The factors of probe spacing, depth, steam pressure, boiler capacity, and time all represent unknowns in the design of steam thawing systems. Ideally, steam probes should be spaced at equal distances in a triangular pattern. This is achieved by staggering the probes in alternate rows, to form a hexagonal pattern (Figure 7.1). This pattern results in the most uniform thawing. Thawing proceeds radially from each probe hole during steaming. Probing or temperature measurement holes in the (P) region are used to determine the completion time for thawing.

In mining practice, the steam-probe spacing has varied from 0.6 to 1.2 m (2 to 4 ft) for thawing in tunnel work to as great as 2.1 m (7 ft) for rapid thawing of seasonally frozen ground. The time required for thawing varied with soil conditions. It was common to steam for eight to twelve hours and to adjust the spacing so that a one-day thawing cycle time was achieved. Greater spacing and longer thawing times were used for deeper thawing.

Two steam-thawing projects near Fairbanks, Alaska, were initiated to provide for preconstruction thaw and consolidation of ice-rich alluvial gravels. The sites were at the Fairbanks Airport Post Office in 1979 and the Big Dipper Recreation Center in 1981. At the post office site, steam pipes consisting of 38 mm (1.5 in) pipes slotted at the lower ends, were installed in pre-augered holes drilled in rows to 2 m above the bottom of the frozen gravel and spaced at intervals of 2.4 m (8 ft). The spacing between rows was 3 m (10 ft), with hole locations staggered in alternate rows. Steam was supplied by three mobile truck-mounted boilers, rated at a total of 65 boiler horsepower. A surface area of 2,950 m² (3530 yd²) was thawed to a depth of 12.2 m (40 ft) by periodic steam injections over a period of 105 days. Contractor comments regarding this work were that the hole spacing was too great for a satisfactory thawing rate and the boilers used appeared to have a significantly overrated thermal output.

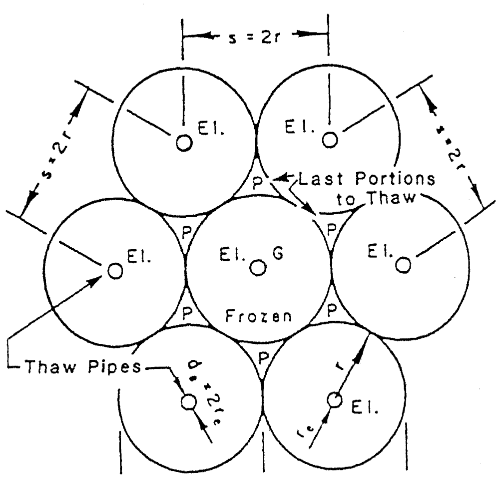

Figure 7.1. Plan view of radial thawing from thaw pipes installed on equilateral triangles.

Thawing at the Big Dipper site was performed to consolidate a 2 to 3 m (6 to 10 ft) layer of ice-rich silts and gravels as an alternative to a pile foundation. Two steam boiler trucks injected steam into pipes installed in borings on 1.5 m (5 ft) centers, and thawing was completed within one week.

More recent steam-thawing work has been done to prepare for additions at two of the Fairbanks, Alaska, high schools (Steve Adamczak, personal communication). In a 1986 addition to the Lathrop High School gymnasium, the excavation area included a zone of frozen fine sands covering an area of 9 × 17 m (30 × 55 ft). Steam probes were placed in predrilled holes on 1.5 m (5 ft) centers, extending to a depth of 6.1 m (20 ft). Steam was applied to each probe for periods of several hours, with steam supplied by a single boiler truck (Photo 1). Thawing was done continuously and was completed in twelve days at a cost estimated at $40 per cubic yard (0.76 cubic meter). In 1998 and 1999, a gymnasium and a theater were added to West Valley High School, where frozen fine sands with high moisture content were again encountered in portions of the excavation, extending below the water table to a depth of 6.6 m (22 ft). To avoid settling after construction and possible movement of the existing adjacent footings, the area was steam thawed and consolidated before the new addition was built. In the initial 1998 work, steam probes were placed in predrilled holes in staggered rows at locations about 1.5 m (5 ft) apart (Photo 2). Four temperature measurement strings were installed to monitor the thaw progression. Thawing work at this site was done using the same spacing and methods as at Lathrop High. Following this, frozen soils were encountered near the same site in preparing for the theater addition at West Valley. Thawing was done while driving probes by pushing and steam-pressure jetting operations (Photo 3), until the desired depth of 2.4 to 3 m (8 to 10 ft) was reached. Probes were placed on 0.6 to 0.9 m (2 to 3 ft) spacings, to speed the thawing work, which was completed in several days.

The rate of steam thawing depends on the temperature and pressure of steam injection and on the permeability of the thawed soil. If the steam expands and flows throughout the thawed column of soil surrounding the probe hole, heat transfer will be much more rapid than if the primary steam route is back alongside the probe. This uncertainty makes accurate thaw-rate calculations and cost predictions difficult.

Hot and Cold Water Thawing

The systems used for hot and cold water thawing are basically similar, with the exception of a heat exchanger or boiler stage used for hot-water thawing. In cold-water thawing, the maximum possible use should be made of solar energy to increase the temperature of the water prior to thawing. The application of water thawing should be confined to relatively free-draining granular soils; otherwise a quicksand quagmire may be created by the upward hydraulic gradients imposed by this method. Actual removal of soil fines by flushing, and improvements in soil permeability, have been reported by those using this method (Tsytovich, 1975).

The maximum speed and highest efficiency for water thawing will result when the primary water flow path is along the contact between the frozen and thawed soil. This ideal situation results when an open, porous soil structure occurs along the thawing front as the cone of thawed soil settles away from the thawing face (Figure 7.2).

Water quantities required in central Alaska for summertime cold water thawing of placer gravels, when holes are located at 4.9 to 9.8 m (16 to 32 ft) spacings, ranged from 4 to 8 m^3 of water per m^3 of soil thawed (800 to 1600 gal/yd^3). The time required for thawing was roughly 5 days/meter of depth for the 4.9 m spacing and 8 days/m for the 9.8 m hole spacing, (1.5& 2.33 days/ft) , according to dredge field thawing experience in the Fairbanks area reported by Crawford and Boswell (1948). In this area, the thawing season air temperature averages +11° C (52° F) and is approximately 165 days in length. More time and greater water quantities would be needed in cooler regions.

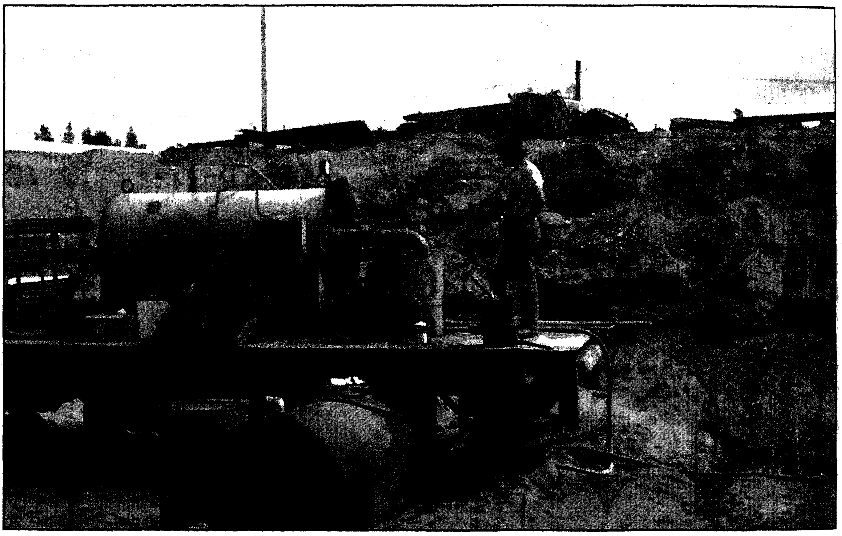

Photo 1: Steam boiler on truck, connected to thaw probes. (All photos in this series were provided by Steve Adamczak, Shannon and Wilson Consultants, Fairbanks.)

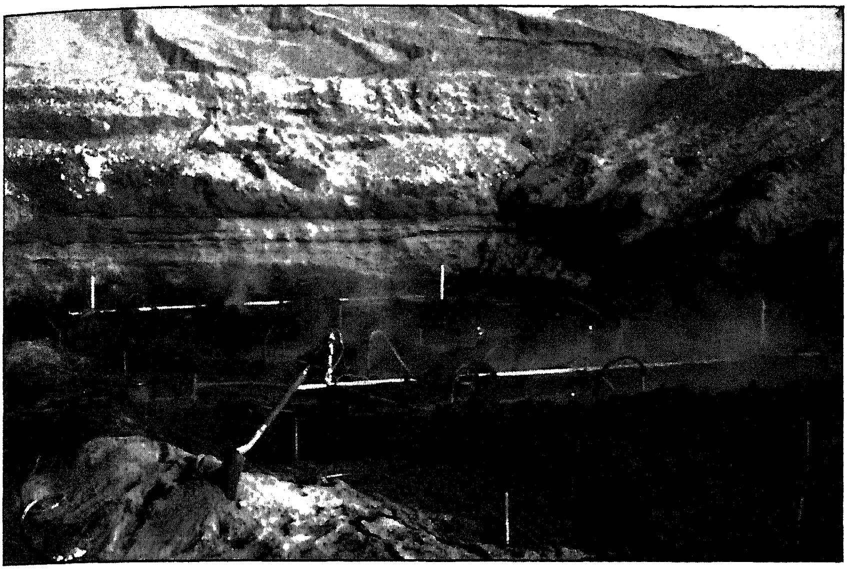

Photo 2: System of connected thaw pipes at West Valley High School, Fairbanks

Photo 3: Inserting thaw pipes while steaming holes

Cold-water thawing methods for the Fairbanks and Nome dredging operations became fairly standardized during the 1930s and 1940s, with predrilled holes located on 8.6 m (32 ft) centers to thaw to depths greater than 14 m (46 ft), and hand or machine-driven points on 4.3 m centers (16 ft) for deposits less than 14 m in thickness. Driven points used 19 mm (0.75 in) pipe fitted with 37 mm (1.5 in) wide, forged chisel tips which had open grooves leading from the water port toward the cutting edges of each chisel face. Those points were redriven daily to follow the advancing thaw front and were not intended to penetrate the frozen soil. It was reported that thawing efficiencies were higher for the deeper thaw holes due to the longer flow paths and greater time for heat exchange between soil and water (Cook, 1978).

Calculation of the thawing rates for different hole spacings, depths, water temperatures and pressures, and soil types is made difficult by the uncertainties of water-flow paths and the conductive and convective heat transfers involved in the problem.

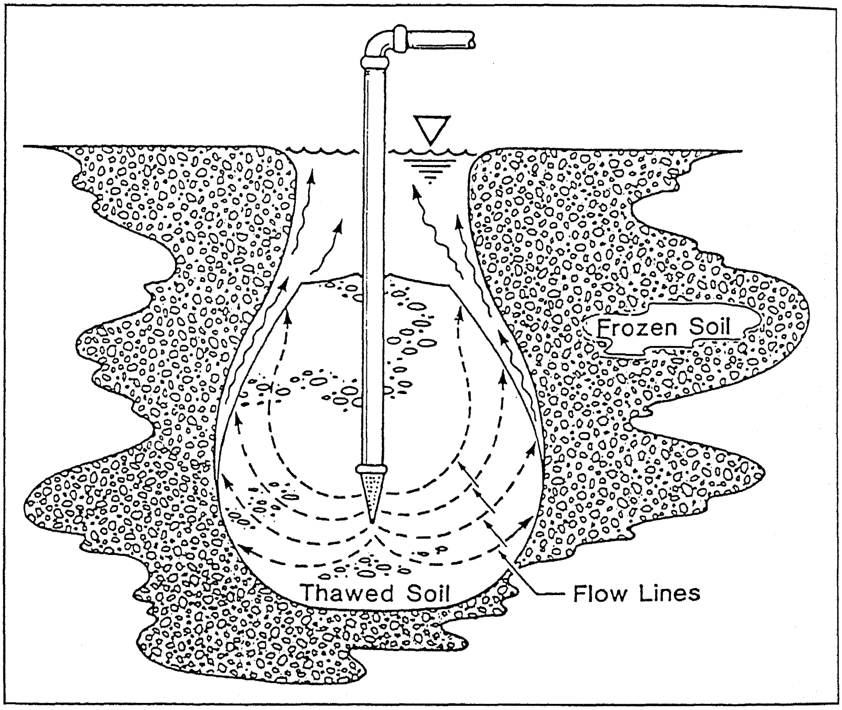

Figure 7.2. Sectional view of water flow to thawing face, in water thawing process

Electric Thawing

Electric heating of soil for purposes of thawing can be performed by inserting electrical resistance-wire elements into boreholes, by imposing an alternating current between electrodes inserted into the soil and using the soil's resistance to generate a "Joule" heating effect, or by thawing from the surface down by use of electrically heated blankets or wire loops. The first method is discussed by Jumikis (1966, 1985) but apparently is rarely used and will not be further discussed here. The latter approach has been used extensively in Russia (Rzhanitsin et al., 1963 and Tsytovich, 1975), but apparently has not been used in North America (Johnston, 1981).

The use of electrically heated blankets to accelerate thaw from the surface was tried experimentally near Prospect Creek during construction of the Trans-Alaska Pipeline, but unfortunately has been only minimally reported in the literature (Rooney, 2000). In this study, a deposit consisting of 1.5 to 2 m (5 to 7 ft) of ice-rich silt overlying a gravel till of low to moderate ice content was thawed to a depth of 9 m (30 ft) over a one-year heating period. The area treated was 920 m^2 (1100 yd^2). The purpose was to measure the amounts of thaw-related consolidation for validation of prediction models.

Electrical thawing with alternating currents is considered most suitable for silt and clay soils. In these slow-draining soils the introduction of additional water during thawing, as occurs during water or steam thawing, would result in undesirable increases in soil moisture. Electrical thawing has the additional advantage that it can be easily done in winter.

When an alternating voltage is imposed between a pair of electrode rods inserted into a homogeneous soil, the highest current flow density will be along the shortest path between the electrodes. Heat will be generated all along the current flow paths in proportion to the square of the current times the electrical resistance along each path, resulting in much more uniform heating than with other thawing methods. As a result of this uniform heating and thawing, consolidation also occurs more uniformly. Soil electrical resistance, commonly termed "resistivity," is expressed in units of ohm-meters. The electrical resistivity of soils generally decreases significantly during thawing, as shown in Figure 7.3. As a result, the electrical current flow and heat input will rise after thawing of the most direct current path between electrodes, and lateral heat transfer by conduction will become a factor in the rate of thawing. Because of the great variations between resistivity values of different soil types and soils of different salinities, erratic thawing patterns may occur in nonuniform soil conditions and more time will be required to complete the thawing operation, compared to rates in uniform deposits.

Electrical power supply systems for ground thawing should be sized based on the frozen and thawed soil resistivity and the volume of soil to be thawed. The critical factors that determine the rate of thawing are the electrode spacing, the soil resistivity, and the applied voltages. The electrical resistance (R) between a pair of parallel electrodes in a homogeneous medium may be calculated by the following formula (Jumikis, 1985):

$$R = (p/2\,\pi\,H_{el})\ ln(S/Re)$$

where
R = soil resistance, ohms
p = soil resistivity, ohm-meters
H_{el} = embedded length of electrodes, meters
S = electrode spacing, meters
Re = radius of electrodes, meters

The power (heating) input between the two electrodes may then be calculated by the electrical power formula:

$$P = \frac{V^2}{R}$$

where
P = power lost in heating the soil, watts
V = applied voltage, volts
R = soil resistance, ohms

Based on calculations of the total energy required to raise the soil from its initial temperature to the thawing point, to thaw the soil moisture, and finally to raise the soil to the desired final temperature, an estimation of the thawing time and energy requirements can be made. Allowances must be made in these calculations for heat losses to the surface and to the underlying soils. The calculated thawing energy for a silty clay with a frozen moisture content of 30% and an initial temperature of –2° C amounts to 100 kilowatt-hours (kWh) per cubic meter (76 kWh/yd^3), according to Jumikis (1985). Therefore, electrical energy costs for thawing appear to be reasonable, particularly if electrical transmission lines are accessible.

In practice, the voltages used for electrical thawing range from 110 to 440 volts. For safety, a grounded electrical system should be used and the site fenced off. Higher voltages have been used on occasion. A 10,000-volt thawing system was reportedly used for excavation of 3,000 cubic meters of soil prior to dam construction in the Magadan Region of Russia (Rzhanitsin et al., 1963). In Russian practice, electrodes of similar potential

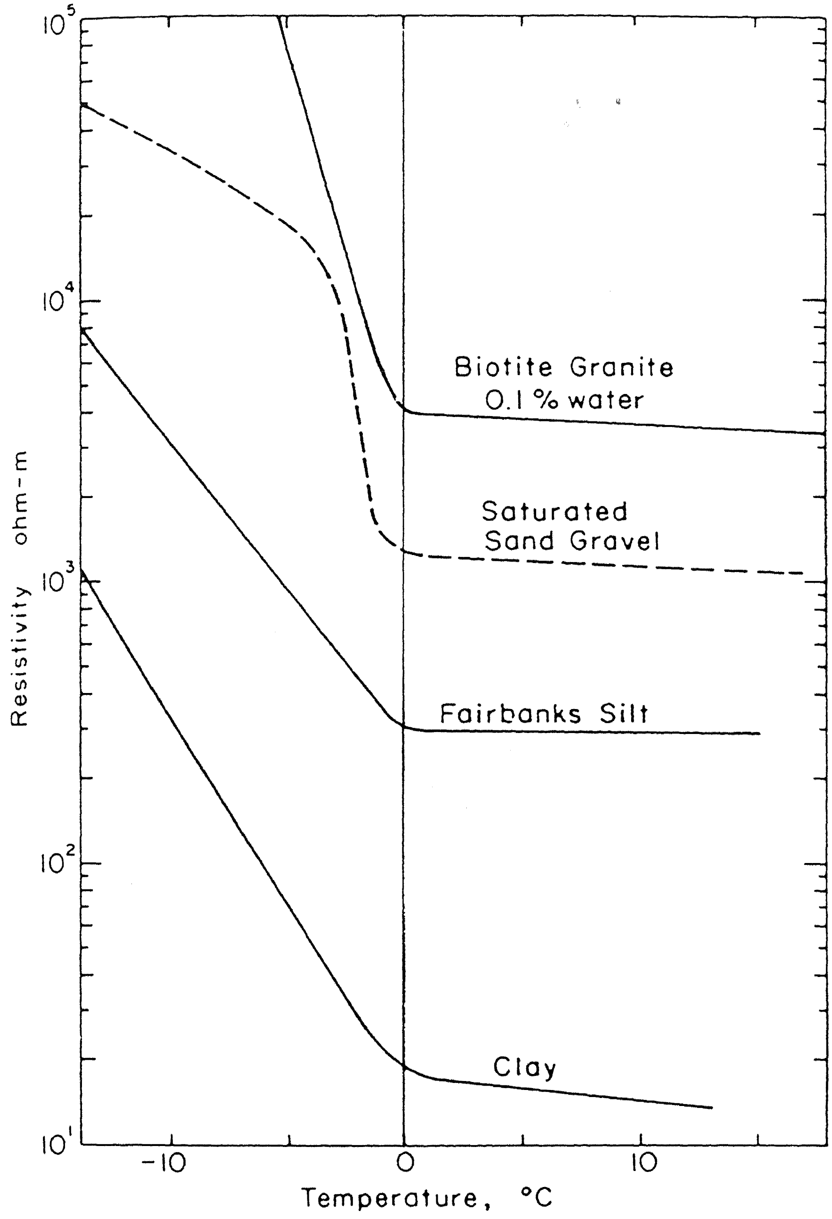

Figure 7.3. Resistivities for soils and granite rock as a function of temperature (after Hoekstra and McNeill, 1973).

are usually arranged in rows on 2 to 3 m centers (6 to 10 ft), with spacing between rows of 2.5 to 4.0 m (8 to 13 ft). Two alternatives are to use an equilateral triangular electrode array, which results in a hexagonal electrode arrangement (Jumikis, 1985) or a square grid layout with ground rods at the center of each square, as shown conceptually in Figure 7.4. The basic electrical circuit diagram for applying single-phase power on a square grid with center grounding is shown in Figure 7.5.

Electrodes may be either solid rods or water pipes, installed in predrilled holes or driven into the soil with vibrators or air hammers. When drilled holes are used, a calcium-chloride solution should be poured around the electrodes to provide good electrical contact. The use of drilled holes and perforated pipe electrodes, while more expensive than driven electrodes, provides a vertical drainage system for water generated by the thaw and consolidation process.

Consolidation can be accelerated by pumping from the electrode wells, or by electro-osmosis treatment of the soil following the AC thawing stage. In electro-osmosis, a DC voltage is applied to the electrodes and the soil pore-water migrates to the cathode where it is drawn off by a suction pump (Canada Institute for Scientific and Technical Information, 1981). Treatment by this method to consolidate a clayey soil typically takes 2 to 3 months and requires 60 to 80 kWh/m^3 (Rzhanitsin et al., 1963)

Solar Thawing

Solar thawing may be either active or passive. Active solar thawing refers to the use of a solar heat collector system combined with a pumping system to transfer that heat to the soil. Cold water thawing systems, where solar energy is used to warm the water prior to injection, is a form of active solar thawing. Discussions in this section will be confined to passive solar systems where direct solar surface heating is used and efforts are made to alter the surface energy balance, shown conceptually by Figure 6, to capture the maximum possible heat energy.

By increasing the incoming short-wave solar radiation reaching the soil surface and at the same time reducing the surface heat losses to the atmosphere that result from convection, reflection, evaporation of surface water, and surface radiation, the net energy flow into the ground can be increased and vertical thawing intensified. The simplest and most obvious surface modification is to strip away all surface cover and shade-causing vegetation and expose the soil surface to direct solar radiation, or to create the same effect by burning the organic cover. Long-term thaw acceleration induced by periodic brush removal and surface stripping has been studied

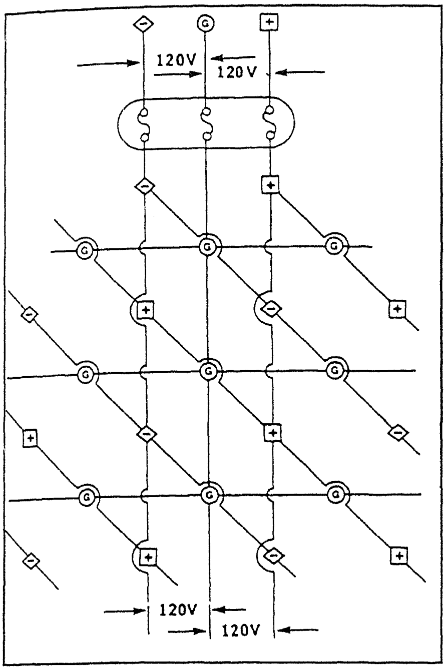

Figure 7.4: Suggested pattern for installation of ground-thawing electrodes with single-phase alternating current, for square grid with center grounding

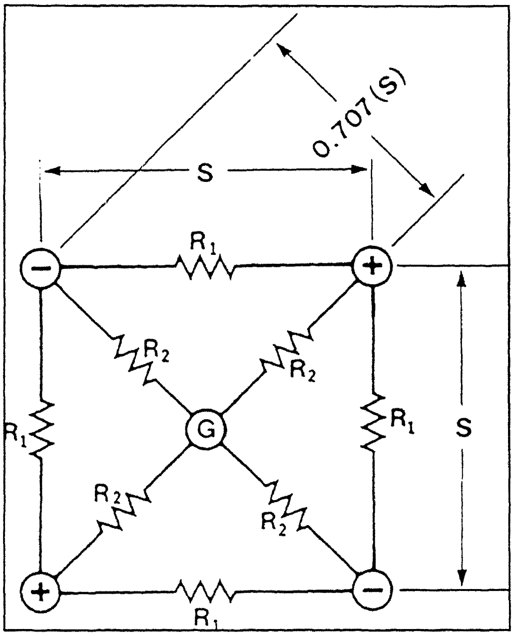

Figure 7.5: Basic single-phase electric thawing circuit for square grid array