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Frost protection of buried PVC water mains in western Canada

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Although desirable for many reasons, controlled low-strength material – controlled density fill (nonshrinkable fill) has the potential to promote rapid frost penetration within the trench when used as a backfill material in waterworks construction and repair projects. This paper describes results of a two-dimensional finite-element heat-transfer model study carried out to investigate the effectiveness of various insulation systems for frost and frost-heave protection of buried waterlines. Combinations of nonshrinkable fill with horizontal insulation boards, cylindrical pipe insulation, and inverted U-shaped insulations were investigated. It was shown that, while moderate thicknesses of insulation could be found to protect the pipe from freezing, thermal-bridging effects make the location of the maximum frost penetration depth sensitive to details of the insulation geometry. The use of different combinations of insulating backfills was also investigated, and it was shown that a backfill layer of moderate insulating value placed high in the trench may be most advantageous.

Key words: frost, frost protection, insulation, waterlines, nonshrinkable fill, numerical analysis.

Bien qu'étant souhaitable à beaucoup d'égards, un matériau de remblai CLSM-CDF sans retrait peut favoriser la pénétration du gel dans les tranchées où il est utilisé lors de travaux hydrauliques et de projets de réparation. Cet article décrit les résultats d'une étude par un logiciel de transfert de chaleur (éléments finis à deux dimensions) faite pour évaluer l'efficacité de différents systèmes d'isolation visant à protéger des conduites d'eau enterrées du gel et du soulèvement dû au gel. Des combinaisons de remblai sans retrait avec des panneaux d'isolant horizontaux, des isolants tubulaires autour des conduites et des isolants en U-renversé ont été examinées. On a montré que l'on peut empêcher les conduites de geler avec des épaisseurs modérées d'isolant, et que la profondeur maximale de pénétration du gel est très sensible aux détails géométriques de l'isolation à cause des effets de pont thermique. L'utilisation de diverses combinaisons de remblais isolants a été aussi examinée et on a montré que le plus avantageux était d'utiliser une couche de remblai de valeur isolante modérée, placée assez haut dans la tranchée.

Mots clés : gel, protection contre le gel, isolation, conduite d'eau, remblai sans retrait, analyse numérique.

[Traduit par la rédaction]

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1. Introduction

In regions of intense seasonal frost, such as Western Canada, damage to buried services, such as pipe freezing, or differential frost heave and pavement settlement problems have long been recognized by engineers (Crawford 1955; Chan et al. 1981; Sasaki 1985). To protect buried utilities from frost, it is generally considered appropriate to require designs to be such that the frost front does not penetrate below the top surface of the utility. To achieve this level of frost protection in these regions, it is often necessary to bury water-distribution pipes to depths well below 2 m. This increases excavation and reinstatement costs substantially. The most economical and beneficial approach is to reduce the burial depth to the minimum necessary to provide both frost and structural protection for the pipe.

For new construction as well as for utility trench reinstatement, it is desirable to use a backfill material that combines low material costs, small labour effort for handling and placing, and little or no tendency for subsequent settlement of the filled trench. The material must be easily removable to facilitate future repairs and should allow work to proceed with minimal disruption to traffic. Cold climates further restrict the choices to materials suitable for winter placement. This range of conditions can best be met with a pourable material requiring no compaction, and nonshrinkable fill (controlled low-strength material – controlled density fill (CLSM–CDF)) a widely available low-strength sand – cement – fly ash mix, is commonly employed in

warmer climates. During recent years the use of nonshrinkable fill in waterworks construction and repair projects has begun to spread to Western Canada. It is attractive on the grounds that it satisfies most of the criteria mentioned previously. Unfortunately, nonshrinkable fill typically has a relatively high thermal conductivity and a low moisture content. This combination of material properties has the potential to promote rapid frost penetration, a situation that is exacerbated by the cold conditions of the region. It is this concern and the perceived need to find a suitable palliative that prompted the study reported here.

Useful current sources of guidance for the frost-protection design of insulated services are the works of Gunderson (1975, 1978) and Greeley (1987). Insulation of buried utilities placed at shallow depths in frost-susceptible, non-frost-susceptible, and rocky soils using either horizontal boards or inverted U-shaped sections of rigid extruded polystyrene is treated within these references along with appropriate design nomograms. Farag et al. (1991) studied the freezing of a shallow (1 m burial depth) underground pipeline protected by various configurations and depths of horizontal boards of extruded polystyrene using a specially designed finite-element package. Coutermarsh and Phetteplace (1991) also used this method to investigate frost shielding for a water pipe buried at a depth of 1 m using 100 mm thick extruded polystyrene inverted U-shaped insulation. General design information for buried pipes is also provided in the design manual of cold climate utilities by Smith et al. (1986).

FIG. 1. The finite-element mesh.

In this paper a two-dimensional finite-element heat-transfer model is used to evaluate the loss of frost protection for deeply buried polyvinyl chloride (PVC) waterlines caused by using a relatively conducting trench backfill. Calculations are presented to illustrate the effectiveness and potential pitfalls associated with typical insulating systems added to offset the effects of the conducting backfill. Insulating scenarios investigated included horizontal boards placed at different elevations within the trench, cylindrical insulation surrounding the pipe itself, and inverted U-shaped insulation placed over the pipe. In addition, calculations are presented to show the potential advantages of using an insulating backfill material in conjunction with the nonshrinkable fill. The effectiveness of wet materials in providing frost protection is also illustrated.

2. Numerical model

An extensive literature exists on conductive heat transfer with solid-liquid phase change. Finite-element methods are now most widely used because of the relative ease with which complex geometries, boundary conditions, and material nonlinearities may be accommodated. The main difference between various finite-element heat-flow programmes, as it affects this study, lies in the way in which latent-heat effects associated with freezing and thawing are implemented. Procedures available range from relatively crude apparent-heat-capacity methods in which latent heat is incorporated by adding its contribution to the heat capacity of an entire element undergoing phase change, to computationally intensive high-accuracy moving-mesh techniques in which the location of internal freezing-thawing boundaries

is determined dynamically at the same time as the solution for the unknown temperatures.

The transient two-dimensional finite-element heat-conduction programme AFEMS developed by FEM Engineering, Inglewood, Calif. was used to model the frost-protection systems. This programme is limited to simple conduction with phase change, and no attempt has been made to treat either frost heave or moisture redistribution. The programme accounts for phase change employing the fixed-domain enthalpy method of Morgan et al. (1978). The numerical results are written to a file that summarizes nodal temperatures and heat fluxes at user-specified times. The results can be plotted by the graphical software. The model was verified for accuracy by comparison against two independent one-dimensional numerical models (Goodrich 1978; L.E. Goodrich and K. Sepehr, manuscript in preparation)¹ and shown to give acceptable results, provided appropriate precautions are taken in designing the mesh. Disappointingly small mesh spacings were found to be necessary near the surface to ensure mesh-independent results.

3. Boundary conditions

The symmetry of the problem permits selection of an adiabatic boundary along a vertical line through the centre of the pipe (Fig. 1) so that only half of the domain needs be modelled. A zero-flux boundary condition may also be taken for the far-field boundary of the mesh provided the boundary is placed far enough away from the area of significant bidimensional heat flow (i.e., the trench and pipe zone). A problem domain width of 10 m was chosen for the present calculations. Since geothermal heat flux is insignificant in this context, the bottom boundary condition was also taken as adiabatic. The lower domain boundary was set at 20 m after verification that this depth was sufficient to correspond to negligible seasonal temperature change.

Since the calculation of the maximum frost penetration is of primary interest in this study, an equivalent constant surface temperature, rather than a time-dependent temperature, was used to represent the surface boundary condition. The equivalent design air temperature can be calculated by dividing the most severe freezing index (freezing degree-days) occurring in a 30 year period by the number of days with below-freezing temperatures for that year. The surface freezing index used is related to the air freezing index via a constant multiplier coefficient (n factor). Under freezing conditions, a value of 1.0 would be an appropriate assumption for bare street surfaces. This assumption is most likely to err on the conservative side, if at all. The coldest winter in the period 1960–1990 for the city of Edmonton had a freezing index of 2228 degree-days (Edmonton Municipal Airport) according to data published by Environment Canada. With the above assumptions this yields an equivalent surface temperature of -14.8°C .

4. Initial ground temperature

Consistent with the simplified surface boundary treatment, the initial ground temperatures were assumed to be uniform throughout. The value used was calculated from the 30 year mean monthly air temperatures using appropriate freezing and thawing n factors to estimate monthly sur-

¹L.E. Goodrich and K. Sepehr. Discontinuous element formulation for thermal problems. In preparation.

TABLE 1. Physical and geothermal properties used in analyses

Material	Moisture content (% dry wt.)	Dry density (kg/m ³)	Latent heat (MJ/m ³)	Frozen		Unfrozen	
				Thermal conductivity (W/(m·K))	Heat capacity (J/(kg·K))	Thermal conductivity (W/(m·K))	Heat capacity (J/(kg·K))
Sand	10	1710	57	4.0	1046.5	2.7	1255.8
Nonshrinkable fill	15	1800	9.0	4.5	1151.1	2.75	1465.1
Lightweight aggregate	10	750	25	0.25	1884.15	0.25	2930.9
Lightweight aggregate	50	750	130	1.5	1884.15	0.4	2930.9
Lightweight aggregate	95	750	240	1.8	2825.5	0.7	4187
Clay	35	1400	160	2.0	1480	1.75	2210
Asphalt	0	1850	0	1.5	1674	1.5	1674
Polyvinyl chloride	0	1400	0	0.19	1047	0.19	1047
Water	—	1000	334	2.20	2093	0.6	4187
Polystyrene	0	60	0	0.035	1255	0.035	1255

face temperatures. An n factor of 0.9 for winter (freezing temperature) months and 1.5–2.0 for summer months is typical of road surfaces (see, for example, Lunardini 1981). To ensure conservative estimates a freezing n factor of 1.0 and thawing n factor of 1.5 were assumed.

5. Heat transfer during freezing of the water in the pipe

To model the cooling of the buried water main conservatively, heat advected along the pipe axis was ignored in the numerical calculations. Nonflowing water in the pipe was, however, modelled, including the effects of freezing, but without attempting to account for convection in the unfrozen water during the freezing process. This grossly simplifies the actual processes but can be defended on the basis that it constitutes a conservative assumption.

6. Material properties

Table 1 summarizes the physical and thermal properties for all the materials used in the analyses. Thermal conductivities of nonshrinkable fill and of lightweight aggregate are composite numbers based on measurements made by the National Research Council of Canada and the University of Calgary (described in internal publications of National Research Council in 1987, and reports to Consolidated Concrete Ltd. in 1991, City of Calgary in 1989, and City of Edmonton in 1990). The values assumed for soils are based on well-known empirical formulae (Kersten's formulae as given in SI units in Johnston 1981), whereas those for the remaining materials are standard textbook values quoted in Lunardini (1981). The calculations presented assume the native soil to be a saturated clay. This situation results in the greatest contrast in frost-penetration rates between the native soil and the trench zone (backfilled with granular material or nonshrinkable fill). If the native soil were a well-drained granular material, frost penetration would be much more rapid beyond the trench zone. Although these cases are not included in the present study, some qualitative comments are given in the text.

7. The finite-element mesh

The finite-element meshes used in the analyses model a 10 m wide by 20 m deep region. Mesh spacing is nonuniform, and linear quadrilateral isoparametric elements were used throughout. Fine meshes and small time steps are

required in areas where thermal gradients are expected to be high (i.e., around the pipe, and in the insulation). In addition, it is necessary to use a fine mesh (and corresponding small time steps) whenever there is a possibility of an instantaneous temperature change (for example, at the top of the mesh) to avoid causing numerical instability in the solution process. Wider spacing is used away from the pipe at the far-field side of the mesh and towards the bottom. Figure 1 shows a portion of a finite-element mesh for a typical case of a buried water pipe protected by a 100 mm thick board of inverted U-shaped insulation (see Results from analysis).

8. Results from analysis

The AFEMS finite-element model was used to investigate the thermal consequences of burying a 200 mm diameter water pipe in a 900 mm wide trench with the bottom of the pipe located at a depth of 2.55 m from the surface. This geometrical configuration is currently used in the City of Edmonton and can be considered as representative of typical design practice in Western Canada. The effectiveness of several possible frost-protection scenarios was evaluated.

Figure 2a shows the "reference" geometry consisting of a trench in wet native clay, backfilled with a 1500 mm thick layer of nonshrinkable fill on top of a 1000 mm thick layer of sand surrounding the pipe and extending to the bottom of the excavation. The pipe is made from PVC plastic with a wall thickness of 12 mm and is assumed to be filled with nonflowing water. The predicted frost-penetration depth at the end of the design winter is shown in Fig. 2a. As can be seen, the frost penetrates below the buried waterline and is only stopped by the wet native soil. It is revealing to note the shape of the freezing isotherm in the vicinity of the trench. The isotherm is drawn steeply downwards as a result of the more rapid freezing within the trench region than in the native soil. Lateral heat input from the surrounding soil zones does not greatly diminish the frost penetration within the trench proper. Note also the tendency for the maximum frost penetration to occur at a position intermediate between the pipe centreline and the trench wall. The latent heat present in the water-filled pipe does slow the downward progress of the zero isotherm but the pipe is, unfortunately, completely frozen in the process.

Figure 2b shows the predicted design frost penetration for the case where the entire trench backfill consists of sand,

FIG. 2 (a) Maximum frost penetration depth for nonshrinkable fill – sand trench backfill. (b) Maximum frost penetration depth for all-sand trench backfill.

a frequent practice in many regions of Western Canada. The maximum frost-penetration depth for this case is similar to that calculated for the nonshrinkable fill, a result which is to be expected since nonshrinkable fill and sand have similar material properties (see Table 1). Again the waterline is predicted to freeze completely, although the cooling is not as severe as in the previous case.

It is concluded, based on these analyses, that the current design for trench backfill materials is potentially inadequate to protect PVC water mains from freezing in years when the freezing index reaches the 30 year maximum value (i.e., under standard design conditions). To make matters worse, the calculations also indicate the possibility of freezing within the frost-susceptible material underlying the trench. Furthermore, service connections would presumably have frozen long before the water main itself. To circumvent these problems two approaches appear feasible: replacement of the nonshrinkable fill with a more suitable material, or its use in combination with insulation layers placed in an appropriate configuration. Several potential alternatives are examined in the remainder of this study.

8.1. Horizontal board insulations

Extruded polystyrene horizontal board insulation has been used in the past to reduce the flow of heat to the ground surface from the soil in the vicinity of a buried pipe, and design procedures are reviewed in Gunderson (1978) and Greeley (1987). The present simulations were made for a full-width (900 mm wide) horizontal insulation with thicknesses of 100, 75, and 50 mm placed 100 mm above the top of the PVC water pipe. As in the previous cases, calculations pertain to the design freezing index and assume

no-flow conditions for the water in the pipe. Figures 3a–3c illustrate that adding full-width horizontal boards to the reference geometry, with thicknesses ranging from 100 to 50 mm, provides full protection for the buried utility, as the maximum frost line does not penetrate to the pipe itself. Even the 50 mm thick extruded polystyrene board (Fig. 3c) appears to provide more than sufficient frost protection to the waterline, although it should be noted that there is a tendency for the frost line to penetrate deeper in the zone on either side of the waterline. This tendency would be more problematic if deep soil temperatures were colder and frost penetration were greater in the native soil, as would occur with drier coarse-grained materials. It would seem possible to counteract this by modifying the locations and (or) geometry of the insulation while still retaining the 50 mm thickness. Two calculation runs were made to explore the effects of the height of placement of the insulation. In the first of these, the insulation was located at the interface between the sand and the nonshrinkable-fill backfill (Fig. 3d), since, as well as being simpler to construct, this would also give a high thermal resistance between the surface and the frost line over a longer time than would be the case with deeper placement. This effect is well known and generally exploited in the design of insulated roadways, to mention but one example. But, as Fig. 3d shows, for the conditions assumed in the present case, the higher location, in fact, exacerbates the situation and results in an unacceptable frost penetration into the waterline. This may occur since higher placement increases the area for thermal bridging through the conducting sand in the zone above the frost line.

An insulation layer thinner than 50 mm may also be acceptable if one is prepared to relax the design constraint

FIG. 3. Maximum frost penetration depth with horizontal board insulation.

FIG. 4. Maximum frost penetration depth with inverted U-shaped insulation.

and allow the frost line to just penetrate the PVC pipe wall, and Fig. 3e indicates that 25 mm would be very nearly adequate. Although not illustrated, a calculation was also made in which the 25 mm insulation layer was split into 12.5 mm layers located at the top and bottom faces of the nonshrinkable-fill layer. The results indicated a marginal improvement as regards frost depth within the trench in the zone adjacent to the pipe, but freezing in the pipe itself was practically unchanged from Fig. 3e.

8.2. Cylindrical pipe insulations

The use of cylindrical-shaped insulation sheaths on water pipes is a well-known alternative for frost protection of buried pipes. Cylindrical insulations consisting of extruded polystyrene of various thicknesses (75, 50, and 25 mm) were simulated for the otherwise standard geometry and design boundary conditions. Figures 4a–4c show predicted frost-penetration depths at the end of the design winter. In all cases this insulation configuration appears to provide somewhat greater frost protection for the pipe itself than the corresponding thickness of full-width horizontal board and does so using less material. It may be seen that, although a 25 mm thickness is sufficient to avoid significant freezing within the water main (the frost line was predicted to just penetrate the PVC pipe wall), in all cases the frost line also penetrates some distance into the clay at the bottom of the trench. For the conditions considered this situation raises the spectre of frost heave potentially affecting the integrity of the waterline. Although no calculations have been performed, it can be surmised that, for dry granular soils, the minimum insulation thickness would need to be increased to compensate for the colder temperatures at pipe level associated with the more rapid frost penetration.

8.3. Inverted U-shaped insulations

Inverted U-shaped insulation sections placed over waterlines, as illustrated in Fig. 5, have been investigated and applied in certain instances. They are particularly attractive for shallow pipe burial (see, for instance, Gunderson 1978; Greeley 1984; Farag et al. 1991; and Coutermarsh and Phetteplace 1991). Calculations were made to examine the appropriateness of this arrangement in the present context where the pipes are buried at a substantial depth. The calculations assume the overall conditions of the reference geometry but with the addition of a horizontal insulation layer located at the bottom of the nonshrinkable fill (700 mm above the pipe) and extending across the entire width of the trench. The vertical sections extend downwards along the trench walls to the bottom of the trench. Figures 5a–5d show the predicted maximum frost penetration for insulation thicknesses of 100, 75, 50, and 25 mm. The calculations show that the freezing isotherm would remain well above the waterline for 50 mm and greater thicknesses and they indicate that a 25 mm thickness would, in fact, be adequate (just) to avoid freezing within the pipe.

It is also interesting to note that, even though the insulation retards the rate of frost penetration within the trench relative to that in the native soil, as with the other insulation systems considered, the deepest frost penetration occurs in the soil just outside the trench wall (see Figs. 5a–5c). As was verified by separate calculations (not shown), this is a consequence of thermal bridging through the highly conductive nonshrinkable-fill backfill in the upper part of the trench. This effect could be undesirable in the presence of frost-susceptible native soils, since it would exacerbate the potential problem of differential frost heave that could occur when non-frost-susceptible backfills are used. Calculations

FIG. 5. Maximum frost penetration depth with cylindrical pipe insulation.

FIG. 6. Maximum frost penetration depth with insulating backfill material.

TABLE 2. Summary of results

Case No.	Native soil	Insulation ^a			Trench backfill				Frost penetration from surface (mm)
		Type	Configuration	Location above pipe (mm)	Dry sand (10% mc)	Wet clay (35% mc)	Lean concrete (15% mc)	Lightweight aggregate	
1	Dry sand (10% mc)	na	na	na	All sand, 2500 mm	All clay, 2500 mm			6000 (well below pipe)
2	Wet clay (35% mc)	na	na	na					2140 (well above pipe)
3	Wet clay (35% mc)	na	na	na	All sand, 2500 mm				2630 (below pipe)
4	Wet clay (35% mc)	na	na	na	Bottom 1000 mm		Top 1500 mm		2650 (below pipe)
5	Wet clay (35% mc)	100 mm EP	HB	100	Bottom 900 mm		Top 1500 mm		2250 (above pipe)
6	Wet clay (35% mc)	75 mm EP	HB	100	Bottom 925 mm		Top 1500 mm		2300 (above pipe)
7	Wet clay (35% mc)	50 mm EP	HB	100	Bottom 950 mm		Top 1500 mm		2340 (just above pipe)
8	Wet clay (35% mc)	25 mm EP	HB	100	Bottom 975 mm		Top 1500 mm		2360 (just penetrates pipe)
9	Wet clay (35% mc)	50 mm EP	HB	700	Bottom 950 mm		Top 1500 mm		2370 (penetrates pipe)
10	Wet clay (35% mc)	75 mm EP	CP	Around pipe	Bottom 1000 mm		Top 1500 mm		2330 (inside insulation)
11	Wet clay (35% mc)	50 mm EP	CP	Around pipe	Bottom 1000 mm		Top 1500 mm		2340 (inside insulation)
12	Wet clay (35% mc)	25 mm EP	CP	Around pipe	Bottom 1000 mm		Top 1500 mm		2350 (just above pipe)
13	Wet clay (35% mc)	100 mm EP	IU	600 ^b	Bottom 900 mm		Top 1500 mm		1700 (well above pipe)
14	Wet clay (35% mc)	75 mm EP	IU	625 ^b	Bottom 925 mm		Top 1500 mm		1800 (well above pipe)
15	Wet clay (35% mc)	50 mm EP	IU	650 ^b	Bottom 950 mm		Top 1500 mm		2050 (well above pipe)
16	Wet clay (35% mc)	25 mm EP	IU	675 ^b	Bottom 975 mm		Top 1500 mm		2360 (just penetrates pipe)
17	Wet clay (35% mc)	1000 mm LWA (10% m.c.)	na	na			Top 1500 mm	Bottom 1000 mm	2360 (just penetrates pipe)
18	Wet clay (35% mc)	1000 mm LWA (50% m.c.)	na	na			Top 1500 mm	Top 1000 mm	2350 (just above pipe)
19	Wet clay (35% mc)	1000 mm LWA (10% m.c.)	na	na			Bottom 1500 mm	Top 1000 mm	2200 (above pipe)
20	Wet clay (35% mc)	1000 mm LWA (50% m.c.)	na	na			Bottom 1500 mm	Top 1000 mm	2400 (penetrates pipe)

NOTES: mc, moisture content; na, not applicable.

^aCP, cylindrical pipe; EP, extruded polystyrene; HB, horizontal board; IU, inverted U-shaped; LWA, lightweight aggregate.^bDistance from pipe to horizontal layer.

have not been carried out but it appears probable, given the results of Fig. 3, that a more cost-effective strategy would be to shorten the sides of the U-section to place the horizontal portion closer to the pipe. But the amount of insulating material required would still be substantially more than if a simple 50 mm horizontal insulation board were used, and the labour would also be greater. For these reasons, there appears to be little advantage to the use of such inverted U-shaped insulations in the present context.

8.4. *Insulating backfill — lightweight aggregate*

Instead of using insulating layers that, besides increased material cost, entail substantial hand labour, the possibility of an insulating backfill that could be simply dumped into the trenches, with little, or preferably, no compaction, is attractive. Loose granular insulating materials have often been considered as inappropriate for below-ground applications because they inevitably lose their insulating value unless they can be kept dry. For frost-protection applications, however, the increase in apparent thermal conductivity resulting from the presence of the water can, in principle, be offset by the increased latent heat available. As a result, in some cases, saturated granular insulations can provide frost protection as good as or better than dry insulation. Expanded clay or shale-based lightweight aggregate is a material of this type that tends to combine a relatively high moisture content with a relatively low thermal conductivity.

Figures 6a–6c show maximum frost-penetration depths calculated for conditions identical to the reference configuration except that the sand backfill was replaced by lightweight aggregate. The calculations were made for gravimetric moisture contents of 10%, corresponding to freely drained material; 50%, corresponding to a worst-case scenario of alternate flooding and subsequent draining; and 95%, corresponding to complete saturation.

The results indicate that a 1.0 m thickness appears to be not quite adequate if the material is well drained (the waterline is predicted to begin to freeze). This improves to marginally acceptable at the intermediate moisture content (the frost line just traverses the PVC pipe wall), while under saturated conditions the predicted frost line remains well above the top of the pipe. But it is significant to note that, under saturated conditions, for the same thickness of material, the predicted frost line remains well above the top of the pipe. Another interesting feature of these results is that, although the intermediate moisture content (Fig. 6b) offers frost protection for the pipe itself similar to that afforded by the fully drained case (Fig. 6a), it shows slightly greater frost penetration within the trench and surrounding soil. This is presumably a consequence of the higher thermal conductivity in the moist case than in the fully drained one, which would result in greater thermal bridging effects through the nonshrinkable fill. But the saturated case (Fig. 6c) shows the least frost penetration of the three cases, both in the trench and in the surrounding native soil zone. The higher thermal conductivity of the lightweight aggregate is more than compensated by the higher latent heat.

It might be anticipated that placing the lightweight aggregate layer as high as possible in the trench would produce the greatest benefit. This is to be expected, since the total thermal resistance between the surface and the freezing isotherm is at a point augmented by the insulating layer for a greater length of time than it would be if the insulation were placed lower down and, as Fig. 6d illustrates, a substantial gain

appears possible. For Fig. 6d the lightweight aggregate layer was assumed to have properties identical to those of Fig. 6a. It is significant to note that not only is the pipe totally protected from freezing but also frost penetration in the native soil is now shallowest just outside the trench wall. This is a reflection of the fact that during most of the freezing period the frost line would have been higher up within the trench zone than in the native soil. The effectiveness of this geometry presumably results from the fact that the insulating fill placed at the top of the trench reduces lateral losses into the coldest zone of the native soil at the same time as it reduces vertical heat losses in the trench. When compared with Fig. 6c, Fig. 6e shows, however, that, for an assumed intermediate moisture content, with lightweight aggregate at least, placing the material high in the trench could lead to greater, not less, frost penetration within the trench itself. This result underscores the importance of maintaining dry conditions if this or similar loose granular materials are to be placed high in the trench. Several possible candidate materials exist that could serve as insulating backfills and further studies will be carried out.

9. Conclusions

The calculations demonstrate that using combinations of sand and nonshrinkable fill in waterline trenches in wet, fine-grained soils, as has become current practice in the recent past, will result in the occurrence of much more rapid downward freezing within the trench zone than within the surrounding native soil. For typical configurations used in Western Canada, the trench could easily freeze to the bottom in a design year and, for no-flow conditions, the waterline would freeze completely. In addition, the enhanced freezing at deep levels also implies the possibility of soil displacements in the vicinity of the pipe associated with frost heave.

Remedial measures evaluated include modifying the existing design by the addition of polystyrene insulation layers in three different geometrical configurations as well as replacement of the sand by insulating backfill materials. The calculations showed that full-width horizontal insulating board 50 mm thick would be adequate to stop frost from reaching the top of the waterline but also indicated that the vertical position within the trench is critical. Placed at the interface between the sand and the relatively conductive nonshrinkable fill, the insulation layer is largely bypassed by heat flowing outward from the lower trench zone, and the same insulation thickness becomes inadequate to prevent substantial freezing of the line. The calculations for cylindrical pipe insulation show that this configuration is very capable of offering adequate protection from freezing for the water inside the line, even the thinnest insulation studied (25 mm) being viable. In addition, this geometry should require the least amount of insulating material of the three cases examined, which could translate into cost savings. But the results also show that this configuration potentially allows frost penetration into the trench bottom directly below the pipe. Inverted U-shaped insulations do offer increased protection from lateral heat losses but, for the wet, fine-grained soil conditions and deep burial depth assumed, this is unnecessary, and there is no real advantage over horizontal insulation while material and labour costs would be greater. Finally, calculations made with the sand at the bottom of the trench replaced by lightweight aggregate show that this or similar granular materials could be viable even when

wet, since the degradation of thermal insulation is partly offset by latent heat liberated during freezing. The study concludes, however, that the greatest protection can be achieved by using a dry insulating backfill placed as high as possible in the trench. A summary of results from the analysis for various cases is shown in Table 2.

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