SECTION 8
SHAFT-SINKING IN UNSTABLE AND WATERBEARING GROUND

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SHAFT-SINKING IN UNSTABLE AND WATERBEARING GROUND

1. DIFFICULTIES AND AVAILABLE EXPEDIENTS

Underground water is the principal cause of difficulties arising in sinking a shaft in unstable ground, as sand, gravel, clay, or silt. Even in dry soils, the removal of lateral support around an excavation may cause a fall, or flow, of the material into the excavated space, and when water is present this tendency is greatly increased. The first requisite of the shaft is, therefore, a lining or wall; but, if water is pumped out the ground-water will flow under the lining into the excavation, carrying with it the finer particles of the soil; or partially liquefied clay or silt may be forced up into the shaft by the superincumbent weight. In such case, continued excavation and pumping may cause a continued flow, with slips and falls of the ground, distortion of shaft lining, subsidence of the surface around the shaft mouth and settlement of the sinking equipment and adjacent buildings. This situation may prevent further progress, except by a change of method. Hence, sinking methods requiring pumping have been largely replaced by those in which pumping is unnecessary.

Boulders in soft ground often cause trouble and expense. They may force the shaft out of plumb, or their removal may require excavation to some depth below the lining, at the risk of flow of the surrounding ground with the consequences noted above. The presence of many boulders may cause large and unforeseen increase in cost, or even jeopardize success.

Seal to rock. The shaft having been sunk to rock, or other stable and impervious stratum, a watertight seal must be made between the shaft lining and the rock, and this, at a depth where the hydrostatic pressure of the ground-water is a maximum, may be difficult.

Lateral pressure against the shaft lining varies in different kinds of ground and increases with the depth. Pressure per sq ft above ground-water level is usually not more than 30 lb per ft of depth below surface; below ground-water level, rarely more than 60 lb per ft of depth below surface, except that in partially liquefied clay or silt it may reach 90 lb.

Borings. The success and cost of shafts are so dependent upon the nature of the ground that careful preliminary study of subsurface conditions must be made. The borings are often too few in number or too inconclusive, and a shaft is sunk under adverse conditions which might have been avoided by locating it elsewhere, or which could have been more easily and cheaply surmounted by adopting some other method. Borings in soft ground are usually of the kind known as “wash borings” (Sec 9), which may be of little value unless properly sampled in their original and undisturbed position in the ground strata.

Methods of sinking in unstable ground are now well standardized. Older methods, such as vertical poling boards (analogous to the method used for tunneling), lining the shaft by horis timbers suspended from trusses across the shaft mouth, or vertical shields jacked down below the timber lining, have been replaced by cheaper and more reliable methods. Among these are:

(a) Wood or steel sheet-piling, braced by horis timbers or steel beams; or wood lagging placed horizontally between the flanges of steel beams, which are driven in advance of the excavation. These methods may be used to depths of 50 to 75 ft, or more, in dry ground, or where the water level has been previously lowered by pumping.

(b) Drop-shafts, with walls of reinforced concrete built above the surface, which sink as excavation advances. This is usually the cheapest and most reliable method for depths of 50 to 200 ft, or more.

(c) The pneumatic method, which is generally used in connection with drop-shafts in sinking through quicksand, or strata of boulders below the ground-water level, or when the sealing of the shaft to rock may be difficult. The limit of depth attainable by this method is about 115 ft below the ground-water level.

(d) Forced drop-shafts, for depths not attainable by ordinary drop-shafts.

(e) Freezing method, which is used for very deep shafts also.

(f) Grouting methods.
2. SHEET-PILING

Wood sheet-piling may be used as a temporary lining for small depths above water-level (Fig 1). This consists of planks, 10 to 12 in wide and 3 to 4 in thick, driven vertically around the sides of the excavation and braced by horizon timbers. The edges of the plank are usually tongued and grooved (Fig 2), or splined (Fig 3). The piles are set up in the bottom of a preliminary pit, around two sets of horizon bracing which serve as a guide frame, and are driven by hand, or by steam or air hammers, as excavation advances. Usually the piles are not more than 24 ft long and, if this length is not sufficient, two or more drives of piles are made, successively deeper. As each drive, below the first, must be set to clear the breast timbers above, the necessary excavation is thus increased. If cross-bracing is required it will interfere with the driving of the piles below, and it is therefore desirable, when the horizon dimensions of the shaft permit, to drive the piles around octagonal frames (Fig 4).

Lowering the ground-water level, by use of well-points, is often possible with wood piling. Well-points are perforated pipes, usually 2.0 in outside diam and 3.5 ft long, connected with 1.5 to 2-in pipes and driven 3 to 5 ft apart around the space to be excavated. The tops of the pipes are joined to a header pipe, just above water-level, and a pump is connected with the header. The bottoms of the well-points should not be much more than 25 ft below the pump. Pumping should begin some time in advance of the excavation, depending upon the nature of the ground. Lowering the ground-water level is most successful in medium and coarse sand and gravel. In very fine sand, clay and silt it is rarely feasible. The location of the well-points, when used in connection with wood sheet-piles, is shown in Fig 4, 5.

Wood lagging is a method of temporary shaft lining, which has recently come into use (Fig 5). It consists of square-edged wood planks, 10 to 12 in wide and 3 to 5 in thick, placed as the excavation advances behind the flanges of previously driven vert steel H beams. The steel beams are braced by sets of horizon timbers or steel beams. They may be 12 in deep, 53 lb per lineal ft, or larger or smaller, as required; driven to their full length in advance of the excavation, by steam or compressed-air hammers, and may be pulled out and salvaged on completion of the permanent lining. This method is applicable to depths of 50 ft or more, in dry ground, or to about 25 ft below original ground-water level, when this can be previously lowered by well-points, as already described. But the feasibility of the method depends upon whether the steel H-beams can be driven in proper location. With many boulders this may not be possible. The ground-water level cannot be lowered below the tops of the well-points, and when these are driven to rock the water level may be 4 or 5 ft above the rock; in which case it may be necessary to use vert sheet-piles, wood or steel, to complete the excavation to rock.

Steel sheet-piles can be used as a temporary or permanent lining. These are rolled, with edges which interlock with each other (Fig 6), in a great variety of widths and weights, and in flat, U-shaped and Z-shaped sections. Widths are from 8 1/2 to 19 5/8 in, weights per ft, from 21 to 64 lb, and the section moduli from 1.4 to 9.3-in cubed. They are rolled by Carnegie-Illinois Steel Co, Bethlehem Steel Co, Inland Steel Co, and the Jones & Laughlin Co, in the U.S, and the Larsen, Kloeckner and Hoesch sections in Germany.

The special advantage of steel sheet-piles is that they are driven in advance of the excavation to their full length, down to rock or other impermeable stratum. There is thus a shield between
the surrounding ground and the excavation. Steel sheet-piles are braced by sets of horis timbers or steel beams, placed as excavation proceeds. In very soft ground the piles when exposed by excavation may be best inward by ground pressure, to obviate which temporary bracing may be required at short vert intervals. Joints between sheet-piles are not entirely waterfite and pumping is often necessary. The piles are threaded into each other and set up in a preliminary pit around two sets of the horis bracing, used as a guide frame. They are driven by steam or compressed-air hammers, 2 or 3 ft at a time, successively around the frame until all are down to their full length. A permanent concrete lining may be built inside of the sheet-piles, after which the piles may be pulled

and salvaged. Shafts can be sunk to 75 ft depth by using steel piles, except in presence of many boulders.

In general, a combination of methods is used for sinking (Fig 7): wood sheet-piles, or wood lagging between vert steel beams, down to water-level, and steel sheet-piles below. Most of the excavation by any of these methods can be done by clam-shell or orange-peel buckets, operated by a stiff-leg derrick and a three-drum hoisting engine. The boom of the derrick should be at least 60 ft long, so that the mast and hoisting engine may be set far enough from the shaft mouth to be unaffected by the sinking operations.

Cost of sinking is usually least for horis wood lagging. Steel piling costs more than the other modes of support, but can be used in partially liquefied clay or silt, where other methods are not feasible. At present-day prices and hourly labor rates of 40 cts for com-
Fig 5. Wood Lagging on Sheetig
Shaft Sinking in Unstable Ground

Mon labor, 75 cts for carpenters and $1 for hoisting-engineers, the cost of a 40-ft shaft, sunk by each method, is about as follows: wood sheet-piles, $13 300; wood lagging, $12 100; steel sheet-piles, $14 900. Each of these shafts would be 14 ft square in inside horiz dimensions. The cost, including a permanent lining of reinforced concrete and contractor’s profit, is based on the assumption that the steel piling and steel H-beams used in the wood-lagging method, would be salvaged. The cost of a shaft with steel sheet-piling, also 14 ft square, but 75 ft deep and 55 ft below ground-water level (Fig. 7), would be about $33 600, including concrete lining and contractor’s profit. In this case, however, it is assumed that the steel piling would be left in place.

3. DROP-SHAFTS

Shafts 50 to 200 ft deep, or even more, are now usually sunk by this method. The shaft walls are built above the ground surface and sink as excavation proceeds. As no pumping is required, the water press in the surrounding ground is balanced and, except in soft clay or silt, there is little tendency for outside soil to flow into the excavation.

Reinforcing. Drop-shafts are usually of reinforced concrete. The cutting edge at the bottom is usually V-shaped in section, so that it will sink into the ground below the excavation level. To prevent injury to the cutting edge by boulders or by blasting, it is shod with steel plates 1/8 in thick, or more. These plates should extend up on the outside of the walls 3 to 5 ft, and to an equal, or greater, distance along the sloping inside faces. They are connected together through the concrete by steel diaphragms placed at frequent intervals, and the whole shoe should be well anchored by steel bars to the concrete walls. The shaft walls should be reinforced horizontally throughout their height, to sustain the ground pressure and any unbalanced loads. Vertical reinforcement should also be provided for bending stresses and for the suspension of the lower part of the shaft from the upper, in case of inflow of ground at the shaft bottom (Fig. 8).

Friction. In order that a drop-shaft may sink as the excavation proceeds, and thus furnish lateral support to the surrounding ground, the friction which develops between the ground and outside surface of the walls must be overcome. Friction increases with the depth below the surface and varies in different kinds of ground: least in silt and successively greater in sand or gravel, clay and boulders. The average friction, between the surface and bottom of a drop-shaft, may be from 100 to 1000 lb, or more, per sq ft of contact surface. With many boulders the friction may be very great, so that the drop-shaft becomes permanently locked between them. Usually the friction is from 350 to 700 lb per sq ft, and in most cases it is safe to estimate the aver at 500 lb per sq ft for depths of 100 ft or less, and 700 lb below 100-ft. To overcome or reduce the friction, there are several expedients. The walls are built thick enough to sustain the ground pressure and also to furnish the weight necessary to overcome friction, taking into account loss of weight due to buoyancy of the ground-water.

Drop-shafts are usually sunk from the bottom of a preliminary pit, 15 to 20 ft deep, thus reducing the area of contact between the ground and shaft walls. The pit is backfilled after the shaft is finished. If the friction is greater than anticipated, additional weight, in the form of pig iron, or sand, can be loaded upon the walls above the surface. Friction may sometimes be reduced by raising the level of the water in the shaft above that of the ground-water, thus causing a back flow under the bottom of the walls and up around them; or, the water in the shaft may be pumped down below ground-water level, thus causing a flow of ground-water into the shaft. This must be carefully done because of the danger of an inflow of soft ground.

Jetting around a drop-shaft by water or compressed air is often effective in reducing friction. Piping for this purpose must be installed in the walls as the drop-shaft is built. Jetting nozzles are usually placed at two levels, one 5 to 8 ft above the bottom of the walls, the other 8 to 12 ft above the first. The nozzles are 1-in diam and discharge horizontally, or upwards at an angle of 22 1/2 degrees from the vert. Each set of nozzles is connected by 2-in pipes with a horiz header 2 1/2 to 4-in diam, and each header is connected with the top of the shaft by a 4-in riser. The nozzles should be about 6 to 7 ft apart horizontally; sometimes an additional set, discharging vertically downwards, is placed in the shaft walls.

When other means are not effective, light charges of dynamite, exploded in the shaft bottom, may start downward movement. This may be done in combination with the other expedients.

Sinking. Excavation is done by orange-peel or clam-shell buckets, operated by the equipment described in Art. 2. The shaft must be kept vertical and, in uniform ground, this can be done by excavating uniformly around the cutting edge. Deviation from the vertical may be remedied by excavating on the high side, or placing additional weight
Fig 7. Combination Method of Sinking
Concrete after caisson is landed and excavation is completed below cutting edge

Fig 8. Drop-shaft
on that side. It is especially important to keep the shaft vertical during the early part of the sinking. It is sometimes desirable to sink a deep shaft in two sections, the lower section from the bottom of the upper section. An example of this is a shaft for the St. Albert Colliery, St. Albert, Canada (Fig 9).

If boulders are encountered, the ground under them may be cut away until they roll into the excavation, but care must be taken to avoid an inrush of ground and displacement of the shaft. Drilling and blasting by divers may be required. It is important to keep the sides of the shaft well in excess of the resistance due to friction, or to make use of the other expedients already mentioned, so that the cutting edge may always be buried in the ground below the bottom of the excavation. This is especially necessary in very soft ground.

Sealing to rock. When the cutting edge has reached rock or other firm stratum, a watertight connection must be made between the shaft bottom and the rock. Just above the rock level there is often a stratum of boulders, gravel and sand, through which the ground-water flows under heavy press. It may then be necessary to use the pneumatic method (Art 4). It is possible, however, to seal the whole bottom of the shaft with concrete and grout with cement around the shaft bottom, through holes drilled through the concrete. The concrete is then removed.

The sealing of the St. Albert shaft is an example. The upper section of shaft was sunk 107 ft through sand and clay, and 13 ft into a 25-ft stratum of clay, the presence of which made it easy to pump out the upper shaft, and start the lower, which was sunk through the clay stratum, and sand and gravel below it, to rock at 200 ft depth. As the rock was soft shale it was excavated by orange-peel bucket until the cutting edge reached a depth of 215 ft. A weighted wooden box of conical shape (Fig 10) was then lowered, and concrete (1–2–4 mixture) placed around and over the box until the whole shaft bottom was sealed. The concrete was placed by covered buckets, lowered through the water and emptied through their tripping bottoms. After allowing the concrete to set the shaft was pumped out and cement grout was forced into the surrounding ground through holes drilled through the concrete. When the grout had set the concrete plug and the wooden box were removed in sections (Fig 10). Only a small infiltration of water occurred, which was soon stopped by fine materials flowing in from the surrounding ground.

Cost. At present day prices and labor rates (Art 2) and including contractor's profit, the cost of a drop-shaft, 14 ft square in inside dimensions, sunk and sealed without unusual difficulty, would be $450 to $500 per vert. ft. In Art 2 the cost of a shaft 14 ft square inside and 75 ft deep, sunk with steel sheet-piles, was given as $33 000. A shaft of same size, sunk as a drop-shaft, would cost about $37 200. In the first case the depth is almost the limit to which a shaft can be sunk by piling, while drop-shafts can go to much greater depths at a decreasing cost per linear ft, as depth increases. In presence of boulders, sinking by steel piling would involve difficulties that might prove insurmountable, whereas, with dropshafts boulders are readily handled unless present in great numbers, and even then they can be removed by using the pneumatic method (Art 4). For very soft ground, however, steel piling has a very definite place.
SHAFT SINKING IN UNSTABLE GROUND

I. Shaft 2, Roundout siphon, Catskill aqueduct. The caisson for soft-ground portions of shaft 2 was cylindrical, 20 ft outside diam, walls 2 ft 6 in. thick. Shoe was built of 0.6 by 20-in steel plates, with 4 by 1-in filler at cutting edge, and was anchored to concrete by 80, 5/8 by 60-in rods, attached alternately to inner and outer plates. Concrete consisted of 1 cement, 2 sand, 5 stone. Inner and outer forms were 2 by 6-in vertical wood lagging, supported by angle-iron rings, tied through walls with 5/8-in rods. Caisson was built in 5- and 10-ft lifts to full depth of 55 ft, lifts being bonded together by 1-in vertical reinforcing rods, 4 ft o-c.

Finished shaft was 10 ft 8 in by 23 ft in clear. Borings showed 80 ft soft ground, the upper 6 ft being sandy loam, and the rest a material resembling blue clay when dry, but was completely saturated in place, flowing "like cold molasses and very sticky." On bed rock, and surrounded by soft soil, were numerous hard boulders of all sizes. The shaft site was leveled, shoe assembled upon short planks, beginning a lift, and concrete was placed and allowed to set for a week; 10 ft more was then placed and when sufficiently set, sinking was begun. Mud was loaded into shaft buckets, sometimes with shovels, sometimes with water buckets, by men standing on plank rafts. Concrete was added as caisson sank. At a depth of 45 ft a layer of very soft mud was encountered, which ran in under one side of shoe, throwing caisson 2 ft out of plumb.

Operations to be followed in numerical order:
1. Make grout holes and grout up as indicated
2. Cut away first section of plug as shown
3. Excavate and place portion of lining before cutting plug to full size
4. Cut away second section of plug as shown
5. Cut away third and last section of plug to full opening and commence lining upwards

Fig 10. Method of Opening the Seal, St. Albert Shaft

A trench was therefore dug through surface loam on high side of caisson, the material from it was piled against low side, and when sinking was resumed the caisson straightened up. About 6 ft from rock, the shoe was stopped by boulders for long enough time to allow mud to stick to caisson walls, so that after boulders were blasted out it was necessary to load caisson with 200 tons of clay, and also to agitate the mud with compressed air blown through 1.25-in pipes built into the wall. A layer of hardpan was found just over the rock, into which the cutting edge sank deep enough to seal the caisson automatically. Average progress, from building shoe to sealing of caisson was 1.2 ft per day, including concreting and delays. Cost per ft, before 1914: concrete and shoe, $61; labor excavating, $32; general expenses, $32; total, $133. Before sinking was stopped by boulders, at depth of 50 ft, skin friction was less than 30 lb per sq ft; afterward, at same depth, over 500 lb.

II. Colliery shaft for D, L & W RR Co, near Wilkes-Barre, Pa (Fig 11). Caisson was of concrete, rectangular section, with rounded corners, and divided into 3 compartments by cross walls. End compartments were arranged to permit further subdivision by timber buntins. Outside dimensions, 28 by 59 1/2 ft; total height 90 ft. Thickness of walls at bottom: sides 7 ft; ends, 8 ft 2 in; outer surfaces vertical, inner surfaces stepped, in lifts of 9 ft 8 in; thickness at top, 3 ft 8 in; main walls reinforced vertically and horizontally with 1 and 1.25-in rods. At 7 ft above shoe, caisson was closed by an air-tight deck, for sealing caisson to rock under air pressure (12).

Ground was leveled, shoe assembled, and 20 ft of concrete placed. Sinking was carried on day and night, each shaft consisting of a foreman and 16 men in shaft. After shoe reached rock, the soft ground was held back temporarily with timber blocks wedged into place under horizontal
portion of the shoe. As this stratum was not firm enough to make a permanent seal, the shoe was
undercut and shaft excavated 4 to 5 ft larger all around than inside section of caisson at bottom. In blasting, great
cars was taken not to break the ledge under shoe and block-
ing. Sound rock was found 16 ft below cutting edge, and a
wall was built up to underside of caisson. Drain pipes dis-
posed of water breaking through blocking, and were grouted
after wall was finished and concrete had set. During con-
struction of this wall, water was led to the pipes by building
a small brick dam upon the ledge. Total depth of soft
ground, 70 ft; average progress, including building of caisson
and construction of temporary seal, about 7 in per day. Skin
friction, somewhat less than 700 lb per sq ft.

III. Colorado River siphon, Arizona (17). Shaft 30 ft
outside diam. Walls 3.5 ft thick, except for 10 ft above
cutting edge (Fig. 11a). Shoe was assembled on bottom of
a pit 10 ft deep, and concrete walls were carried up 10 ft
before sinking began. Excavation by hand to depth of 73 ft,
making 62 ft sunk and about same height of walls built in
71 days. Pumps were used for lower 45 ft. When inflow
amounted to about 1,000 gal per min, inrushes of ground
under shoe prevented further progress; the caisson was then flooded and dredged with a 1/2-cu yd
clam-shell bucket. Ground was quite firm, and after caisson had sunk 5 ft farther it stuck, although all material that dredge could reach was dug out to depth of 10 ft below shoe. Advance of 11 ft was made by lowering water level inside caisson, and a further advance of 2 ft by exploding dynamite charges in pipes jetted down on outside to depth of 5 ft below shoe. 16 ft more were gained by blasting underneath shoe, with dynamite placed by divers. Caisson then stuck fast, being held by skin friction of over 400 lb per sq ft. The 34 ft done by dredging to this point took 50 days. Successful attempt to relieve skin friction by water jetting around the outside was now made; by which, and with use of dynamite, the caisson was sunk to final depth of 139 ft, a further penetration of 32 ft in 38 days. From completion of first 10 ft of wall above the shoe, 128 ft of caisson was built and sunk in 160 days. Max skin friction about 400 lb per sq ft even when caisson was flooded.

IV. Two shafts for Norwood-White Coal Co, near Des Moines, Iowa (1921), both 8 by 12 ft, sunk through 110 ft quicksand. Previous 12 ft high, with simple cutting edge on bottom sec, were placed as excavation by clam-shell proceeded. Good joint secured by cutting edge settling in impervious material over rock. Main shaft was nearly water-tight and only 8 in out of plumb. Air shaft in poorer alinement and more leaky. Life of mine being estimated at 10 yr, expensive shafts not warranted (20).

4. PNEUMATIC METHOD

This is generally used in connection with the drop-shaft method where there is danger of an inflow of soft ground; when there are many boulders below water-level; or when making the seal between shaft lining and rock proves difficult. The procedure is exactly the same as described in Art 3, except that provision is made in the shaft for an air-tight deck, to be put in if the pneumatic method becomes advisable. The space below this deck is filled with compressed air, to drive out the water from the interstices of the ground, so that men can work in the shaft bottom.

Special equipment. The deck is of timber or reinforced concrete, designed to withstand the maximum air pressure that may be required, or to sustain the weight placed upon it for sinking. Edges of the deck project into a notch in the shaft walls. It is usually necessary to pump down the water before installing the deck, which is preferably placed 7 or 8 ft above the cutting edge. It may be advisable to provide an upper notch in the shaft walls, in which the deck can be set if the lower notch is under water.

Access to the working chamber below the deck is through a cylindrical steel shaft, bolted to the deck and extending vertically to a point above ground water-level. This shaft is usually 36 to 60 in diam and 1/8 in or more in thickness, as may be required to withstand the air pressure. It is made in sections 10 to 15 ft long, bolted together with rubber gaskets at the joints. The shaft is equipped with ladder rungs.

To prevent escape of compressed air through the shaft an air-lock is mounted on the top. This is essentially a chamber with two doors and means whereby compressed air can be admitted to or discharged from it. When the lower door is closed and the upper door open, men or a bucket can enter the lock. The upper door is then closed and compressed air is admitted until the pressure within the lock equals that in the working chamber. On opening the lower door, the men go down the ladder to the working chamber, or the bucket is lowered. To leave the working chamber, the operation is reversed. Several types of air-lock have been devised, but at present those generally used are the Matteson lock and the Moran lock (Fig 12, 13).

The upper door of the Matteson lock is in the side, opening and closing by rotating about the axis of the lock. The rope by which the bucket is hoisted runs through a stuffing-box in the top. The bucket can not, therefore, be hoisted through the top, but must be dumped through the side door; or the hoisting rope may be detached and another hooked to the bucket. The upper door of the Moran lock is in the top, and is in two sections which close around the hoisting rope; or, in another form, there is a single door closing around a slot provided with a stuffing-box, which is vertically above the
center of the lower door. When a bucket is lowered into the lock it is swung over until the hoisting rope enters the stuffing-box, and the door is closed. The air in the lock having been equalized, the lower door is opened and the bucket lowered into the working chamber. Usually, only one shaft and air-lock are required; men, buckets and materials passing through the same lock. Air-locks should be placed above the level of the ground-water, so that in case of a sudden loss of air pressure and the flooding of the working chamber, the workmen can escape into the lock.

Excavated materials are shoveled into buckets and hoisted from the working chamber by a derrick and double-drum hoist at the surface. Buckets are 24 to 33 in diam and 38 to 46 in high, depending on the shaft diam and size of the lock. To facilitate dumping, they have a steel bail at the top and a ring on the bottom.

When the excavated material is granular, or is soft clay, and the air pressure is sufficient, the spoil can be discharged from the working chamber to the surface by a blowpipe. This is a 4-in pipe running vertically from a point above the surface, through the deck and into a water-filled pit in the bottom of the working chamber. A quick-acting valve is placed in the pipe just below the deck. The excavated material is piled around the bottom of the pipe, the valve is opened for a short interval, and the air pressure forces the spoil up and out of the upper end of the pipe. The stream of spoil issuing from the blowpipe is deflected by an elbow, the back of which is of chilled cast-iron to resist wear and is renewable.

Compressed air is supplied to the working chamber by a low-pressure compressor, with a standby in case of breakdown. The piping, 3 to 4-in diam, should be in duplicate. For drilling, a high-pressure compressor may also be necessary. Smaller pipes are provided for electric light wires and a signal whistle. The principal features of a drop-shaft equipped for the pneumatic method are shown in Fig 14.

Weighting. To cause the shaft to sink, by overcoming the uplift of the compressed air plus the external friction, the walls must usually be heavier than those of an ordinary drop-shaft, or weight is added on top of the shaft, or on the deck. But, the escape of the compressed air under the cutting edge and up the outside of the shaft may materially reduce the exterior friction. In ground other than soft clay or quicksand, the shaft may sometimes be started by suddenly reducing air pressure in the working chamber (the men having left it).

Air supply. The air pressure may be greater or less than corresponds to the depth below ground-water level. A thick bed of clay may cut off water and so reduce the pressure; or the water may lie below such a stratum, artesian in character and under heavy pressure. Greater depths than would otherwise be attainable can be reached in
gravel, boulders or loose rock, by maintaining a lower pressure than is required and blowing out through blowpipes the water entering the working chamber. Or the water level may be lowered by pumping through holes in the shaft walls above the deck. The supply of air for ventilation (30 cu ft per man per min) is usually less than is necessary to replace air escaping under the cutting edge.

Physiological effect. Men can usually work in compressed air, up to a pressure of 18 lb per sq in (equivalent to 41.6 ft below ground-water level), with little inconvenience. At higher pressures, the working time in each 24 hr must be reduced, and time spent in passing from the compressed air to the normal air must be increased. The maximum pressure in which men can work is about 50 lb (equivalent to 115.5 ft below water level). All men who are to work in compressed air should be examined and qualified by a physician (see Caisson Disease, Sec 15).

Table 1. Requirements of New York Law for Caisson Work

<table>
<thead>
<tr>
<th>Pressure, lb per sq in above, normal</th>
<th>Shifts and rest intervals</th>
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<td></td>
<td>Total hr worked per 24 hr</td>
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</tr>
<tr>
<td>43–48</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>48–50</td>
<td>1</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Sealing to rock by the pneumatic method is similar to that for ordinary drop-shafts, except that the men in the working chamber have direct access to the work, which therefore can be done in a more positive manner. The problem is to stop the inflow of water, while still preventing the escape of compressed air below the cutting edge into the surrounding ground. This may be done by plastering with moist clay, or by a strip of waterproofing, but grouting, with cement or chemicals is often necessary.

Fig 15 shows the procedure in sealing a number of shafts sunk in connection with the NY City tunnel, of the Cataract aqueduct. The ledge rock was leveled, the shaft walls supported on posts, and excavation carried 3 ft into the rock, one ft larger in diam than the shaft shoe. The rock walls were lined with a 1 to 2 mortar wall, with a 4/4-in clearance outside the shoe. Grout pipes imbedded in this lining were sunk into the rock. A thick layer of oakum was placed under the cutting edge of the shoe, and the posts supporting the drop-shaft were shot out, thus allowing the shoe to drop on the oakum. Grout was then injected into the rock through the pipes imbedded in the shaft walls.

Wages of compressed-air workers. At the present time (1937), union wages of compressed-air workers in NY City and vicinity are $12 per day for pressures up to 18 lb per square inch above normal. For each increase in pressure (approximately as in Table 1) the rate is increased by 50cts to a maximum of $15. For placing concrete in the working chamber, 50 cts are added to the rate paid at the working pressure. Gang foremen receive $1 additional. Double time is paid for work on Saturdays, Sundays and holidays. In other parts of the U S, particularly in the South and Middle West, rates are considerably lower.

Costs of shafts sunk by the pneumatic method vary greatly with their diam, character of ground and depth sunk under compressed air. To the ordinary cost of the drop-shaft method must be added cost of assembling, installing, repairing and dismantling the sinking equipment (air compressors, air coolers and receivers, boilers or electrical connections and the special equipment already described); fuel or electric power; maintenance of compressed-air supply; experienced supervision; dressing and bathing facilities for the compressed-air workers; and the greatly increased cost of excavation done under compressed air. A shaft 14 ft square inside and 125 ft or more in depth, sunk in part and sealed by this method, may cost, including contractor's profit, $550 to $600 per vertical ft, or more, depending upon character of the ground.

Advantages. Notwithstanding its higher cost, the pneumatic method, within the limit of depth for which it can be used, is the most reliable. The men have direct access to the work; boulders can be blasted and the excavation made without danger of influx of the surrounding ground, or displacement of the shaft. Even if a drop-shaft becomes lodged in the ground by boulders and refuses to sink farther, a new shoe can be assembled below the first one and jacked down, using the weight of the shaft walls as a reaction. Walls can be built on the new shoe as it moves downward. For these reasons all drop-
shafts should be provided with notches in the walls, at one or more levels, so that, if necessary, a deck can be put in and the pneumatic method used.

I. Shaft 29, N Y aqueduct (Fig 14). For structural reasons not related to sinking, both vertical and horizontal reinforcement of concrete was made unusually heavy. The wall thickness of 2 ft, for a required inside diam of 15 ft 6 in, was at least 1 ft less than ordinarily required for a caisson of same depth. The deck was a 3-ft slab of reinforced concrete, cast integral with caisson walls, and was cut out after seal was made. Except for the concrete deck, the design was typical: a 36-in circular opening was provided in deck and a vertical line of 36-in flanged steel pipe (air shaft) was led from opening to top of caisson, where air lock was attached. Opening was formed by casting bottom length of air shaft into the deck; (where deck is of wood or iron, the lower flange of air shaft is bolted to it). Air shaft was long enough to keep lock always above ground-water level, so that, in case of accident to lock or to air-compressing plant, the caisson men would not be trapped by rising water. Air shaft had ladder runs so arranged as not to interfere with operation of bucket.

![Diagram of shaft construction and sealing details](image)

Fig 15. Sealing Details for Drop-shafts

Besides the air shaft, one or two 3-in inlet air pipes, fitted at bottom with check valves, a 0.75-in whistle (signal) pipe, a high-pressure air pipe, a conduit for electric wires, and sometimes a 4- or 6-in discharge or "blow" pipe, are led through deck. In deeper caissons, 2 air shafts were provided, fitted respectively with a material lock and a man lock.

II. Kidder shaft, Cleveland-Cliffs Iron Co, Mich. Caisson was 24 ft outside diam (Fig 16). Air shaft, 10 ft diam, was used first as a dredging shaft for a clam-shell bucket, which excavated to a depth of 87 ft. As it then became necessary to use compressed air, a deck and air lock were bolted to the top. Ledge rock was reached at 104 ft. Shoe was sealed to rock at 113 ft. Average progress, 0.72 ft per day elapsed time.

III. Two caissons, near Terre Haute, Ind, 16 and 20 ft inside diam, were sunk in 1923 by pneumatic caissons, through 140 ft of sand and gravel, 111 ft of which were water-bearing. Caissons and working chamber roofs were of concrete. Air press reached 61 lb per sq in. One caisson landed on a coal stratum and then penetrated fireclay before reaching rock. Lubricating pipes were used. Shafts were near Wabash River and water conditions were probably affected by this proximity. Some difficulty in controlling the sinking of the caissons.
Table 3. Details of Sinking 5 Reinforced Concrete Caissons, Catakill Aqueduct

<table>
<thead>
<tr>
<th></th>
<th>Shaft 19</th>
<th>Shaft 20</th>
<th>Shaft 22</th>
<th>Shaft 23</th>
<th>Shaft 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter, ft</td>
<td>19 1/8</td>
<td>19 1/8</td>
<td>19 1/8</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Inside diameter, ft</td>
<td>15 1/8</td>
<td>15 1/8</td>
<td>15 1/8</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Total height, ft</td>
<td>45</td>
<td>105.3</td>
<td>100</td>
<td>123</td>
<td>105.6</td>
</tr>
<tr>
<td>Number of locks</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Concrete proportions</td>
<td>1 1/2 : 2 : 4</td>
<td>1 1/2 : 2 : 4</td>
<td>1 1/2 : 2 : 4 to</td>
<td>1 1/2 : 2 : 4 to</td>
<td>1 1/2 : 2 : 4 to</td>
</tr>
<tr>
<td>Depth sunk under compressed air:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In sand, ft.</td>
<td>33.7</td>
<td>33.7</td>
<td>13.7</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>In rock, ft.</td>
<td>11</td>
<td>77</td>
<td>50.3</td>
<td>105</td>
<td>59.5</td>
</tr>
<tr>
<td>Average progress:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concreting, ft per working day</td>
<td>3.75</td>
<td>2.85</td>
<td>3.56</td>
<td>3.23</td>
<td>3.08</td>
</tr>
<tr>
<td>Sinking under pressure in sand, ft per hr.</td>
<td>.0275</td>
<td>.0346</td>
<td>.0393</td>
<td>.0591</td>
<td>.028</td>
</tr>
<tr>
<td>Sinking under pressure in rock, ft per hr.</td>
<td>.00035</td>
<td>.0075</td>
<td>.0056</td>
<td>.004</td>
<td>.0025</td>
</tr>
<tr>
<td>Hours constructing seal</td>
<td>64</td>
<td>35</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>Average progress, ft per day elapsed time, from placing shoe to completion at total depth...</td>
<td>0.82</td>
<td>1.18</td>
<td>1.25</td>
<td>1.20</td>
<td>1.22</td>
</tr>
<tr>
<td>Maximum air pressure, lb per sq in.</td>
<td>17</td>
<td>39</td>
<td>28</td>
<td>46</td>
<td>29.5</td>
</tr>
<tr>
<td>Weight of caisson, tons.</td>
<td>460</td>
<td>1,050</td>
<td>978</td>
<td>2,323</td>
<td>1,780</td>
</tr>
<tr>
<td>Weight of caisson, with max load of sand and pig-iron, tons.</td>
<td>700</td>
<td>2,100</td>
<td>2,470</td>
<td>4,612</td>
<td>4,046</td>
</tr>
<tr>
<td>Frictional resistance, lb per sq ft of outer surface, at various depths of shoe</td>
<td>300 to 400</td>
<td>630</td>
<td>630 at 81</td>
<td>1,111 at 85</td>
<td>1,011 at 29</td>
</tr>
<tr>
<td>Contract price per ft for sinking only (concrete and reinforcing steel paid separately)</td>
<td>$8466</td>
<td>$8471</td>
<td>$8456</td>
<td>$8735</td>
<td>$8614</td>
</tr>
</tbody>
</table>

Note.—All these caissons were weighted with excavated sand piled on top of deck around air shafts. In each case, a pit was excavated and timbered square to depth of about 20 ft. The shoe was set on heavy timbers, and caisson built to its full height before sinking was started. Contract price allowed a fair profit to contractor.

5. FORCED DROP-SHAFTS AND HONIGMANN METHOD (30-35)

Until it becomes necessary to reach the more deeply buried orebodies, American practice can furnish no such examples of deep shaft sinking in soft soils, by freezing, cementation and forced drop-shafts, as are common in Europe. There, exhaustion of the easily accessible deposits has compelled high development of the art, intensive study of methods and large expenditure of money. Hence, for detailed information, it is necessary to consult the large volume of European technical literature on this subject.

General description. To penetrate depths of quicksand and other unstable, water-bearing material, beyond the limit of open or pneumatic caissons, a method has been developed in Germany of jacking down a telescopic series of iron drums, inside of and reacting against a previously installed concrete curbing. The latter is strong and heavy, and built into it, near the top, is an internal cast-iron flange, the reaction ring. This, anchored by vertical rods extending to the shoe, resists thrust of the jacks, which are attached to and bear against under side of ring. The caisson is sunk by dredging in the open to a depth of 50 or 60 ft; then a concrete floor (seal) is placed in the bottom (under water if necessary), and shaft is unwatered. A cast-steel shoe, with an outside diam slightly less than inside diam of curbing, is set on the concrete floor, and a cylindrical drum, of flanged and bolted cast-iron segments (similar to shaft tubing, Sec 7) is built up from shoe to under side of the jacks. The concrete seal is then broken, thus admitting water to natural level, and the drum is jacked down, the material being excavated under water by grab bucket, "mammoth" pump, oracker borer (described below). Finally, the jacks are removed and more segments of lining added as required. With hydraulic jacks, a drum 20 ft outside diam can usually be forced down 250 to 300 ft before it sticks. If
FORCED DROP-SHAFTS AND HONIGMANN METHOD 8-17

rock lies still deeper, the bottom is again sealed, the shaft is unwatered, a second drum of smaller diam is built inside the first, the jacks are shifted inward to bear upon it, and sinking is resumed. Frequently a second drum has been necessary; less often, a third (3).

Details of construction of curbs, drums and sinking plant are shown in Fig. 17 and 18. A head-frame handles the machinery, which includes: trepan, similar to those used in the Kind-Chaudron boring method for rock (Sec 7), for breaking up the concrete floor and any boulders or partly cemented ground that may be met; the curbing, with reaction ring and hydraulic jacks; and sinking drums. The outer drum (Fig 17) is the patented Pattberg compound, the cast-iron shell of which is lined with 22 in of strong brick or concrete, for additional weight and stiffness; the second is a simple iron-segment drum. The compound drum is made necessary by the great earth press at depths of 300 or 400 ft. a number of shafts having been lost by collapses of unsupported iron drums, notwithstanding use of segments 3.5 in thick. The segments are about 5 ft high, flanged and bolted on both horiz and vert joints, and 8 to 10 of them make up a ring. The shoe must be very strong and heavy, and anchor and reaction rings and all bolts must be designed to carry safely the full thrust of the jacks. For considerable depths, the grab bucket used in ordinary caissons has been superseded by the mammoth pump in firmer, and the sack-borer in softer, soils.

Mammoth pump (Fig 17) is essentially an air-lift pump (Sec 15). Inside the hollow stem of the trepan is a small pipe carrying compressed air to a point near bottom of the cutting tool and releasing it into the stem. The air lightens the column of water in the stem, and discharges it at the surface, carrying with it the material pulverized by the borer.

Sack-borer (Fig 18) is a large auger-like tool, with its stem in center of shaft. The stem is composed of a series of lengths of heavy flanged pipe, terminated at upper end and by a splined section, on which is mounted a large horizontal gear-wheel. A wire rope, hoisting machine drum to swivel link at top of stem, suspends the sack-borer. The stem is rotated through the gear-wheel by another engine, and is lowered gradually by hoisting rope. New sections of borer stem are added as shaft is deepened. Cross arms are attached to the stem at intervals, having rollers at their ends which bear against sides of shaft and keep stem in line. Material cut by the rotating borer is swept into two heavy, open-mouthed canvas sacks, fastened to backs of cutters. From time to time the borer is raised and emptied. In an improved form, the sacks are mounted on a frame sliding on guides attached to cross arms on stem, and are hoisted by an independent engine. The sack-borer is best adapted to clay and sand.

I. Shaft 5, Rheinpreussen colliery, Homburg am Rhein, Germany, was started in 1901 with a brick caisson 20.2 ft inside diam, walls about 3.5 ft thick. This reached a depth of 65 ft. Concrete plug, 9 ft thick, was then placed on the bottom, under water, the shaft was pumped out, the anchor ring, rods and reaction ring (designed for a pressure of 3000 tons) were erected, and an inner truly vertical, brick lining was built, reducing inside diam to 23.8 ft. A compound sinking drum with outer and inner diam of 25.52 and 21.32 ft respectively was then constructed, and sinking was begun with a percussion borer and mammoth pump. The concrete was bored through in 4 days, and thereafter the average progress was about 5 ft per day. The compound drum stuck at 245 ft, and shaft was filled for 60 ft with sand and gravel (instead of concrete). Shaft was next pumped out and an iron drum, 3.5 in thick and 19.36 ft inside diam, was built up to the jacks. This drum stuck at 315 ft; the shaft was again partly filled and pumped out, and another drum, 17.38 ft inside diam, was forced to a depth of 343 ft, where the shoe entered clay firm enough to permit shaft to be pumped out. A fourth drum, 15.3 ft inside diam, was finally forced to the coal measure, at a depth of 508 ft. The sinking took 3 years, the average progress being about 6 in per day (3).

II. Starkrade shaft, near Holtze, Germany, was started with a brick caisson 24.6 ft inside diam, which was sunk to a depth of 59 ft. The excavation was continued by hand to 131 ft, where an iron sinking drum, 22 ft inside diam, was constructed. This drum was forced to 284 ft; a second drum, 19.3 ft diam, to 438 ft; and a third, 16.75 ft diam, to 448 ft. Here the water was found to be successfully shut out, and sinking was continued by hand (3). For cost, see Table 3.

Average cost per ft of sinking by dropping method in Germany, at various depths, is given by Henry Louis (1) as follows: 82 to 164 ft $256; 164 to 328 ft $593; 328 to 492 ft $817; 492 to 656 ft $1,040.

Sassenberg process of hydraulic flushing reduces skin friction and adhesion in some soils. Short and long rings above it are about 1.5 in larger outside diam than the rest of the lining, and in the shoulder thus formed are water passages, connected through pipes to a high-press pump. By operating this pump during sinking, the drum is partially surrounded by a film of water.

The forced-drop-shaft has been used in sinking a number of shafts. At present, however, it has been replaced by the Honigmann method, or by freezing, or cementation.

Honigmann method (35). The essential difference between this and a forced-drop-shaft is that the lining is installed after the excavation is completed, instead of closely following the cutting tool. The advantage of this is that the cast-iron tubing can be assembled and bolted together above the surface, before it begins to sink. Access for calking the outside of the joints can therefore be had, and the cost of assembling and placing the lining is reduced.

Honigmann observed that the walls of a boring in sand fell in, even when the hole is filled with water to a level above that of the ground-water, but if the walls were coated with clay they remained
Fig 17. Honigmann Method, Mammoth Pump and Borer. Shaft IV and V, Rheinpreussen Colliery, Germany. A, Suction Pipe and Overflow; B, Compressed Air; C, Caisson; D, Shoe; E, Anchor Rode; F, Compound Lining; H, Cast-iron Lining (Riemer)

Fig 18. Sack Borer. Adolf Shaft, Eschweiler Mining Co, Germany (Riemer)
Table 3. Cost of Sterkrade Shaft

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick caisson, 59 ft @ $285</td>
<td>$16,800</td>
</tr>
<tr>
<td>1st iron drum sunk 133 ft @ $502</td>
<td></td>
</tr>
<tr>
<td>Segments</td>
<td>$32,900</td>
</tr>
<tr>
<td>Labor and supplies</td>
<td>33,900</td>
</tr>
<tr>
<td>2nd iron drum sunk 169 ft @ $715</td>
<td>66,800</td>
</tr>
<tr>
<td>Segments</td>
<td>75,300</td>
</tr>
<tr>
<td>Labor and supplies</td>
<td>45,900</td>
</tr>
<tr>
<td>3rd iron drum sunk 15 ft @ $6,060</td>
<td>121,200</td>
</tr>
<tr>
<td>Segments</td>
<td>71,500</td>
</tr>
<tr>
<td>Labor and supplies</td>
<td>19,300</td>
</tr>
<tr>
<td>Depreciation of plant and fittings, 50% of new value</td>
<td>43,300</td>
</tr>
<tr>
<td>Total</td>
<td>$338,900</td>
</tr>
<tr>
<td>Less salvage on tubing recovered from inner drums</td>
<td>35,700</td>
</tr>
<tr>
<td>Total cost for 376 ft</td>
<td>$303,200</td>
</tr>
<tr>
<td>Cost per ft</td>
<td>$807</td>
</tr>
</tbody>
</table>

Standing. The theory is that the increased head of water in the boring, over that in the ground, causes a pressure against each grain of sand in the walls. As the water flows between and around the grains of sand the pressure is equalized, with no force to resist the force of gravity which caused the sand to fall. But, if the walls of the hole are coated with clay, no water can enter between and behind the sand grains in the walls, and there is therefore a pressure against the inside face of each grain to keep it in place. This idea he applied to large borings like shafts.

The boring tool of the Honigmann method (Fig 17) is an inverted cone, with the apex at the center of the excavation, provided with steel knives which cut the ground as the tool is rotated. The hollow stem is extended through the tool to the bottom of the conical pit thus made. Compressed air is carried down through a small pipe in the stem and discharged just above the bottom. The stem thus becomes a mammoth pump (Fig 17), which discharges at the surface the material loosened by the borer. The shaft is filled with an emulsion of clay to a level considerably above that of the ground-water, to provide support for the excavation walls. At the surface the spoil deposited from the discharged water by sedimentation, the water being returned to the shaft with an additional admixture of clay if necessary. To coat the sides of the shaft properly, the percentage of clay in the water varies with the character of the ground. In clayey soil, 15% is considered sufficient; in sand, 20% and in gravel, 35%.

The shaft excavation is never made to its full diam in the first cut. It is begun with a diameter of 6.5 to 8 ft and completed to the bottom. The diam is then increased by one or more successive cuts, with larger tools mounted on the stem. Between the tools, the stem carries a cylindrical guide fitting closely to the walls of the first cut, which must be true and plumb; otherwise, the installation of the sinking lining would be difficult.

The first ring of the tubing or lining, which has a cutting edge on the bottom, is assembled over the mouth of the shaft. It is laid out in a true circle, leveled with its axis coinciding with the shaft axis, and hung by threaded rods to the tower over the shaft. This ring is bolted up with lead gaskets in the vertical joints. The second ring is assembled and similarly bolted to the first. The gaskets are then caulked from the outside and a false bottom of concrete is placed in the bottom of the assembled rings. By means of the threaded rods the two rings are lowered in the shaft and additional rings are added and caulked. Because of the false bottom, the assembled rings will eventually float in the water, and, to continue sinking, water must be run into the cylinder. When the lower edge of the tubing reaches a point about 3 ft above the shaft bottom, the space under the false bottom and around the outside of the lower rings is filled by a trowel with cement grout between the lining and shaft-walls. The lining is then lowered into the grout, and when it has set, the grouting behind the lining is continued to the top of the shaft. The false bottom is then cut out by jackhammers, after borings through it have tested the watertightness of the grouting.

This method is simple and ingenious in all its details. It requires little material and equipment and few men, and is much less costly than the freezing method hereinafter described. It is best suited to soft ground, but strata of cemented sand and gravel, sandstone or limestone can be passed if not too thick. A great advantage is the security afforded the workmen, in not being exposed to asasant during sinking and lining the shaft. The method can not be used, however, if a subterranean water course or absorbent stratum is encountered, which might carry away the water in the shaft. This situation developed while a shaft, 17 ft net diam, was being sunk for the Dutch Govt; after reaching a great depth, the work had to be abandoned. Another disadvantage is that the excavation may get out of line, if inclined hard strata are encountered. Trouble may also arise
because of the swelling of the walls of the excavation and sticking of the lining during its descent. To obviate this the bottom of the lining is furnished with a conical piece which is removed after the false bottom is cut out.

The Honigmann method has been used successfully for a shaft 19.7 ft net diam, excavated to a diam of 24 ft and sunk to a depth of 1 385 ft. The Dutch company (La Société Miinabouw) holding the rights states the cost and rate of progress as follows (39):

<table>
<thead>
<tr>
<th>Depths, meters</th>
<th>Cost per meter</th>
<th>Monthly progress</th>
</tr>
</thead>
<tbody>
<tr>
<td>to 100</td>
<td>15 000–25 000 francs</td>
<td>15–20 meters</td>
</tr>
<tr>
<td>100–200</td>
<td>25 000–37 000 &quot;</td>
<td>10–12 &quot;</td>
</tr>
<tr>
<td>200–350</td>
<td>37 000–52 000 &quot;</td>
<td>9–11 &quot;</td>
</tr>
<tr>
<td>350–500</td>
<td>52 000–75 000 &quot;</td>
<td>8–10 &quot;</td>
</tr>
</tbody>
</table>

The above costs apply to 1933, or early 1934, when the franc was worth 6 1/4 to 6 1/2 cents, U S currency. Furthermore, these costs are much lower than would be possible in the U S.

6. FREEZING METHOD (3, 6, 7, 8, 14, 18, 22, 24)

General principles. This method was invented by F. H. Pootsch in 1883 and introduced into this country by Charles Sobysmith. Its essential feature is the solidifying, by freezing, of water-bearing ground in which the shaft is sunk. The freezing is sometimes continued into water-bearing rock. The method has been much used in recent years in England and on the Continent, for shafts 200 to more than 2 000 ft deep. Vertical holes, 2 to 4 ft apart, are bored on the circumference of a circle outside the periphery of the proposed shaft. Into each hole are lowered pairs of concentric pipes, through which brine, cooled to low temperature, is circulated. The brine passes down through the inner pipes and up through the space between the two, the outer pipe being closed at the bottom. This method has been used even when the ground-water is saline and in circulation. It is, therefore, so widely applicable in all kinds of soft ground and fissured rock, and its details have been so well worked out, that for very deep shafts, it has largely replaced all other methods.

Freezing pipes. The holes for these are bored by the usual methods and, in soft ground, are cased (Sec 9). They must be vertical, or nearly so; otherwise the distances between them, at the bottom, may be too great to permit the formation of a complete ice wall. In very deep shafts, due to the difficulty of keeping the borings vertical and properly spaced, the freezing is sometimes done in stages, each 200 to 300 ft deep. Each section of shaft is then excavated and lined before freezing the succeeding section. In this case, the holes for the freezing pipes are driven outward, at a slight vertical angle, from the bottom of the preceding section. In the most recent practice, however, the holes are bored continuously from the surface to the bottom of the proposed shaft; their direction being checked at frequent intervals and, in case of deviation, is corrected, or in case of great deviation, additional borings are made. The usual form of freezing pipes is shown in Fig 19. The outside pipe, 4 to 6 in diam, closed at the bottom, is lowered into the casing and tested hydraulically. The casing is then withdrawn so that the ground may close around the freezing pipe. The inner pipe, one in or more in diam, is lowered into the outer pipe. Both pipes are connected at the top to header pipes, to and from which the brine is pumped from the central freezing plant.

Additional borings should be made, one at center of the proposed shaft and others inside and outside of the circle of the freezing pipes. These are used to take the ground temperatures at different levels, for checking the formation and maintenance of the ice wall. As saline solutions freeze at lower temperatures than pure water a leak in the piping may cause a weak spot, or a hole, in the ice wall, making necessary a longer period of freezing.

Ice wall, in its several phases of formation, is shown by Fig 20. It must be thick enough to withstand the pressure to which it will be subjected, and the freezing pipes are located accordingly. Frozen sand is stronger than clear ice. Abby's experiments show that frozen saturated sand crushes at about 2 500 lb per sq in at a temperature of -25° C, and at about 1 700 lb at -12° C. It should therefore carry safely 300 lb per sq in and.
assuming full hydrostatic pressure on the outside of the ice cylinder, the thickness of the wall, for a shaft 300 ft deep and 20 ft diam should be about 7.5 ft.

Freezing plant. Ammonia, compressed and expanded, is generally used as the refrigerating medium. Carbolic acid is occasionally used because lower temperatures are obtainable. The brine, chilled by expansion of the ammonia and circulated through the freezing pipes, is commonly CaCl₂, but MgCl₂ is recommended, as it has less tendency to precipitate at low temperatures and clog the piping. The capacity of the freezing plant depends upon the diam and depth of shaft, thickness of the required ice wall, and the time allotted to the freezing of the ground.

Sinking, after the ground is frozen, is done by drilling and blasting with light charges, but, to avoid cracking the ice wall, pneumatic hammers are often preferable.

Lining. Shafts of 200–300 ft, or even more, may be lined with concrete, but care must be exercised because of the effect of the frozen ground upon the concrete. Shafts of great depth are usually lined with cast-iron rings (tubbing), bolted with lead gaskets and backed with concrete.

Thawing. After completing sinking and lining, the ground is thawed by filling the shaft with water, or by gradually raising the temperature of the circulating brine and continuing circulation for a long period, or by the aeration of the shaft. During this time, in deep shafts, the lining requires continual tightening and calking.

Average speed of sinking, considering the process as a whole, depends largely upon the boring, and is quite variable. If holes prove to be nearly plumb, both boring and freezing are expedited; but, if some of the holes deflect badly near the bottom, new holes must be bored, and the irregular spacing of the pipes makes necessary a longer freezing period.

<table>
<thead>
<tr>
<th>Table 4. Speed of Sinking by Freezing</th>
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<tbody>
<tr>
<td><strong>Shaft</strong></td>
</tr>
<tr>
<td>Anhalt government salt mine, No 6</td>
</tr>
<tr>
<td>Marie mine</td>
</tr>
<tr>
<td>Consolidated Sophie lignite mine</td>
</tr>
<tr>
<td>Castlereagh shaft</td>
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<tr>
<td>Theresa shaft</td>
</tr>
</tbody>
</table>

I. Shaft 6, Anhalt government salt mine, Leopoldshall, Stassfurt, Germany. Twenty-six 5-in holes were bored in a circle, 20.25 ft diam and cased to depth of 325 ft. The boring was difficult, and, as shown in Table 4, consumed 17 months. Freezing was continued for 3 months before sinking was begun. After only 30 ft had been sunk, a small leak broke through in shaft bottom, and flooded shaft. Sinking was stopped and freezing continued for 2.5 months more, after which a progress of over 60 ft per month was maintained to a depth of 202 ft. The shaft was lined with iron tubing (Sec 7), the space behind being filled with concrete mixed with water containing calcined soda. Sinking and lining were prosecuted alternately until the tubing was sealed to rock at 325 ft. Aside from difficulty of boring the holes, this sinking was entirely successful (3).

II. Theresa and Castlereagh shafts, Dawdon, County Durham, England, were first sunk (with pumping) through very wet rock to depths of 330 and 204 ft respectively. It was then decided to continue them by freezing through underlying sand to the coal measure at a depth of 463 ft. Thirty-eight holes were bored around each shaft, including two extra at each, on 30-ft circles, 7 well drills being used. The holes were 8 and 10 in diam, lined with 6.25-in casings. The freezing plant comprised two 135-hp steam engines, driving 4 ammonia compressors. As shown by Table 4, the freezing of Theresa shaft was especially slow, 13 months elapsing before sinking could be begun. Both shafts were successfully sealed to rock in 2.5 years (19).

III. Chapin shaft, Iron Mountains, Mich (7) was sunk in 1898–9, through 95 ft sand, gravel and boulders, with water level 10 ft below surface. Twenty-six 10-in casing pipes were put down in a 20-ft circle; inside of these were 8-in freezing pipes, inlining 1.5-in circulating tubes. Casings were then withdrawn. Ice machine was a Linde (ammonia type) of 50 tons daily refrigerating
capacity (1 ton equals cooling effect of 1 ton melting ice). Freezing fluid was saturated solution of commercial CaCl₂; velocity of flow in the 1.6-in. pipes, 2 ft per sec. In about 21 days after starting ice machine, the frozen ring was complete and excavation was begun. Rock was reached in 135 days (including a 30-day stoppage, when shaft was allowed to fill with water). There were some trouble and delay from leakages through ice wall, the elapsed time being about 200 days.

IV. In Campine district, North Belgium, so great an advance has been made in developing the freezing process for shafts 1 500 to 2 000 ft deep to the recently discovered coal measures, that previous applications of the process do not maintain their former importance as examples to be studied. Sinking in stages by freezing has in some of these shafts alternated with cementation. Some of the most notable work is the sinking of 2 shafts for the Helchteren and Zolder project, where 2 034 ft of ground were frozen by a single current of refrigerating fluid in 7 months' time. Sinking and lining took 21.5 months; cost, aside from fuel and tubbing, $1 177 per ft (22).

H. Muller gives (1917) estimates of cost, under two different assumptions, for a shaft sunk 300 ft by freezing in stages, at $1 100 and $1 600 per ft, respectively (29).

V. Two shafts, sunk by freezing for the Houthaelen Coal Mines (42) in the Campine district were completed in 1932 and 1934. Cementation was first tried and abandoned. Shaft I was sunk to 2 106.3 ft; shaft II, about 230 ft from shaft I, to 2 139.1 ft. Both passed through 1 968.4 ft of water-bearing ground to a much fissured stratum of sandstone about 33 ft thick, overlying the coal. The soft ground above the sandstone was as follows:

<table>
<thead>
<tr>
<th>Tertiary deposits</th>
<th>Secondary deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand 426.5 ft</td>
<td>tufa 203.4 ft</td>
</tr>
<tr>
<td>clay 232.9 &quot;</td>
<td>chalk 147.6 &quot;</td>
</tr>
<tr>
<td>sand 183.7 &quot;</td>
<td>marl 350.6 &quot;</td>
</tr>
<tr>
<td>clay and marl 298.6 &quot;</td>
<td>sand 76.7 &quot;</td>
</tr>
<tr>
<td>sand 16.4 &quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>810.3 ft</td>
</tr>
</tbody>
</table>

In each case a preliminary pit was sunk, 42.7 ft diam and 15.6 ft deep.

The bourns for the freezing pipes, begun Sep 5, 1927, for shaft I and Nov 20, 1927, for shaft II, were spaced about 3.5 ft c-c, on the circumference of a circle 36.1 ft diam. The bourns were 2 066.9 ft deep for shaft I and 2 093.2 ft for shaft II, continuous from surface to full depth. The plumbness of the bourns was checked by the Deni-Forsky telecinograph and in case of deviation the direction was corrected (Sec 9). The theoretical number of freezing pipes for each shaft was 32, but 5 additional bourns were required for shaft I and 4 for shaft II. The bourns were cased to 1 148 ft, below which no casing was installed. The freezing pipes were lowered into the bourns and their headers, in the bottom of the preliminary pits, were connected with the freezing plant.

Net diam of each shaft was 16.4 ft. The cast-iron tubbing lining was 19.4 ft outside diam; behind it was placed 1.3 ft of concrete, so that the diam of the excavation was 22 ft. At center of each shaft an additional boring was made, in which were placed concentric pipes for drawing off water at 4 levels, viz: at bottom of the preliminary pit, at bottom of the clay (556 ft below surface), at top of the tufa (1 158 ft depth), and in the marl at 1 739 ft. These pipes were to draw off excess water after the closing of the ice-wall. The amount of the water was 24 525 gal in shaft I and 41 889 gal in shaft II. For test purposes additional bourns were made from the bottom of the preliminary pits. These were on the circumference of circles, around the center of each shaft, with diameters of 21.3, 32.5, 30.1, and 41 ft. The total length of casing for bourns was 132 981 ft; of outer freezing pipes, 152 334 ft; and of inside freezing pipes, 147 711 ft.

The freezing plant was in six units (total, 2 891 h p), each unit of a capacity equivalent to 100 tons of ice per day, melted from and at 32°F. The elec power for the sinking operations was 1 285 h p, supplied from an outside source. A standby Diesel unit of 800 h p was installed. Ammonia was used at a pressure of 15.4—26.4 lb, reduced to 1.1—2.2 lb at the condensers. Chloride of sodium, at 27°—38° Baumé, with point of freezing at about —16.8°F, was used as the circulating brine.

The ground was frozen to 2 050.5 ft for shaft I and 2 091.5 ft for shaft II. Freezing for shaft I began June 13, 1930 and to Dec 6, 1930, when excavation was begun, 19 842 500 000 btu had been used for refrigeration; equivalent to 68 898 tons of ice melted from and at 32°F. At a depth of 2 106.3 ft (Dec 15, 1932), 45 637 750 000 btu had been used, equivalent to 155 454 tons of ice melted from and to 32°F. For shaft II freezing began Jan 29, 1931, and when excavation was begun (July 6, 1931) 17 858 250 000 btu had been used, equivalent to 62 008 tons of ice melted. At depth of 2 139 ft (Jan 9, 1934) 67 464 500 000 btu had been used, equivalent to 234 252 tons of ice melted. The flow of brine through each freezing pipe was 282.4 cu ft per hr, at velocity of 3.07 ft per sec in the descent and 0.95 ft per sec in the riser pipe.

The performance of the freezing plant and the formation and maintenance of the ice-wall was, at all times, under strict surveillance. Temperatures of the ammonia throughout its circuit were taken every 3 hr; also the temperatures at the start and return of the brine, and the pressure and discharge of the pumps. A weekly check of the discharge from each freezing pipe was made.
Cementation and Grouting Methods

8–23

Meters installed at the central station measured the general discharge of the brine and electric indicators warned of any considerable loss. The closing and progress of formation of the ice-wall was checked: (a) by temperatures taken at every 328 ft down to the 1,040-ft level, at the center boring of the shaft and in each of the other 4 series of borings made for this purpose; (b) by amount of water pumped from each of the 4 levels in the center boring.

Excavation and lining of shaft I began Dec 6, 1930; completed Dec 16, 1932; aver progress per working day, 3.33 ft. Shaft II, begun July 6, 1931, reached 1,177.8 ft June 3, 1932, when a rupture of the ice-wall occurred, due to breakage of one of the freezing pipes. After repairs, excavation was resumed Jan 12, 1933 and completed Aug 1, 1934. Average progress per working day, 3.65 ft. Nearly all excavation was done by jackhammer; only in sandy tufa and chalk were the ordinary mining methods used. At the bottom of the preliminary pit the non-frozen core was about 20 ft diam; at 295 ft, this core was only 3–7 ft diam and thence to 1,148 ft the ground was frozen to the center, or nearly so. At top of the tufts was found a non-frozen core containing water under pressure. Below, the ground was completely frozen.

These shafts were lined with cast-iron tubbing, the possible pressures upon which were computed as the hydrostatic pressure multiplied by the following coefficients: 1.8 for sand; 1.5 for mixed sand, clay and marl; 1.25 for marl; 1.0 for tufa and chalk. The ultimate compressive strength of cast-iron was taken at 85,000 lb per sq in, for thicknesses of 3 1/2 in or more, and 71,000 lb per sq in for thicknesses of 3 1/2 in or more. Safety factor of 6.3 was used in soft ground and 5.3 in firm ground, the thickness being determined by the cylinder formula. These computations gave thicknesses of 15/15 to 61/15 in. The rings were about 5 ft high; bolted with lead gaskets. In upper parts of shafts the excavation was made to some depth before starting lining, which was then built up from the bottom. Below this, lining kept pace with excavation. The lining segments were provided with holes for grouting.

On completing excavation and lining, and before thawing was begun, all bolts in the lining were tightened, lead joints were caulked and cement grout injected at a pressure equal to half the pressure which each ring might be called upon to support. Thawing was done by progressively warming the brine in the freezing circuit, and by rotation of the shaft interior. Other shafts sunk by this method in the Campine district have been thawed by inundating the shafts, with the idea of keeping the thawing in balance and avoiding a sudden thaw, but this method stops all work below and prevents observation of the behavior of the lining. As thawing advances itself for some time after it is placed, joints which open must be cared for. After thawing was ended, another caulkling and tightening of bolts was necessary. Before this, leakage through joints was about 600 gal per hr per 328 ft of depth, but after recaulking and tightening the joints, leakage was only about 6.5 gal per hr per 328 ft; practically watertight. Thawing of shaft I was begun Nov 22, 1933 and completed Oct 6, 1934, 40% years after beginning work. The time for thawing shaft II was not reported. The frozen pipes were removed down to the 1,148-ft level. The holes which were occupied by them were filled with cement grout.

7. CEMETATION AND GROUTING METHODS (25–28, 43)

The idea of filling fissures and voids, in the ground, with cement is old. By injecting cement in a boring in the Lens mines, M. Reumaux succeeded in 1882 in closing a large flow of water. From 1900 the method has been much used for shaft sinking. In 1904–7, La Compagnie des Mines de Béthune sunk 4 shafts by cementation, and later several others at Lens and Liévin were successfully completed. Thereafter, the method spread over France and other countries (39). It is most successful in fissured rock; in quicksand, it is entirely unsuccessful, because the bore-holes can not be kept open except by casing, or by clay coating (Honigmann method, Art 5), both of which prevent cementation. Also in porous ground such as tufts the cement coats the surface but does not penetrate the pores. Fissured chalk and limestones lend themselves best to this method. In the first applications, 6 to 8 borings, 5.5–6 in diam, were made to full depth around the site of proposed shaft. A mammoth (air-lift) pump was lowered gradually into each bore hole, so that the induced flow of ground-water would wash out the mud from fissures and voids. Then water under pressure was pumped into the holes, to force any remaining mud back into the ground, and cement grout was injected under pressure. In the Saclier method the grout is injected into all holes simultaneously; in the later Portier method injection is made into each boring singly, one at each end of a shaft diameter, then at each end of a diameter perpendicular to the first, and finally at ends of other diameters. Pressure is maintained until the grout has set, otherwise it might be washed out by the flow of ground water.

Francois method employs 20–24 borings, 1.5–2 in diam, in two concentric circles around the site of the shaft. They are not immediately bored to full depth, but deepened after each injection of cement. The pressure on the grout is 1,500 to 3,000 lb per sq in or even 4,500 lb. The grout is injected into each hole separately. After injection, boring is resumed when the grout has taken its initial set, but is not yet hard. In certain clayey ground chemicals are first injected, to coat the ground particles and facilitate flow of the grout. The theory of the Francois method is that more bore holes of the larger number used are likely to reach fissured ground, and small diameter holes cost less than larger ones.
SHAFT SINKING IN UNSTABLE GROUND

Also, injection of grout in a part of the bore hole, instead of its whole length at one time, is more likely to fill the smaller fissures, and great pressures still further increase the chances of success. The chemicals used before grouting are silicate of sodium and sulphate of aluminum, injected separately; the combination of the two forming silicate of aluminum, a white colloidal precipitate. This, under pressure is dehydrated, leaving a solid filling in the capillary fissures which the grout could not enter and covering the clayey walls of larger fissures, thus facilitating entrance of the grout.

Only the Portier and François methods are now used. Both are cheaper than freezing, or the Honigmann method, but are applicable only to cementable ground. Shafts sunk by cementation are lined with reinforced concrete, or with cast-iron tubing.

Injection of other materials has also been used to shut off water, but only in shallow shafts.

Joesten method uses sodium silicate, injected under pressure and followed by an injection of calcium chloride. These form an insoluble calcium silicate, which sets so quickly that the casing pipes must be pulled as the calcium chloride is injected, to prevent their being immovably set in place. The chemicals penetrate to a distance of about 3 ft around the end of the casing pipes, which are spaced accordingly. This method is especially useful to consolidate the ground around the bottom of a shaft, at its junction with the rock, but has recently been used successfully for shaft sinking itself.

Asphalt grouting has been used considerably in the US, and is better than cement grouting for fissured rock where there is a large flow of water. The asphalt is pumped into the ground as a hot fluid, which solidifies in the water. Its injection is facilitated by steam, or by a method patented by G. W. Christians, consisting of an electrical resistance wire in each casing which keeps the asphalt hot. The asphalt is injected at a pressure of 50 lb, or more, and can be forced for a long distance into open fissures.

Clay grouting (43). In case of large cavities, as frequently found in limestone, thoroughly mixed clay and water, pumped in under a pressure of 100 lb per sq in, or more, has been successfully used. At the Madden Dam, Panama Canal Zone, as much as 70 000 cu yd of clay grout were used to fill cavities around the rim of the reservoir, at a cost, exclusive of drilling, of $5.35 per cu yd. Clay grouting is not efficient in seams containing running water, as it is easily eroded.

Choice of method for sinking in soft, water-bearing formations is often a matter of great difficulty, and the reconnaissance borings, upon the results of which the decision rests, should be in sufficient number and so carefully made that a thorough knowledge of the ground is obtained. The cementation method is probably the cheapest when the ground can be cemented, but it can not be used in quicksand or clay. Honigmann method is almost as cheap, in some cases cheaper, when the ground is soft, and lime and depth of shaft are not too great. The freezing method has the widest application, but is too costly for ordinary depths where another method could be used. It can however compete with the Honigmann method in harder ground for shafts of large diam and great depth.

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