Current Construction Practices in the Installation of High-Capacity Piling

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Structural and economic considerations are causing a trend toward the use of high-capacity piling for highway bridges. They are being employed in combined loading to resist bearing, uplift, and lateral forces with design loads from 200 to 1,500 tons. These piles must be installed to penetrations in soil sufficient to develop their capacity, and this requires special techniques and equipment. Installation techniques include weighting, driving, vibration, jetting, drilling, rotation, and lubrication. Because the capacity of a pile is determined by both the structural capacity of the pile and the capacity of the soil, i.e., the pile-soil system, installation techniques must not permanently decrease the soil-supporting capacity. After installation, pile-soil capacities may be improved by consolidation of surrounding soils, concrete plugs, grout injection, and expansion of the pile tip. A review of important recent installations of high-capacity piles of various types is instructive in illustrating the various combinations of techniques that have been successfully employed. A review and analysis of problems also directs attention to those areas requiring further development. The variables facing both the designer and the contractor include character of the soils, depth of water or soft material, loads to be carried, access for equipment, magnitude of the job, available equipment for transporting, lifting, and installing, and available facilities for fabrications or manufacture. It is essential that the design and installation be integrated if success is to be obtained with these high-capacity piles. Thus, the maximum benefits of high-capacity piles can be made more widely available to the bridge engineering profession.

•AS HIGHWAY BRIDGES are built in congested waterfront areas and in deep water, both structural and economic requirements demand higher capacity piling. Such piles preferably serve as structural columns as well as piles, taking combined bending and direct load and extending up as high as possible to at least the groundline or waterline and, where feasible, on up to the underside of the deck.

High-capacity piles involve the interaction of pile and soil. They must penetrate a sufficient distance to develop the bearing capacity, be installed in such a manner as to take the lateral bending capacity (pile-soil interaction), and be installed with sufficient accuracy to minimize eccentricities. Inherently, these piles are long, large, heavy, and expensive. They require large equipment for transporting and handling. Proper methods must be developed for their successful installation. These methods must be considered both by the designer and by the constructor so that a comprehensive and well-integrated procedure is attained.

High-capacity piles are being simultaneously developed on at least 3 major fronts: bridges for highways and railroads, building foundations, and marine structures for harbor, coastal, and offshore facilities. Design loads range from 200 to 1,500 tons. Each of these applications is making use of the technology developed by the others, and this is mutually stimulating. The total number of such installations to date is relatively limited; therefore, it is important to gather experience from as many of these related applications as possible.

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Installation techniques are primarily directed at achieving the required penetration without reducing the carrying or lateral capacity of the soil. A secondary purpose may be to consolidate (or prestress) the soil during installation in order to improve its carrying capacity.

For high-capacity piles, it is frequently extremely difficult to obtain the required penetration. Many different techniques may be required. Frequently, simultaneous or consecutive use of two or more of these techniques is desirable or necessary. Basic techniques include weighting; driving; vibration; jetting; predrilling; drilling out of core; lubrication by injection, electro-osmosis, or air-bubbling; and rotation and oscillation.

Pile capacity, after obtaining penetration, may be improved by techniques such as consolidating surrounding soils, as by vibration; using a concrete plug; injecting grout; and expanding pile tip.

TYPICAL INSTALLATIONS OF HIGH-CAPACITY PILING

A review by specific cases or categories of some of the important uses of high-capacity piling of different types may give a broad view of the scope involved.

1. Steel H-piles used for a highway bridge in California have 200- to 225-ton capacity, on 14-in. by 14-in. by 200-lb piles 140 ft long and have been driven to end-bearing through mud and sand into soft rock.
2. Composite prestressed and H-piles, i.e., the top half is prestressed concrete, and the bottom half is steel H-pile, have been used for highway bridges in California (200-ton capacity and 213 ft long) and in New South Wales, Australia (240-ton capacity and 200 ft long).
3. Drilled-in-caissons, i.e., pipe piles drilled into rock, are much used for building foundations in New York and are occasionally used elsewhere, e.g., at a large paper mill in Oregon. Typically, they are 24 in. in diameter with ½-in. walls filled with concrete. They take loads up to 300 tons. By inserting a structural steel core, loadings have been increased to 1,000 tons per pile and more.
4. Pipe piles, both closed and open-ended, have been driven through varying strata to bearing on rock or in sand. They are usually filled with concrete to increase their structural load-carrying capacity.
5. Prestressed concrete piles have been used extensively for building foundations at very high capacities; e.g., high-rise buildings in San Francisco, have 200-ton capacity piles, 18- by 18-in. square section, 138 ft long (Fig. 1).
6. Prestressed concrete cylinder piles (Fig. 2) for bridges and harbor structures have design loads to 200 and 300 tons. Piles have been both closed and open-ended with 36- to 54-in. diameters and up to 250-ft lengths and are capable of taking large lateral loads and bending movements as well as vertical loads. They are used on major highway and railroad bridges in California, Oregon, Washington, Louisiana, South Dakota, Virginia, and New York. They are also used for harbor structures in Malaya, Fiji Islands, Indonesia, and Singapore and for offshore platforms in Lake Maracaibo. Similar cylinder piles, although usually not prestressed, are extensively used in Russia for river crossings.
7. Prestressed concrete caisson piles have very large diameters (4 m or 14 ft) and are used for the Oosterschelde Bridge in The Netherlands (Fig. 3) where they are up to 165 ft in length.
8. Large reinforced concrete piles for offshore structures have been installed in the Gulf of Mexico and especially Lake Maracaibo. Of particular interest are tapered piles that have increased cross section at point of maximum bending.
9. Steel cylinder piles, concrete filled, are used in the Lower Yarra River (Westgate) Bridge in Melbourne, Australia, where they are sunk through silts and decomposed basalt into hard basalt rock. At a Naval shipyard in California, similar steel cylinder piles were sunk through muds and debris, then a socket was drilled ahead into soft rock and concreted.
10. Steel cylinder piles for offshore platforms have ranged from 30 to 42 in. in diameter. They are characterized by extreme length (up to 300 ft of penetration in soil in water depths of 300 ft, for a total length of 600 ft). They have been driven to extremely

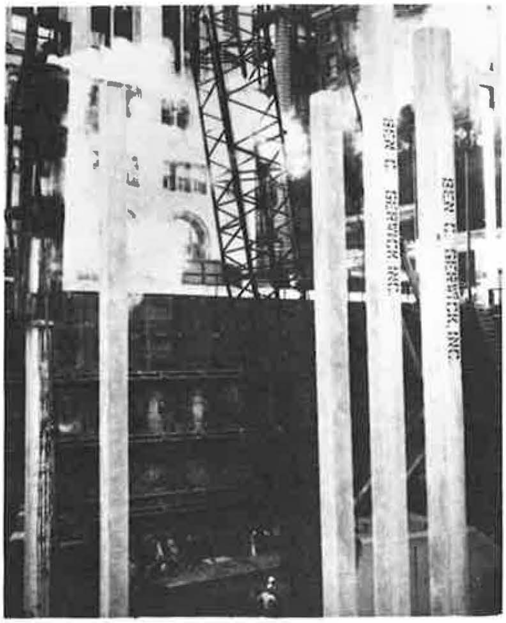

Figure 1. High-capacity prestressed concrete piles used in Wells-Fargo Building, San Francisco.

Figure 2. Prestressed concrete cylinder pile used in Napa River.

high ultimate loads (up to 3,000 kips). When penetration has reached refusal above the predetermined tip, then insert piles of smaller diameter have been driven ahead and beyond to the required penetration.

11. Steel caisson piles up to 12 ft in diameter and 200 ft in length (Fig. 4) have been used in marine terminals in Cook Inlet, Alaska, to take combined vertical and horizontal loads (due to ice, wind, mooring, current, and earthquakes). These have been sunk

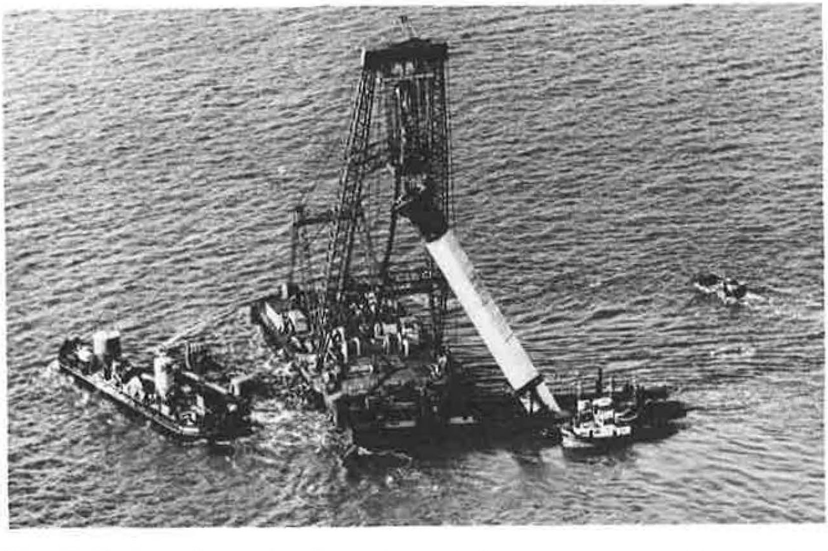

Figure 3. Prestressed concrete caisson pile used in Oosterschelde Bridge, The Netherlands.

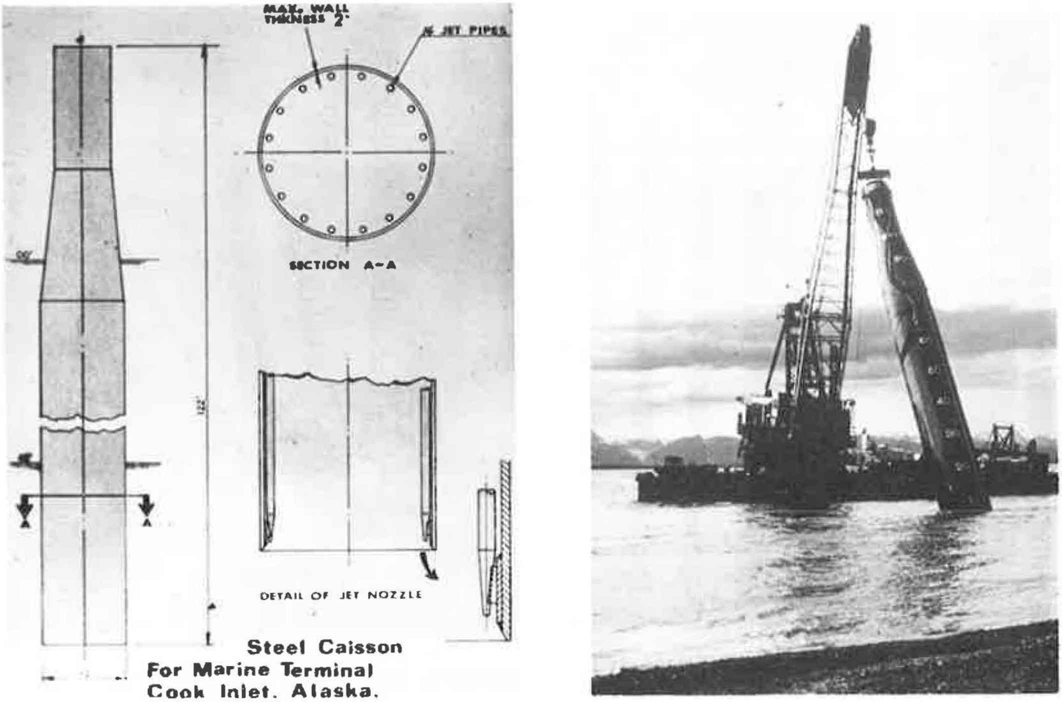

Figure 4. Steel caisson pile used in Cook Inlet, Alaska, to withstand vertical and horizontal loads.

through sands, gravels, cobbles, and glacial till. Such caisson piles have been proposed for the future Turnagain Arm Highway Bridge near Anchorage, where difficulty of installation is combined with extremely high ice loads.

12. Drilled-in piles (caissons) have been drilled in various diameters and depths, a reinforcing cage placed, and concrete poured. On occasion, steel casings are used to line the drilled hole. Precast column sections and structural steel sections have been set in drilled holes and grouted or concreted to lock the core to the soil.

TYPICAL INSTALLATION TECHNIQUES

Weighting

Extremely large concrete piles have been sunk in the soft silts of Lake Maracaibo by the application of weights. Concrete blocks, in increments, up to a total of several hundred tons, are placed, forcing the pile to the required tip elevation and bearing capacity.

It has been proposed to apply pull-down force by means of prestressing tenders inserted in holes drilled through the pile to rock or firm soil, anchored by grout, and then jacked against the pile. Such a method could be very effective and practicable in favorable site conditions. These weights, or pull-down forces, are much more effective, particularly in granular soils, if applied in intermittent, repeated fashion rather than as just a static load. This can be accomplished if the deadweight can be supported separately, i.e., on the adjacent ground or water, and the force applied by hydraulic jacks.

For the Oosterschelde Bridge in The Netherlands, 14-ft diameter concrete caisson piles were sunk in unique fashion. A yoke was placed over the pile and was attached to a matching yoke on the bow of the derrick barge. The barge was literally lifted up onto the pile, exerting a downward thrust of 600 to 1,000 tons. Sinking was aided by internal excavation while the combined weight of the caisson and thrust of the barge was applied.

Driving

Increasingly large hammers have been employed to install high-capacity piles. As a result of experience and, more recently, information from the wave equation theory, rams are made ever heavier, but the velocity of impact is held about the same, e.g., the equivalent of 3 ft of free fall. Ram weights for steam hammers are commercially available up to 60,000 lb, and even larger ones are under development.

The wave equation theory has established that an increased cross-sectional area of the pile gives a greater total force for penetration, although, of course, an increased cross-sectional area may also develop greater soil resistance. Thus for steel piles, thicker walls increase drivability substantially. For offshore piles, minimum wall thicknesses of 1 in. and greater are commonly employed.

One favorable result from the wave equation, confirmed by experience, is that, except for dampening, there is no decrease in drivability due to increased pile length. The old belief that the mass of the pile had to be accelerated is shown to be erroneous.

Proposals have been made to use much increased ram weights, up to 200 to 400 tons and even 1,000 tons, raised and lowered by hydraulic means to achieve even more drivability and greater bearing capacity. One such hammer that is under development for offshore piles (U. S. patent applied for) provides a means for release of the water pressure (hydraulic ram effect) that would oppose the impact from the hammer.

Jetting

Jets may be effectively used to cut ahead of the pile and to lubricate the sides against skin friction. Cutting jets must be of high pressure and must be located at the tip. Lubricating jets are low pressure, high volume, and must deliver water at intervals along the sides.

Jets may be built into the piles, such as internal jets in prestressed concrete piles. Details and operation must be such as to prevent plugging or blocking of the jet during driving. Side nozzles may be provided to permit lubricating water to escape.

External jets must be capable of control so that the nozzle can be kept in proper relation to the pile. Sometimes external jets tend to become stuck in sand. Tiny holes cut in the jet pipe at intervals along the sides will lubricate it and prevent sticking.

Jetted and Driven Steel Caissons

Large diameter (4 to 12) steel caissons have been installed in the sands, silts, and glacial till of Cook Inlet, Alaska, by a combination of jetting and driving. Because the weight of these caissons is more than 100 tons, it is obvious that the driving energy available, say 60,000 to 90,000 ft-lb, is inadequate in terms of conventional driving formulas. However, the hammer does send very effective compressive waves from the head to the tip.

Jetting is needed to sink the caisson, but the problem is how to get the water to the cutting edge. After considerable development and experience, the solution that has emerged is to install jet nozzles at 24-in. intervals around the circumference just inside the caisson walls with the nozzles held back 2 to 6 in. from the tip, and thus protected by it. These jet nozzles are fed by riser pipes welded to the pile walls and manifolded at a ring just below the pile head, where hoses from special jet pumps are connected.

Jetting alone is used to sink the caisson as far as possible, the caisson being alternately raised and lowered a few feet. Then the hammer is used with the jets still running until the tip is within a few inches (12 to 24 in.) of desired elevation. The pile is then seated by hammer alone.

In addition to lubricating the sides and breaking up the sand ahead, the jets also prevent a plug of densified sand from forming in the caisson tip.

Vibration

A number of heavy-duty vibrators have been developed to sink large piles through granular materials. One of these, the Bodine hammer, utilizes a substantial power at frequencies up to the sonic range. It has been extremely effective in demonstrations after all jetting has ceased, the sand grains will be reconsolidated. It is not a question of driving 2 ft or 5 ft or some arbitrary distance; rather, it is a minimum number of blows even if the pile only moves 1 in. During this period the water will drain outward from the pile, causing further consolidation. In some poorly graded sands, it will be found desirable to drive say 100 blows and then, after an interval of 30 minutes to an hour or more, drive another 100 blows. This later driving will often achieve a few more inches' penetration and a secondary consolidation of the sand.

Expansion of Pile Tip

The pile tip may be expanded to increase end-bearing capacity. Such expansion not only increases the bearing area but also consolidates the soil and mobilizes its resistance. One means of expansion is the ramming of concrete from the tip. Through a hollow casing, a load of fresh concrete is placed and a ram is installed and driven down, forcing the concrete out as the casing is slightly retracted. This same effect can be accomplished by air pressure; the casing is capped, and air is applied.

Other methods proposed for expanding the tips of steel pipe piles include controlled explosives and hydraulic rams. So far these have been judged unsuitable for high-capacity piles; however, they have been used for anchor piles. Also a mechanically spreading cone can be enlarged by driving on a ram. This also has so far been limited to small-sized anchors but may be developed for highly loaded piles in the future.

Concrete Plugs

Where the core of the pile has been removed to or near the tip, a concrete plug may be placed to increase the end-bearing area. Densely compacted soil at the extreme tip does not need to be removed; it is usually satisfactory to place the concrete plug on top of this soil "plug" and hold it in position.

Concrete plugs may be placed by tremie methods. Care must be taken that the hydrostatic head of the fresh concrete does not crack or burst the walls of the pile. Plugs also may be placed by placing a course of gravel, then grout-injecting it. In such cases the walls of the pile should be cleaned by jetting prior to placing the concrete to ensure bond.

PROBLEMS OF INSTALLATION AND SOLUTIONS

The installation of high-capacity piling, involving the use of unusual and large equipment and the necessity to penetrate deeply through firm strata, has very naturally been accompanied with problems. The individual problems deserve careful analysis; however, within the scope of this paper all that can be done is to call attention briefly to some of the problems that have arisen and to note the corrective or preventive actions needed. On occasion these problems have been serious to the designer or contractor or both, but in general they have been successfully overcome and they can, with foresight, be alleviated for future installations. This can only be done, however, when both the design engineer and the construction contractor work together. The following are among these problems.

1. Steel H-piles driven to soft rock show extreme variations in penetration into the rock, making it difficult to determine lengths. A displacement type of pile, such as a pipe pile or precast concrete pile, would mobilize the supporting capacity of the rock with a shorter and more uniform penetration. If H-piles are to be used, radical length variations should be anticipated and the piles brought to the site purposefully long. After being driven to the required indicated bearing (blows per inch resistance), they can be cut off and the cutoff top section respliced for subsequent use.
2. After drilled-in caissons are seated and the core excavated, sand runs in under the tip during drilling of the socket. This generally requires that the pile be reseated with the hammer once or twice to seal off the tip. The pile should be kept full of water (saltwater is even more effective), and the operation of drilling and baling tools should be controlled to prevent sudden drop in effective head at the tip during withdrawal of the tools.

3. Prestressed concrete piles fail in horizontal cracking under driving because rebound tensile stresses occur during the period when the tip of the pile has little or no resistance, i.e., during soft driving. The driving compressive wave then reflects from the tip as a tensile wave and causes cracking, usually at the upper third point. The solution includes the use of a new thick cushion block of softwood on the head of each pile to be driven. The velocity of impact of the ram should be reduced. This can be done by shortening the stroke of the hammer. The "free-end" condition should be minimized by predrilling, rather than driving, through an overlying crust into soft mud below, or by control of jetting or drilling so that the tip always has reasonably firm resistance.

4. Longitudinal cracking of prestressed concrete cylinder piles can be caused by a variety of phenomena including excessive buildup of hydrostatic head inside during jetting, wedging of soil during driving, or freezing. Spiral requirements for prestressed concrete cylinder piles have often been on the minimal side. They should be increased, throughout the length, but particularly at the head and tip. Vents of large size should be provided to enable any excess hydrostatic head to be vented. If the driving ram must work with the pile head below water, very large vents must be provided in the driving head to prevent a hydraulic ram-bursting effect. To prevent freezing in cold weather, vents well below water surface will allow water circulation. Styrofoam or wood logs have been floated inside hollow core piles to reduce excessive pressures from freezing. When prestressed concrete piles are filled with concrete, the internal head will increase very rapidly. Rate of placing must be closely controlled to the time of set to prevent bursting the pile.

5. Piles sunk by jetting and lubrication show inadequate lateral resistance. The soil has been disturbed, and the grains have been spread apart by the jetting action. To reconsolidate these, the most easily applied step, in many cases, is to consolidate the soil by the vibration and shock of continuing hammer blows. In some cases, a required number of hammer blows, e.g., 200, has been specified to aid in this reconsolidation. Another means of overcoming this problem is by grout injection of the soil surrounding the pile tip.

6. Problems with drilled-in piles involve sloughing of the walls of the socket during drilling and prior to concreting. This phenomena often occurs in serpentine and shale rocks. The basic solution is to reduce the time of exposure and to prevent air from contact with the rock by keeping the hole filled with water. The plug should be poured by tremie concrete techniques immediately after excavation.

7. For high-capacity piles, conventional means of determining bearing capacity are no longer applicable. There are, however, several ways for evaluating bearing capacity. (a) From soil mechanics study of shear, friction, and cohesion values and a knowledge of the shape and surface characteristics of the pile, a bearing value can be computed for a specific penetration. (b) Use of an adequate dynamic formula, such as the wave equation, is relatively valid if a large enough hammer is employed, but it must be interpreted in the light of soil test data. (c) Load tests may be used, although it is very difficult to find practicable means of load testing piles whose design capacity is far above conventional values. Nevertheless, load tests have been performed by reaction against dead loads and by reaction piles. A method with promise is to drill in prestressing tendons into underlying rock and to jack against these to supply the downward thrust for the test load. (d) Load tests on a scale device may also be used. In Lake Maracaibo, Heerema has jacked a small-diameter pipe ahead of the pile tip, working through a hollow core in the pile. Skin-friction and end-bearing values are determined for this and extrapolated to the pile itself.

8. Inability to achieve the required predetermined penetration is perhaps the most common and most serious problem. Hollow-core piles permit removal of the core and drilling ahead. They also permit, as an ultimate remedy, the installation of an insert pile that can be driven ahead, freed as it is from skin friction. With solid-tip piles, corrective steps are extremely difficult on piles that have already been driven to refusal. Side jetting may reduce skin friction, and a heavier hammer may provide more drivability. For subsequent piles, however, a number of effective steps may be taken, such as predrilling, increase in hammer size, and jetting or lubrication of sides.

9. To prevent damage and distortion to tips of piles when rocks or boulders are hit, the tip should be reinforced by a shoe of high-yield point steel, either pipe or box section, filled with concrete to prevent local distortion.

It is interesting to note that one or more of these problems have arisen in the first attempts at installation of several of the types of high-capacity piles referred to in the review of typical installations. At the same time, in all of these cases, solutions such as those given were found and the installations were completed satisfactorily.

EVALUATION OF PILE TYPES AND INSTALLATION METHODS

The selection of pile types for high-capacity piles must be based on structural performance, economics, and practicability. This paper is essentially a discussion of the latter. It should be interpreted in a positive sense, for the ability and ingenuity of contractors and equipment manufacturers should not be underrated.

Certain conclusions concerning practicability may be drawn. Piles that are open-ended permit the use of auxiliary techniques to overcome obstacles such as boulders, harder strata than anticipated, rock, and debris. Piles with inherent rigidity such as heavy-walled pipe piles and prestressed concrete piles suffer less deformation upon encountering obstacles. The piles having greater section modulus such as cylinder piles and caisson piles have the ability to give lateral support in both bending and shear provided that the installation methods adopted do not weaken the soil. There are a number of steps available by which bearing capacity and lateral support may be restored or increased.

Obsolete formulas for pile-driving should be revised in the light of new field data and the information obtained from the wave equation theory. Where high-capacity piles are involved, specifications must either require performance or else specify in detail the equipment and methods to be employed, but not both. Furthermore, limitations and restrictions should be imposed on techniques that may reduce the carrying capacity of the soil. Installation of high-capacity piles requires an integration of the efforts of the design engineer and the constructor if the best results are to be obtained.

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