
PART VI
Appendix F
Construction of Pile Foundation

F.1 Introduction

The pile driving process needs to fulfill assumptions and goals of the design engineer just as much as the design process has to foresee the conception and installation of the pile at the site. This is only possible through the selection of the right driving equipment especially hammer with proper assembly mounted on the most suitable leader, operated according to the specified practices of installation that consists of a series of principle and subsidiary procedures.

There are three methods of driving piles: jacking, vibratory driving, and driving. The first two, jacking and vibratory driving are comparatively rare. The reaction needed to push a pile into the ground is equal to the limit pile capacity, which can be a very large load. Until recently, this made jacking suitable only for small piles; large, heavy rigs are now available that can jack normal size piles for onshore applications.

Vibratory driving is only suitable for loose sands, particularly if saturated, because liquefaction of the sand results from the vibration, making it easy to drive the pile into the ground. Vibratory driving is routinely used to drive sheet piles and less frequently used to install relatively small steel H-piles.

The most common method of installing displacement piles is by driving the piles into the ground by blows of an impact hammer. Piles installed in this manner are referred to as driven piles. In order to understand this method of installation, we need to examine first the equipment that is required. A brief description of the driving equipment and procedures as given by Salgado (2011) are presented as under.

F.2 Piling Driving Equipment

Pile driving equipment are broadly classified into three groups; the leader for positioning the pile for driving, the hammer for delivering energy for driving and the driving system components for better and safe distribution of energy on the top of the piles. Hammers are used to install the driven piles. The leader, the pile and the hammer are often carried by a special crawler rig or crane.

F.3 Installation of Driven Piles

Driven piles are installed by the kinetic energy developed through the

- (a) Ramming action of piling hammer which can be
 - Drop Hammers
 - Single-Acting Air/Steam Hammers
 - Double-Acting Air/Steam Hammers
 - Differential-Acting Air/Steam Hammers
 - Hydraulic Hammers
 - Diesel Hammers (Single acting & Double acting)
- (b) Vibration and weight of vibro-hammers which can be
 - Electric Motor Vibrohammers
 - Hydraulic Vibrohammers
 - Sonic Resonance Vibrohammers

As such, there are three methods of installing displacement piles: jacking, vibratory driving, and driving. The first two, jacking and vibratory driving are comparatively rare. In jacking, the reaction needed to push a pile into the ground is equal to the limit pile capacity, which can be a very large load. Until recently, this made jacking suitable only for small piles. However, large, heavy rigs are now available that can jack normal size piles for onshore applications. Vibratory driving is only suitable for loose sands, particularly if saturated, because liquefaction of the sand results from the vibration, making it easy to drive the pile into the ground. Vibratory driving is routinely used to drive sheet piles and less frequently used to install relatively small steel H-piles.

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Sometimes, to penetrate the pile through a compact ground layer or a rock layer, predrilling is used. By predrilling, it is ensured that driven piles reach their designed minimum tip depths, and also, their risk of being tip or head damaged due to increased hammering impact loads are avoided. Another benefit of predrilling is increased driving speeds and much lower ratios of early refusal.

In addition, water jetting is used to penetrate piles through dense granular layers and to guarantee their penetration to minimum penetration depths without getting damaged. Both predrilling and water jetting need to be stopped several meters (about 1.5 – 3 m) before the final penetration point and driving refusal must be obtained in the undisturbed soil.

F.4 Pile Driving Leads

Pile driving leads or leaders are steel frames used to correctly position the pile for driving and to keep the pile head and hammer aligned concentrically during driving. Leads, with length exceeding that of the pile to be driven by 5-7 m, are attached to a crane in one of the two ways shown in Figure 6.F.1. Fixed leads are connected near the top with a horizontal hinge at the tip of the boom. A hydraulically operated horizontal brace allows the operator to adjust the inclination of the lead to install battered piles and to adjust verticality. Hanging leads are suspended from the crane boom by a cable. Stabbing points at the base of the lead allow the operator to adjust position and inclination, but it is more difficult to position the pile with hanging leads than with fixed leads. If hanging leads are to be used to drive piles that require a high degree of positioning accuracy, a suitable template should be provided to maintain the leads in a steady or fixed position. Construction tolerances on positioning depend to some extent on the diameter of the piles and whether they are isolated piles or are part of a group. For group piles, pile location may be off by as much as 75 mm and deviation from vertical as large as 1 in 25 may be acceptable.

Leads that are not properly restrained may cause pile damage, particularly to concrete piles. When driving long slender piles, the use of intermediate pile supports in the leads may be necessary to prevent pile damage that may be caused by long unbraced pile lengths. Leads are not absolutely necessary for every pile driving operation, but they are normally used to maintain concentric alignment of the pile and hammer and to obtain the required accuracy of pile position and alignment while driving the pile, especially for battered piles. Even if leads are not used, it is highly advisable to use a template to maintain the pile at the right location throughout driving.

F.5 Piling Hammers

Pile driving hammers are devices used to deliver blows to the head of a pile in order to drive it into the ground. The type of hammers can be highly varied. Figure 6.F.2 taken from Hannigan et al (1998) gives a classification of Piling Hammer Types. Simple drop and steam hammers are still being used but single, differential or double acting diesel, and hydraulic hammers are more common. Also, vibrating and sonic hammers are being used more and more often due to environmental or urban impact factors.

Pile hammers vary in the rate at which blows are delivered, the maximum amount of energy delivered in any one single blow, and the duration of the blow. To a large extent, these performance parameters reflect the mechanism of operation of the hammer. There are basically four types of hammers: gravity or drop hammers, single-acting hammers, double-acting hammers, and differential hammers.

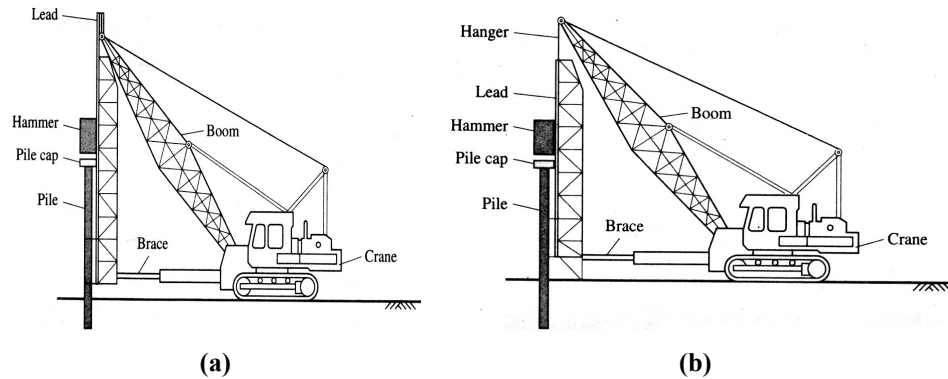


Figure 6.F.1 Crane mounted leads; (a) Fixed and (b) Hanging

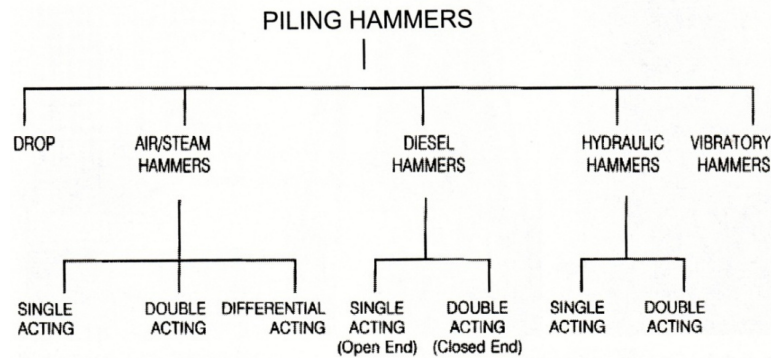


Figure 6.F.2 Pile driving hammer classification (Hannigan et al, 1998)

Table 6.F.1 summarizes the main features of each type of pile driving hammer. Drop hammers are the simplest, relying solely on gravity for delivering the blows to the pile head. A drop hammer is usually made of a single block or a system of steel blocks, which may be removed or added as needed. Drop hammer weights are typically in the range of 10-50 kN (1-5 tons). Because the weight of the hammer is usually fixed during the driving of any given pile, the only variable available to the operator for adjusting the energy delivered by hammer blows is the drop height. There is an implied danger when driving concrete piles through hard, strong soil (under so called hard driving conditions). The operator may drop the hammer from too large a height, generate excessive large stresses in the pile, and damage it.

In single acting hammers, the ram is connected to a piston located within a cylinder [Figure 6.F.3(a)]. The piston is lifted by either steam or compressed air (in what is called the upstroke) and then allowed to fall by the action of gravity (the downstroke). When it does, the ram impacts the head of the pile, driving it some distance into the ground. The weight of a single acting hammer (in the 20 to 150 kN range) is much larger than that of a drop hammer, but the fall height (stroke) is much smaller (up to 1.5 m, typically).

In a double-acting hammer [Figure 6.F.3(b)], either steam or compressed air is used to increase the pressure on the piston, both on its way up and on its way down, so that the ram impacts the pile with greater force and higher velocity and does so more times per minute. This is possible because these hammers are closed at the top. The stroke is typically less than that for the single acting hammer, resulting in higher production rate. The stroke cannot be controlled visually because the hammer is closed. The differential hammer is much like the double-acting hammer, but it relies on the different areas of the upper and lower parts of the piston to generate the repeating up and down strokes.

Table 6.F.1: General Characteristics of Different Types of Piling Hammers

Hammer	Ram weight (kN)	Stroke (m)	Max. strike rate (bpm)	Conditions under which use indicated	Caution
Drop	10-50 (½ to 2 times pile weight)	Wide range	5-10	Noise restrictions	Possible damage during hard driving of concrete piles
Single acting	20-150	< 1.5	40-60		
Double acting / Differential	0.5-180		90-300	Underwater operations; Sheet pile driving	
Diesel	10-150		40-100	All types of piles (with diameter up to 2.2m) in most soil conditions	Soft clays (where combustion may not occur)

Hydraulic hammers are moved by oil pressure and can be of single or double acting varieties. Their principle of operation Intake is essentially the same as that of other single- and double-acting hammers. Diesel hammers, such as the one shown in Figure

6.F.3(d), also come in both the single and double acting varieties, but they differ from other hammers in one important aspect. In single acting hammers, extra "zip" is added to the blow by combustion of fuel injected before the down stroke is completed. In a double acting hammer, a bounce chamber is present in the upper part of the hammer, providing quicker and stronger rebound from the upstroke. These hammers tend to be smaller and lighter than double acting hammer. Other hammers, as the extra energy and blow duration obtained from the fuel combustion makes them very efficient.

The amount of fuel injection into the chamber of diesel hammers can be controlled, allowing adjustment for lighter or harder driving conditions. However, in soils alternating loose/soft layers with extremely hard layers, the bounce of the ram will vary from low to high, which may be damaging to concrete piles. Diesel hammers may be attached directly to the pile head, not strictly requiring the use of leads for their operation.

F.6 Driving System Components

The components of a driving system are the hammer (Impact block) itself and a number of additional components that may or may not be present, as shown in Figure 6.F.4. Each of these components is referred to by various names, the most common being:

- (i) Anvil (striker plate)
- (ii) Cap block or hammer cushion
- (iii) Driving head (helmet, cap, anvil block)
- (iv) Follower
- (v) Pile cushion (used for driving precast concrete piles)

All of these elements, except the follower, aim to diffuse some of the energy from the hammer blow in order to avoid damage to the pile or any of the driving system components. The driving head goes on top of the pile; it is shaped in a way that allows it to slide along the leads, forcing the alignment of the pile and the hammer. The follower is an extension used when a pile needs to be driven to a level below the level of operation of the rig, such as when the heads of the piles for a bridge, for example, will be located under water. The pile cushion is used to further diffuse and better distribute the energy on top of concrete piles, which are more susceptible to damage during driving.

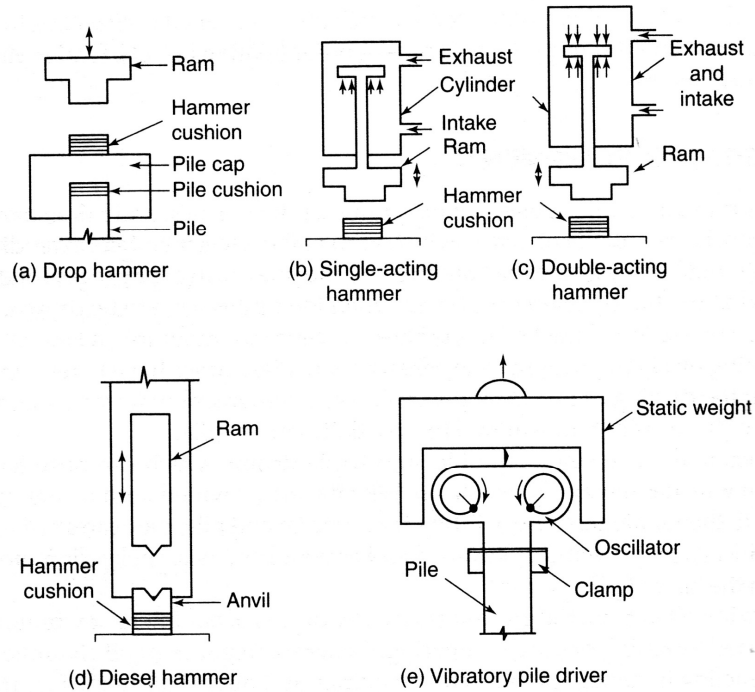


Figure 6.F.3 Principles of pile driving hammers

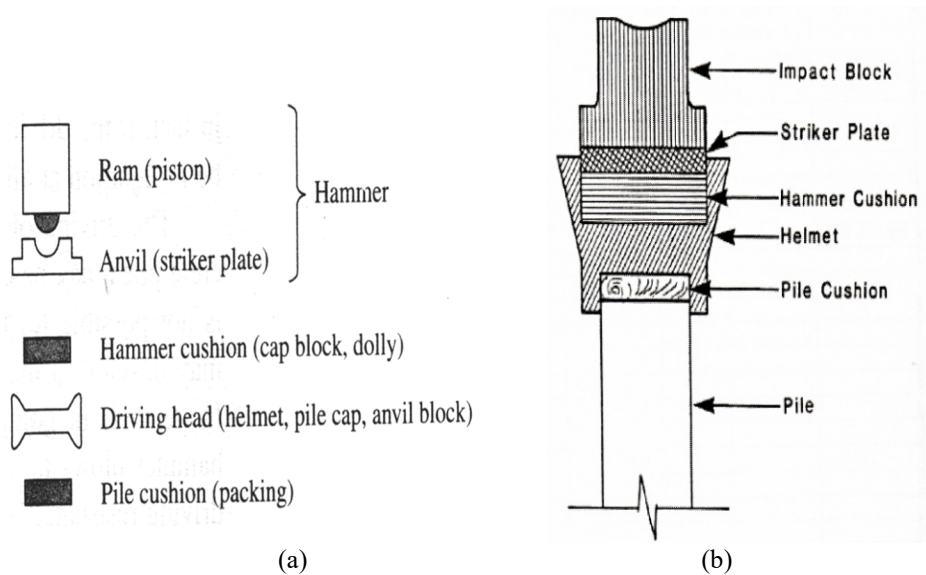


Figure 6.F.4 (a) Driving system components; (b) Positioning of the components

F.7 Driving Procedures

As mentioned earlier, the key to efficient pile driving is a good match of the pile with the hammer and other driving system components. When this is done, the operator will not be forced to try anything out of the ordinary to drive the piles to the required depth. For example, if an excessively light drop hammer is used, the operator may feel compelled to raise the hammer to excessive heights, which may in turn damage concrete piles. Mismatches of this sort quite often result either in inability to drive the pile as specified or in pile damage.

When using drop hammers, the key decision is the weight of the hammer. A drop hammer is typically a cylindrical weight that is raised to a certain height using a winch and dropped on top of the pile. The weight of drop hammer ranges from one half to twice the pile weight. The corresponding drop heights are in the 0.2 to 2m range. It is usually preferable to select heavier rather than lighter hammers, as the drop heights are then smaller and the likelihood of damage to concrete piles, in particular, is much lower. The ratio of hammer weight to pile weight for other types of hammer lies in the range of 0.25 to 1.0, but the selection of a suitable hammer also depends on other factors and is best done with the aid of computer-based drivability analysis. For example, the energy delivered by diesel hammers to piles increases with the driving resistance; in fact, if the driving is too easy, as in the first few meters in soft clays, there may be no ignition at all in the hammer, which would make it very inefficient.

The driving of precast concrete piles is probably the most challenging. Concrete piles may be damaged when driven through soft or loose soil, something that is not possible for either timber or steel piles. This is so because tensile stresses may develop in the pile under the conditions stated and, concrete is very weak in tension. In general, in going through soft/loose soil layers, the operator should use light hammer blows to avoid this. As a general rule, light blows are always used when driving resistance is small.

Immediately after driving, the pile resistance may be either higher or lower than the resistance it will ultimately have. The process by which pile resistance increases with time after driving is referred to as setup or freeze. When pile resistance decreases with time after driving, the process is referred to as relaxation. At least approximate estimation of the rate at which these processes take place is important to plan continuing pile driving around previously driven piles, to plan and perform load tests, and to take account in design of the real, long term resistance of the pile.

F.8 Pile Hammer Selection Guidelines

Selection of pile and pile hammer is usually done using wave equation program. If wave analysis is not done following Tables 6.F.2(a) and 6.F.2(b) may be used as an approximate guide. (Tables 6.F.2(a) and 6.F.2(b) were prepared by adapting the Table presented in “Pile Driving Equipment”, US Army Corps of Engineers, July 1997.)

Table 6.F.2(a): Guidelines for Selection of Pile Hammers: Sandy Soils

SPT (N) Value	Soil Density	Open End Pipe Piles	Closed End Pipe Piles	H-Piles	Sheet Piles	Concrete Piles
0 - 3	Very Loose	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA (A, S, H)
4 - 10	Loose	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA (A, S, H)
10 - 30	Medium	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA (A, S, H)
30 - 50	Dense	DA, SA, V (A, S, H)	SA, V (A, S, H)	SA, V (A, S, H)	DA, SA, V (A, S, H)	SA (A, S, H)
Over 50	Very Dense	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)	DA, SA, V (A, S, H)	SA (A, S, H)

LEGEND: DA = Double Acting; SA = Single Acting; A = Air/Diesel; S = Steam; H = Hydraulic; V = Vibratory

Table 6.F.2(b): Guide lines for Selection of Pile Hammers: Clayey Soil

SPT (N) Value	Soil Density	Open End Pipe Piles	Closed End Pipe Piles	H-Piles	Sheet Piles	Concrete Piles
0 - 4	Soft	DA, SA, V (A, S, H)	DA, SA (A, S, H)	DA, SA, V (A, S, H)	DA, SA, V (A, S, H)	DA, SA (A, S, H)
4 - 8	Medium	DA, SA, V (A, S, H)	SA (A, S, H)	DA, V (A, S, H)	DA, SA, V (A, S, H)	SA (A, S, H)
8 - 15	Stiff	DA, SA (A, S, H)	SA (A, S, H)	DA, SA (A, S, H)	DA, SA (A, S, H)	SA (A, S, H)
15 - 30	Very Stiff	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)
Over 30	Hard	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)	SA (A, S, H)

General Guidelines for Selecting a Pile Hammer

Single Acting Steam and Air/Diesel Hammers

- * Dense sands and stiff clays need heavy hammers with low blow counts. This makes single acting hammers ideal for such situations.

Double Acting Steam and Air Hammers

- * Double acting hammers have light hammers compared to single acting hammers with same energy level. Light hammers with high velocity blows are ideal for medium dense sands and soft clays.

Vibratory Hammers

- * Avoid vibratory hammers for concrete and timber piles. Vibratory hammers could create cracks in concrete.
- * Avoid vibratory hammers for clayey soils. Vibratory hammers are best suited for loose to medium sands.
- * Vibratory hammers are widely used for sheet piles since it may be necessary to extract and reinstall piles. Extraction of piles can be readily done with vibratory hammers.
- * In loose to medium soil conditions, sheet piles can be installed at a much faster rate by vibratory hammers.

Hydraulic Hammers:

- * Hydraulic hammers provide an environmental friendly operation. Unfortunately rental cost is high for these hammers.

F.9 Noise Level In Pile Driving

Another important aspect of selection of pile driving method is the noise level. Following Table 6.F.3 is provided by White et. al. (2000) as a guide for noise produced during pile driving by selected methods.

Table 6.F.3 Guidelines for Noise Level during Pile Driving

Installation Method	Observed Noise Level (dB)	Distance of Observation (m)
Pressing (Jacking)	61	7
Vibratory (Med. Fre.)	90	1
Drop Hammer	98-107	7
Light Diesel Hammer	97	18

F.10 Construction of Bored Cast-In-Situ Pile/ Drilled Shaft

Bored Cast-in-situ piles/shafts are very much preferred in cities as they do not cause any disturbance to surroundings. In bored cast in-place piles, the holes are first bored with a temporary or permanent steel casing or by using bentonite slurry to stabilize the sides of the bore. Holes can also be formed by augers. A prefabricated steel cage is then lowered into the hole and concreting is carried by the tremie method. Boring holes by using bentonite mud is much more popular than using casing pipes. One of the great advantages of this method is that large diameter piles (up to 5 m in diameter) can be installed by this method. Hence, these piles are very much used for bridges and other heavy structures. However, it should be clearly remembered that bored piles smaller than 400 mm in diameter are not normally recommended for use in practice. The sides of cast in-situ small diameter piles are liable to cave in. In such cases, there will be no continuity in the length of piles. In the following Sections methods of advancing the holes, choice of tools to be used and other related topics described by Varghese (2005) are reproduced.

F.10.1 Method of Advancing the Hole for Bored Pile/Drilled Shaft

There are various methods of advancing bore holes with the circulation of bentonite. Some of these methods are now discussed.

Method 1: Piles installed by bailer and cutting tools: This is crude but the simplest method of advancing the hole when using the chisel and bailer bucket to advance the hole. The slurry is formed by simply adding the bentonite into the hole and mixing it in the hole, with the level of the suspension inside the bore hole always kept about 1 m above the ground water level, or if necessary to the top of the level of the casing. When meeting cohesionless materials, the slurry may be thickened. The aim is to help the stabilization of hole by forming an impermeable thin film around the bore hole. The bentonite suspension is assumed to penetrate into the sides under positive pressure. After a while it forms a jelly, thus making the sides impervious by producing a plastering effect. This is described as a crude method of installing bored piles because adding bentonite in the hole as in this method does not give us the full benefit of piling. The up and down movements of the bailer cause the soil from the sides and bottom to flow in. It is also very difficult to remove all the loose materials that collect at the bottom in the end. Hence as far as possible, the bailer method should not be used on important works.

Method 2: Continuous mud circulation (CMC) method (Figure 6.F.5). This method is a more refined one than the above method. In this case, bentonite of sufficient viscosity and velocity (as delivered by a mud pump) is maintained in continuous circulation so that particles are suspended in the mud and brought to the surface by the flow of

bentonite. The level of the bentonite suspension is kept constant. For this purpose, a mud pump of sufficient capacity (depending on diameter and depth of hole) is employed for continuous circulation. Material in the bore hole is loosened (spoil formed) by means of a suitably designed chopper or reamer or drilling bit. The bentonite solution is circulated by pumping. It serves the two purposes of (a) stabilizing the bore hole and (b) conveying the spoil from bottom of the hole to the top. The mud pump capacity should be able to maintain the volume and velocity to lift up the spoil from the bore hole. It will depend on the diameter and depth of the hole to be bored. The mud pump may be used in the following four different ways:

- (i) Direct mud circulation (DMC): In this method, the bentonite suspension is pumped into the bottom of the hole through the drill rods and it overflows at the top of the casing. The mud pump should have the capacity to maintain a velocity of 0.41 to 0.76 metres per second to float the cuttings.
- (ii) Reverse mud circulation (RMC): For large diameter holes, the pump is more efficient if the bentonite suspension is fed directly at the top of the hole and it is pumped out from bottom of the hole with suitable rotary pump fitted at the bottom of the drill rods. This method is called the reverse mud circulation method. Whereas borehole sizes in direct circulation are limited by the mud pump capacity, in reverse circulation method even a medium sized pump can create enough bailing velocity to bring cuttings up and the inner diameter of the drill pipe need not be large.
- (iii) Rapid direct mud circulation (RDMC): This is an improved version of the DMC where a tube carrying compressed air is also sent to the bottom of the bore. The air helps in mixing up the loosened soil with the bentonite slurry more effectively so that even heavy particles are forced out of the bore suspended in the bentonite. However, in all cases where rapid excavation of the bore is planned, the tendency of sides to cave in should be carefully examined.
- (iv) Air lift reverse mud circulation drilling (ARMC): This method of drilling is used for large diameter holes. Compressed air is used in this method to circulate the drilling fluid and cuttings to the surface.

It has also been observed in the field that with bentonite clay there is more caving in during the time there is no work than during the working period. This may perhaps be due to thickening of the bentonite into a gel when not in agitation. This gel may exert less lateral pressure than bentonite in liquid mud form. Hence concreting of holes should be planned immediately after circulation of bentonite and never in a hole, in which work was suspended overnight.

F.10.2 Limitations of Bentonite Method

The bentonite method has some limitations. A brief list of these is as follows:

- (i) Pile diameters should not be small. Normally, they should be 400 mm to 5 in in diameter.
- (ii) It will have potential danger if used in artesian conditions.
- (iii) It is difficult to use this method in soils with permeability greater than 1 in per second or in soft clays with shear strength less than 20 kN/m².
- (iv) It is difficult to clean the bottom of the hole when boring ends in coarse materials, disintegrated rocks, etc. which do not come up easily along with the suspension.
- (v) It is difficult to install raker piles by this method.
- (vi) In non-cohesive soils or fine sands, the rate of progress of work should be slow enough for the bentonite to penetrate into the soil and produce the plastering effect. The rate of progress should be suitably adjusted. Otherwise side collapse may occur.
- (vii) If subsoil or ground water contains salts, it will adversely affect the action of bentonite. Protection of sides from caving in may be found to be difficult.

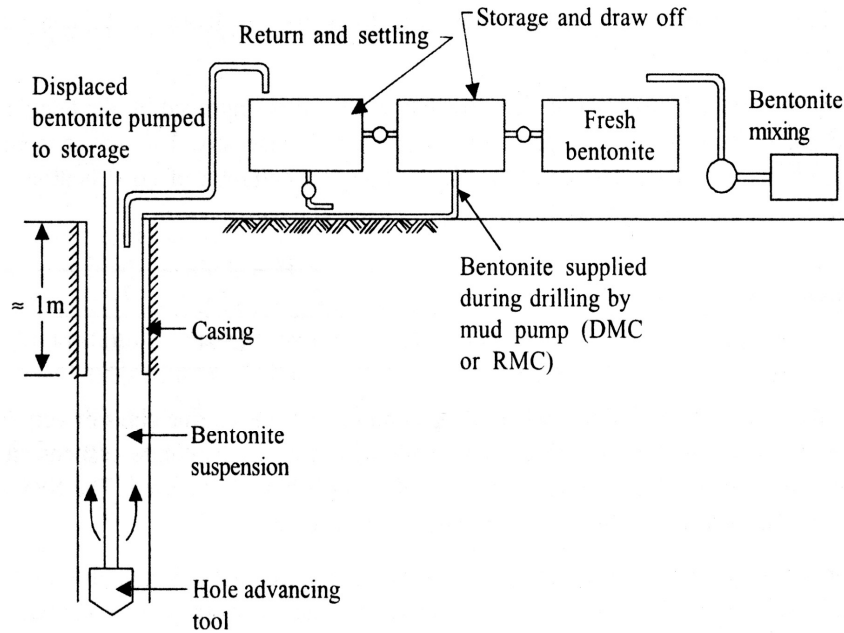


Figure 6.F.5 Schematic diagram and layout of equipment for boring using bentonite suspension (after Varghese, 2005).

F.10.3 Actions to be Taken Prior to Concreting

The following precautions are very important for success in the construction by bentonite stabilization:

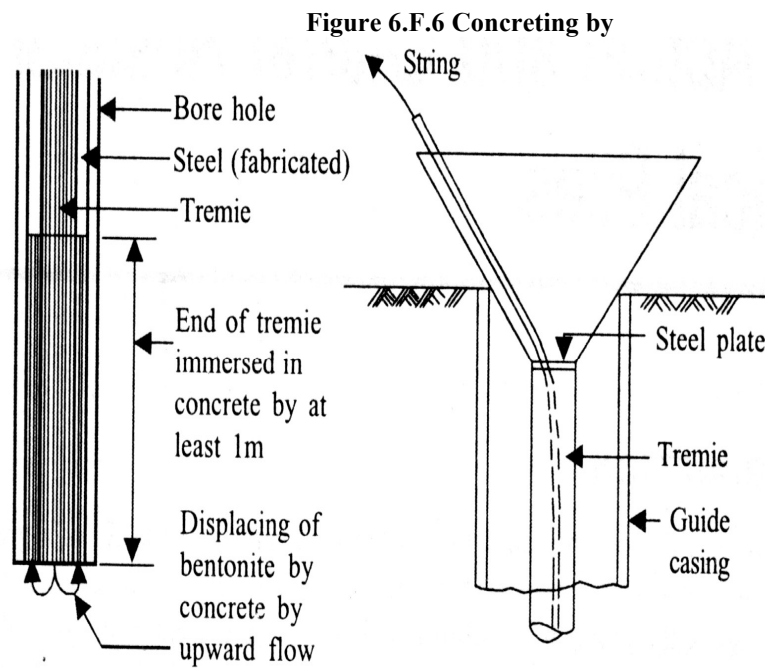
- (i) The specific gravity of bentonite should be checked at intervals by taking samples from the bottom. If it exceeds 1.25, replacement of bentonite at the bottom may be necessary without decreasing the level of bentonite in the hole. The density should be brought down to about 1.12 by flushing before concreting.
- (ii) As the tendency of caving in is more, when the bentonite is not in circulation, operations for final concreting should always start as soon as the hole is completed and cleaned.
- (iii) Before the steel cage is lowered, the hole should be flushed with fresh bentonite slurry for at least 15 minutes (in direct circulation by the mud circulation chisel resting at the bottom) so that it is completely cleared. Accumulated debris at the bottom can considerably increase the settlement when the piles are loaded. This aspect is very important in construction of bored cast in-situ piles. Many load tests (especially in bearing piles) have produced inconsistent results due to carelessness in cleaning the bottom of the hole before concreting.

F.10.4 Concreting of Piles

The precautions to be taken in the use of tremie concrete in piles. After cleaning the holes, the reinforcement cage is lowered into the hole. The bore is once again flushed and concrete poured through a tremie pipe of 200 mm in diameter. Concrete of slump 150 mm, cement content not less than 400 kg/m³, water cement ratio > 0.5, maximum size of aggregate 20 to 25 mm with suitable plasticizer is recommended for use. The procedure is as follows:

First, a guide casing, if not already provided, is placed over the hole for proper seating of the tremie funnel. The tremie is lowered to the bottom of the hole. To start with, the bottom of concreting funnel is closed with a steel plate. After filling the funnel to its full capacity the steel plate is removed and concrete discharged. The bottom of the tremie should always be at least 2 m within the concrete so that the bentonite is replaced from bottom upwards. Only the initially poured concrete is in contact with the bentonite as shown in Figure 6.F.6. Concreting is carried out to at least 60-90 cm above the cut off level. If the cut off level is at the ground level the top concrete is allowed to spill over till good concrete is visible.

When bentonite piling was introduced before its final adoption, much doubt was raised about the strength of concrete placed in bentonite (which is a suspension of clay) as well as about the bond characteristics of steel that have been coated with bentonite. However, tests have shown that placing concrete by displacing bentonite suspension from bottom (in contrast to pouring concrete into bentonite suspension) does not affect concrete strength. Similarly the bond between steel and concrete is also not very much reduced in this process. Hence the importance of properly placing concrete by tremie by displacement of bentonite from bottom up should be strictly followed in the field.



tremie (after

Varghese, 2005)

PART VI
Appendix G

Other Methods of Estimating Ultimate Axial Capacity of Piles and Drilled Shafts, and Design Charts for Settlement

G.1 Method Based on the Standard Penetration Test (Canadian Foundation Engineering Manual):

This method is based on N-values obtained from Standard Penetration Test (SPT). This method has been described in Canadian Foundation Engineering Manual published by Canadian Geotechnical Society (CGS, 1985).

The capacity of a single pile in granular soils can be estimated from the results of SPT using the following expression as suggested by Meyerhof (1976).

$$R = mNA_t + nN'DA_s \quad (6.G.1)$$

Where,

- R = pile capacity (N)
- m, n = constants depending on type of pile (driven or cast-in-situ bored piles)
- N = SPT index at the pile toe
- A_t = pile toe area
- N' = average SPT index along the pile
- D = pile embedment length
- A_s = pile unit shaft area

The Standard Penetration Test is subject to a multitude of errors, and a lot of care must be exercised when using test results. For this reason, in this method a minimum factor of safety of 4 should be applied to calculate allowable capacity of a drilled shaft or bored pile.

G.2 Method Based on the Theory of Plasticity (Canadian Foundation Engineering Manual)

In this method the capacity of a single pile may be determined from the friction angle of the soil by use of the theory of plasticity (or bearing-capacity theory).

The capacity of a pile in a soil of uniform density increases in a linear manner with increase in effective overburden pressure at least to a certain depth called the critical depth. Investigations of single piles indicate that there is very little increase in toe resistance or unit shaft resistance below the critical depth. The ratio of the critical depth to the pile diameter increases with increase in the angle of shearing resistance. For most applications, the ratio ranges between a value of 7 at $\phi' = 30^\circ$ to a value of 22 at $\phi' = 45^\circ$.