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Sherard

[11] **3,720,065**

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[54] **MAKING HOLES IN THE GROUND AND FREEZING THE SURROUNDING SOIL**

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[21] Appl. No.: **160,146**

Related U.S. Application Data

[63] Continuation of Ser. No. 838,219, July 1, 1969, abandoned.

[52] **U.S. Cl.**.....**61/36 A,** 61/53.64, 175/17, 175/20

[51] **Int. Cl.**.....**E02d 3/12**

[58] **Field of Search**.....61/36, 39, 53, 53.52, 53.64, 61/36 A, 11; 166/302, 278; 175/17, 20

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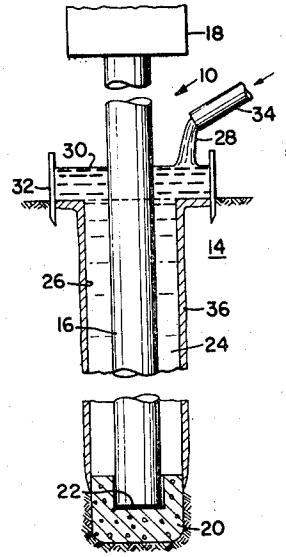
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[57] **ABSTRACT**

A method and apparatus for forming holes in the ground and for freezing the soil forming the walls of the holes for the purpose of temporarily solidifying zones of unstable soil adjacent to excavations and for forming open holes in unstable soil below the water table that are useable to make cast-in-place concrete piling, sand drains and water wells. The general method comprises the steps of forming a hole in the ground by driving or pushing a mandrel downward, which mandrel has a stem with cross-sectional area smaller than a drive foot on its lower end; supplying a flowable material in the space in the ground around the mandrel stem which prevents the hole from caving in, keeps the ground water out of the hole and freezes the soil surface comprising the walls of the hole.

17 Claims, 13 Drawing Figures



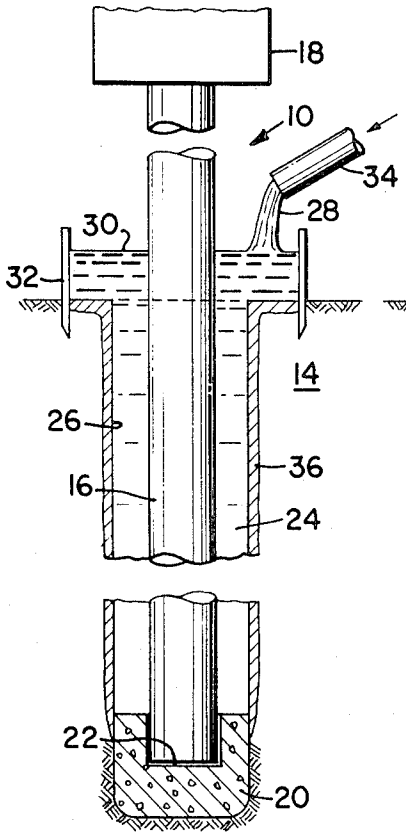


FIG_1

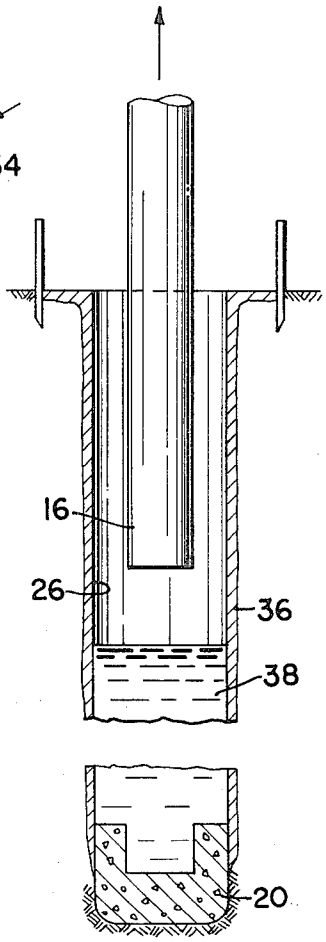


FIG_2

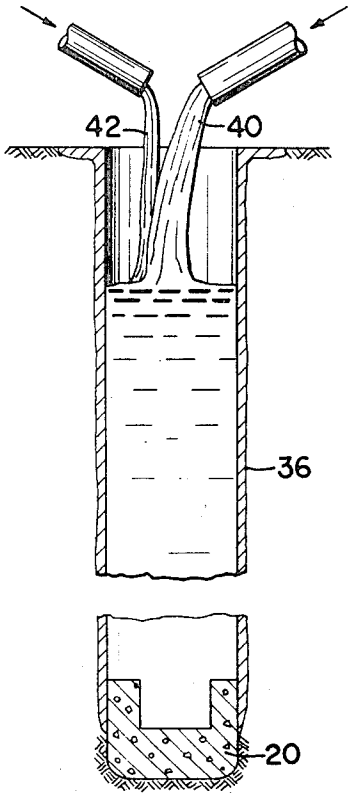


FIG_3

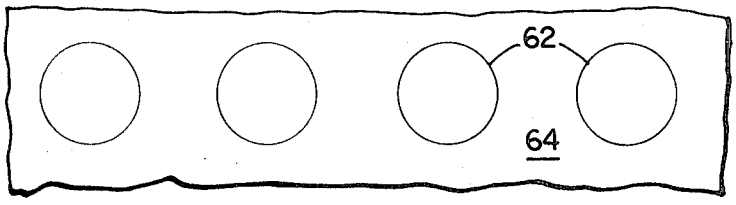


FIG_7

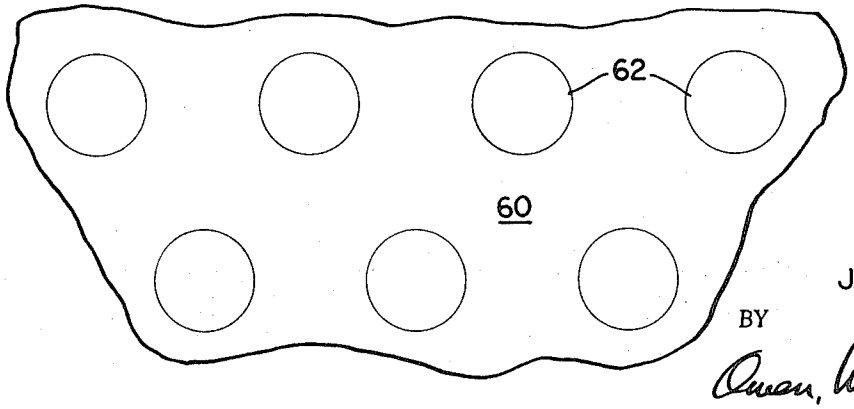


FIG_8

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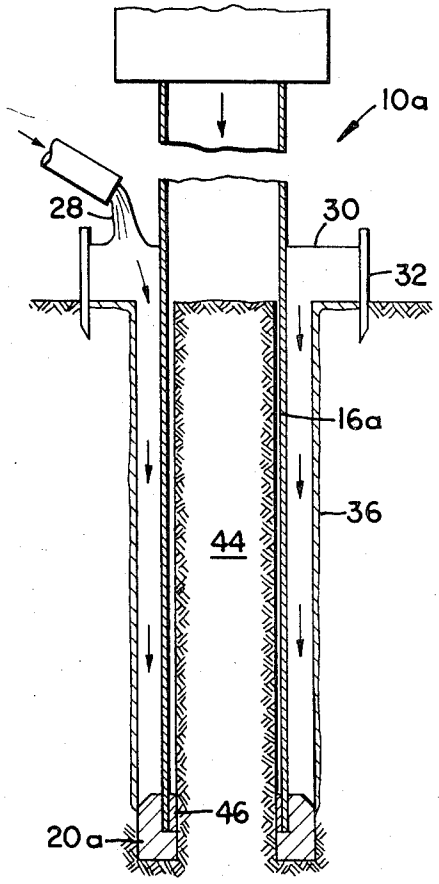


FIG_4

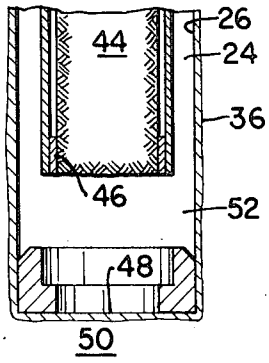


FIG_4A

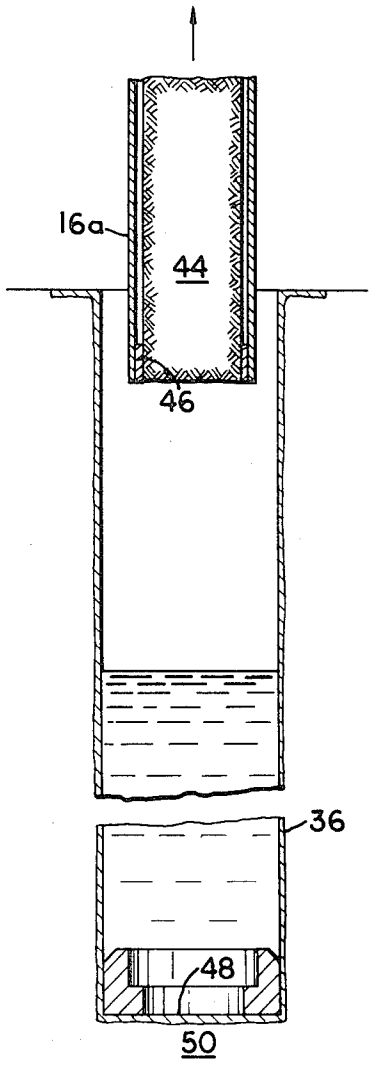


FIG_5

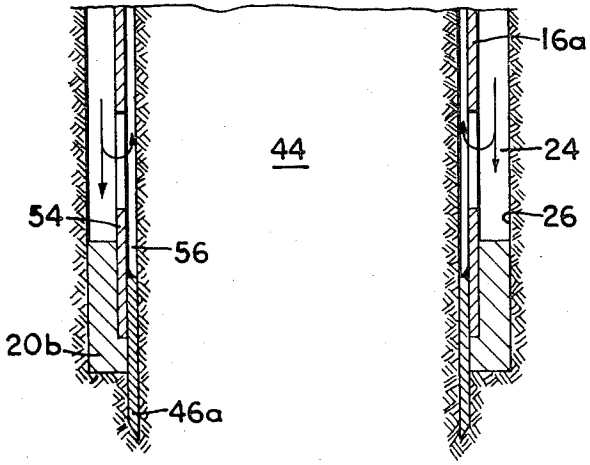


FIG_6

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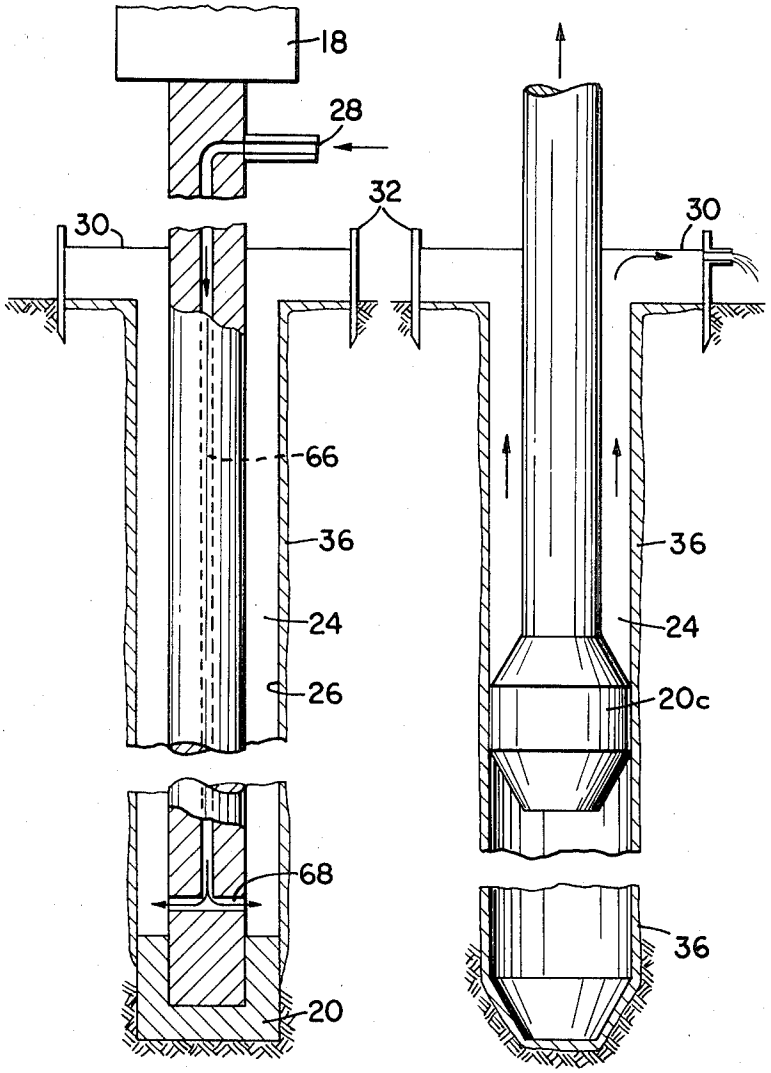


FIG_9

FIG_10

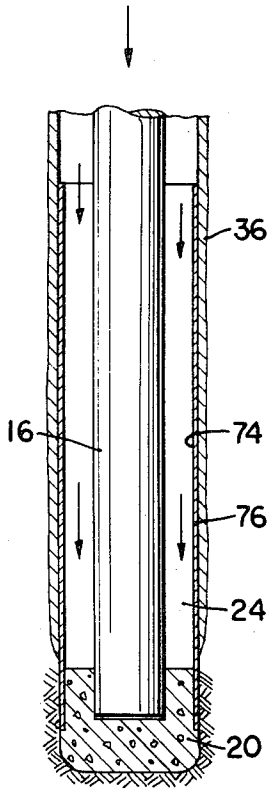
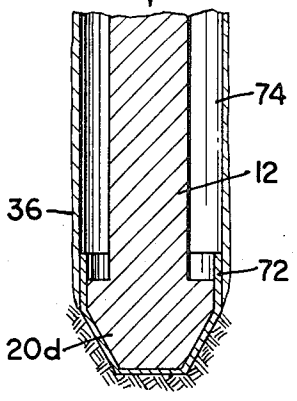


FIG_11

FIG_10A



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MAKING HOLES IN THE GROUND AND FREEZING THE SURROUNDING SOIL

This application is a continuation of application Ser. No. 838,219, filed July 1, 1969, now abandoned.

This invention relates to a method of forming a hole in the ground while freezing the soil surrounding the hole, and is adaptable for making holes below ground for such purposes as forming cast-in-place concrete piling, sand drains, and water wells; or for making a series of relatively closely spaced holes in the ground to freeze and thereby stabilize soil surrounding the holes for construction purposes.

In prior art methods for making holes in the ground in saturated or unstable ground, for such purposes as making cast-in-place concrete piling, water wells, etc., the walls of the holes were prevented from caving and the ground water was prevented from entering the hole by one of two main techniques, either a metal casing was installed or the hole was kept filled with a liquid, such as a colloidal mud. Depending on the type of structure being formed in the hole and the construction method employed, the metal casing or internal fluid was either subsequently left in place and incorporated as a part of the structure or removed from the ground. In both of these main prior art methods certain technical and economic disadvantages and problems arose associated with holding the hole open and preventing the entry of ground water from the walls of the hole. I discovered that these problems could be solved in making holes in the ground below the water table by creating a thin skin or casing of frozen soil on the peripheral surface of the hole. Such a temporary, frozen skin is impervious, has considerable strength and, as a result, can prevent the hole from caving and keep out the ground water. I have found that this method of forming the hole in the ground is technically satisfactory for the construction of cast-in-place concrete piling, sand drains, and water wells and is considerably more economical than the prior art methods in many circumstances.

It is well known that in unstable wet soil such as loose sands below the water table and in soft, wet silts and clays, it is difficult and expensive to make excavations for tunnels, shafts, deep building foundations and the like. However, such materials can be transformed temporarily to relatively hard and impervious materials by freezing them. An early method of freezing soils for construction purposes consisted primarily of circulating cold brine through a closed pipe circulation system, the brine being cooled by a refrigerating plant. More recently attempts were made to freeze the soil for construction purposes using low temperature liquified gases which were circulated through closed pipe circulation systems installed in boreholes. However, the cost of freezing soil by such methods was so high that the procedure was used only rarely in civil engineering construction and usually only in emergency situations. Freezing was used to some extent to solidify the ground around mine shafts at relatively great depths (e.g. 1,500 to 2,000 feet) because it was the cheapest method available for this problem. For shallow excavations, however, such as to depths of 100 feet or less, the cost of freezing by prior art methods was so high relative to other methods of construction that it was rarely employed prior to the present invention.

It is, therefore, a general object of the present invention to provide a method of making a hole in the ground and freezing the soil surrounding it which overcomes the technical disadvantages of the prior art methods and which is more economical and rapidly carried out than any other method.

Another general object of my invention is to provide a method for making holes in the ground for such purposes as forming cast-in-place concrete piles, sand drains and water wells in unstable soils below the water table in which a frozen soil casing prevents the hole from caving and keeps the ground water out, thereby eliminating the need for a metal casing or mud in the hole.

In general, my method comprises driving or forcing a straight, elongated structural member, which will be called herein a "mandrel," into the earth. The mandrel is so constructed that it has a drive foot on its lower end which drive foot is larger in cross-sectional area than the mandrel stem. Hence, there is a space created in the ground behind the drive foot as it penetrates downward. In most of the construction methods according to the principles of the present invention, this space is filled with a cold fluid as the mandrel is driven and thus as soon as the space is created, and by this means the soil in the walls of the hole is frozen. The method is used in soil deposits, as opposed to rock formations, and generally to a depth not exceeding about 150 feet.

One of the most important advantages of my method over all prior art ground freezing methods is that it does not require a circulation system with supply and return pipes, pumps, manifolds, a refrigerating plant or a pumping installation. Also, in my method the freeze holes are formed in the ground by the most economical and rapid manner possible, that is, by driving a mandrel into the ground; and the refrigerant is placed into the ground in the general case by pouring it directly from the ground surface and letting it flow downward by gravity. Another major advantage of my method is that no metal casing is required in the holes in the ground, thereby eliminating the cost and time for installing such casings and removing them at the end of the job. The holes are formed and made stable, even in very soft or very pervious soils below the ground water level, in one continuous and simple operation and the refrigerant is contained in the ground in the uncased hole.

Another major advantage of my method is the speed with which the ground can be frozen. In the prior art brine method, the freezing holes were commonly spaced two to four feet apart and a time period of the order of 20 to 60 days was required to freeze the soil between the holes. Using the methods of the present invention, holes can not only be put down much more rapidly but the soil between them can be economically and practically frozen in a few days or even in less than one day.

When freezing is used for solidification of soil around excavations for civil engineering construction projects there are normally two steps; that is, the initial ground freezing and the maintenance of the ground in a frozen condition for a period of weeks or months, or even years, depending on the nature of the project. In current art methods it was necessary to keep the refrigerant circulating at a reduced rate during the

months or years that it was desired to keep the ground frozen. In order to do this it was necessary to keep the circulating system and refrigerating plant at the site during the whole time and to maintain a crew to operate it. Hence, the cost of maintaining the ground frozen was frequently many times the initial freezing cost depending on the length of time that it was necessary to keep the ground frozen. In the method of the present invention, once the ground is frozen no expensive plant or equipment is required at the site to maintain the soil in a frozen state.

In most prior art ground freezing methods a circulating system was used with loss of refrigerating energy above ground. Even though the above ground piping was covered with thermal insulation, there was an inevitable gain of heat from the air by the piping above the ground. In my invention, since the refrigerant is placed directly in the hole, not only is the cost of the piping and circulation system eliminated, but the loss of refrigerating power from the above ground portion of the system is also avoided.

Prior art methods for freezing soil walls around excavations for construction purposes in which a cold fluid was circulated or pumped to the freezing holes, had another major disadvantage in that it was necessary to have a network of piping on the ground surface leading to the freeze holes. Such pipes created obstacles which prevented the free travel of construction equipment around the edge of the excavation and thereby severely limit the flexibility of the construction activity. With my method there is no surface piping and the equipment can be operated freely over the top of the frozen soil zone.

Another disadvantage of the prior art brine method occurred when it was desired to freeze a continuous wall to serve as an underground impervious wall in circumstances where the ground water was flowing, such as in a river bed. In such circumstances it proved very difficult, and sometimes practically impossible, to freeze all the soil between the holes since the flowing ground water supplied heat to the ground in the vicinity of the freezing holes at a faster rate than it is possible to carry it away with a brine circulating system. Several costly failures of freezing attempts were experienced because of this action. Using the methods of the present invention this problem is readily overcome in all soils because: (1) larger freezing holes are used presenting a larger area of soil in contact with the cold fluid so that the surrounding soil is frozen more rapidly; (2) the cold fluid is placed in direct contact with the soil, instead of being contained in pipes and the fluid is colder than brine and (3) the unit cost and speed of putting down the holes are so favorable that the holes can be easily placed very close together.

In prior methods of soil freezing for construction purposes the cold fluid was usually circulated below ground in pipes with diameter in the range between 4 and 6 inches. These pipes were not made larger in diameter because it is not economical to handle and install larger pipe. In the method of the present invention, in which no permanent metal pipes are used in the freeze holes, the holes are easily made larger, commonly ten to eighteen inches in diameter. The use of these larger holes is an important part of the present invention when used for soil solidification since it permits the placement of relatively large quantities of refrigerants, such as dry ice, directly into the ground; whereas, using the small diameter holes of the prior art methods, it was generally necessary to remove heat from the ground by circulating a cold fluid.

The use of larger diameter pipe, which is made possible by my method, has a number of major advantages in addition to the greater speed of freezing the surrounding ground. One of these is that the frozen cylinder of soil around the hole has considerably greater strength to act as a vertical beam when used as a part of a frozen soil retaining wall to support the sides of an excavation. This is true because, as is well known, both the compressive and tensile strength of the frozen soil increases greatly with decreasing temperature and the temperature of the frozen soil surrounding any given hole increases rapidly with distance from the hole. Hence, the first few inches of frozen soil just outside the walls of the freeze hole have the greatest strength. As a result a frozen soil cylinder around a 16'' diameter freeze hole has many times the strength to act as a vertical beam than a similarly frozen cylinder around a 6 inch diameter freeze hole, other things being equal. In some applications this greater strength is a major advantage.

Yet another important advantage of using larger freeze holes, as can be done easily by the methods of the present invention, is that a lesser total volume of soil needs to be frozen in order to freeze an underground wall or zone of given dimensions below ground. This is true because the combined total volumes of the individual freeze holes is larger with respect to the total volume of the soil zone or wall being frozen. Since the volume of the hole itself does not have to be frozen, less refrigerating energy is needed to freeze an underground wall or zone of given width.

Other objects, advantages and features of the present invention will become apparent from the following detailed description of the method steps and the apparatus for performing them, taken in conjunction with the accompanying drawings, in which:

FIGS. 1, 2 and 3 are schematic views in elevation and in section showing a hole being formed in the ground and walls frozen by a method using the principles of the present invention in which the mandrel consists of a solid cylinder and the drive head is detachably fixed to the lower end;

FIGS. 4, 4*a* and 5 are schematic views in elevation and in section of a hole being formed in the ground and frozen using another apparatus embodiment according to the principles of the invention in which a portion of the soil in the path of the downward penetrating mandrel is taken inside a hollow pipe mandrel;

FIG. 6 shows a modified form of the apparatus of FIG. 4 used especially for taking undisturbed soil samples for exploration purposes;

FIG. 7 shows a plan view of a continuously frozen wall of soil formed by a series of holes along a line formed according to the principles of the present invention;

FIG. 8 shows a plan view similar to that of FIG. 7 in which the frozen wall of soil is created by two lines of holes formed and frozen according to the methods of the present invention;

FIG. 9 is a schematic view in elevation and in section of yet another apparatus embodiment according to the principles of the present invention in which the flowable material is pumped down into the hole;

FIG. 10 is a schematic view in elevation and in section of a hole being formed in the ground using yet another apparatus embodiment according to the principles of the invention in which the drive foot is rigidly and permanently attached to the end of the mandrel;

FIG. 10*a* is a fragmentary view in elevation and in section of the lower end of a mandrel for making holes according to the principles of the invention in which a detachable cover is used outside the drive foot;

FIG. 11 is a fragmentary schematic view in elevation and in section of another apparatus embodiment according to the principles of my invention showing a shield for the temporary support of the soil forming the walls of the hole before it is frozen.

While the drawings illustrate the various steps of my method for forming holes and freezing the soil surrounding them, and also certain embodiments of the apparatus for carrying out the method, it is to be understood that these illustrations are not intended to limit the invention but are presented merely to illustrate its application in the forms shown.

In broad terms, my general method comprises the steps of (1) driving or forcing a rigid and strong, elongated mandrel member into the ground, which mandrel member has a drive foot on its lower end with larger cross-sectional area than that of the main stem of the mandrel so that there is a space formed in the ground behind the drive foot; (2) placing flowable material which is at a low temperature in the space so formed; (3) withdrawing the mandrel from the ground leaving an open cylindrical hole with frozen soil walls. Subsequently, additional refrigerant may be put into the hole in increments to continue freezing of the ground surrounding the hole or the hole may be used for other purposes. The aforesaid general method steps will be better understood as they are explained in greater detail together with a description of the apparatus according to my invention.

Referring to the drawing, FIGS. 1 through 3 show one embodiment of an apparatus **10** forming a hole **12** in a soil deposit **14** according to the principles of my invention. The apparatus comprises a solid straight cylindrical mandrel stem **16** which is driven into the ground by a suitable pile driver **18**, such as the kind normally used for installing foundation piling. Attached to the lower end of the mandrel is a drive foot **20** having a diameter greater than the diameter of the mandrel stem **16**. The diameter of the hole **12** so formed is, therefore, approximately equal to the diameter of the drive foot and larger than the diameter of the mandrel stem. In this embodiment the mandrel stem **16** fits slideably within a socket **22** in the drive foot **20** so that the mandrel stem can be easily detached from the drive foot.

An annular space **24** formed between the wall **26** of the hole **12** and the mandrel stem **16** is generally kept filled with a fluid or flowable material **28** which has a low temperature (well below the freezing temperature of water). In most practical applications of my invention this fluid flows down into the hole from a small reservoir **30** which may be created on the ground surface by the tanklike structure **32**. Thus, as the mandrel is being driven or forced downwardly the annular space **24** created around the mandrel stem is constantly filled with the fluid from the reservoir **30**. As the mandrel moves downward the fluid also flows downward by gravity and the pressure of the fluid acts to support the earth walls of the hole and to prevent ground water from seeping into the hole. Thus a metal casing is not needed to hold the hole open or prevent the entry of ground water. The surface reservoir is replenished from a pipe or hose **34** from a suitable source such as a tank truck.

A number of various fluids can be used with methods according to the principles of the present invention. In the embodiment of FIGS. 1, the fluid must be flowable enough so that it can flow downward under the action of gravity alone and fill the space created around the mandrel stem behind the drive foot as the mandrel penetrates the ground. In all embodiments the pressure of the fluid in the hole at any depth in the first instance of time before the ground is frozen must be great enough so that no large amount of ground water enters the hole. Also in unstable soils the pressure in the fluid must be high enough to prevent caving of the wall **26** of the hole before the soil is frozen. Also, of course, the flowable material **28** must be capable of remaining in a fluid form when at temperatures well below the freezing point of water.

For methods of forming holes with frozen walls according to the principles of the present invention using the apparatus embodiments shown in FIGS. 1, I have found that ordinary gasoline is a very satisfactory flowable material. In the general case the gasoline is precooled by mixing it with crushed or pulverized dry ice (solidified carbon dioxide). In a preferred embodiment, the fluid poured into the hole is a slurry of gasoline and pulverized dry ice. When used in this fashion the gasoline is normally reduced to a temperature in a range between −50°F. and −100°F. at the surface. At these temperatures the gasoline-dry ice slurry has a viscosity somewhat greater than that of water, but it is still flowable enough to travel easily downward into the ground according to the principles of the invention without appreciable frictional drag. It has enough viscosity, however, so that it has no great tendency to flow out into the pores of the adjacent ground, even in coarse soils, in any great quantity except in rare circumstances.

Referring now again to FIG. 1, it is apparent that the wall **26** of the hole is directly exposed to the cold gasoline-dry ice slurry as soon as the hole is formed by the downward penetrating mandrel foot **20**. The pressure in the gasoline-dry ice slurry in the annular space **24** at any given elevation is roughly equal to the weight of the column of liquid slurry above; that is, the pressure head is approximately equal to the level of the surface of the reservoir **30**. In the general case this pressure at any given elevation is greater than the ground water pressure and is ample to prevent the wall of the hole from caving.

It is apparent that as the gasoline-dry ice slurry penetrates the ground along with the mandrel, heat flows from the adjacent ground to the slurry because of the temperature gradient, which action causes the temperature of the soil forming the wall of the hole to be lowered. The heat removed from the soil causes the dry

ice fragments in the slurry to sublimate and bubbles of gaseous carbon dioxide rise to the surface through the fluid slurry. By the time the mandrel has penetrated the ground to the final depth desired in the general case a thin frozen skin of soil already exists on the walls of the hole over most of its length. Subsequently, the mandrel **16** is left in the ground for a short period of time, usually less than 5 minutes, until a shell **36** on the wall of the hole has been frozen to a thickness of the order of magnitude of one-fourth to one-half inch, or more. This thin cylindrical shell of frozen soil is strong and acts, subsequently, as a structural casing.

After the frozen soil shell **36** is formed, the pressure of the fluid in the annular space **24** is no longer needed to support the wall of the hole or to keep the ground water from entering. The mandrel stem **16** is then pulled from the ground, as shown in FIG. **2**. As the mandrel is withdrawn, the fluid in the annular space **24** flows downward and fills the bottom **38** of the hole, as shown in FIG. **2**. The detachable drive foot **20** is left in the ground at the bottom of the hole. Subsequently, the gasoline and remaining dry ice may be pumped out, having a dry and stable hole which can be used for such purposes as forming a cast-in-place concrete piling.

When the hole is being formed as part of the activity of freezing a zone or wall of ground, the gasoline in the bottom **38** of the hole, FIG. **2**, may be left in place and the remainder of the hole filled with more pulverized dry ice **40** by dumping it in from the surface as shown in FIG. **3**. After the hole is completely filled with dry ice, more liquid **42** such as gasoline may be added by pouring from the surface as shown in FIG. **3** so that all the voids between the dry ice particles are filled with liquid gasoline for the full depth of the hole. Because of the presence of the gasoline the dry ice sublimates more rapidly than it would if it were not surrounded by liquid, and as a consequence the soil surrounding the hole freezes relatively more rapidly than it would if the hole is filled only with dry ice.

With the hole filled with dry ice and gasoline after the step of FIG. **3**, the soil is gradually frozen to an increasingly greater distance from the hole. At intervals, additional quantities of dry ice are dropped in to replace the quantity which boils away so that the hole is kept essentially filled with dry ice and gasoline until the soil is frozen in a cylinder around the hole with the desired diameter. Using dry ice and gasoline a time period of 2 to 6 days is frequently required to freeze the soil around the hole to the distance desired. Additional dry ice may be dropped into the hole at intervals of several hours. Commonly, a total quantity of dry ice in the range between 2 and 6 cubic feet is used per lineal foot of freeze hole during the freezing period.

Subsequently, during the time when the frozen zone around each hole was simply being maintained in a frozen condition, more gasoline is poured into the hole and smaller quantities of dry ice are added at less frequent intervals (such as, for example, 100 pounds per day per hole) for the purpose of perpetuating the equilibrium condition achieved. This quantity of dry ice is determined by calculation or experiment as being just sufficient to prevent any substantial retreat of the frozen soil zone and to maintain the desired average temperatures. The adequacy of the quantity of refrigerant being used to maintain equilibrium is verified by observing the variation of the temperature of various points in the ground with buried temperature measuring instruments. At the end of the job, when the frozen soil is no longer needed, the gasoline remaining is pumped out and the holes are generally backfilled with sand or earth. In an alternate method for maintaining equilibrium after the ground zone is frozen to the general dimensions desired, all the liquid gasoline is removed from the freeze holes and these are filled with chunks of dry ice. In this condition, surrounded by gas rather than liquid, the dry ice sublimates at a relatively slow rate which is usually adequate to maintain equilibrium.

Alternatively, as the mandrel was withdrawn from the hole in the step of FIG. **2** an additional supply of the flowable material may be poured into the small reservoir **30** so that it flows down into the hole to replace the volume of the mandrel being withdrawn, thereby eliminating the separate step of filling the hole shown in FIG. **3**. In this alternative step, the hole is completely filled with the flowable material **28** after the mandrel is withdrawn and there is always a fluid pressure in the hole. This alternative, therefore, has the advantage that it is not necessary to rely upon the frozen skin to support the walls of the hole to prevent the entry of ground water and that the mandrel may be withdrawn from the hole without any waiting period. In this alternative the flowable material poured into the hole as the mandrel is being withdrawn may consist primarily of pulverized dry ice with only enough gasoline liquid carrier to make the mixture flowable. In another alternative method step a steel pipe mandrel is used in lieu of the solid mandrel shown in FIGS. **1** and **2**. In this alternative, after the mandrel has penetrated the ground to the depth desired using the technique shown in FIG. **1**, the pile driver is removed from the upper end of the mandrel and the hollow interior of the pipe mandrel is filled with dry ice or a slurry of dry ice and gasoline so that when the mandrel is withdrawn from the ground the hole is left essentially filled with a mixture of dry ice and gasoline.

In another alternative the gasoline remaining in the bottom **38** of the hole when the mandrel is withdrawn, FIG. **2**, is removed from the hole by bailing or pumping and the then empty hole is filled with liquid nitrogen instead of gasoline, by pouring it in from the surface, as shown in FIG. **3**. The rapid boiling of the liquid nitrogen, and its very low temperature causes much faster freezing of the soil adjacent to the hole than can be obtained with dry ice and gasoline.

whatever the refrigerant which is dropped back into the holes in the step of FIG. **3**, during the freezing time a cover of wood Whatever other insulating material is usually placed over the top of the holes. This causes the escaping gas to develop some pressure before it leaves the hole. Such hole covers also allow equipment and men to work on the ground surface surrounding the freeze holes without restriction.

It is apparent that other cold fluids can also be used during the formation of the hole in the first stage of freezing as described above in connection with FIG. **1**. I have found that a slurry of gasoline and pulverized dry ice is very satisfactory because of the widespread availability and not great cost of gasoline. Also, the freezing temperature of gasoline is well below the subli-

mation temperature of dry ice (about −109°F.). The better grades of kerosene oil can also be used satisfactorily to form a kerosene-dry ice slurry. Kerosene acts essentially in the same way as gasoline except that is will freeze if too much dry ice is added and, therefore, it is necessary to add the dry ice more slowly, and consequently to freeze the soil more slowly. Various other liquid carriers for the dry ice can also be used in lieu of gasoline.

Liquid nitrogen can also be used very satisfactorily at many sites as the fluid in the first step of forming the hole as discussed above in connection with the description of FIG. 1. The liquid nitrogen is poured into the surface reservoir **30** and flows down into the ground as shown in FIG. 1. When used this way the liquid nitrogen changes to a gaseous form much more rapidly than dry ice in the gasoline slurry so that the space **24** in the ground around the mandrel stem is filled with a mixture of rapidly boiling liquid and gaseous nitrogen. Hence, the pressure in the fluid filled space **24** is generally less than when a fluid slurry of gasoline and dry ice is used. When liquid nitrogen is used as the fluid, however, very little pressure is needed to support the walls of the hole and prevent ground water from entering because the walls are frozen almost instantaneously. From experiments comparing the rate of freezing caused by liquid nitrogen and a liquid slurry of gasoline and pulverized dry ice when exposed to a typical wet and soft soil I found the following average results:

	Time After Exposure to Soil	Thickness of Frozen Soil Skin Formed
Gasoline & Dry Ice	60 secs.	⅛ in.
	5 min.	½ to ¾ in.
Liquid Nitrogen	5 secs.	⅛ in.
	20 secs.	½ in.
	5 min.	2 in.

As seen from these results when liquid nitrogen is used as the fluid the walls of the hole are frozen very rapidly. Also the one-eighth inch thick frozen skin formed in 5 seconds is sufficiently strong to act as a structural casing and ground water barrier in most circumstances. Liquid nitrogen may be more frequently used as the fluid during the formation of the hole, (FIG. 1), for the purpose of making concrete piling, since the hole is left dry when the mandrel is removed from the ground, and the frozen soil is colder and has higher strength than when dry ice is used as the refrigerant.

I have found also that a fluid mixture of liquid nitrogen and a pervious cohesionless granular soil, such as sand or pea gravel, serves well as the flowable material used to fill the space **24** as the mandrel penetrates the ground, FIG. 1. This filling has the advantage over liquid nitrogen alone that the gaseous nitrogen which rises out of the hole is forced to travel upward through the pores of the sand or gravel. This prevents the violent boiling action which sometimes causes masses of liquid nitrogen to be thrown out of the hole (geysering action). The sand admixture also causes the fluid pressure in the hole to be higher since the gas must build up some pressure in order to percolate upward through the pores of the sand. Similarly a mixture of liquid mitrogen and gravel or sand is sometimes used as the hole filling materials in the step described above in connection with FIG. 3. In methods in which the hole is filled with liquid nitrogen and a cohesionless soil, such as pea gravel, after the liquid nitrogen boils away leaving the void spaces in the gravel empty, additional liquid nitrogen can be added easily to continue the freezing operation. This can be done either by pouring it from the surface and letting it percolate down through the pores of the gravel or by installing a small pipe in the gravel filled hole (not shown on the drawings) and pumping it to the bottom.

It will be understood readily by those experienced in the art that the method of forming holes and freezing the surrounding ground as described above in connection with FIGS. 1 through 3 can be carried out at an extremely rapid rate. For example, it is easily possible to install 50 to 75 freeze holes per day according to the method of FIGS. 1 and 2 with one crew and pile driving rig, a rate which is many times the maximum possible with prior art methods of drilling holes and installing metal casings and internal circulation pipes. Any kind of a conventional pile driver can be used; however, I have found that it is very convenient and economical to use a vibrating type which can make holes very rapidly in most of the types of soils for which freezing is desirable. In some soft soils, it is possible to push the mandrel into the ground with a static weight.

Also it is convenient to make considerably larger holes than were commonly made in the prior art methods. For example, the mandrel stem **16** of FIG. 1 can commonly be 8 to 10 inches in diameter and the drive foot or shoe **20** will commonly be 12 to 16 inches in diameter, or more. This contrasts with the usual prior art procedures of circulating a cold fluid within 4 to 6 inches diameter pipe placed in a hole formed by a drill rig. It is seen, therefore, that the soil surface on which the freezing action is taking place in the method of my invention is much greater than that of the prior art methods.

Another advantage of the methods of the present invention is that there is little or no friction between the outside surface of the mandrel stem **16** and the soil in the adjacent wall **26** of the freeze hole, since these two surfaces are separated by the annular space **24**, FIG. 1, which is filled with the flowable material **28**. Hence, almost all the energy of the pile driver is transmitted to the drive foot where it is effective in causing the downward penetration of the mandrel and little or none of the energy is wasted in overcoming side friction. This allows the mandrel to be driven more rapidly than it is possible to drive a conventional piling of comparable size with the same hammer. It also has a number of other main advantages when the method is used to form holes for cast-in-place concrete piles. One of these is the fact that the resistance or rate of driving, such as in terms of inches of downward penetration per hammer blow, is a direct quantitative measure of the resistance drive foot to penetration. This provides the engineer with a better indication of the supporting capacity of the pile tip than he has in the case of conventional piling driving where the driving resistance observed includes both the resistance of the tip and an indeterminant amount of side friction. Also, the mandrel stem **16** can be pulled out of the ground, as shown in FIG. 2, without the necessity for overcoming side friction so that it is not necessary to have the large equipment which is usually required to pull a driven pipe from the ground.

While I have shown schematically in FIG. 1 the mandrel stem 16 being a solid cylinder of circular cross-section, it is apparent that it can practically be made with different shapes and of various materials. For example, the mandrel can be a heavy steel pipe with holes cut in its sides so that the flowable material placed into the reservoir 30 enters the interior of the pipe as well as flowing down into the ground in the annular space 24, FIG. 1. Another suitable mandrel stem is a structural steel H-beam. When using liquid nitrogen as the flowable material during the downward penetration of the mandrel, certain steel alloys, such as some stainless steels, are superior to ordinary steels for the mandrel stem because they are less affected by the relatively low temperatures. Concrete mandrels can also be used.

The detachable drive foot 20 is often made of precast concrete, which may be reinforced, such as with wire fiber reinforcing, to make it tough and capable of withstanding the driving action without breaking. It may also be made of cast iron or steel or may be fabricated by welding from a short piece of heavy steel pipe and an end plate.

In the apparatus embodiments shown in FIGS. 1 and 2, the soil in the path of the downward penetrating mandrel is pushed to the side. This is the cheapest possible way in which a hole can be made in the ground; that is, the soil is not removed from the ground at all but simply pushed out of the way. This procedure can be used in most of the soil types for which it is desired to use the freezing process. In some soils, however, such as very dense sands, it is not easy to drive a closed end mandrel and an alternative form of apparatus is used, as shown in FIG. 4, in which a mandrel stem 16*a* is a heavy-walled pipe and its drive foot 20*a* has a hole in the center. Using this apparatus embodiment, wherein a portion of the soil in the path of the downward penetrating mandrel enters the interior of the mandrel stem in the form of a soil plug 44, holes can be put down rapidly in almost any dense sand. Another advantage of the method and apparatus shown in FIG. 4 is that there is less displacement of the soil with less heave of the ground surface and less possibility of damage to nearby structures as a result.

In the apparatus of FIG. 4, I have shown a piece of heavy pipe 46, having an outside diameter approximately equal to the inside diameter of the mandrel which is welded to the lower end of the mandrel stem 16*a*. This piece of pipe 46 has a number of purposes. First, it acts to strengthen the lower end of the mandrel. Second, it causes the soil plug 44 which penetrates the interior of the mandrel to have an outside diameter which is less than the inside diameter of the pipe mandrel stem 16*a* so that the plug can penetrate upward into the mandrel stem without high frictional resistance developing between the soil plug 44 and the inside surface of the mandrel stem 16*a*. Third, it acts to grip the lower end of the soil plug 44 and prevent it from falling out as the pipe mandrel is being withdrawn from the ground.

As seen in FIG. 5 after the walls of the hole have been frozen, as discussed above in connection with the method of FIGS. 1 and 2, the mandrel is withdrawn from the hole carrying the soil plug 44 with it. The soil plug is subsequently removed from the interior of the mandrel by any of several available means well known in the art which are not part of this invention. In the embodiment of FIGS. 4 and 5, I have shown the drive foot 20*a* to be in the form of an annulus and to be detachable so that it is left in the bottom of the hole when the mandrel is withdrawn. In this embodiment it may be necessary to freeze the soil surface 48 which is left in the bottom of the hole after the mandrel is withdrawn. In order that the cold fluid will be in contact with the surface 48 an additional step in the process is carried out. In this step, directly after the mandrel has penetrated the ground to the depth desired it is pulled upward a short distance, such as a few inches, as shown in FIG. 4*a*. This breaks the soil plug 44 free from the underlying soil 50 creating the soil surface 48 at the bottom of the hole. As the mandrel is raised a few inches to the position shown in FIG. 4*a*, the flowable material in the annular space 24 flows downward to fill the space 52 created beneath the mandrel. The fluid pressure in this space is greater than the ground water pressure so that there is no tendency for the ground water to flow into the space. Subsequently, the mandrel is held in the hole with its bottom raised a few inches above the bottom of the hole as shown in FIG. 4*a* during the period of time required to freeze a thin shell of soil surrounding the walls of the hole. At the end of this time the bottom of the hole 48 is also frozen and the mandrel is withdrawn from the ground, as shown in FIG. 5, leaving a body of fluid in the bottom of the hole, as discussed previously in connection with the apparatus embodiments of FIGS. 1 and 2.

With a slight modification, the apparatus of FIG. 4 may be used to take relatively large diameter and long undisturbed samples of soft soils, such as silts and clays. Such samples are needed for a number of civil engineering purposes and until the present invention there was no generally satisfactory and economical method for taking them. FIG. 6 shows schematically the variation of the apparatus of FIG. 4 when used for taking undisturbed samples. As seen in this figure the pipe section 46*a* on the lower end of the mandrel stem is beveled and extends below the drive shoe 20*b* in such a way that the soil plug 44 is trimmed with a knife edge and the bevel is outward so that all the soil being penetrated outside the knife edge is pushed to the outside. Also, in this embodiment the mandrel 16*a* has holes 54 in its walls just above the drive shoe 20*b* so that the cold flowable material in the outer annular space 24 flows through the holes 54 and fills the inner annular space 56 between the inside of the mandrel and the soil plug 44. This flowable material which fills the thin inner annular space 56 separates the soil core 14 and inside walls of the mandrel 16*a*, thereby eliminating frictional drag. Thus, the natural soil structure is not disturbed as the soil plug 44 progressively penetrates the hollow interior of the mandrel stem.

After the mandrel has penetrated to the depth desired using the embodiment of FIG. 6 to take an undisturbed sample, it is allowed to sit until the soil sample or plug 44 inside the mandrel has a frozen skin. This frozen skin causes the soil sample or plug, which may be soft and wet in its natural state, to be temporarily rigid and strong. Hence, when the core is taken to the surface it may be removed from the interior of the mandrel easily without disturbing the natural structure of the soil. As the mandrel is being pulled out of the hole

the soil core 44 is held inside the mandrel by the fact that the lower end is frozen against the steel ring 46*a* inside the lower end of the mandrel.

In all the above discussions I have been talking about methods used for freezing the ground around a single hole. In general, however, for most applications of the method for solidifying unstable ground it is desirable to freeze a continuous soil zone such as a wall or a large mass, with a number of closely spaced freezing holes. FIG. 7 and 8 show continuous frozen walls 60 in plan view created by a series of closely spaced freezing holes 62, on one and two lines respectively. For the purpose of making an impervious wall using the methods of the present invention, it is generally sufficient to use a single line of holes as shown in FIG. 7. The holes 62 are frequently spaced between 24 and 48 inches on center, though they may be placed further apart. Using a single line of holes, a frozen wall with a width of 2 to 5 feet can be made conveniently. Where a thicker frozen zone is required two or more lines of holes may be used as shown in FIG. 8.

FIGS. 7 and 8 illustrate one of the main advantages of the present invention over prior art methods for soil freezing. In these figures it is seen that the total volume of the freezing holes 62 is relatively large compared to the total volume of the wall or zone of frozen soil. Hence, for a given thickness of frozen wall it is necessary to freeze a lesser volume of soil, which has the advantage of requiring less time and less refrigerating energy. Another way to look at this is that a large portion of the total volume of the frozen zone consists of the volume of the holes, which does not have to be frozen. Another advantage of the configuration, as shown in FIG. 7, is that the space between the individual holes is relatively small so that there is very little possibility that the thin soil strip 64 between the holes would not be frozen even if the ground water is flowing and has a tendency to supply heat to the zone of ground being frozen.

As discussed earlier, another important advantage of using large holes is that the strength of the frozen zone is much higher than when smaller holes are used. When a frozen zone of the general configuration of FIG. 7 is formed with holes of about 16 inches in diameter using liquid nitrogen as the refrigerant, the frozen wall has strength in vertical bending and compression which is of the same order of magnitude as that of a reinforced concrete wall of equivalent width. This is true because the strength of many frozen soils in the first few inches from a face exposed to liquid nitrogen is of the order of several thousand pounds per square inch. At a distance of more than a few inches from the wall of the hole the temperature of the frozen soil is considerably higher and the strength is considerably lower. Hence, particularly the bending strength of the wall, for use as a vertical structural wall, increases very rapidly with increasing diameter of the freeze holes.

Those experienced in the art will readily understand the methods of my invention as described hereinabove, when employed for freezing a continuous wall or zone of soil, have a considerable advantage over prior art methods because the refrigerating energy placed in each individual freeze hole can be easily varied widely without extra cost. This gives a flexibility in the freezing operation not available in the prior art methods. For example, it is frequently desired to freeze a vertical wall around an excavation to act as a structural retaining wall and as an impervious barrier to keep the ground water out of the excavation. In such an application, when the excavation is made it may be found that a leak of ground water enters the excavation at one location, indicating that the frozen zone is not continuous. Using the methods of my invention this can be remedied easily by simply accelerating the rate of freezing in the one or two holes in the vicinity of the leak, by adding large quantities of dry ice or liquid nitrogen directly to the hole or holes involved. In the prior art methods in which a cold liquid is circulated in relatively small holes connected in series to a manifold it is not possible to accelerate the rate of freezing at a local point in a rapid or economical manner. Similarly, this flexibility of my method has the great advantage in some circumstances that it is easily practical to freeze some portions of an underground frozen wall or zone to much lower temperatures than the average and hence to make these colder parts much stronger. These colder and stronger zones can be used as structural buttresses to strengthen the underground wall selectively in those areas where the strength is needed.

The flexibility gained by the fact that the refrigerant is placed directly in each individual hole also makes it practical to freeze only the soil surrounding the lower part of the hole if desired. This is easily done by keeping only the lower part of the hole filled with refrigerant, during the freezing stage. In the step as described above in connection with FIG. 3, in which the refrigerant is poured into the hole at intervals during the freezing period, only enough refrigerant is poured in to fill the lower portion of the hole. The rising cold gas keeps the soil skin around the upper part of the hole frozen but does not have enough refrigerating power to freeze the soil rapidly to an appreciable distance around the hole. With the prior art methods of ground freezing, in which a cold fluid was circulated, it was not possible to freeze the ground around the lower part of the holes selectively.

In the methods described herein above according to the principles of my invention I have described the use of a cold flowable material during the downward penetration of the mandrel. Also, it is apparent that it is not necessary that the flowable material in the annular space 16 be cold during the time when the mandrel is penetrating the ground. For example, methods can be used according to the principles of my invention in which the hole is formed in the ground exactly as described above in connection with the apparatus embodiments of FIGS. 1 and 2 except that the gasoline is at normal atmospheric temperature during the downward penetration of the mandrel. In such a procedure the temperature may be lowered by dropping dry ice into the gasoline filled annular space 24 after the mandrel has penetrated the ground to the depth desired. Alternatively, the dry ice can be dropped into the gasoline filled hole only after the mandrel 16 is withdrawn from the ground.

It is apparent, therefore, that various methods of cooling the flowable material can be used within the general principles of the present invention. Regardless of the method of cooling the flowable material, the principles of the invention is the same; that is, the hole

is formed by driving or pushing a mandrel into the ground with a drive head which has a cross-sectional area larger than that of the stem. The space thus formed around the mandrel stem is filled with a flowable material in such a way that the pressure in the annular space **24** is adequate to prevent the walls of the hole from caving and to prevent the entry of ground water into the hole. Said flowable material may be cold when it enters the ground or may be caused to become cold subsequently. After a thin shell of frozen soil is created on the walls of the hole, the flowable material and its pressure may be removed.

In FIG. **1**, I have shown the annular space **24** being filled completely with the flowable material poured into the reservoir **30**. In practice it is necessary to keep the annular space completely filled only in unstable soils where a considerable fluid pressure is needed in the hole to prevent the walls from collapsing, or in very pervious soils below the water table to prevent the ground water from entering the hole. In many soils it is not necessary to keep the annular space **24** completely filled with the flowable material all the way to the ground surface. In many soils using liquid nitrogen as the flowable material it may be only necessary to keep a few feet of the annular space **24** directly above the downward penetrating drive foot, FIG. **1**, filled with nitrogen. This is true because the nitrogen freezes the soil very rapidly and, hence, in those soils where there is no great tendency for the hole to collapse rapidly the frozen skin on the walls of the hole is formed before the hole can cave in and it is, therefore, not necessary to support the walls of the hole temporarily with fluid pressure.

In other circumstances the hole may be unstable in only certain parts of its length, and naturally stable in others, so that the flowable material in the annular space is only needed during the formation of certain portions of the hole. For example, in the circumstance where a hole is being put down through a soil formation consisting of an upper layer of saturated, cohesionless sand and a lower layer of stiff clay, it is apparent that it is necessary only to provide support for the hole during the upper **20** feet where it passes through the unstable sand. In the underlying stiff clay the hole will probably be stable without the influence of the pressure of the flowable material or the cold temperature. Hence, in many circumstances, it may be necessary to cause the cold flowable material to flow into the annular space **24** during the downward penetration of the mandrel as described in connection with FIG. **1** for portions of the length of the hole. Procedures according to the principles of the present invention in which only the unstable portion of the length of the hole is frozen are particularly used for making holes for the purpose of forming concrete cast-in-place piling, sand drains and water wells. This is true because for these purposes freezing is employed only for the purpose of stabilizing the soil temporarily so that the hole will stay open long enough to fill the hole with concrete or sand or to install a well screen, as the case may be. Hence, it is desirable to freeze the minimum quantity of soil consistent with obtaining a stable hole, from the standpoint of economy.

I have described hereinabove methods in which the space formed in the ground by the downward penetrating drive shoe around the mandrel stem is filled with a fluid or slurry which flows downward from the surface reservoir **30**. This is the method used in the general case since it is the cheapest and most rapid method and requires the least amount of equipment. On the other hand, this flowable material can also be caused to fill the space in the ground created by the downward penetrating drive shoe by pumping it down through a closed conduit. As shown schematically in FIG. **9** the fluid can be pumped down into the hole through a closed conduit **66** and discharged through orifices **68** located above the drive foot **20**. This embodiment has the technical advantage over the more general embodiment discussed above in connection with FIG. **1** that higher fluid pressures can be developed in the annular space **24** in the lower part of the hole, which pressures are desirable in certain soils having unusual instability and consequent tendency to cave and close the hole behind the downward penetrating drive foot **20**. Hence, methods in which the fluid is placed into the hole during the downward penetration of the mandrel by pumping them down are within the general scope of the invention. In this embodiment the surface reservoir **30** is used only to confine the fluid at the top of the hole. When liquid nitrogen is used as the flowable material pumped down into the hole in the embodiment of FIG. **9**, the annular space **24** is filled with a mixture of gaseous nitrogen and boiling liquid nitrogen, and the reservoir **30** on the ground surface is not used.

In FIGS. **1** through **5**, I have shown the drive foot **20** on the lower end of the mandrel stem **16** as being detachable and left in the ground at the bottom of the hole. This is a convenient arrangement particularly when gasoline and dry ice is used as the fluid because the gasoline-dry ice slurry can be allowed to remain in the hole as the mandrel stem is withdrawn from the ground. Also, with a detachable drive foot there is no resistance to the withdrawal of the mandrel stem from the ground in the steps of FIGS. **2** and **5**. Further the detachable drive foot is often used for forming holes for cast-in-place piling because the drive foot left in the ground forms the tip of the piling. Methods according to the principles of the present invention can be used equally well, however, with apparatus in which the drive foot is rigidly and permanently attached to the lower end of the mandrel stem and in which the drive foot is withdrawn from the hole. This method is particularly useful when liquid nitrogen is employed as the fluid during the downward penetration of the mandrel, although it can be used with any of the flowable materials.

FIG. **10** shows the method step of withdrawing the mandrel from the ground using apparatus in which a drive foot **20***c* is rigidly attached to the mandrel stem. The hole **70** left in the ground below the upward moving drive foot is essentially free of liquid. The pressure in this empty hole **70** is generally above atmospheric pressure since it is normally filled with gas being generated by the small amount of refrigerant (liquid nitrogen or particles of carbon dioxide) remaining on the walls of the hole. If the mandrel is withdrawn from the ground more rapidly than gas is generated, the pressure in the hole **20** can theoretically be less than atmospheric pressures. However, the hole remains stable because the walls are supported by the thin frozen skin that has formed as previously described.

When a gasoline-dry ice slurry is used as the fluid in combination with the apparatus of FIG. **10**, most of the slurry in the annular space **24** is forced upward and out of the hole as the mandrel is withdrawn by the drive foot **20***c* acting as a piston. The liquid rises to the surface, overflows from the surface reservoir **30** and is generally picked up with a pump, not shown, and reused during the formation of the subsequent neighboring holes. It is apparent that using the method embodiment of FIG. **10**, a larger upward force is needed to withdraw the mandrel from the ground than is needed in connection with the apparatus embodiments in which a detachable drive foot is left in the bottom of the hole.

FIG. **10***a* shows an intermediate design for the lower end of the mandrel. In this embodiment, the mandrel stem **16** has an enlarged drive foot **20***d* rigidly and permanently attached to its lower end and, in addition, there is a detachable cover **72**, such as of steel plate, around the outside of the enlarged drive foot **20***d*. When the mandrel is withdrawn from the ground, the drive foot cover **72** remains in the bottom of the hole.

Holes for the formation of cast-in-place concrete piling are made either by the general method shown schematically in FIGS. **1** and **2**, in which the soil is pushed to the side by the downward penetrating mandrel, or by the method of FIGS. **4** and **5**, in which some of the soil is taken inside the mandrel and subsequently removed from the ground. For the formation of piling, liquid nitrogen is frequently used as the refrigerant since it freezes more rapidly than the other cold fluids; creates colder and stronger frozen skins around the hole; and leaves the hole dry and empty soon after the mandrel is withdrawn from the ground.

In the general case the concrete is not placed in any hole until the holes for all the neighboring piles have been formed. By this means it is ascertained that none of the holes are squeezed shut or otherwise damaged by the pressures created in the ground associated with the mandrel driving for the subsequent nearby holes. When all the holes in a given area have been formed, they are all carefully inspected by looking down into them with a light to assure that they are free of water and clean. Subsequently they may be filled as shown in FIG. **3** by dumping concrete into them from the surface in the same manner as the dry ice **40** or by other methods well known in the prior art which are not part of this invention, such as dropping the concrete into the hole through a pipe or a flexible conduit or by pumping it down with a concrete pump.

Ordinary concrete is generally satisfactory to fill the holes. The fact that the holes are surrounded by a skin of frozen soil has no detrimental influence on the properties of the concrete piling formed. This is true because there is not enough refrigerating power in the thin frozen soil skin to freeze the water in the concrete. In the typical case the wet concrete is at atmospheric temperature, generally in the range between 50° and 70°F, when it is put in the hole. After it is placed in the hole some heat flows from the wet concrete outward. This action causes some thawing of the adjacent frozen soil skin and a reduction in the temperature of the concrete. Simultaneously, the cement in the concrete commences to hydrate, giving off an additional supply of heat. At the same time heat continues to flow inward toward the frozen soil skin from the surrounding ground. The net result is that the frozen soil skin around the pile is completely thawed within a few hours and the temperature of the concrete always remains well above freezing.

It will be readily understood by one experienced in the art that the method of making concrete piling according to the present invention has many advantages over prior art methods. The prior art method for making cast-in-place concrete piling which approaches the method of the present invention most closely is that in which a thin steel shell is placed around the outside of a structural mandrel and driven into the ground. This is a particularly satisfactory type of piling as it is possible to leave the shell unfilled until most of the piles in the general area are driven into the ground and then to inspect each empty shell immediately before filling it with concrete. Thus, the engineer can be confident that any given pile in an area is not damaged by the subsequent driving of the neighboring piles.

The method of the present invention has a number of important advantages over this prior art cast-in-place concrete pile made with a thin steel shell. First, the cost of the refrigerant is usually considerably less than the cost of the steel shell. Second, other things being equal, a considerably greater number of piles can be driven each day using methods of the present invention. This is true for a number of reasons. The most important of these is that with the prior art method a considerable amount of time is required for each pile to slip the thin steel shell around the mandrel before driving it into the ground. Using the method of the present invention there is no delay in the construction activity between driving consecutive piles caused by the need for handling the thin steel shell. Another main advantage of the present invention over the prior art method of driving piles with thin steel shells results from the fact that there is no contact between the soil and the walls of the mandrel stem during the driving. Thus, piling can be driven more rapidly using the method of the present invention, because none of the driving energy is absorbed by the side friction.

Another important advantage of the method of the present invention over the prior art methods is obtained when using the method an apparatus embodiment as described in connection with FIG. **4**. When a considerable number of closely spaced piling are driven at a site, particularly in fine-grained saturated soils, troubles are sometimes experienced as a result of the fact that the soil is displaced in order to make room for the driven piling. This causes pressures to develop below ground which can damage buried structures and piling that is already in the ground, and can heave the ground surface and damage adjacent structures. In such circumstances, it is desirable to use so-called "non-displacement" piles. In the prior art there was no economical or practical method by which a cast-in-place non-displacement concrete pile could be made using the technique of providing a thin metal shell and allowing the hole to stay open for inspection before concreting. Using methods of the present invention as shown in FIGS. **4** and **5**, non-displacement piles with a thin shell of temporarily frozen soil can be allowed to stand open for inspection and then concreted.

When forming holes for piling using liquid nitrogen as the flowable refrigerant the fluid pressure in the annular space **24** is not very high and it is sometimes desirable to provide temporary support for the lower part of the hole to assist in keeping the hole open until the soil is frozen, especially in very pervious soils below the water table. This may be done by providing a short cylindrical skirt **74**, such as a piece of light steel pipe, just above the drive foot as shown in FIG. **11**. This cylindrical skirt or shield, which is rigidly attached to the drive foot **20**, may have a length of the order of 2 to 4 hole diameters and an outside diameter approximately equal to the outside diameter of the drive foot, as shown. The skirt serves as a temporary support for the soil surface comprising the newly formed wall of the hole to provide time for the nitrogen to cool and freeze the soil. The liquid nitrogen in the annular space **24** surrounding the mandrel stem **16** causes the skirt **74** to be very cold so that the thin zone of soil **76** just outside the skirt is gradually frozen during the short period of time that it is supported by the skirt. For example, if the mandrel is penetrating the ground at the rate of 9 feet per minute and the skirt is 3 feet long, the soil forming the walls of the hole just above the drive foot is supported by the skirt for a time period of 3/9 minutes or 20 seconds. As discussed above this is generally long enough to create a frozen soil casing around the hole with a thickness of the order of one-half inch which is thereafter ample to support the walls and keep the water out.

Thick deposits of soft, saturated silts and clays are sometimes consolidated and made stronger and better able to support superimposed loads by the installation of "sand drains" which are vertical, cylindrical sand columns installed in closely spaced holes formed in the soft soil deposit. Heretofore, such holes were frequently made by simply driving and pulling a cylindrical sand-filled pipe mandrel. This procedure had two main disadvantages. First, the driving and pulling procedure created a thoroughly remolded skin or "-smear" of impervious soil on the walls of the hole, which skin acted to reduce the rate at which water could flow from the pores of the soft clay deposit to the sand drains. Second, the penetration of the closed end mandrel displaced the soft soil by pushing it to the side which had the disadvantage that the natural structure of the soil was disturbed. This was undesirable because it increased the compressibility of the material and decreased its permeability.

Sand drains are constructed according to the methods of the present invention which overcome the main disadvantages of the prior art methods. Sand drains are constructed using the same procedure as discussed above for "non-displacement" concrete piles except that the hole is filled by dumping sand from the surface in the step of FIG. **3** instead of the dry ice **40** or concrete. This method of construction according to the principles of the present invention has the great advantages over all prior art methods that the disturbance around the pile and the formation of the skin or remolded soil "smear" on the walls is held to an absolute minimum. This is true because most of the soil in the path of the downward penetrating mandrel is taken inside the mandrel so that there is no important disturbance to the structure of the soil several inches away from the hole. Also, the only element of the apparatus which rubs against the soil comprising the walls of the hole is the drive foot which has a length of only a few inches. After the drive foot has passed downward the soil in the wall of the hole is subsequently exposed only to the cold fluid in the annular space **24**, FIG. **4**. Consequently, there can be no important influence on the efficacy of the drains because of a surface skin of remolded material or because of the disturbance of the natural structure of the soil surrounding the drain.

Water wells can be formed in holes constructed according to the principles of the present invention, either by the "displacement" method as described in connection with FIGS. **1** and **2** or by the "non-displacement" method as described in connection with FIGS. **4** and **5**. The initial hole in the ground with temporarily frozen walls is formed as described hereinabove for the other purposes. Usually liquid nitrogen is used as the flowable refrigerant because of its low temperature and also because it is odorless and does not contaminate the ground water, even temporarily. After the initial hole is formed the well installation is completed in the same way that a well is formed in a hole created in the earth by any other method, such as drilling. A perforated or slotted well casing with diameter smaller than the diameter of the hole is placed in the ground and the annular space between the exterior surface of the well casing and the walls of the hole is filled with filter gravel. After a few hours the frozen soil skin melts when the wall is subsequently developed by surging and pumping following the practice well known in the art.

The methods of the present invention have advantages over the prior art methods particularly for shallow wells, such as less than a hundred feet in depth, and for situations in which a considerable number of closely spaced wells are needed, such as for dewatering excavations and for relief wells at the downstream toe of a dam or the downstream toe of a river levee. An an example, a series of closely spaced relief wells, such as 20 feet on center, are frequently constructed to depths of the order of 50 feet at the downstream toe of a dam underlain by a deep deposit of sand. In the prior art such wells were customarily constructed with a drill rig, often using the reverse rotary method, and one to two holes per day was a relatively rapid rate of formation of the holes. Using the method of the present invention, with the vibrating pile driver suspended from the boom of a rubber tired crane, production rates of 15 to 30 holes per day can easily be obtained.

To those skilled in the art to which this invention relates, many changes in construction and widely different embodiments will suggest themselves without departing from the spirit or the scope of the invention. As an example, I have shown herein apparatus and method steps in which essentially all the refrigerant is added to the annular space **24** separating a mandrel stem from the soil walls **26** of the hole. Equally well, the mandrel can be made in the form of a hollow pipe and the interior of said pipe can be filled with refrigerant. As another example I have discussed herein primarily the use of dry ice and liquid nitrogen as refrigerants and gasoline as a liquid carrier for the dry ice. It is apparent, however, that many other refrigerants and liquids can be used within the scope of the invention. In all the drawings I have shown the drive foot having a circular

cross-section and forming freeze holes of circular cross-section. Equally well the holes can be made with other cross-sectional shapes such as a square, a rectangular, a cross, or any other shape which is reasonably symmetrical with the axis of the mandrel so that the hole drives straight.

As a further example I have shown in FIG. 4 an apparatus embodiment in which a portion of the soil in the path of the downward penetrating mandrel is caused to enter the interior of the mandrel in the form of a soil plug. In the typical procedure using this apparatus the soil plug is carried out of the ground as shown in FIG. 5 when the mandrel is withdrawn. Alternatively, methods can be used in which the soil entering the interior of the mandrel is removed by other procedures. Finally, while I have shown in all the drawings the method being used to make vertical holes, it is apparent that sloping holes can be formed as well.

I claim:

1. A method of forming a hole in the ground and freezing the surrounding soil comprising the steps:

a. providing a mandrel having a straight stem section and a drive foot at or near its lower end, said drive foot having a cross sectional area in the direction transverse to the mandrel axis which is larger than the transverse cross sectional area of the solid portion of the mandrel stem;

b. moving said mandrel downwardly to cause said drive foot to penetrate into the ground so that an elongated hole is formed, the area of which hole is larger than the cross-sectional body area of the mandrel stem, thus creating a longitudinal space in the ground adjacent the mandrel stem behind said downward penetrating drive foot;

c. simultaneously with the downward penetration of the mandrel causing a liquefied gas to flow into said longitudinal space, said liquefied gas having the property that it will absorb heat and change its state from a liquid to a gaseous form under atmospheric conditions;

d. simultaneously with downward movement of the mandrel, freezing the walls of the hole and creating a strong and impervious skin of frozen soil on said wall; and

e. removing the mandrel from the ground leaving an open hole with frozen walls filled only with gas at atmospheric pressure.

2. The method of claim 1 in which said liquefied gas is caused to fill said space by flowing downwardly into the ground under the action of gravity from a source of supply at the surface.

3. The method of claim 1 in which said liquefied gas is caused to flow into said longitudinal space by pumping it down through a closed conduit

4. The method of claim 1 in which said liquefied gas is nitrogen.

5. The method of claim 1 including the extra step of detaching said mandrel stem from said drive foot and leaving said drive foot in the ground at the bottom of the hole when the mandrel stem is withdrawn from the ground.

6. The method as described in claim 1 wherein said mandrel stem section has a hollow interior sand said drive foot has a central opening so that some of the soil lying in the path of the downward penetrating mandrel enters the interior of the mandrel stem in the form of a soil plug, said soil plug remaining inside said mandrel stem and being removed from the ground with it during its withdrawal from the hole.

7. An apparatus for forming an open cylindrical hole in the ground extending downwardly from the ground surface, which hole will remain temporarily open and free from ground water, even in unstable soil below the water table, because a skin of soil comprising the wall of the hole is frozen, comprising:

a. a rigid elongated mandrel means for making a hole in the ground having a main stem portion and a drive foot at its lower end, said drive foot having a cross-sectional area in the transverse direction to the mandrel axis which is larger than the solid transverse cross-sectional area of the mandrel stem;

b. driving means for exerting a downward force on the upper end of said mandrel stem, thereby causing it to penetrate and form a hole in the ground, and thereby creating a longitudinal space adjacent to said mandrel stem behind said downward moving drive foot;

c. means for causing liquefied gas to flow into said longitudinal space directly above said drive foot of said mandrel means as it is moved downwardly, said liquefied gas having the property that it absorbs heat and changes state from the liquid to a gaseous form under atmospheric conditions, thereby freezing the soil walls of the hole to prevent them from collapsing and to prevent any ground water in the adjacent soil from entering said space; and

d. means for withdrawing said mandrel from the ground.

8. The apparatus as described in claim 7 wherein said means for causing said liquefied gas to flow into said space comprises a reservoir on the ground surface surrounding the mandrel which reservoir is filled with said liquefied gas.

9. The apparatus as described in claim 7 wherein said means for causing said liquefied gas to flow into said space comprises means for pumping said liquefied gas down into the ground.

10. The apparatus as described in claim 7 wherein said drive foot is detachable from said mandrel stem portion.

11. The apparatus as described in claim 7 wherein said mandrel stem is a hollow sleeve and said drive foot is an annulus, so that a portion of the soil in the path of the downward penetrating mandrel is caused to enter the interior of the mandrel in the form of a soil plug.

12. The apparatus as described in claim 11 including means at the lower end of said mandrel stem for forming a space around said soil plug as it enters the hollow interior of said hollow sleeve mandrel stem.

13. The apparatus as described in claim 12 including means for causing said liquefied gas to flow into said space around said soil plug inside said mandrel stem.

14. The apparatus as described in claim 13 used particularly for the purpose of taking undisturbed soil samples wherein said annular drive foot is beveled to a knife point at its lower end.

15. The apparatus as described in claim 7 in which said drive foot has a sheet metal skirt attached to its

upper side for the purpose of providing temporary support to the solid forming the walls of the newly created hole until such time as the soil is frozen.

16. A method for making an uncased hole in the ground comprising the steps of:

forming the hole progressively from the ground surface downward;

placing a liquefied gas continuously in the lower part of the hole, said liquefied gas being in direct contact with the ground material forming the walls of the hole, said liquefied gas having the property that it absorbs heat and changes state from the liquid to the gaseous form under atmospheric conditions, and simultaneously creating a strong and impervious skin of frozen soil on said walls immediately as they are formed at the bottom of the hole.

17. A method for forming an uncased hole in the ground progressively from the surface downward comprising the steps of:

creating the hole by driving or pushing a mandrel with an enlarged lower end downwardly into the ground;

placing a liquefied gas continuously in the lower part of the hole directly above said enlarged lower end of said mandrel, said liquefied gas being in direct contact with the ground material forming the walls of the hole, said liquefied gas having the property that it absorbs heat and changes state from the liquid to the gaseous form under atmospheric conditions, and simultaneously creating a strong and impervious skin of frozen soil on said walls immediately above said enlarged lower end of said mandrel as the walls are formed.

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