical solution is to call for non-frost-susceptible backfill; a clean, free-draining soil. The material must be coarse enough to inhibit capillary rise of groundwater. Without capillary water ice lenses cannot form and frost heave forces will not occur. Experience has shown, on the other hand, that failure to provide proper backfill can result in progressive tilting of the structure, Fig. 1.

Many tests, some quite complex, have been proposed in recent years for determining the frost-susceptibility of soils. However, it is considered practical and safe to rely on the time-proven criteria based on grain size. Generally these require that the minus 74 micron fraction (passing No. 200 sieve) not exceed 3 percent in well-graded soils and 10 percent in uniform soils.

The specifications for RE structures call for the use of granular material so as to provide adequate frictional resistance along the reinforcing strips. Generally, the specifications recommend that soil must contain no more that 15 percent passing the 74 micron size (No. 200 sieve). Because such material may be slightly frost-susceptible, it would be prudent to tighten the above specification for application in northern climates where frost penetration is substantial and the groundwater table is high. It is also important to specify sound aggregate which will not deteriorate under freeze-thaw conditions creating additional fines. At Mont St. Pierre, Québec, the backfill behind the facing panels of the sea wall consisted of clean gravel containing no more than 4 to 5 percent material passing the 74 micron size.

The recommendation to use only non-frost-susceptible material behind RE structures need, of course, be applied only within the width and depth of frost penetration, taking into account the effect of the high thermal conductivity of the reinforcing strips. The increase in depth of frost caused by the presence of the strips has not yet been determined. Probably an arbitrary increase of 50 percent above the normal frost depth for the region would be ample for design until data are available to permit a less conservative approach. Readings are now being obtained from instrumented RE structures in Canada to define the increase in frost penetration depth.

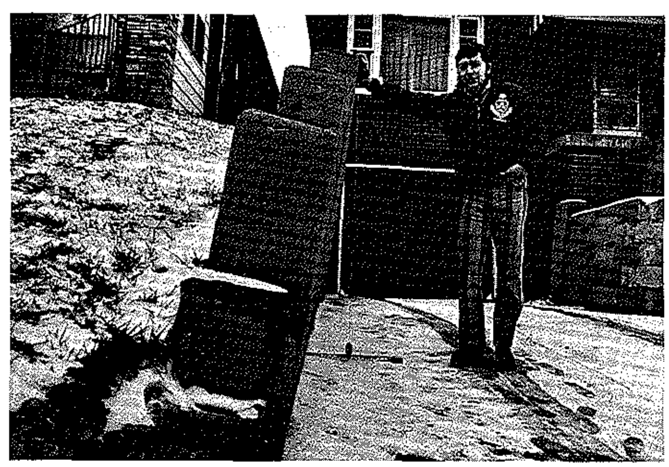

Fig. 1. Conventional retaining wall without proper backfill and drainage reveals tilt caused by successive cycles of frost heave and thawing.

Associated with the recommendation to provide non-frost-susceptible soil, is the requirement to provide good drainage through the front face, as well as behind and possibly below the structure. This recommendation might be particularly relevent to structures established against a hillside where surface runoff may be high, and natural springs may occur. This precaution is considered standard practice for similarly located conventional structures in a cold climate.

Perhaps special attention should be given to the properties of the backfill below free-water level in RE waterfront structures. In this case, not only is it advisable to adopt the non-frost-susceptible criteria but also to require a very coarse granular material with particle sizes larger than 1 or 2 mm. Crushed aggregate would be considered excellent. This coarse gradation will not only ensure the easy expulsion of pore water during ice expansion associated with freezing, but will also facilitate compaction during construction. It will also have the advantage of allowing rapid drainage in tidal fluctuations.

Effects of Differential Thermal Expansion Coefficients

Having established that the materials used will indeed be non-frost-susceptible, it is now possible to examine the effect of temperature change on these materials relative to the effect of temperature change on the reinforcing strips.

It is well established that thermal expansion and contraction can induce substantial strains in unconfined granular deposits. A good example of the results of thermal effects is the occasional presence of both longitudinal and transverse cracks in roads and highways, sometimes reaching a depth of 0.5 m. More spectacular results can be seen in the patterned ground features of the Arctic.

In the case of RE the condition arises after the soil mass and enclosed reinforcing strips are frozen at 0°C, followed by a temperature drop, say to -25°C. In the following list of thermal expansion coefficients it is assumed that the backfill is composed primarily of quartz compacted to a void ratio of $e = 0.47$, which is typical of a densely compacted granular soil. The coefficient for saturated backfill represents a weighted value reflecting the presence of voids filled with ice.

Table 1. Linear Thermal Expansion Coefficients

Material	Coefficient per °C
Ice	0.000051
Steel strips	0.000012
In-situ dry granular backfill (sandstone)	0.000009
In-situ saturated granular backfill	0.000022

Two cases present themselves. In the first case the backfill is situated above the water table and may thus be assumed to be dry. As indicated in Table 1 the dry backfill is less sensitive to a temperature drop than the steel strips. Therefore, as the temperature drops and the steel attempts to contract it will be restrained by surface friction arising from the surrounding granular fill. This action will increase the tensile stress in the steel. If it is assumed that no stress re-distribution and no re-arrangement of particles in contact with the steel can occur, then the tensile stress in the strips could rise by approximately 1.5 kgf/mm^2 (2000 psi) over a temperature drop of 25°C. This represents approximately 12 percent of the mean suggested allowable stress. However, this change in stress is not expected to develop for several years. It is believed that as annual thermal stress changes occur, soil particles within the backfill will rotate and slide into tighter packing under the continuing compressive forces exerted by the tensioned reinforcing strips. Progressively the backfill will consolidate to become a stable material having a thermal expansion coefficient similar to sandstone.

In the second case it is assumed that the structure is fully saturated as would occur in waterfront construction. As mentioned earlier, it is expected that all stresses within the mass will remain unchanged during freeze-up. As temperatures fall below 0°C the ice-laden soil mass attempts to contract more rapidly than the steel strips, thus reducing the tension in the strips. Because of the natural plastic deformation characteristics of ice, it is expected that the stress in the steel strips will drop less than the calculated 5 kgf/mm^2 (7000 psi) over a temperature fall of 25°C. The reduction in stress will, of course, occur only over that length of strip that is contained within the frozen depth of the backfill.

It is concluded that the effects of differential thermal expansion are small if the soil is unsaturated. In the completely saturated case the stress changes are on the safe side and may be neglected. The big advantage that RE has over more rigid conventional structures is that the granular backfill is subjected to a permanent compressive stress, thus reducing the possibility of progressive tilting or failure, due to repeated frost-induced heaving.

EFFECTS OF FROST OUTSIDE THE STRUCTURE

There are two principal external effects to be anticipated in a cold climate for both conventional and RE waterfront structures: adfrozen ice masses, and moving ice sheets and ice blocks.

Adfrozen Ice Masses

Wherever tidal movements occur, particularly in fresh water, it is not uncommon to see masses of ice suspended on the front faces of waterfront structures, Fig. 2. This is the case in Quebec City, a fresh water harbour subjected to 4 m average tides and a reversing current of the St. Lawrence River. The

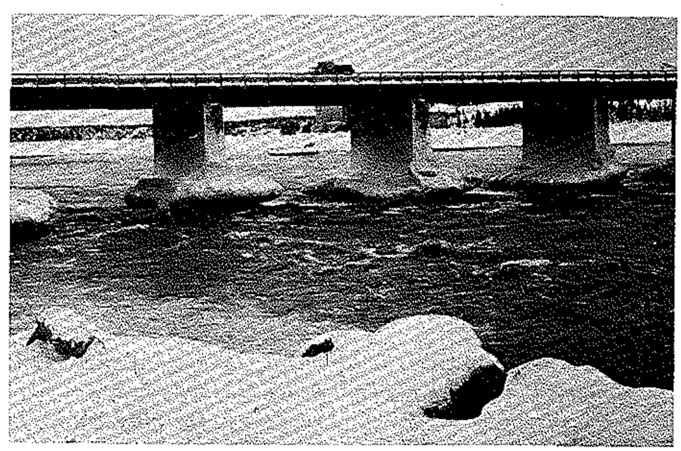

Fig. 2. Adfrozen ice masses suspended between high and low tide levels on waterfront structures. (Courtesv of the Laboratoire d'Hydraulique Lasalle.)

width of ice that forms along the dock walls is zero at the elevation of both high and low tides and increases to a width of more than 2 m between these limits. Such hanging ice masses create bending moments that must be accounted for. In RE structures subjected to these ice conditions, extra strips or wider strips can be planned for the wall section between low and high tides to provide for the necessary resistance.

Moving Ice Sheets and Ice Blocks

Floating ice may consist of a static sheet, an ice jam, or simply floating blocks subject to currents and wind action. A static sheet of substance may develop by mid-winter. As spring approaches, or if tides and storms prevail, the sheet can break up to form floating ice sheets and blocks. Subjected to river currents, ice jams can form at river bends and at natural or man-made restrictions.

The assessment of practical design forces is extremely difficult and must be analyzed for each location. In the case of a static ice sheet, it is not uncommon to use a maximum thrust of 15 tonnes per linear meter for structures along the St. Lawrence River, although in confined locations the force can be much greater. At the time a static sheet is developing in front of the RE structure, freezing is also occurring within the structure, thereby forming a solid frozen mass capable of resisting the growing pressures of the ice sheet. This condition also occurs in conventional construction. The thickness of an ice sheet will vary considerably, being dependent not only on the degree days of frost but also on the thickness of snow cover which can act as a substantial insulation. Approximate methods are available to compute its thickness. As an example, the thickness of the ice sheet is estimated to reach 0.65 m in the Montreal region and 1.75 m at Churchill Falls in Labrador.

When the ice breaks up and begins to move in large sheets it is able to impart either a normal impact or a glancing blow. In either case the controlling factor is usually the crushing strength of ice. Although it can normally very between 675 and 2700 kPa (100 to 400 psi), its strength may be taken at the time of spring break-up as 1000 to 1300 kPa (150 to 200 psi) applied to the area of the structure exposed to the greatest thickness of floating ice, Fig. 3.

It is indeed difficult to predict the forces imparted by ice sheets because of the many variables involved. Thermal regime, currents, winds and land configuration are some of the variables that play vital roles, Figs. 4, 5 and 6.

It is judged that RE structures can withstand, on an equal basis with conventional construction, all design forces imposed on waterfront contruction in a cold climate. The RE facing panels may be made as heavy and as large as required to resist ice impact and erosive forces. Canadian practice has introduced a modified panel. This was necessary because the standard RE panel configuration might not have provided adequate frictional resistance against glancing blows of ice masses. Each panel includes two vertical buttress wings which extend rearward at right angles from the back surface of the panel. Embedded in the fill, the wings mobilize substantial passive earth pressure resistance when the panel is subjected to an oblique horizontal force. This design feature also

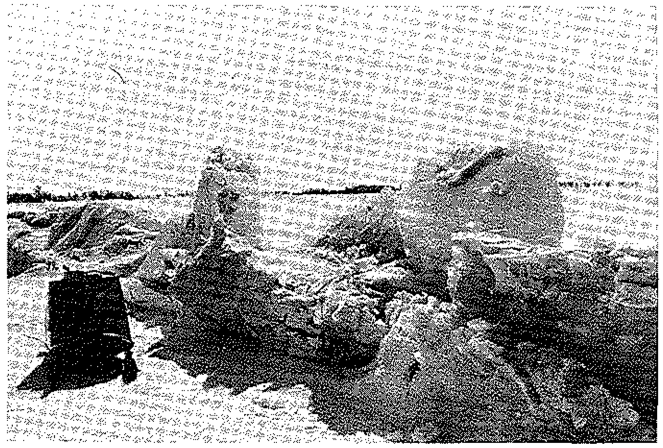

Fig. 3. Ice-sheet piling against wharf, Lac St. Pierre, Quebec. (Courtesy of J. V. Danys, Marine Aids, Transport Canada.)

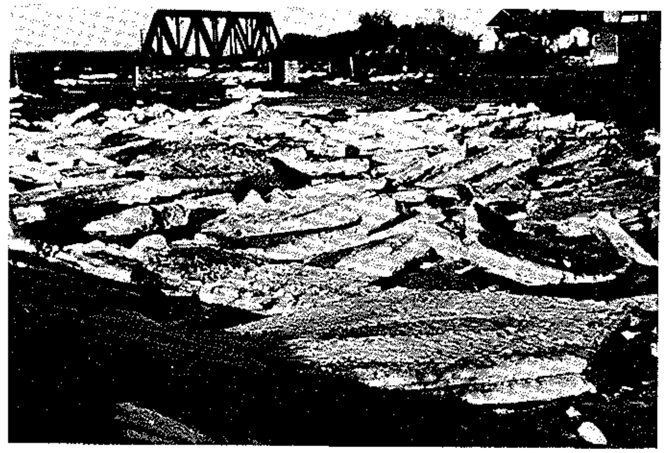

Fig. 4. Chunk ice on Moira River, Ontario. (Courtesy of S. S. Lazier, Queen's University.)

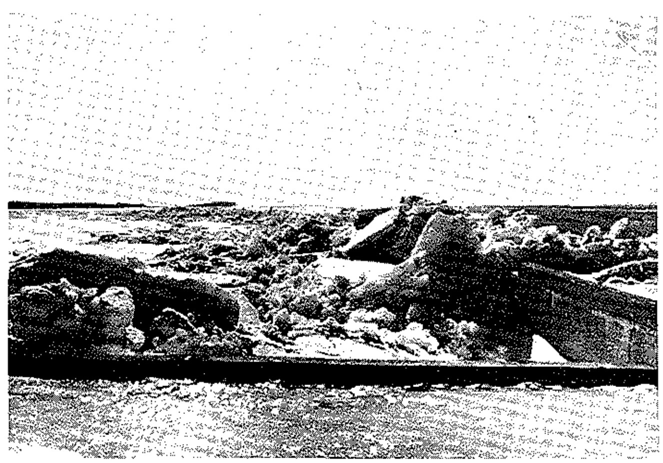

Fig. 5. Pressure ridge caused by thermal forces. (Courtesy of S. S. Lazier, Queen's University.)

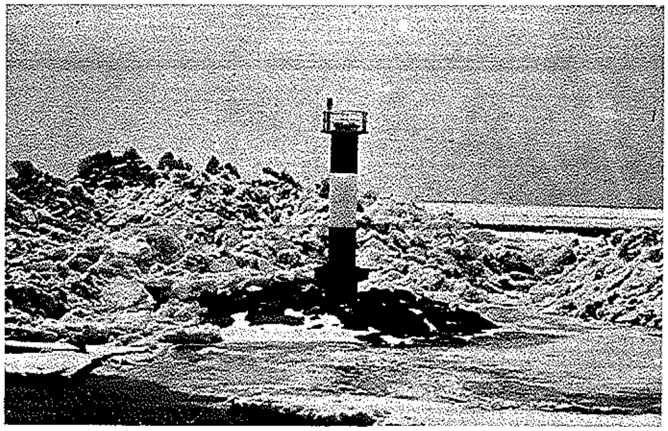

Fig. 6. Ice piling against artificial light-tower island on St. Lawrence River. (Courtesy of J. V. Danys, Marine Aids, Transport Canada.)

Fig. 7. Panels with buttress wings for resisting oblique impact and frictional forces imparted by ice masses, Carleton, Quebec.

facilitates erection of the panels, particularly in tidal conditions. The special panels were adopted on three projects in the Province of Quebec; Mont St. Pierre, Carleton and St. Omer, Fig. 7.

WINTER CONSTRUCTION

Winter construction in a freezing climate generally imposes additional costs. These costs are associated with the fabrication of a temporary enclosure for the structure, the supply of heating and insulation, and the general decrease of labour productivity. To avoid these costs construction must often be scheduled for the warm months.

Reinforced Earth presents a significant advantage over conventional retaining structures in that it can be carried out at freezing temperatures without the need of protection and heating. The precast panels can be erected and the backfill placed and compacted at subfreezing temperatures. It is required that the backfill be snow-free, relatively dry and compacted additionally to compensate for the increased moisture tension and resistance to compaction. To ensure this condition, selecting a very coarse granular soil would be advantageous. The flexibility of the RE system is expected to absorb, without damage, the slight settlements that might occur during spring thaw as a result of winter construction.

PROTECTION AGAINST CORROSION

It is common practise in many Northern parts of the North American Continent to sprinkle large quantities of salt on roads, sidewalks, parking lots, etc. to melt accumulations of snow and ice. To avoid the corrosive effect of the resulting brine percolating down to the reinforcing strips, it is recommended to place an impervious synthetic liner beneath the road pavement. The liner should be sloped to one edge where the water could flow into a drainage system. This solution is not unlike the protection often given to highway bridge decks where the reinforcing steel must be protected from the electrolite penetrating the microfractures of reinforced or prestressed concrete. On the other hand, mention should be made of a beneficial effect of cold climates. Cold climates slow down chemical reactions and thus normal corrosion is retarded considerably. Soil temperatures at a depth of 2 metres rarely exceed 8°C throughout most of Canada.

CONCLUSIONS

It is concluded that a cold climate does not impose restrictions on Reinforced Earth, established either above the water table or as waterfront structures. The only mandatory requirement is the use of non-frost-susceptible granular backfill with provisions for proper drainage. This, incidentally, is also a requirement for conventional earth-retaining structures in cold climates.

In a freezing waterfront environment, RE is believed equal to conventional construction and should be designed for the same external forces. Facing panels and reinforcing strips can be designed for any anticipated ice loads.

A cold climate will retard the rate of normal corrosion. In connection with corrosive effects caused by percolating salt water from road surfaces, it is recommended to introduce an impervious liner below the pavement to divert this flow to a drainage system.

The ever-present horizontal compressive forces in the backfill, induced by the tension in the reinforcing strips, are believed to be an important asset in preventing progressive frost-heave tilting or failure. This can be a decided advantage over conventional rigid structures.

Finally, another advantageous feature of an RE structure is that it can be built in the winter, provided that a moisture-free and snow-free backfill is used. The built-in flexibility of the system allows minor settlements caused by winter construction to occur without affecting the integrity of the structure.