Review of Frozen Ground Excavation Methods
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by C. R. McCullough
PREFACE

This is a report on a library study conducted for USA SIPRE by Mr. McCullough, Associate Professor of Civil Engineering, North Carolina State College, under a purchase order with North Carolina State College. The work was done under SIPRE Project 22.4-9, Principles of frozen ground excavation.

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SUMMARY

Present methods of frozen ground excavation include thawing prior to excavation by means of solar heat, steam jets, water and electric needles, valveless pulsejet engines, and hydraulic methods as well as fracturing by hand, with saws, drop and pneumatic hammers, and cutter and scraper blades. The use of explosives for excavating frozen ground is not included in the scope of this report. Evaluation on the basis of a literature survey indicates that modification of bulldozers to permit installation of pneumatic hammers horizontally along the base of the blade shows considerable promise. The use of alternate cutter and scraper blades for trench excavation has proved satisfactory, and drop hammers are suitable for enlarging existing excavations. Sawing frozen ground has not yielded satisfactory results. The potentiality of resonant sound waves for loosening frozen ground should be studied.
REVIEW OF FROZEN GROUND EXCAVATION METHODS
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C. R. McCullough

INTRODUCTION

Engineering problems that have been dealt with satisfactorily in regions of temperate climate often present unique aspects in areas of climatological extremes. Earth excavation is a graphic example. With today's construction equipment, particularly in the earth-moving field, excavating in temperate regions is not a major problem. On the other hand, in tropical regions, the prevailing climate imposes certain restrictions. The characteristically dense vegetation presents a problem in clearing and the wide-spread distribution of clay-like soils, together with a 7- to 9-month "wet season" with 100 or more inches of rainfall, combine to immobilize present earth-moving equipment during most of the year. Other problems, such as drainage, accelerated equipment deterioration, etc., plague the tropical earth mover.

Arctic terrain imposes even more severe restrictions on excavating than do tropical climates. Frozen ground or permafrost, characteristic of such areas, presents the most acute problem. In addition, the general inaccessibility of these regions presents major transportation and supply problems. The limited experience of construction engineers in arctic regions accentuates the problem.

This report is concerned primarily with a library study on the subject of excavations in frozen ground. The author was directed to "... review all known proposals for loosening solid materials (frozen ground) such as by thermal shock, dynamic impact, sonic vibration or mechanical force... The report will recommend and outline basic research that will lead to a better fundamental knowledge of the problem in those areas that appear to be fruitful of result. Other laboratory tests, less basic in nature, but which utilize novel and unique application of principles now available but not previously considered with regard to excavating frozen ground, are desired."* This report does not contain information on drilling techniques, the use of explosives in making excavations, or the penetration of projectiles in frozen ground, which are being investigated under other SIPRE projects.

It appears reasonable to assume that frozen ground will react to excavating methods in a manner intermediate between unfrozen soil and bedrock. It would also seem that the properties of the mass to be excavated should influence the selection of methods. For example, a technique suitable for excavating a frozen uniformly silty material may not be at all applicable to a silty soil containing some coarse-grained particles. Even within a mass containing a soil of uniform texture, the ice content and the geometric configuration of segregated ice masses within the soil may influence the efficiency of a particular method of excavation.

In addition to the properties of the frozen ground, the size and shape of a proposed excavation can have an important bearing on the method to be employed. Furthermore, military operations in peacetime may permit the use of a method which would be entirely unsuitable in time of war. For example, from the limited amount of research data available, certain types of explosives and blasting techniques show considerable promise for the excavation of foxholes, but a noise-producing method would not be feasible under wartime conditions that make concealment and surprise a major consideration.

* Letter dated 10 July 1956, from Mr. W. K. Boyd, chief, Frozen Ground Branch, USA SIPRE.
REVIEW AND EVALUATION OF PRESENT METHODS

Most of the methods currently used to excavate frozen ground utilize standard earth-moving equipment to some extent. These methods, however, can be categorized according to the manner of preparing the frozen ground for handling: (1) thawing the frozen mass prior to actual excavation, then handling the thawed mass with standard equipment used in a conventional manner; (2) fracturing the mass into sizes convenient to handle with standard equipment, without any appreciable thawing action.

Methods of thawing frozen ground prior to excavation

Solar method. One of the least efficient methods of thawing frozen ground, from the standpoint of time involved, consists of removing the insulating vegetation and allowing the sun's heat to thaw the ground's surface. The thawed material is removed periodically by bulldozers. The rate of thawing depends upon the latitude, prevailing climatic conditions, topographic situation, and soil type, but the sun's rays will normally thaw 1 to 4 in. of frozen ground per 24 hr. In some instances, it may be possible to accelerate the thawing process slightly by reflective devices. Thawing has been accelerated by the simple expedient of building fires on the ground surface and using large heat-reflective surfaces above the open flame.

Evaluation: The fact that extensive equipment is not necessary is the primary advantage of the solar method. Another advantage is that the size and shape of the excavation has no effect on its efficiency. The major disadvantages are: a) A long time is required for thawing. b) In northern latitudes, north-facing slopes receive little direct sunlight, and the rate of thawing is further decelerated. c) Removal and disposal of thawed material may constitute a major problem especially with fine-grained soils which flow when very wet.

Steam jets. Steam jets have been used frequently to thaw localized areas for column-footing excavations, for setting anchor posts, etc. The most common arrangement is to connect a short length (2 to 3 ft long) of about 1-in. diam pipe (which serves as a nozzle) with a flexible tube to a boiler. The nozzle is directed toward the area to be thawed and forced into the ground as thawing proceeds. The pressure of the steam prevents the nozzle from clogging.

Evaluation: The use of steam jets for thawing frozen ground is normally restricted to small excavations. If the excavation is large (for example, more than 10 ft²) the removal of the thawed material is a problem.

Water needles. An extension of the steam jet principle consists of circulating water through a series of pipes installed in previously-drilled holes. The needles are usually joined in a parallel series by means of a general collector connection. One type of water needle consists of two pieces of pipe with internal diameters of 2.5 in. and 1 in., the smaller pipe inserted into the larger. Hot water is fed into the internal pipe. The hot water flows to the bottom of the small pipe, enters the large pipe, rises to the top, and flows to the next needle. In one installation (Chelnokov, 1953) the needles were approximately 48 in. long and spaced at intervals of about 3 to 4 ft in a grid arrangement. It was reported that one boiler, heating water to 40-70°C, was adequate to serve 50 to 60 needles simultaneously. The total heating surface of the boiler was 60 ft² and its water capacity 106 gal. The thawing process required several days.

Evaluation: The use of water needles for thawing frozen ground is applicable only to major excavations. In addition, a drilling rig of some type is necessary to drill holes suitable for the water needles. Extensive, although not expensive, equipment is necessary. Several days are required for thawing to 4 ft depths.

Electric needles. According to Chelnokov (1953), the most inexpensive method of electrical heating in use in the Soviet Union utilizes tubular electric heaters. The casing of the tubular heater is made of two seamless steel pipes with an internal diameter of 12 mm. Spiral heating elements of Nichrome wire are mounted inside the pipe. The pipes are filled with pressed magnesium powder which has dielectric properties and good thermal conductivity. The design of the apparatus protects the terminals and spirals from short-circuiting and prolongs the life of the spirals.
The heaters are rated for 127-220 v, each heater having a capacity of $\frac{1}{2}-1$ kw. The spirals attain a temperature of 350°C. The heaters are inserted into previously-drilled holes, the number depending on the power available and the volume of ground to be excavated. The interval between needles is usually from 1.6 to 4.5 ft. Only the ground immediately surrounding the needles is heated, and that only to about 1-2°C. Mechanical excavators can easily remove the thawed ground in the vicinity of the needles, together with the fragments of frozen ground between the heated zones. The time required for heating varied from 12 to 14 hr.

A more recent Russian design for a similar electric tubular heater is called the "liquid static needle" (Chelnokov, 1953). The needle is filled with mineral oil, which has good dielectric properties. The heat source is a welded wire spiral. The temperature of the oil in the upper part of the needle exceeds 100°C. About 30 needles are connected to an a-c network of 220 v. The total capacity of the system is about 6 to 7 kw.

A third design for a tubular heater consists of a metal gas pipe about 4 ft long, with an internal diameter of 2.5 in. The heat source consists of Nichrome wire wound around an ebonite rod. Transformer oil occupies the space between the rod and the pipe and heats up to 60°C.

Evaluation: The use of electric needles is also restricted to major excavations, and even the least expensive method will generally cost more than water needles. Its primary advantage over water needles is the saving of time. Electric needles are used most frequently in areas where the ground is frozen to depths of about 4 ft or less.

Valveless pulsejet engine. The Naval Research Laboratory has used a valveless pulsejet engine for digging relatively small holes in frozen ground (Anon., 1955). Various engine designs were tested using the 2.5-in. valveless chamber and inlet. It was reported that these valveless engines with extra-long "tails", 2-in. diam, were very successful for holes up to 6 in. diam and 40 in. depth. After the engine is started, the exhaust end is turned toward the ground. The heated high-velocity gases thaw the soil, rotate a scratcher device, and disperse the soil particles upward. A shield at the ground surface directs the flow of the dispersed soil particles.

Evaluation: This method appears to have very definite advantages for digging relatively small holes in frozen ground. The engine is readily portable, weighing approximately 8 lb, and the amount of fuel consumed is relatively small.

Hydraulic method. Near Fairbanks, Alaska, gold mining in glacial valleys is conducted on a large scale using hydraulic dredges. The gold is found beneath a mantle of 20 ft or more of frozen silt. This silt overburden is thawed by spraying water at high velocity against the soil surface.

On one construction job (Anon, 1948b), water was piped from an adjacent stream into an 8-in diam pipe network into which 300 to 400 sprinkler heads were mounted. The network was supported 3-4 ft above the ground surface. The water from the creek had a temperature of 52°F and about 4-6 in. of soil were removed every 24 hr. The ice content of the soil varied from 30% to solid ice. The sprinkler water was recovered by pumping the runoff upstream and depositing it near the stream that served as a source for the sprinkler water. The 12-18 in. of natural thawed zone served to filter out the solids (an average of 25%) from the upstream discharge. The water percolated back into the stream bed and there was actually a gain in water, due to melting of permanent ice in the vicinity of the discharge. The total overburden depth that was removed averaged 20 ft. The maximum depth of overburden removed was 30 ft.
Evaluation: The hydraulic method for thawing frozen ground is most successful when applied to major excavations. The rate of thaw depends on the temperature of the water and therefore, using water from natural sources, assuming a water temperature of about 50°F, a maximum of 6 in. of soil can be removed every 24 hr. The recovery of the solid material in the runoff, if desirable, is a major problem in itself. This method has been used successfully, however, for removing frozen ground to depths of as much as 20 to 30 ft.

Fracturing of frozen ground prior to excavation

Manual operations. The simplest method from the standpoint of equipment, but the least efficient from the standpoint of unit cost, labor and time, is the use of hand tools for excavations. A sturdy pickax and shovel are the only equipment required. Very little progress can be made in one day, and, after the first day, natural thawing in the excavation creates a problem. Major excavations (for example, more than 35 yd³) should not be attempted.

Explosives. Probably the most commonly used method for excavations in frozen ground, the use of explosives of various types and compositions, is not treated here, as several research projects on this subject are now being conducted by USA SIPRE. Pertinent articles encountered in this library study are listed in the bibliography.

Saws. One method of trench construction in frozen ground, tested by the Leningrad branch of the All-Union Research Institute of Road Machine Construction, used a circular saw (Sergeev, 1956). The soil was a very dense clay containing granite chips 4 to 6 cm in diameter. The circular saws were mounted so that they could be used both in a vertical operating plane and also in a horizontal operating plane, for undercutting. It was proposed that the disk saw should be about 800 mm in diameter and 10 mm thick. The proposed peripheral speed was 20 to 25 m/sec. Actually, the project reported used saws 1 to 2 cm thick, operated at a peripheral speed of 15 m/sec.

Evaluation: This method has not proved satisfactory. Gravel particles or rock fragments cause teeth breakage and, in some instances, bending of the entire disk. Even in uniformly fine-grained materials, the frozen mass is so abrasive that replacement of saws is frequent. The undercutting operation proved impractical in that any unevenness of the surface of the ground blocked the progress of the saw.

Drophammers. The Leningrad Branch of the All-Union Research Institute of Road Machinery tested the use of drophammers as pressure cutters for excavating trenches in frozen ground (Sergeev, 1956). Wedges were used to dispose of the blocks produced by the drophammers. The disk-shaped drophammers were equipped with double-hinged strikers. It was reported that, when used with the proper impact force, the cutters were effective in excavating trenches 15 in. wide and 50 in. deep. Stones were demolished by the strikers. The efficiency of the apparatus was extremely low. The method was characterized by high power consumption, rapid deterioration of strikers, and low speed of operations. Upon careful analysis, it was reported that almost the entire power of the impact was utilized in wearing away the strikers.

Gal’perin and Abezgauz (1955) have reported that drophammers mounted on bulldozers for vertical striking action only were able to excavate up to 200 yd³ of ground frozen 3.3 ft deep in a period of 8 hr. Drophammers with 7° wedges as strikers and mounted on tractor-loaders, which were designed to shear off frozen ground by horizontal blows, required two and one-half to three times fewer impacts of the striker to remove the same quantity of frozen ground.

Kulinich (1954) reported the construction of a vertically-sliding blade weighing about 1 ton and operating in a manner similar to that of a drophammer. The blade was mounted on a tractor in place of a regular dozer blade.

Best results were obtained by Liakhov (1955) by using a wedge-shaped striker weighing about 2 ½ tons and dropped vertically. After the striker penetrated the ground, it was pulled horizontally. It was reported that 240 yd³ were excavated in 8 hr. The depth of excavation was 3 to 6 ft.
From 1953 to 1955, drop hammers were used in Moscow to excavate ground frozen to a depth of about 4 ft (Miloslavskii and Trakhtenberg, 1955). The drop hammers were equipped with wedge-shaped strikers and weighed between 3 and 4 tons each. The ground was not frozen below 4 ft depth and it was reported that three impacts of a 3-ton striker, dropping vertically about 30 ft, could fracture frozen clay sufficiently for excavation with standard equipment in an area about 6 ft diam and up to 3 ft deep.

A Russian military-approved modification of their D-157 bulldozer (Sokolov, 1954) consisted of a detachable drop hammer for breaking frozen ground. Quantitative operating data are not given, but it was claimed that satisfactory performance was obtained in deeply frozen ground.

Evaluation: The use of drop hammers is most applicable in areas where the soil is frozen to less than about 4 ft. Once an excavation in frozen ground has been opened, heavy drop hammers (about 2 to 3 tons) with wedge-shaped strikers might be highly successful. The use of drop hammers dealing horizontal blows shows some promise.

Pneumatic hammers. Ron' (1936) reported that an excavation in frozen ground about 25 ft deep was made by three men, each using a pneumatic hammer. About 13 yd³ of frozen ground per day (8 hr) was excavated with each pneumatic hammer. Another Russian report described three special Russian models of jackhammers for use in breaking up frozen ground. Quantitative information was not divulged, except that one of the models proved to be two to three times more efficient than hand tools.

Evaluation: The primary disadvantage of hand-held pneumatic hammers is the length of time required for excavating. The writer has personal experience in this regard, having used a gasoline-powered jackhammer equipped with a spade-like bit for excavating frozen uniform silt in Alaska. No more than 2 yd³ of frozen soil could be excavated by one man in an 8-hr period.

Cutter and scraper blades. A new excavator, designed especially for use in frozen ground, was tested in Russia in 1954 (Sergeev, 1956). The device consists of a Caterpillar chassis and two adjustable parallel booms with endless chains of 280 steel cutting teeth. Parallel cuts up to 6 ft deep can be made at the rate of 65 to 90 ft/hr in frozen clay soil, and up to 120 ft/hr in frozen sandy soil. The life of the cutting teeth was about 2650 ft in dense frozen clay and about 3300 ft in frozen sandy soil mixed with stones.

A trench excavator tested in 1955 in Russia (Sergeev, 1956) had alternate cutters and chopping wedges replacing scoops on the standard trench-excavator chain. The trench cutters were blades reinforced with a hard alloy and attached to rotary supports. The wedges for chopping the frozen clumps were also attached to rotary supports. This machine cut trenches 3 ft wide in ground frozen to a depth of 4½ ft. It was reported that the machine cut trenches in 30% of the frozen ground and chopped the remaining 70% into suitably small fragments. It was also reported that progress made with this machine averaged 15 to 20 ft/hr.

A special cutter attachment for use with a standard excavator was described by Gal'perin, Torgonenko, and Degtiarev (1954). The attachment, resembling a "mechanical pickax", consists of a cutter with a blade at one end mounted on a special head fastened to the arm of the backhoe. Several models of the cutter were tested, and it was concluded that the proper width of cutter blade was about 2½ in. The cutter blade cut ground in a line parallel to the center line of the trench. The depth of cut resulting from each impact averaged about 6 in. The total depth of the trench cut was about 2 ft. Two minutes were required to reach the desired depth. A similar attachment was designed for excavators equipped with dipper sticks rather than backhoes. To prepare frozen ground for excavations other than trenches, this device was used to make a series of checkerboard cuts to depths of about 2½ ft. The ground was unfrozen beneath this depth.

Evaluation: The use of cutter and scraper blades as special attachments to standard excavators has been tried with varying degrees of success. This is one of several methods involving modifications of standard equipment which show some promise with further research.
SONIC VIBRATIONS AND THERMAL SHOCK

During interviews with several physicists at North Carolina State College, it was suggested that the writer contact two additional specialists in the field of vibrations: Dr. Harry F. Olson, Director, Acoustical and Electro-Mechanical Research Laboratory, Radio Corporation of America, and Dr. L. L. Beranek, Technical Director, Acoustics Laboratory, Massachusetts Institute of Technology. Dr. Olson's opinion as to the feasibility of applying ultra-sonic vibrations for breaking up frozen ground coincided with those of the physicists interviewed personally; that is, the power required for such an application would be in the order of magnitude of 100-1000 hp. It does not seem practical at this time to develop transducers and electrical generators with this amount of power. Ultra-sonic vibrations have been used in such mechanical operations as drilling, mixing, disintegrating, etc.; however, ultra-sonic frequencies at this time can only be generated through the use of a vacuum tube; and, as a result, the power used in these mechanical operations is very small — at the most, about 1 kw input to the transducer.

Dr. Beranek made reference to the Bodine Sound-Drive Company in Los Angeles, California. Correspondence with this company revealed that they have a number of large-sized sonic machines capable of generating resonant sound wave phenomena for breaking up frangible masses. At the present time, this company is using these machines for breaking up cement bodies in oil wells for the purpose of pulling casing.

A study of the data available indicates that the application of a thermal shock method is not feasible because frozen ground masses change from solids to semi-liquids upon application of heat, with a resulting loss of brittleness.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the information gained from this study, the writer is of the opinion that the only known method for loosening solids that has not been applied to frozen ground, and that bears considerable promise of successful application, is the use of resonant sound waves for fracturing frozen ground. The writer recommends that a detailed investigation of the potentiality of this method be made by a competent physicist. Such investigation should include a conference with a company with experience in this field. (The Bodine Sound-Drive Company is the only such company that has come to the attention of the writer.) If the results of the investigation warrant, a detailed research program involving a pilot-plant study should be carried out. This investigation would probably require further basic research in rates of transmission of sound waves by frozen ground. It is further recognized that soil textures and degrees of ice segregation constitute variables in connection with this problem.

Several methods show promise of improvement through research. In the opinion of the writer, the use of explosives for excavating frozen ground represents the most fruitful field of research in this connection.

Modifications of bulldozers to permit installation of pneumatic hammers horizontally along the base of the dozer blade appear to have considerable promise. It would also be desirable to modify the tractor treads to improve traction between the tractor and the frozen ground. Cleats of some type might provide the necessary anchoring effect, so that the weight of the tractor could serve as a reaction to the pneumatic hammers.

For trench construction, the use of alternate cutter and scraper blades adapted to present-day trench excavators has proved satisfactory in Russia. The suggested modifications of bulldozers and trench excavators should be investigated in cooperation with manufacturers of this equipment.

Dropm hammers should prove successful for enlarging existing excavations in deep-frozen ground. The adaptation of the principle of sawing frozen ground with
metal chain saws or circular saws has not yielded satisfactory results and investigations in this area are not recommended.

The methods of thawing frozen ground prior to excavation, in the opinion of the writer, show no great improvement potentiality. Such methods have been used with success where either time or cost was not a consideration.

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