CHAPTER 36

CONCRETE DAMS AND SUBSURFACE SOILS

REFRIGERATION is one of the more important tools of the heavy construction industry, particularly in the temperature control of large concrete dams. It is also used to stabilize both water-bearing and permanently frozen soil. This chapter briefly describes some of the cooling practices that have been used for these purposes.

CONCRETE DAMS

Without the application of mechanical refrigeration during construction of massive concrete dams, much smaller construction blocks or monoliths would have to be used, which would slow construction. By removing unwanted heat, refrigeration can speed construction, improve the quality of the concrete, and lower the overall cost.

METHODS OF TEMPERATURE CONTROL

Temperature control of massive concrete structures can be achieved by (1) selecting the type of cement, (2) replacing part of the cement with pozzolanic materials, (3) using embedded cooling coils, or (4) precooling the materials. The measures used depend on the size and type of structure and on the time permitted for its construction.

Cement Selection and Pozzolanic Admixtures

The temperature rise that occurs after concrete is placed is due principally to the cementing materials' heat of hydration. This temperature rise varies directly with cement content per unit volume and, more significantly, with the type of cement. Ordinary Portland cement (Type I) releases about 180 Btu/lb, half of which is typically generated in the first day after the concrete is placed. Depending on specifications, Type II cement may generate slightly less heat. Type IV is a low-heat cement that generates less heat at a slower rate.

Pozzolanic admixtures, which include fly ash, calcined clays and shales, diatomaceous earths, and volcanic tuffs and pumicites, may be used in lieu of part of the cement. Heat-generating characteristics of pozzolans vary, but are generally about one-half that of cement.

When determining system refrigeration load, heat release data for the cement being used should be obtained from the manufacturer.

Cooling with Embedded Coils

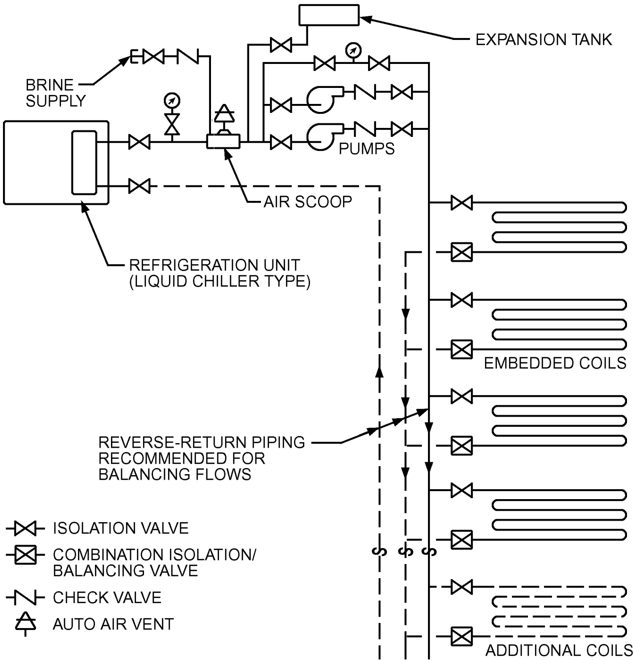
In the early to mid-1900s, the heat of curing on large concrete structures was removed by embedded cooling coils for glycol or water recirculation. These coils also lowered the structure's temperature to its final state during construction. This is desirable where volumetric shrinkage of a large mass is necessary during construction (e.g., to allow the contraction joint grouting of intermediate abutting structures to be completed).

In an embedded coil system, thin-wall tubing is placed as a grid-like coil on top of each 5 or 7.5 ft lift of concrete in the monoliths. Chilled water is then pumped through the tubing, using a closed loop system to remove the heat. A typical system uses 1 in. OD tubing with a flow of about 4 gpm through each embedded coil. Although the number of coils in operation at any time varies with the size of the structure, 150 coils is not uncommon in larger dams. Initially, the temperature rise in each coil can be as much as 8 to 10°F, but it later becomes 3 to 4°F. An average temperature rise of 6°F is normal. When sizing refrigeration equipment, the heat gain of all circuits is added to the heat gain through the headers and connecting piping.

For a typical system with 150 coils based on a design temperature rise of 6°F in the embedded coils and a total heat loss of 6°F elsewhere, the size of the refrigeration plant is about 300 tons. Figure 1 shows a flow diagram of a typical embedded coil system.

Cooling with Chilled Water and Ice

The actual temperature of the mix at the time of placement has a greater effect on the overall temperature changes and subsequent contraction of the concrete than any change caused solely by varying the heat-generating characteristics of the cementing materials. Further, placing the concrete at a lower temperature normally results in a smaller overall temperature change than that obtained with embedded-coil cooling. Because of these inherent advantages, precooling measures have been applied to most concrete dams.



Note: Provide manual air vents at system high points and each loop.

Fig. 1 Flow Diagram of Typical Embedded Coil System

The preparation of this chapter is assigned to TC 10.1, Custom-Engineered Refrigeration Systems.

Glen Canyon Dam illustrates the installation required. The concrete was placed at a maximum placing temperature of 50°F during summer, when the aggregate temperature was about 87°F, cement temperature was as high as 150°F, and the river water temperature was about 85°F. Maximum air temperatures averaged over 100°F during the summer months. The selected system included cooling aggregates with 35°F water jets on the way to the storage bins, adding refrigerated mix water at 35°F, and adding flaked ice for part of the cold-water mix. Subsequent cooling of the concrete to temperatures varying from 40°F at the base of the dam to 55°F at the top was also required. The total connected brake power of the ammonia compressors in the plant was 6200 hp, with a refrigeration capacity equal to making 6000 tons of ice per day.

The maximum amount of chilled water that may be added to the concrete mix is determined by subtracting the amount of surface water from the total mix water, which is free water. Frequently, if a chemical admixture is specified, some water (usually about 20% of the total free water) must be added to dissolve the admixture. This limits the amount of ice that can be added to the remaining 80% of free water available. After the amount of ice needed for cooling is determined, the size of the ice-making equipment can be fixed. When determining equipment capacity, allowances should also be made for cleaning, service time, and ice storage during nonproductive times.

When calculating heat removal, consider ice to be 32°F when introduced into the mixer. Chilled water is assumed to be 40°F entering the mixer, even though it may be supplied at a lower temperature.

Cooling by Inundation

The temperatures specified today cannot be achieved solely by adding ice to the mix. In fact, it is not possible on heavy construction of this type (in view of low cement content and low water/cement ratio specified) to put enough ice in the mix to obtain the specified temperatures. As a result, inundation (deluging or overflowing) of aggregates in refrigerated water was developed and was one of the first uses of refrigeration in dams.

When aggregates are cooled by inundation with water, generally the three largest sizes are placed in large cylindrical tanks. Normally, two tanks are used for each of the three aggregate sizes to provide back-up capacity and a constant flow of materials. Cooling tanks, loaders, unloaders, chutes, screens, and conveyor systems from the tanks into the concrete plant should be enclosed and cooled from 45 to 40°F by refrigeration units, with blowers placed at appropriate points in the housing around the tanks and conveyors.

Peugh and Tyler (House 1949) determined the inundation (or soaking) time required by calculations and actual tests. Pilot tests corroborated their computations of aggregates' cooling times as indicated in Table 1.

Table 1 Temperature of Various Size Aggregates Cooled by Inundation

Time, min.	Aggregate Size, in. 6	3	1.5	0.75	0.375
1	85°F	69°F	49°F	39°F	38°F
2	77	59	41	38 (42)	
5	66	46 (45)	38 (42)		
10	56	40 (42)			
15	50	38			
20	46				
25	44				
30	42				
40	40				
50	39				

Source: Peugh, V.L. and I. Tyler. 1934. "Mathematical theory of cooling concrete aggregates." In House (1949). Numbers in parentheses are from tests by R. McShea.

Note: Temperatures listed are at cobble center with assumed thermal diffusivity of 0.07 ft^2/h. Aggregate initial temperature is 90°F and cooling water temperature is 35°F.

This study indicated that immersion for about 40 min brings the aggregate down to an average temperature of 40°F. Theoretically, smaller sizes can be brought to the desired temperature in less time. Considerations such as the rate at which cooling water can be pumped make it unlikely that a cooling period less than 30 min should be considered. Any excess cooling provides the needed safety factor. However, the limiting factor on the overall cycle is the cooling time for the largest aggregate, which is nearly 45 min, plus about 15 min for loading and unloading. Back-up capacity should be considered for maintaining a constant flow of materials.

Air-Blast Cooling

Air-blast cooling, a more recent development than inundation, does not require particular changes to material handling or additional tanks for inundation; instead, cold air is blown through the aggregate in batching bins above the concrete mixers. Also, the air cycle used in cooling can be used in heating aggregates during cold weather. The aggregate is cooled during the final stage of handling; this does not increase the moisture content.

The compartmented bins where air-blast cooling usually occurs are generally sized so that if any supply breakdowns occur, the mixing plant will not have to shut down before a particular pour can be completed. On this basis, the average concrete octagonal bin above the mixing plant on a large job holds at least 600 yd^3, which is usually more than adequate to allow time for air cooling. However, certain minimum requirements must be considered. If possible, based on a 1 h loading and cooling schedule, at least 2 h of storage volume should be provided for each size aggregate that air will cool. The minimum volume should be 1.5 h plus cycling time, based on the tables shown for cooling 6 in. aggregate.

The bin compartment analysis shown in Table 2 may be used as a starting point in determining the air refrigeration loads and static pressures. This type of analysis should give approximately equal storage periods for each aggregate size used. In practice, after air-cycle cooling is calculated, more air volume is needed in the smaller aggregate compartments, and less in the sand and aggregate, to obtain maximum cooling. This is because of the higher air resistance in the smaller aggregate sections and the fact that air does not cool the sand compartment as effectively.

Computing Air-Blast Cooling Loads. To calculate the required cooling, several assumptions must be made:

Assumption 1. Normally, the lowest temperature of air leaving the cooling coils is 38 to 40°F. Lower air temperatures may be achieved, but should not be trusted: a temperature lower than 35°F usually causes rapid frosting of the coils.

Assumption 2. Heat transfer between the aggregate and air is only 80 to 90% effective. To allow for air temperature rise in the ducts, heat leakage, pressure drop, etc., an empirical factor of 85% may be used.

Table 2 Bin Compartment Analysis for Determining Refrigeration Loads and Static Pressures

Material Size, in.	lb/yd^3	% of Total	No. of Bin Compartments	Bin %
Stones				
6 to 3	800	21.33	4	25.00
3 to 1.5	700	18.67	3	18.75
1.5 to 0.75	650	17.33	2	12.50
0.75 to 0.25	600	16.00	3	18.75
Sand	1000	26.67	4	25.00
Total	3750	100.00	16	100.00

Note: In practice, relative sizes vary; amounts shown are for an assumed design mix of principal classes of concrete. On any given job, several design mixes requiring different amounts for each size are needed.

Table 3 Resistance Pressure

Aggregate Size, in.	Velocity, fpm	Resistance Pressure, in. of water/ft of ht.
6 to 3	300	0.29
3 to 1.5	200	0.32
1.5 to 0.75	100	0.27
0.75 to 0.25	60	0.30

Thus, with 80°F aggregate and 40°F cooling air, the effective temperature differential would be 0.85(80 – 40) = 34°F.

Assumption 3. The rise in temperature of air passing through the aggregate compartment normally will not exceed 80% of the difference between the entering aggregate and the entering air temperatures. Thus with 80°F aggregate and 40°F air, the temperature rise of the air is 0.80(80 – 40) = 32°F. The maximum temperature of the return air is 40 + 32 = 72°F.

Assumption 4. An allowance should be included for heat leakage into air ducts on the aggregate bin sides, normally about 2% of a total air-blast cooling load.

Another important consideration is the static pressure against air flowing through a body of aggregates. The resistance to air flowing through a bin varies as the square of the air volume or velocity; this is summarized in Table 3. The resistance pressure listed is for a unit height of aggregate. To use values in Table 3, the cross-sectional area of the aggregate compartment and the height of the aggregate column must be known. Manufacturers of concrete mixing bins and mixing equipment can supply this information.

Other Cooling Methods

As specifications require lower and lower placing temperatures, direct methods of cooling sand and cement have been attempted to obtain or lower the heat removal required. No method has been proven to cool cement. Sand-cooling methods that have been tried and found to be unsuccessful are

- **Water inundation.** The increase in free moisture content of batched sand makes correctly proportioning the mix difficult.
- Moving sand through **screw conveyors with hollow flights**. Chilled water was pumped through the flights, but because components were cooled below the dew point, resulting in condensation, serious handling problems occurred.
- **Vacuum systems,** which evaporate surface moisture to reduce aggregate temperature. The unreliability of the equipment and the batch nature of the process precluded success.

An alternative method of cooling sand, **air cooling**, is being tried on some projects, but it is too early for final results of this method.

For small pours, **liquid nitrogen** is sometimes used to reduce the temperature of the mixture to the final pour temperature. Nitrogen is used because the initial capital costs are considerably lower than a mechanical system, but because of the high cost of manufacturing nitrogen, the operation cost is much greater than a mechanical system. Cost comparison must be done on a case-by-case basis.

SYSTEM SELECTION PARAMETERS

For larger installations, plant selection depends on a number of factors, including the following:

- Normal pouring rate, yd^3/h (contractor or contract specified).
- Maximum pouring rate, yd^3/h (contractor or contract specified).
- Total allowable mixing water, lb/yd^3 (usually contract specified).
- Required concrete placement temperature (usually contract specified).
- Concrete temperature when coming from the mixer (to be determined considering materials handling to placement site, time in transit, and storage at placement site).
- Average ambient temperature and aggregate temperature during period of maximum placement. The average ambient temperature of the aggregates is assumed to be the mean ambient temperature (including night and day) during the period of storage, which is determined by the amount of storage capacity provided by the contractor and the rate of concrete placement. If the minimum live storage is, for example, 100,000 tons of aggregates and the pouring rate is 2000 yd^3/day, consumption is approximately 3800 tons of aggregates per day. If the job is working a 6 day week, this provides 26 days of storage. Unless weather conditions are unusual, the temperature of rock delivered to the reclaiming tunnel is assumed to equal the average ambient temperature for the 26 days preceding the delivery.
- Specific heat of materials. The specific heat of the aggregates and sand may vary with project location. Typical values are sand = 0.106 Btu/lb·°F; aggregates = 0.12 Btu/lb·°F; water = 1.0 Btu/lb·°F; cement = 0.12 Btu/lb·°F.
- Heat release rate for cement (material specifications).

Where the aggregate cooling range from initial to final temperature of the mix is relatively small (15 to 20°F), or where the required pour temperature is relatively high (65°F or more), chilled water plus ice in the mix or chilled water plus air blast on larger aggregates may handle the entire cooling load. When the overall temperature reduction is greater than this, or when lower pour temperatures are specified, such as 50°F or less, a combination of all three types of cooling will probably be required because only a limited amount of heat removal can be obtained by one of these methods alone.

Cooling by air blast alone is limited by the entering air temperature, which must be maintained high enough to prevent coil frosting. Cooling by inundation, although it requires large inundation tanks, offers the most positive and sure method of cooling. Ice can also be added to the mix to remove the remainder of the heat. The result is a very satisfactory blending of the aggregates and exact control of the amount of water in the mix.

CONTROL OF SUBSURFACE WATER FLOW

Refrigeration has been used successfully since 1880 to freeze moisture in unstable and water-bearing soil and to stop underground flows of water in pervious material or gravelly stream beds. Other common methods of stopping water flow include sheet piling, cement grout, chemicals, and well points. In many cases, freezing has been the last resort after other methods are unsuccessful. In a number of cases, a combination of well points, grouting, and freezing has solved the problem.

Applications include

- Deep excavations for building foundations (to prevent water from seeping into the excavation before the foundation is poured)
- Deep ditches for laying pipe (to keep the banks from sliding in)
- Large dam excavations (to stop water seepage until the dam footings are poured)
- Mining (to temporarily stabilize areas affected by water seepage)

Using refrigeration, the common practice is to lay a series of concentric pipes in a line or arch pattern in the path of the subsurface water flow. A wall of earth is frozen by pumping cold brine down the inside pipe and letting it flow back through the annular space between the inside and outside pipe. The growth of frozen soil on the outside of the concentric pipe proceeds until it connects with the frozen cylinder formed on the adjacent pipe.

Spacing between pipes can vary, depending on the time available to complete the wall of ice, but spacings of 2 to 4 ft on center have been used successfully. Freezing pipes have been successfully used to control subsurface water in both dam and

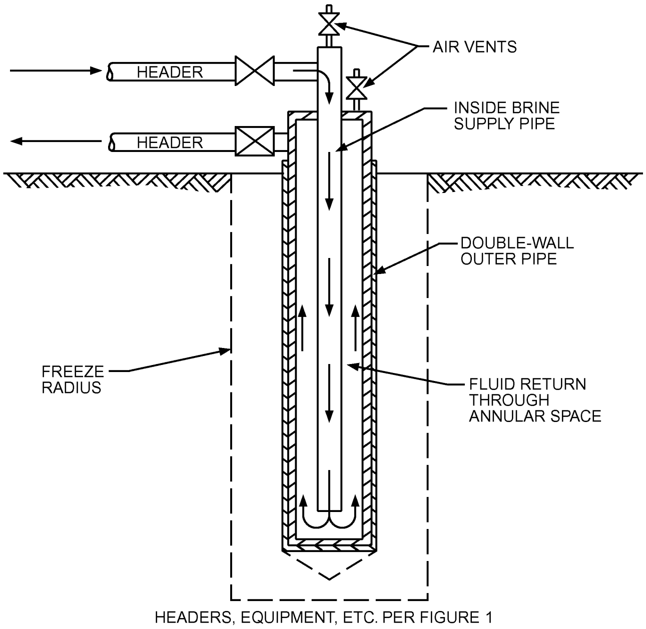


Fig. 2 Typical Freezing Point

mining projects. Figure 2 shows a typical freezing pipe and system diagram.

The brine or refrigerant and method of containment should be carefully selected in system design. If a leak develops in the system, groundwater contamination could result or the soil saturated with the refrigerant may have to be excavated and cleaned, depending on the type of refrigerant used. Double-wall piping, or an environmentally safe refrigerant that vaporizes when exposed to air, should be considered.

Ammonia is generally the basic refrigerating medium, and brine, chilled by the ammonia, is circulated through the freezing pipes. The brine is commonly calcium chloride ($CaCl_2$), but magnesium chloride ($MgCl_2$) is recommended because it is less likely to precipitate and clog piping at low temperatures. To monitor freezing progress, thermocouples are normally located throughout the area to be frozen. Brine temperatures may range from +15 to –20°F, depending on the state of freezing and amount of time available to complete the task.

Liquid nitrogen has been used for small projects.

SOIL STABILIZATION

In latitudes where areas of permanently frozen earth, or permafrost, prevail, methods of soil stabilization for building and equipment foundations are required. These methods range from providing a non-frost-susceptible gravel pad to rigid below-grade insulation plus an active or passive refrigeration system to freeze the soil and keep it frozen. Because many systems are in remote areas, simplicity and reliability are major factors in system design.

THERMAL DESIGN

Piling Design

Frost heave has long been a problem for designers of piles and buildings in the arctic or subarctic. Uplift forces as high as 13.5 tons/ft of perimeter must be taken into account when designing nonthermal piling (Long and Yarmak 1982). Designers have used sleeves, greases, waxes, and plastics to reduce the adfreeze bond in the active layer and to reduce frost heave forces, but Long and Yarmak found that almost all these methods were only temporary. Increased pile embedment remains the only sure way to prevent frost heaving of conventional piling. Thermopiles can effectively eliminate frost heaving forces. The thermopile freezes the active layer radially from the pile. As a result, active layer temperatures adjacent to the pile remain at the same temperature as the rest of the pile.

Slab-on-Grade Buildings, Outdoor Slabs, and Equipment Pads

When a slab-on-grade building, outdoor slab, or equipment pad is constructed on a permafrost area, the resulting soil thawing or thaw bulb must be considered. Thermopiles, thermoprobes, or an active refrigerated foundation system may be required to stabilize the structure, slab, or pad.

Design Considerations

Soil properties have a pronounced effect on the capacity requirements for passive or active refrigeration systems. Soil within the radius of influence is an integral part of the refrigeration system. Highly conductive soils increase the system’s radius of influence and allow more heat to be pumped out of the subsoils. Conversely, poorly conductive soils reduce the radius of influence; thermal lag through the soils is high, and the heat transfer rate low. Soil moisture contents and soil classifications are valuable for estimating thermal conductivities. Back-up capabilities for active and passive systems should be considered to avoid foundation failure.

PASSIVE COOLING

The three processes used by passive systems for heat removal are air convection, liquid convection, and two-phase liquid/vapor convection. All passive refrigeration systems rely on the temperature differential between the soil and winter air to operate. When the temperature of soil in contact with the refrigeration system is lower than the air temperature, the system is dormant.

Air Convection Systems

Air convection has been used to provide subgrade cooling below on-grade and pile-supported structures. For a passive air convection system to work, two design criteria must be met: the air outlet must be higher than the inlet to promote convection, and the air distribution system must be designed so that the friction imposed by the distribution system is low enough to allow convection to begin. Air convection systems are usually designed to take advantage of the prevailing winds at a specific site. The wind can push air through a distribution system at greater velocities than convection would allow; however, wind in the arctic frequently carries large quantities of snow. Distribution ducts can be blocked by snow and ice, causing the system to fail (Long and Yarmak 1982). Ducting fans are built into many air convection systems for active refrigeration back-up.

Liquid Convection Systems

Liquid convection has been used to provide subgrade cooling below on-grade structures. Radiator and heat absorber portions of the system are normally connected by either a double or single pipe with a flow splitter to decrease frictional losses in the system and to provide maximum cooling of the working fluid. Examples of some working fluids are trichloroethylene, kerosene, and methanol and water. Frictional losses within the liquid system are high and limit heat transfer rates. Large-diameter pipes may be used to overcome frictional losses so that high heat transfer rates can be achieved. Some liquid convection systems allow an option for mechanical circulation of the working fluid as an active refrigeration back-up. Liquid systems must be sealed to avoid leakage into subsoils. Introducing the working fluid into permafrost subsoils could depress the soil freezing point and increase the probability of foundation failure.

Two-Phase Systems (Heat Pipes)

Two-phase liquid/vapor convection systems are the most widely used passive refrigeration systems for permafrost foundations and earth stabilization. A typical two-phase unit is constructed of pipe enclosed at both ends and charged with a passive refrigerant gas. The radiator (aboveground condenser) portion of the unit can have a bare or finned surface, depending on heat transfer requirements (Figure 3). The evaporator portion of the unit can have any configuration as long as a slope remains between the evaporator and the radiator (Figure 4).

Refrigeration of the subgrade occurs when the radiator has a lower temperature than the soil in contact with the bottom of the evaporator, where the liquid portion of the refrigerant pools (Yarmak and Long 1982). Condensation occurs in the radiator, initiating evaporation of the refrigerant in the evaporator. The condensate wets the walls of the unit and flows down to the evaporator. Reevaporation of refrigerant condensate with subsequent cooling occurs where the soil in contact with the evaporator is warmer than the soil adjacent to the liquid pool of refrigerant at the bottom of the unit. Then the entire evaporator unit is reduced in temperature, cooling the surrounding soil.

A two-phase system can start with a temperature differential as little as 0.01°F between the radiator and the evaporator. Liquid and air convection systems may require temperature differentials of 4 to 15°F before they start.

Propane, butane, halocarbons, anhydrous ammonia, and carbon dioxide have been used as the refrigerant gas in two-phase systems. Choice of refrigerant gas depends primarily on the allowable internal pressure capabilities of the vessel containing the gas, quality of available gases, molecular stability of the gas, and preference of either the customer or manufacturer of the system. Relatively low-pressure systems using propane, halocarbons, or anhydrous ammonia have been known to gas lock (i.e., gases other than the refrigerant accumulate in the radiator portion of the unit and prevent the refrigerant gas from condensing). Purging or venting of noncondensable gases may be required after start-up.

ACTIVE SYSTEMS

Active ground-freezing refrigeration systems are used to keep building or equipment foundations stable when a passive system will not maintain the required stability. The system is normally a network of underground ductwork or piping through which a cooling fluid flows. Heat is removed using a heat exchanger or cooling coil, with refrigeration provided by medium- or low-temperature refrigeration units. System design can include provisions to bypass the refrigeration units during cold weather. Outside air should

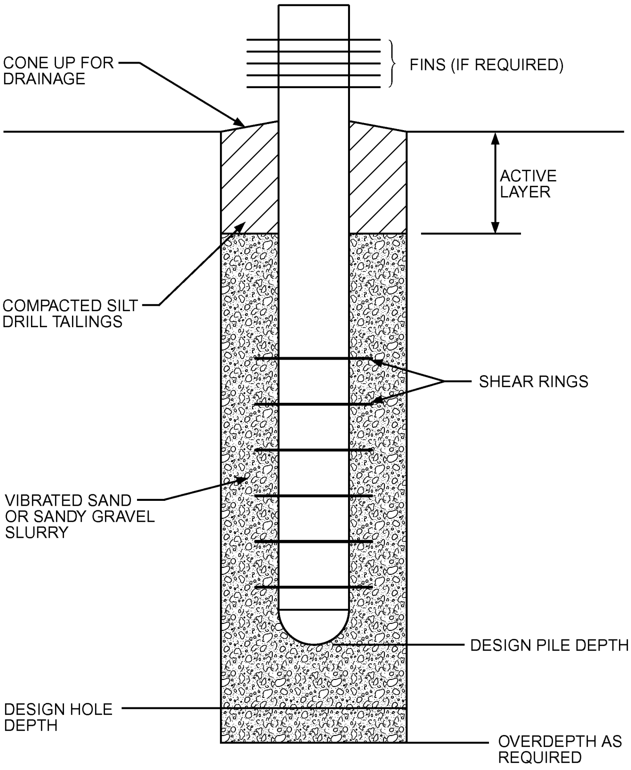


Fig. 3 Thermo Ring Pile Placement

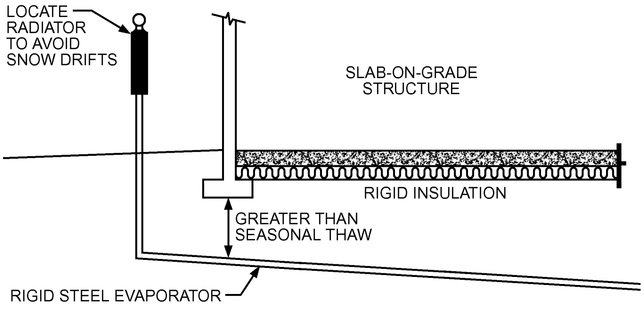
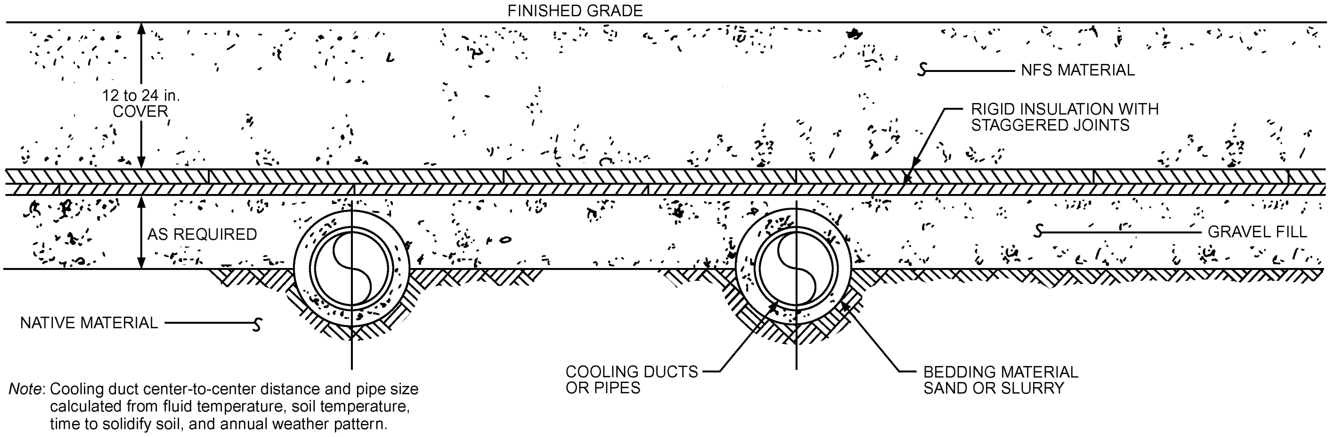


Fig. 4 Typical Thermo-Probe Installation



Note: Cooling duct center-to-center distance and pipe size calculated from fluid temperature, soil temperature, time to solidify soil, and annual weather pattern.

Fig. 5 Active Ground Stabilization System

not be used directly in systems that use air as a cooling fluid because moisture can be introduced into the system in the form of snow and humidity. A defrost system for the cooling coil in a circulating air system should be considered. Figure 5 shows a typical system installation.

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Related Commercial Resources