DO EARTHWORK IN THE COLD WEATHER?

Wayne A. Bieganousky, U. S. Army Corps of Engineers, WES
C. W. Lovell, Purdue University

Abstract

The latest (1973) survey of cold weather earthwork practices in the United States and Canada showed that the level of such activity was increasing. A number of operations may be carried out at unit costs equal to or less than those expected in the summer. Still other operations will have higher unit costs in the cold weather, but can be justified on the basis of benefits or savings to the road user and/or the agency or company doing the construction. Prominent among these savings are (1) the earlier availability of a new and safer facility; (2) the better utilization and retention of employees with year-around construction scheduling; and (3) the reduction in inflation which accompanies earlier project completion dates. This paper synthesizes the reported state-of-the-art, and makes recommendations with respect to the cold weather earthwork practices which seem to be promising for low volume roads. These recommendations are potentially useful to an agency that wishes to re-evaluate and possibly expand its cold weather activity.

The object of the research reported in this paper was to establish and summarize the overall state-of-the-art in cold weather earthwork, specifically for highways, airfields, and building construction in areas of seasonally frozen ground. A more complete presentation of the findings is contained in an unpublished report (3) for the U. S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL). Related research is contained in a published report (28) and a soon-to-be-published paper (29). While the topic of construction of low volume roads are given no particular attention in the literature search and questionnaires directed to practitioners, the potential applications are certainly present. The economic advantages afforded by an earlier completion of the project through cold weather work seem stronger today than ever before.

Literature Review

Temperature Effects on Soil Properties

Unfrozen Soil. The compaction characteristics of soils have been observed to be temperature dependent over the range of temperatures experienced in the field. The source of this behavior is believed to be the viscosity of the water, which determines the ease or difficulty with which soil particles or aggregation of particles can reorientate during the compactive process (22). Hence, a decrease in soil temperature results in a corresponding decrease in maximum dry density and an increase in the optimum moisture content for a given compactive effort. Highter et al (16), researching (in the laboratory) the temperature effects on the compaction and strength behavior of a clay, concluded that the detrimental effects produced by low temperatures might be overcome by modest increases in the compactive effort.

Frozen Soil. The engineering properties of frozen soils are very dependent on temperature. In general, some unfrozen liquid is present, representing the "adsorbed" water. In a frozen soil, the unfrozen water can exist in equilibrium with the ice over a wide temperature range below 0°C. Lovell (21) observed that substantial proportions of the total soil moisture of fine grained soils remained unfrozen at temperatures as cold as -25°C. In Figure 1, the percentage of unfrozen water versus temperature for various soil types is plotted. Observe that essentially all the moisture in the sand is frozen at 0°C (18).

The strength behavior of a frozen soil is dependent, in part, upon the amount of frozen water. With decreasing temperatures, an increasing proportion of the soil moisture becomes frozen and the ice "locks" the soil grains in position. Lovell (21) found that the compressive strengths of partially frozen saturated soils demonstrated a strong temperature dependency. One set of results, considering soils molded at approximate Standard AASHTO peaks, exhibited compressive strength ratios of 4.1 to 1 for silty clay and 2.8 to 1 for clay at temperatures of -18°C and -5°C. Laboratory data or well documented field evidence describing the compaction characteristics of frozen soils is meager. The compaction curves of Figure 2 are schematic for sandy soils at various freezing temperatures and ice contents.

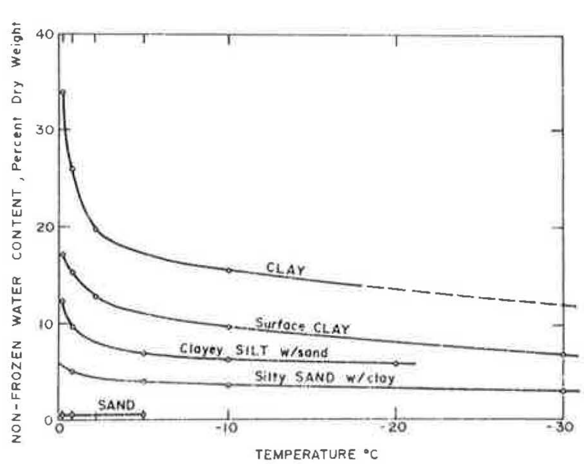

Figure 1. Non-Frozen Water Content of Soils vs. Temperature Below Freezing (From 18).

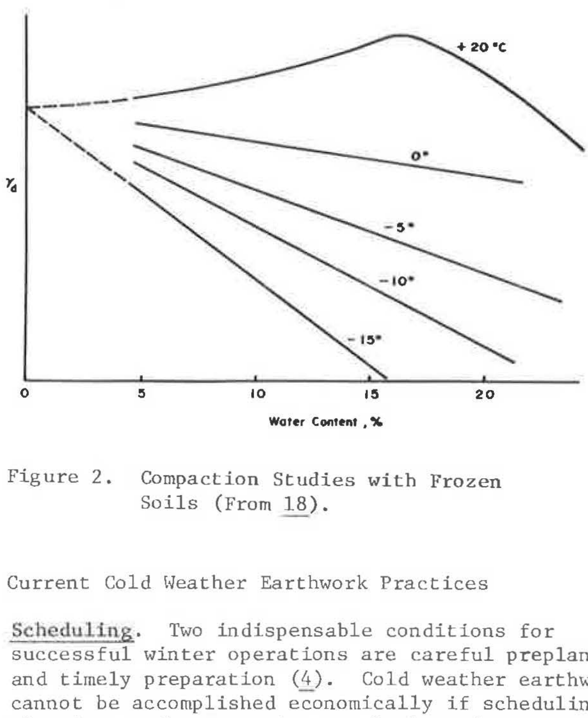

Figure 2. Compaction Studies with Frozen Soils (From 18).

Current Cold Weather Earthwork Practices

Scheduling. Two indispensable conditions for successful winter operations are careful preplanning and timely preparation (4). Cold weather earthwork cannot be accomplished economically if scheduling, planning, and preparation are haphazard.

With proper scheduling, operations fairly insensitive to cold weather, such as rock excavation, can proceed as during warmer periods of the year. The added equipment and supplies deemed necessary to carry out winter operations must be present on the job site in advance. A further example would be the advance preparation of an area to be excavated, prior to the ground freezing.

A vital asset in scheduling is knowing the weather forecast in advance. Up-to-date weather information, which statistically analyses weather trends for different areas in the United States, is available from 50 to 100 companies specializing in forecasting (30).

Siting. The primary considerations in site or route selection for cold weather operations are to avoid problem soils, and minimize haul distances. Wet silty soils, because of their frost susceptibility and ready release of moisture upon thawing, are especially troublesome and should be avoided (9). Heavier plastic clays with 3 to 5% moisture above optimum can be compacted if high impact tampers are utilized. Granular soils are the least sensitive to cold weather effects and give the most satisfactory results.

By minimizing the haul distance, the usual warm weather economics are effected. It is also possible to reduce special problems such as the freezing of borrow material to the truck body (20). Long haul routes also require greater maintenance. In the cold weather, much borrow material and equipment manhours may be required just to keep these routes trafficable (35).

In selecting sites for winter construction, consideration must be given to the project profile with relation to the natural grade. The normal practice is to limit winter work to deep cuts or deep fills. Due to the high cost of ripping frozen overburden and the difficulty encountered in cutting side ditches, shallow embankment profiles are better scheduled for summer operations. Transition sections, cut site to fill site, also incorporate the complication of construction operations within the depth of frost penetration.

Small Area Excavation. Small area excavation includes the procedures most commonly used to excavate for utility trenches, footings, culverts and the like. When working with non-frozen soil during cold weather, the usual procedures can be followed. However, it may be advantageous to provide some means to prevent frost penetration during the non-working periods. A continuous operation (24 hours) is a possibility under some circumstances.

Removal of soil frozen to a moderate depth will require extra effort, and often times challenges the ingenuity of the contractor. Each method has its merits and disadvantages, and the choice of procedure must be based on the particular job. Breaking through frozen ground with power shovels, dozers, front end loaders, rippers, air hammers, and wedges appears to be the popular procedure. In frozen ground 12 to 18 inches (0.3 to 0.5 m) thick, backacting shovels have proven to be the most successful. Bucket attachments which provide deeper penetration into the ground are available (19, 2). Excavation of frozen ground accelerates wear and tear of the equipment, requiring more frequent servicing.

Drilling and blasting to loosen frozen ground is another principal method. Several developments, e.g., delayed shooting, new and inexpensive explosives, and mechanized drilling, have considerably reduced costs and broadened the opportunities for frozen ground excavation (18).

Thawing (another option) is accomplished by many of the following procedures.

(1) Insulation with straw or wood scraps, possibly covered by black polyethelene sheeting to draw the heat (19).

(2) With steam and cover; by jets, steam points, or coils laid on the ground surface (1).

(3) Open fires of coke, tires, straw, wood; could possibly use reflectors or enclosures (10)

(4) Blanket of hot sand.

(5) Flame throwers (26).

(6) Ponding or spraying heated water on the open surface.

(7) Gas Burners (24, 33)

Method number (6) is disadvantageous in that ponding water is slow and will probably increase the moisture content of the soil being thawed.

The excavation and placement of rock embraces few new difficulties as a result of cold weather. The usual procedures employed during warmer periods are generally adequate for winter months. A difficulty may arise if the rock ledge is water bearing. Stockpiled shot rock containing free water may freeze into a solid mass. Frozen overburden will also impede progress in rock excavation (23).

Large Area Excavation. Highway cuts and borrow pits are examples of large area excavations. In cases where the soil is unfrozen and the temperatures do not fall consistently below the freezing mark, it may be sufficient to follow the usual excavating procedures. Modifications may be desirable when the temperatures are at or below freezing. The principal objective is to maintain the soil in an unfrozen state during excavating, hauling and placing operations.

Continuous operations, 24 hours per day, 7 days per week, can be utilized to this end, once a given cut or borrow area is opened. Restrict the excavation to as small an area as possible. This will reduce the surface exposed to freezing temperatures and lessen borrow waste. Loading the hauling equipment with power shovels and front end loaders has two distinct advantages. First, the exposed surface is limited. Secondly, working a high bank will tend to keep the temperature of the borrow material higher than if excavating from the surface down with scrapers.

During cold weather operations, the soil has a tendency to adfreeze to the steel surfaces of the loading and hauling equipment. Provisions must be made for periodic removal of the adhered soil to prevent equipment damage and loss of efficiency. The normal manner in which frozen soil is removed consists of chipping frozen chunks with air hammers, picks and shovels (20). Heating the boxes with the equipment exhaust is another possibility.

Excavation of frozen ground of moderate depth over a large areal extent is usually accomplished mechanically. Thawing is generally not practical. One of the most effective methods is by tractor mounted ripper (13, 14, 32). The forward tip of the ripper reaches beneath the frozen slab and tears out large chunks. Figure 3 depicts the method of successive passes, employed to rip greater depths of frozen ground.

Under some circumstances, the frozen ground may be too hard to penetrate with the ripper. In such a cases, breaking through the frozen crust with explosives may provide a starting point for an effective ripper operation. Several important tips for successful ripping operations are as follows (12):

(1) Hold ripping to a minimum; this operation does not move earth.

(2) Keep the cut small; prevent ripped areas from refreezing.

(3) Watch traction; side hill operations are difficult.

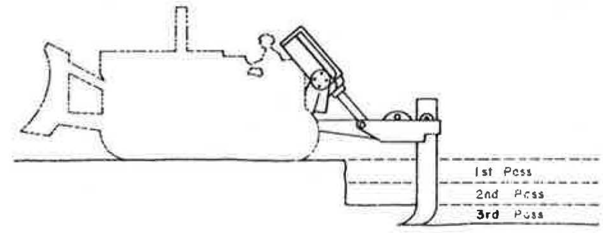

Figure 3. Loosening Ground with Dozer Mounted Ripper; Multiple Passes for Deep Penetration (From 18).

Large rock excavations are generally not affected by cold temperatures and work may proceed as during warmer periods. Peat bogs are unique situations, in that freezing temperatures tend to assist operations. Freezing to a moderate depth in such deposits increases the trafficability and the stability of the side slopes. Once the surface is trafficable, scrapers can easily remove the soil. Large surface areas are worked to expose the peat deposit to the freezing temperatures. Ripping may increase the depth of frost penetration.

Hauling. Hauling of non-frozen borrow to the job site is accomplished with the usual earth moving equipment. During periods of freezing temperatures or for long haul distances, it is advisable to cover the material in the truck with canvas to retain the heat. If feasible, heating the truck boxes or scraper bowls reduces the opportunity for the soil to adfreeze to the compartment.

Keeping the haul road, borrow pit, and spread area in good condition will permit an efficient, high speed operation. Operators must remain alert, particularly during periods of reduced visibility.

Spreading Fill Material. The fill spread will necessarily be kept to a minimum to reduce the surface area exposed to freezing temperatures. The ramp method of placing fill can be adopted to facilitate this end, Figure 4. This technique is

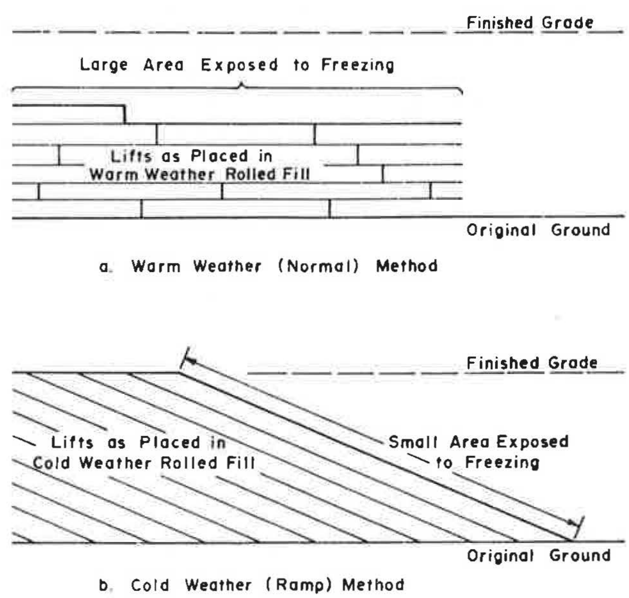

Figure 4. Embankment Profiles, Warm Weather vs. Cold Weather Lifts in Rolled Fills (From 22).

essentially the same as that used to cover and compact in solid-waste landfills. A smooth subgrade is essential for high speed operations and less equipment and operator fatigue. The work areas should be bladed smooth prior to shutting down each day. Lift thicknesses of 6 to 12 inches (0.2 to 0.3 m) for soils and 3 feet (1 m) for rock are generally acceptable. Utilizing the hauling equipment as compaction pieces, as much as practical, will enhance the efficiency of the operation. This practice has merit in either cold or warm weather.

Compaction. The degree of difficulty in obtaining the desired density is a function of the temperature, texture and moisture content of the soil. Dry sands and gravelly soils are relatively easy to compact, and fairly insensitive to freezing temperatures. Low evaporation rates and freezing temperatures make it impractical to lower the water content of wet cohesive soils through spreading and drying. It appears that the maximum water content for effective cold weather placement and compaction is approximately 2 to 3% above optimum. Heavy plastic clays with moisture contents above optimum can be satisfactorily compacted using high speed impact tampers. Silts are avoided, if possible, because of their high susceptibility to frost action (35). Wet cohesive soils have been used with alternating layers of granular soils. The granular soil layers provide horizontal drainage paths for escaping excess water during consolidation and spring thaw.

Use of Frozen Soil. Specifications are very restrictive with respect to the use of frozen soils. It is customarily written that no frozen soil be incorporated in the embankment, or that no foundation be placed on frozen soils. These rigorous specifications are warranted since ignoring them may lead to extensive damage from settlement or shear instability. There are, however, provisions for disposal much more satisfactory than simply wasting the frozen soil.

Some embankment designs permit the placement of frozen material outside the "design" section, i.e., beyond the shoulder break. However, even here the thawed material may produce an erosion problem. Frozen soil may also be used in stabilizing-berm structures. Stockpiling the frozen soil to thaw and reuse at a later date is another alternative. The thawed material can either be used as fill, or to dress up the borrow areas. Figure 5 illustrates the above mentioned dispositions (22).

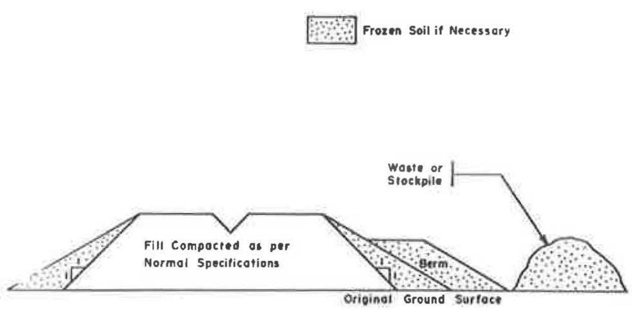

Figure 5. Locations Where Frozen Soil Can be Used without Detrimental Effects (From 22).

Field Engineering and Inspection. The surveying and engineering tasks performed in the field are generally adversely effected by cold weather conditions. The combination of windchill, extreme cold, and reduced visibility impair proficiency and operating effectiveness. One of the most common difficulties is trying to locate reference points in deep snow. Grade control is also harder to maintain because of greater equipment congestion on the confined work areas. More inspection is required during cold weather construction than during warmer periods, if a quality embankment is to be constructed. Eliminating snow, ice, and frozen soil from the fill material may require continuous inspection in the borrow area, depending on the attitude of the contractor and his equipment operators. Continuous operations, 24 hours a day, 7 days a week, will require more staffing to perform the engineering and inspection services.

Equipment. Special precautionary winterizing steps must be performed in order to maintain a fleet of operable construction equipment during the cold weather season (6, 17, 27, 34).

Table 1 illustrates the operational efficiency of construction equipment with respect to temperature (T), light (L) and precipitation (P) (22). Malfunctions resulting from various sources impose greater maintenance and servicing requirements. Hence, greater down time will require a larger fleet of equipment to perform the given task. Rental equipment is generally available to meet this requirement due to the reduction of work during the cold season. Ice, snow and frozen ground will make traction difficult, resulting in a slow speed operation. Equipment will need to be shut down periodically in order to remove adfreezing material from the truck and scraper compartments and crawler tracks. Several precautionary measures taken at shut down will facilitate "starting up" for the next day's operation (6, 12, 17, 27, 34).

Table 1. Relative efficiency of operation of construction machinery. From (22)

Weather Factor	Excavation Machinery	Hauling Machinery
Air Temperature (^{o}F):	E_T %	E_T %
85	87	89
70	99	100
50	100	100
40	99	100
32	99	97
25	98	100
15	92	96
-5	78	88
-25	43	66
Light Condition:	E_L %	E_L %
Bright Sunshine	96	96
Indirect Sunshine	100	100
Dusk	88	96
Subartic Winter Twilight	65	82
Precipitation	E_p %	E_p %
Heavy Rain	81	85
Light Rain	97	98
Dry, Temperature 50^{o}F	100	100
Light Snow	97	95
Heavy Snow	73	76

Personnel. Investigators (15) have found that cold weather affects men psychologically and physiologically. The net result is a loss in efficiency due to the climatic factors. The U. S. Army (8) has found that the elements which govern the comfort, and therefore the efficiency, of workmen in cold weather are air temperature, surface wind velocity, and relative humidity (22). Climatic factors can be related to human working efficiency as shown in Table 2. Any reasonable combination of the climatic variables shown in the three parts of Table 2 can be combined by multiplying the respective working efficiences. For example, at a temperature of 15°C at dusk with a light snow falling the working efficiency for manual laborers is (0.88)(0.92)(0.90) = 0.73 (22).

Table 2. Relative working efficiency of manual laborers. From (22)

Weather Factor	Working Efficiency (%)
Air Temperature (°F):	
85	72
70	95
50	100
40	98
32	97
25	95
15	88
-5	73
-25	33
Light Condition:	
Bright sunshine	97
Indirect sunshine	100
Dusk	92
Subartic winter twilight	56
Precipitation:	
Heavy rain	36
Light rain	89
Dry, temperature 50°F	100
Light Snow	90
Heavy Snow	41

Exposure to very cold temperatures may result in tissue or non-tissue damage. Havers and Morgan (15) present an excellent summary of the physiological reactions to cold weather. Improving the comfort of the individual will improve efficiency. Cabs and heaters will do much for the morale of the operator. If the unit cannot be equipped with a cab, plan as much work as possible so that the wind is at the operators back. Encourage workers to dress properly and to have additional clothing on the job site for unexpected cold or windy conditions. Several layers of clothing provides more warmth, allows more freedom, and permits faster adjustment to changing conditions than one heavy garment (15).

Economic Considerations. Much of the controversy concerning construction seasonality revolves around its economic feasibility. Proponents of cold weather construction regard "tradition" as the major obstacle to overcome; while opponents often emphasize the high cost of winterizing a site. Without cold weather activity, there is much seasonal unemployment and a host of labor problems, e.g., high hourly wages, labor shortages, difficulties in recruiting new workers, costly overtime payment, high unemployment insurance rates, restrictive labor practices, lack of a stable and properly trained work force, and an absence of employee loyalty to the contractor (31). These difficulties spread out, adversely affecting manufacturing wages, production schedules of building suppliers, and costs of building materials. The overall condition feeds inflation and places an economic burden on the nation (31).

Economic studies by various proponents of cold weather work have demonstrated that net economic benefits are expected, provided that planning is adequate (4, 5, 7, 9, 11, 23, 31, 36).

The contractor, although faced with the increased costs of winterization, is credited with the following obtainable benefits:

(1) Greater utilization of equipment and capital.
(2) Stable year round work force of experienced operators.
(3) Availability of rental equipment.
(4) Opportunity to meet completion deadlines; hence no penalty fees.
(5) Supplies readily available.
(6) Savings of cost of construction increases which occur from January to June (4).
(7) Savings in unemployment insurance rates.
(8) Savings derived from not staffing a skeleton crew during shutdown.
(9) Cost savings derived from easier construction under certain circumstances.

The cost of winterizing and performing cold weather earthwork will in part depend on the nature and conditions of the soil to be moved, the specifications covering the grading requirements, the experience of the contractor, and the permissable latitudes in the quality of the end product.

The public, the owner and the manufacturer also stand to benefit economically from cold weather construction. The public receives a new facility sooner, reducing inconvenience, travel time, traffic fatalities, injuries and property damage. Statistics show that Interstate highways facilities are safer than the older facilities they replaced.

"On completed sections of the Interstate system the fatality rate is 2.8 deaths per million vehicle miles, compared with a rate of 9.7 on older highways in the same traffic corridors" (25). Lovell and Osborne (22) attempted to express the increased safety in terms of economic savings.

An earlier completion date also means a reduction in the total elapsed time from financial commitment by the owner to use of the facility. With current high rates of interest on construction loans, there is considerable motivation to reduce construction time. The manufacturing of building products follows the same general seasonal curve as that of the construction industry. A savings in building material costs could be realized if seasonality were reduced. A leveling out of construction activity would enable the manufacturer to plan for nearly constant production each month of the year (36).

Replies to Questionnaires

Up-to-date information on techniques of cold weather earthwork and the state of the art in North American is lacking. One survey was completed in 1966 (37). The authors solicited replies to questionnaires in 1973 from state highway departments, district offices of the U. S. Army Corps of Engineers, and selected Canadian province highway departments. All questions emphasized earth embankment construction during conditions of sub-freezing temperatures. The responses are fully presented only in an internal report (3). Since the tabulations are large and of unsuitable format for presentation here, only a selection of the 1973 responses from the state highway departments is included. Although the information is somewhat old, it is the most recent known to the authors.

The continuation of work or placement of certain embankment materials during adverse weather conditions is commonly determined by the "Engineer". In all but a few state specifications, placement of frozen soils in embankments or placement of fill on frozen foundations is prohibited. Practically every department which allows the placement of fill during subfreezing temperatures reported using granular soils or rockfill. In accordance with state specifications, frozen subgrades are either removed or left in place. When wasted, the frozen soil is generally deposited outside a designated slope beyond the highway shoulder. Frozen subgrades are left in place when they meet a depth-of-frost criterion.

Alaska does not place frozen material in embankment construction, but will permit a frozen subgrade to remain if it is granular, and if the specified density had been obtained prior to freezing. Had the lift not been compacted or if ice lenses have formed, placement of the next life is suspended until thawing of the frozen subgrade has occurred.

The heavy snowfalls in the mountainous areas of California suspend all work except some rock excavation. When absolutely necessary, California accomplishes highway embankment construction during cold weather by maintaining 24 hour shifts to keep the soil in an unfrozen condition. Kansas also uses the continuous construction approach on occasion.

Colorado normally does not permit the placement of soil during freezing weather, but suggested a "dry uncompacted lift" be placed prior to shutdown to act as an insulating blanket. This lift can then be reworked at the start of the following shift.

Combining depth-of-frost-penetration and soil-type criteria, Connecticut determines the acceptability of a frozen subgrade by visual inspection. Suspension of soil placement occurs as a consequence of a frost depth greater than 3 inches (0.1 m), provided the soil type is not predominantly silt or clay.

Peat treatment operations are scheduled in Indiana to take advantage of the beneficial freezing of these unsuitable soils, which facilitates handling and increases machinery efficiency over that experienced during the warmer months. Once the peat has been excavated, it is replaced by granular soils using techniques which will prevent the fill from freezing during placement.

An informal study in Maine showed that the compactive effort required to achieve the specified density at 15^{o}F was approximately six times as great as that effort employed at 40^{o}F.

To reduce the surface area exposed to subfreezing temperatures, Michigan specifications require the contractor to construct the embankment by the ramp method of fill placement. Michigan also reports that a greater inspection effort is required to insure quality in the embankment construction. They also find winter construction gives rise to increased wearing of construction equipment, and noted that a characteristic of sand at or below 15^{o}F was an "apparent cohesion" or "gumminess".

New York (37) reported an investigation into the compaction characteristics of a relatively clean granular soil in the field and laboratory where "...as the temperature dropped below 30^{o}F, the compactive effort necessary to achieve specified densities increased tremendously, and when a soil temperature of approximately 20^{o}F was reached, it was almost impossible to achieve specified densities, regardless of the compactive effort or the type of equipment". As a result of their experience, New York has limited its operations between 1 November and 1 April to approved rockfill only.

Summary and Conclusions

The practices of state highway departments, Canadian provinces and the U. S. Army Corps of Engineers in constructing earth embankments and proceeding with earthwork through the winter months was investigated via a questionnaire in 1973. The replies were tabulated and critically reviewed with respect to the amount of earthwork, procedures utilized, and respective attitudes regarding the feasibility of cold weather earthwork. They showed that cold weather earthwork in the U. S. is performed on only a small scale. Advances in technology are proceeding at a slow rate and increases in the volume of cold weather earthwork have been quite nominal. This is in spite of strong evidence that when such activity is carefully planned it can produce a net saving. The primary reason for such a situation seems to be "tradition". Hopefully those agencies constructing low volume roads will be less restrained by historic precedent, and can be motivated to experiment in order to achieve some of the potential economic advantages.

Acknowledgments

The research reported herein was sponsored by CRREL and the School of Civil Engineering at Purdue University. Appreciation is expressed to Mr. M. M. Bowers former graduate assistant at Purdue.

Bibliography

1. Aids to Winter Building, Swedish Expedients to Beat Snow and Frost. The Builder, Vol. 206, pp. 415-416, February 21, 1964.
2. Backhoes Dig Hard Frost. Alaska Construction and Oil Report, No. 102, September 1970.
3. Bieganousky, W. A., An Evaluation of Cold Weather Earthwork; The State of the Art and Recommendations for its Future Development. An Interim Report to CRREL, Purdue University, June 1973, 93 pp.
4. Bone, A. Turner, Canadian Wintertime Construction Practices. Engineering Journal, Vol. 52, No. 2, pp. 8-13, February 1969.
5. Builders: Fear Not Foul Weather. Engineering News Record, pp. 28, May 9, 1968.
6. Cold Weather Engine Storage and Operation. Engineering and Contract Record, pp. 61, December 1970.
7. Construction Seasonality. Engineering News Record, pp. 11, Oct. 19, 1967.
8. Department of the Army, Arctic Construction. Technical Manual 5-349, 328 pp., Feb. 1962.
9. Cronkhite, R. C., Winter Construction Experience in Alberta. Proceedings, Canadian Good Roads Association, pp. 203-12, 1968.
10. Crory, F. E. and Teeter, R. B., Expedient Thawing of Frost with Charcoal Fire. Technical Note, U. S. Army Terrestrial Sciences Center, August 1968.
11. Cumulative Regulatory Effects on the Cost of Automotive Transportation, or RECAT, Final Report of the Ad Hoc Committee. U. S. Office of Science and Technology, Feb. 1972.
12. Eight Winter Earthmoving Tips. Roads and Streets, Vol. 104, pp. 72, Nov. 1961.

13. Frost Ripper Doubles Paydirt. Construction Equipment and Materials, pp. 44-5, September 1953.
14. Haley, W. A., Rippers Speed Winter Earthmoving. Excavating Engineer, Vol. 53, No. 1, pp. 36-9, Jan. 1959.
15. Havers, John A., and Morgan, Robert M., Literature Survey of Cold Weather Construction Practices. Special Report 172, CRREL, May 1972.
16. Highter, W. H., Altschaeffl, A. G. and Lovell, C. W., Low-Temperature Effects on the Compaction and Strength of a Sandy Clay. HRR No. 304, pp. 83, 1970.
17. Jansa, R. H., Cold Weather Tips for Diesel Engines. The Oil and Gas Journal, pp. 145-6, April 6, 1970.
18. Kaplar, Chester, W., Cold Weather Excavation and Foundation Work. Presented at the University of Wisconsin, Milwaukee, February 1972.
19. Keeping Site Work Moving All the Winter. Engineering, Vol. 196, pp. 430-432, October 4, 1963.
20. LeBourdais, Eric, Frozen Ground Helps These Scrapers. Engineering and Contract Record, pp. 64-70, June 1966.
21. Lovell, C. W., Jr., Temperature Effects on Phase Composition and Strength of Partially Frozen Soil. Fundamental and Practical Concepts of Soil Freezing, HRB Bulletin 168, pp. 74-95, 1957.
22. Lovell, C. W., Jr., and Osborne, A. M., Feasibility of Cold Weather Earthwork. Joint Highway Research Project, Report No. 1, Purdue University, pp. 84, Feb. 1968.
23. McIntyre, A. G., Winter Grading in Alberta Resources Railway. Norwegian Road Research Laboratory, May 11, 1970.
24. Minnegasco Goes Full Speed With Hot Rod. Gas Age, pp. 32-3, January 1964.
25. Moley, Raymond, Automobile Safety III. Newsweek, Vol. 67, No. 6, pp. 88.
26. Outardes 4: Grab Bag of Ideas. Engineering News Record, pp. 94, May 25, 1967.
27. Raymond, D. L., A Synopsis of Cold Weather Operation Problems of Engine Powered Equipment Experienced in the Northern States and Border Areas of Canada. Cleveland Section, SAE, Jan. 6, 1964.
28. Roberts, W. S., Regionalized Feasibility Study of Cold Weather Earthwork. Special Report No. 76-2, CRREL, July 1976, 190 + pp.
29. Roberts, W. S., Lovell, C. W. and West, T. R., Predicting Feasibility of Cold Weather Earthwork. to be printed in the proceedings of the ASCE Cold Weather Specialty Conference, Anchorage, Alaska, May 1978, 12 pp.
30. Rosendal, Hans E., All Weather Construction Conference. presented at the University of Wisconsin, Milwaukee, February 1972.
31. Seasonal Unemployment Can Be Reduced. Engineering News Record, pp. 231-2, March 21, 1968.
32. Tractor-Rippers Can Handle Deep Frost. Road and Streets, pp. 90-1, January 1959.
33. Use Gas Burners To Thaw Frozen Ground. Heating, Piping and Air Conditioning, pp. 46, December 1964.
34. What To Do When the Temperature Drops. Contractors and Engineers, Vol. 68, No. 4, pp. 39, April 1971.
35. Winter Grading Normal in Northern Manitoba. Heavy Construction News, pp. 16, October 7, 1968.
36. Year-Round/All Weather Construction. BRAB Research Correlation Conference, Washington, D. C., 30 April - 1 May, 1968.
37. Yoakem, Delmar, A Survey of Winter Construction Practices Earthwork Concrete and Asphalt. Special Report 76, CRREL, July 1966.