Book: Soil Mechanics and Foundation Engineering, Vol.II Foundation Engineering, VNS Murthy: 3rd Edn.

CHAPTER

EIGHT DEEP FOUNDATION 1

PILE FOUNDATION TYPES OF PILES SELECTION AND INSTALLATION

8.1 INTRODUCTION

Chapters 4 to 7 have dealt with bearing capacity and settlement of shallow foundations. The usage of the words *shallow* or *deep* for the foundations is only a matter of convenience for the understanding of the nature of the problem and the manner by which this could be solved. In the case of shallow foundations the shear stresses between the soil and the foundations and within the soil above the base of the foundation are normally neglected. The soil above the base level is considered only as a surcharge. It has been found out both from analytical and experimental studies that the effect of this assumption on the bearing capacity of shallow foundations is not considerable so long the depth of the foundation is not greater than its least width. However, when the depth is considerable, it is very essential to consider the shear stresses between the foundation and the soil as otherwise the design would be highly conservative and therefore uneconomical.

Shallow foundations are normally used where the soil close to the ground surface and upto the *significant depth* possesses sufficient bearing strength to carry the superstructure load without causing distress to the superstructure due to settlement. However, where the top soil is either loose or soft or of swelling type the load from the structure has to be transferred to deeper firm strata. In such cases, deep foundations are the obvious choice. There are two types of deep foundations. They are

1. Pile foundations,
2. Well or Caisson foundations.

Piles are the long slender members either *driven* or *cast-in-situ*. They may be subjected to vertical or lateral loads or a combination of vertical and lateral loads. Caissons or Well foundations are heavier in section and they are sunk to the required depth. They are normally used to carry very heavy loads such as the loads from bridge piers or multistoried buildings.

Piles are also used to take up uplift loads. Piles may be used as single piles or in groups with vertical and/or batter piles. The problem of pile foundation has been considered under the following headings in this book,

1. Types of piles, selection and installation,
2. Vertical load bearing capacity and settlement of single vertical pile,
3. Behaviour of single vertical and batter piles subjected to lateral loads,
4. Behaviour of pile groups subjected to vertical and lateral loads.

Types of piles, selection and installation have been discussed in this chapter and the other topics mentioned above are dealt with in the subsequent chapters.

8.2 CLASSIFICATION OF PILES

Piles may be classified as long or short in accordance with the L/d ratio of the pile (where L = length, d = diameter of pile). A short pile behaves as a rigid body and rotates as a unit under lateral loads and its L/d ratio is limited to 10. But when subjected to vertical loads, the load transferred to the tip of the pile bears a significant proportion to the total vertical load on the top. In the case of a long pile, the length beyond a particular depth loses its significance under lateral loads, but when subjected to vertical load, the frictional load on the sides of the pile bears a significant part to the total load.

Piles may further be classified as vertical piles or batter piles. Vertical piles are normally used to carry mainly vertical loads and very little lateral load. When piles are inclined at an angle to the vertical, they are called as *batter piles* or *rakerpiles*. Batter piles are quite effective for taking lateral loads, but when used in groups, they also can take vertical loads.

8.3 TYPES OF PILES ACCORDING TO THEIR COMPOSITION

Piles may be classified according to their composition as

1. Timber Piles,
2. Concrete Piles,
3. Steel Piles.

Timber Piles. Timber piles are made of tree trunks with the branches trimmed off. It shall be of sound quality and free of defects. The length of the pile may go upto 15 m or more. If greater lengths are required, they are to the spliced. The diameter of the piles at the butt end may vary from 30 to 40 cms. The diameter at the tip end should not be less than 15 cms.

Piles entirely submerged in water last long without decay provided marine borers are not present. When a pile is subjected to alternate wetting and drying the useful life is relatively short unless treated with a wood preservative, usually creosote at 250 kg. per m^3 for piles in fresh water and 350 kg. in sea water.

After driven to final depth, all pile heads, treated or untreated, should be sawed square to sound undamaged wood to receive the pile cap. But before concrete for the pile cap is poured, the head of the treated piles should be protected by zinc coat, lead paint or by wrapping the pile heads with fabric upon which hot pitch applied.

Driving of timber piles usually results in the crushing of the fibres on the head (or brooming) which can be somewhat controlled by using a driving cap, or ring around the butt.

The usual maximum design load per pile does not exceed 25 tonnes. Timber piles work out cheaper at places where timber is available in plenty.

Concrete Piles. Concrete piles are either precast or *cast-in-situ* piles. The precast concrete piles are cast and cured in a casting yard and then transported to the site of work for driving. If the work is of a very big nature, they may be cast at the site also.

Precast piles may be made of uniform sections with pointed tips. Tapered piles may also be manufactured when greater bearing resistance is required. Normally piles of square or octagonal sections are manufactured since these shapes are easy to cast in horizontal position. Necessary reinforcements are provided by taking care of handling stresses. Piles may also be prestressed. Fig. 8.1 indicates maximum moments in pile, depending on the location of the pickup points. The pickup points on the pile should clearly be marked to avoid overstressing the pile by inadvertance. Minimum reinforcement in a pile should be at least 1 percent.

Maximum load on a prestressed concrete pile may go upto 200 tonnes and on precast pile 100 tonnes. The optimum load range is 40 to 60 tonnes.

Steel Piles. Steel piles are usually rolled *H* shapes or pipe piles. *H*-piles are proportioned to withstand large impact stresses during hard driving. Pipe piles are either welded or seamless steel pipes which may be driven either open-end or closed-end. Pipe piles are often filled with concrete after driving, although in some cases this is not necessary. The optimum load range on steel piles is 40 to 120 tonnes.

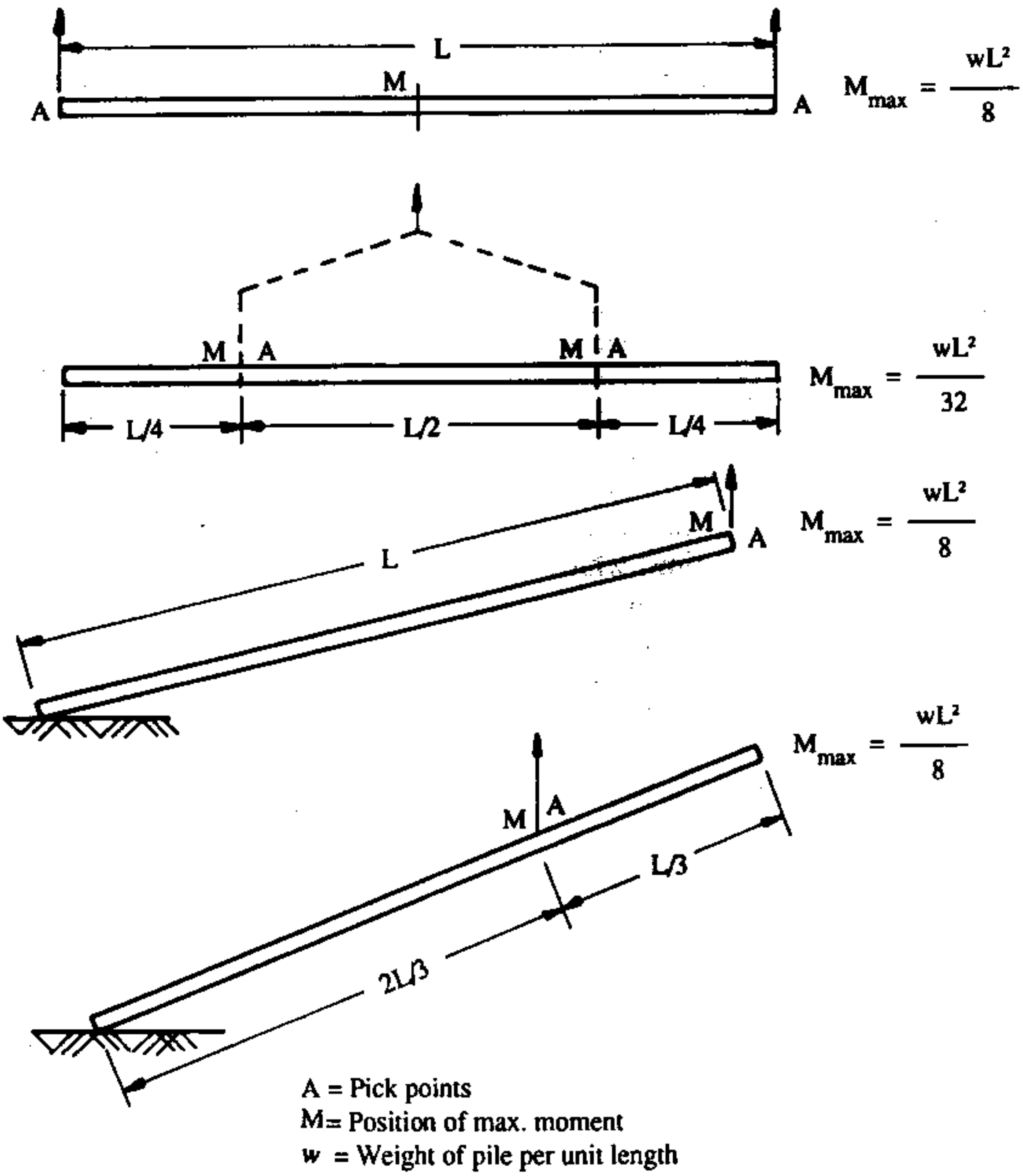


Fig. 8.1 Maximum moments in piles at pickup points

8.4 TYPES OF PILES ACCORDING TO THE METHOD OF INSTALLATION

According to the method of construction, there are three types of piles. They are

1. Driven piles,
2. *Cast-in-situ* piles and
3. Driven and *cast-in-situ* piles.

Driven Piles

Piles may be of timber, steel or concrete. When the piles are of concrete, they are to be precast. They may be driven either vertically or at an angle to the vertical. Piles are driven using pile hammer. When a pile is driven into granular soil, the soil so displaced equal to the volume of the pile driven, compacts the soil around since the displaced soil particles enter the soil spaces of the adjacent mass which leads to densification of the mass. The pile that compacts the soil adjacent to it is sometimes called as *compaction piles*. The compaction of the soil mass around a pile increases its bearing capacity.

If a pile is driven into saturated silty or cohesive soil, the soil around cannot get compacted because of its poor drainage qualities. This displaced soil particles cannot enter the void space unless the water in the pores is pushed out. The stresses developed in the soil mass adjacent to the pile due to the driving of the pile have to be borne by the porewater only. This results in the development of porewater pressure and a consequent decrease in the bearing capacity of the soil.Besides, the soil adjacent to the piles gets remoulded and loses to a certain extent its structural strength. The immediate effect of driving a pile with a soil of poor drainage qualities is, therefore, to decrease its bearing strength. However, with the passage of time, the remoulded soil regains part of its lost strength due to the reorientation of the disturbed particles (which is termed as *thixotrophy*) and due to consolidation of the mass. The advantages and disadvantages of driven piles are:

Advantages

1. Piles can be precast to the required specifications.
2. Piles of any size, length and shape can be made in advance and used at the site. As a result, the progress of the work will be rapid.
3. A pile driven into granular soil compacts the adjacent soil mass and as a result the bearing capacity of the pile is increased.
4. The work is neat and clean. The supervision of work at the site can be reduced to a minimum. The storage space required is very much less.
5. The driven piles may conveniently be used in places where it is advisable not to drill holes for fear of meeting ground water under pressure.
6. Driven pile is the most favoured for works over water such as piles in wharf structures or jetties.

Disadvantages

1. Precast or prestressed concrete piles must be properly reinforced to withstand handling stresses during transportation and driving.
2. Advance planning is required for handling and driving.
3. Requires heavy equipment for handling and driving.
4. Since the exact length required at the site cannot be determined in advance, the method involves cutting off extra lengths or adding more lengths. This increases the cost of the project.
5. Driven piles are not suitable in soils of poor drainage qualities. If the driving of piles is not properly phased out and arranged, there is every possibility of heaving of the soil or the lifting of the driven piles during the driving of a new pile.
6. Where the foundations of adjacent structures are likely to be affected due to the vibrations generated by the driving of piles, driven piles should not be used.

Cast-in-situ Piles

Cast-in-situ piles are concrete piles. They are constructed by making holes in the ground to the required depth and then filling it with concrete. Straight bored piles or piles with one or more bulbs at intervals may be cast at site. The latter type is called as *under-reamed piles*. Reinforcement may be used as per the requirements. *Cast-in-situ* piles have advantages as well as disadvantages.

Advantages

1. Piles of any size and length may be constructed at the site.
2. Damage due to driving and handling that are common in precast piles are eliminated in this case.
3. These piles are ideally suited in places where vibrations of any type are required to be avoided to preserve the safety of the adjoining structure.
4. They are suitable in soils of poor drainage qualities since *cast-in-situ* piles do not significantly disturb the surrounding soil.
5. Under-reamed piles provide greater bearing areas and as such are suitable for carrying higher loads. They may many times, prove economical as compared to straight bored piles capable of carrying the same designed loads.

Disadvantages

1. Installation of *cast-in-situ* piles needs careful supervision and quality control of all the materials used in the construction.

2. The method is quite cumbersome. It needs sufficient storage space for all the materials used in the construction.
3. The advantage of increased bearing capacity due to compaction in granular soil that could be obtained by a driven pile is not there in a *cast-in-situ* pile.
4. Construction of piles in holes where there is heavy current of ground water flow or artesian pressure is very difficult.

The straight bored and under-reamed piles are shown in Fig. 8.2*a*.

Driven and Cast-in-situ Piles

This has the advantages and disadvantages of both the driven and the *cast-in-situ* piles. The procedure of installing a driven and *cast-in-situ* pile is as follows:

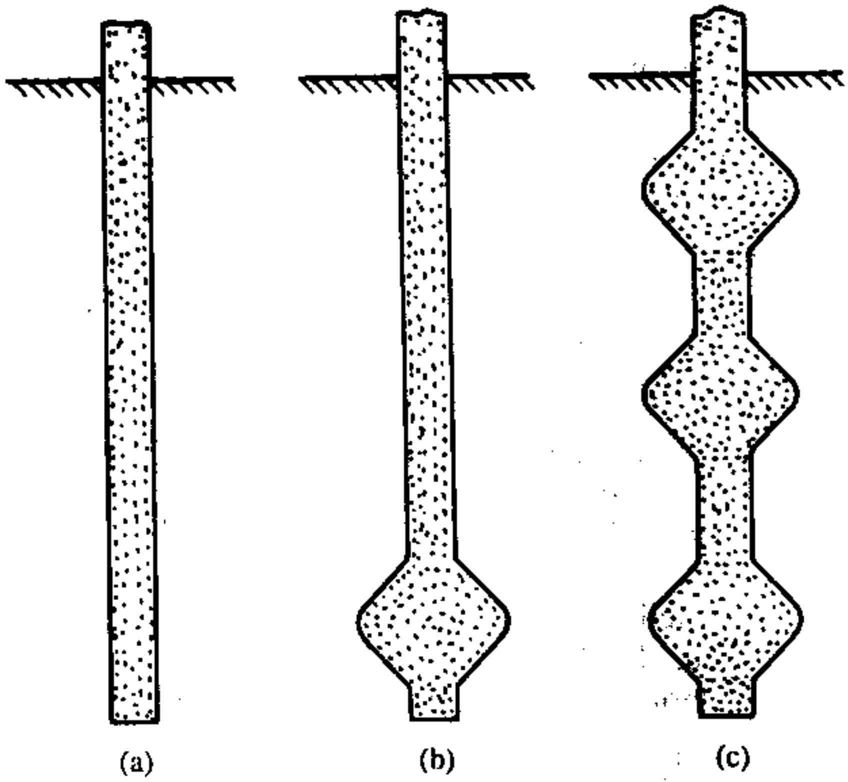
A steel shell is driven into the ground with the aid of a mandrel inserted into the shell. The mandrel is withdrawn and the concrete is placed in the shell. The shell is made of corrugated and reinforced thin sheet steel (mono-tube piles) or pipes (Armco welded pipes or common seamless pipes). The piles of this type are called as shell type. The shell-less type is formed by withdrawing the shell while the concrete is being placed. In both the types of piles the bottom of the shell is closed with a conical tip which can be separated out from the shell. By driving the concrete out of the shell an enlarged bulb may be formed in both the types of piles. Franki pile are of this type. The common types of driven and *cast-in-situ* piles are given in Fig. 8.2*b*. In some cases the shell will be left in place and the tube is concreted. This type of pile is very much used in piling over water.

8.5 USES OF PILES

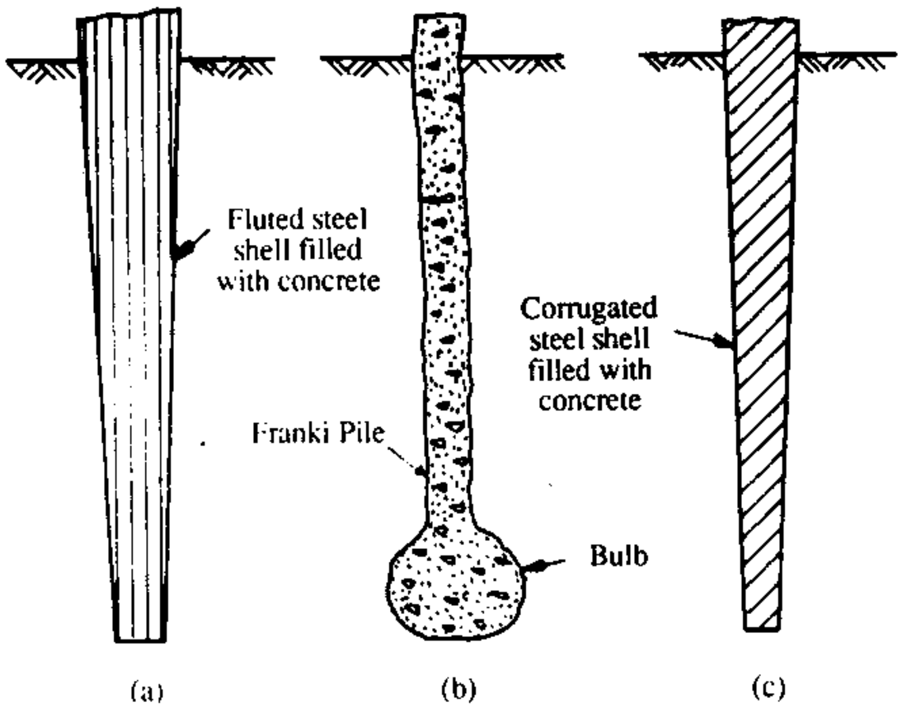
The major uses of piles are:

1. To carry vertical compression load.
2. To resist uplift load.
3. To resist horizontal or inclined loads.

Normally vertical piles are used to carry vertical compression loads coming from super-structures such as buildings, bridges etc. The piles are used in groups joined together by pile caps. The loads carried by the piles are transferred to the soil adjacent to it. If all the loads coming on the tops of piles are transferred to the tips, such piles are called *end-bearing* or *point-bearing piles*. However, if all the load is transferred to the soil along the length of the pile such piles are called as *friction piles*. If, in the course of driving a pile into granular soils, the soil around the pile gets compacted, such piles are called as

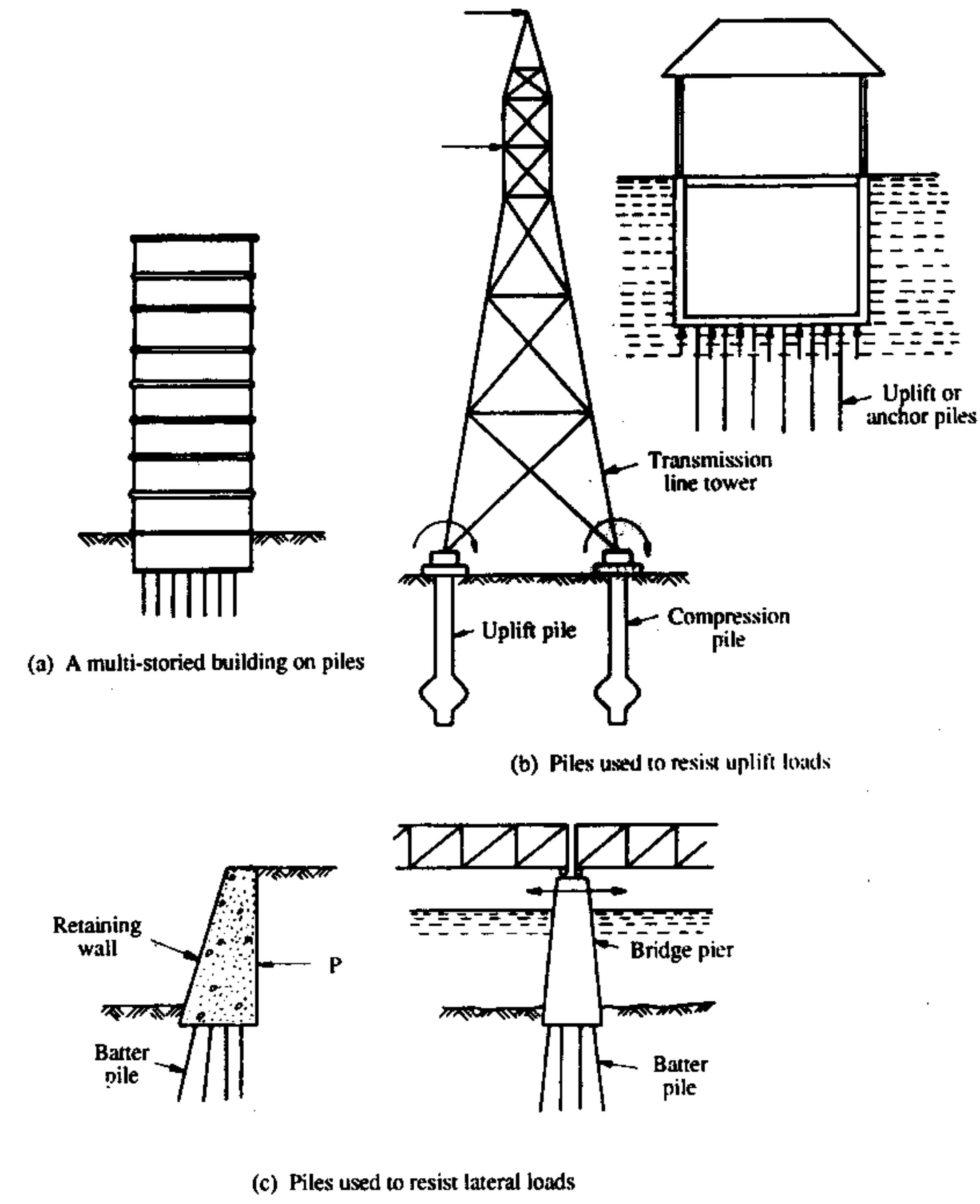


A. *Cast-in-situ* (a) straight bored, (b) single bulb, and (c) multi bulb piles.



B. Driven and *cast-in-situ* piles.

Fig. 8.2 Types of *Cast-in-situ* and driven *Cast-in-situ* concrete piles.



(a) A multi-storied building on piles

(b) Piles used to resist uplift loads

(c) Piles used to resist lateral loads

Fig. 8.3 Uses of piles

compaction piles. Fig. 8.3*a* shows piles used for the foundation of a multi-storied building to carry loads from the superstructure.

Piles are also used to resist uplift loads. Piles used for this purpose are called as *tension piles or uplift piles or anchor piles*. Uplift loads are developed due to hydrostatic pressure or overturning movement as shown in Fig 8.3*b*.

Piles are also used to resist horizontal or inclined forces. Batter piles are normally used to resist large horizontal loads. Fig. 8.3*c* shows the use of piles to resist lateral loads.

8.6 SELECTION OF PILE

The selection of the type, length and capacity is usually made from estimation based on the soil conditions and the magnitude of load. In large cities, where the soil conditions are well known and where a large number of pile foundations have been constructed, the experience gained in the past is extremely useful. Generally the foundation design is made on the preliminary estimated values. Before the actual construction begins, pile load tests must be made to verify the design values, the foundation design must be revised according to the test results. The factors that govern generally the selction of piles are:

1. Length of pile in relation to the load and type of soil.
2. Character of structure.
3. Availability of materials.
4. Type of loading.
5. Factors causing deterioration.
6. Ease of maintenance.
7. Estimated costs of types of piles, taking into account the initial cost, life expectancy and cost of maintenance.
8. Availability of funds.

All the above factors have to be largely analysed before deciding a particular type.

8.7 INSTALLATION OF PILES

8.7.1 Introduction

The method of installing a pile at the site depends upon the type of pile. The equipments required for the purpose also vary. The following types of piles are considered for the purpose of installation

1. Driven piles

The piles that come under this category are,

a. Timber piles,

b. Steel piles, *H*-section and pipe piles,

c. Precast concrete or prestressed concrete piles, either solid or hollow sections.

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CHAPTER
NINE
DEEP FOUNDATION 2

VERTICAL LOAD BEARING CAPACITY OF SINGLE VERTICAL PILE

9.1 INTRODUCTION

The bearing capacity of groups of piles subjected to vertical or vertical and Lateral loads depends upon the behaviour of a single pile. The bearing capacity of a single pile depends upon

1. Type, size and length of pile,
2. Type of soil,
3. The method of installation.

The bearing capacity depends primarily on the method of installation and the type of soil met with. The advantages and disadvantages of different types of piles with respect to the method of installation have already been discussed in Chapter 8. The bearing capacity of a single pile increases with the increase in the size and length. The position of the water table also affect the bearing capacity.

In order to be able to design a safe and economical pile foundation, we have to analyse the interactions between the pile and the soil, establish the modes of failure and estimate the settlements from soil deformation under dead load, service load etc. The design should comply with the following requirements.

1. It should ensure adequate safety against failure; the factor of safety depending on the importance of the structure and on the reliability of the soil parameters and the loading systems used in the design.
2. The settlements should be compatible with an adequate behaviour of the superstructure to avoid impairing its efficiency.

9.2 BEHAVIOUR OF SINGLE PILE UNDER VERTICAL LOAD

9.2.1 Statement of the Problem

Fig 9.1*a* gives a single pile of uniform diameter *d* (circular or any other shape) and length L installed in a homogeneous mass of soil of known physical properties. A static vertical load is applied on the top. It is required to determine the ultimate bearing capacity Q_u of the pile.

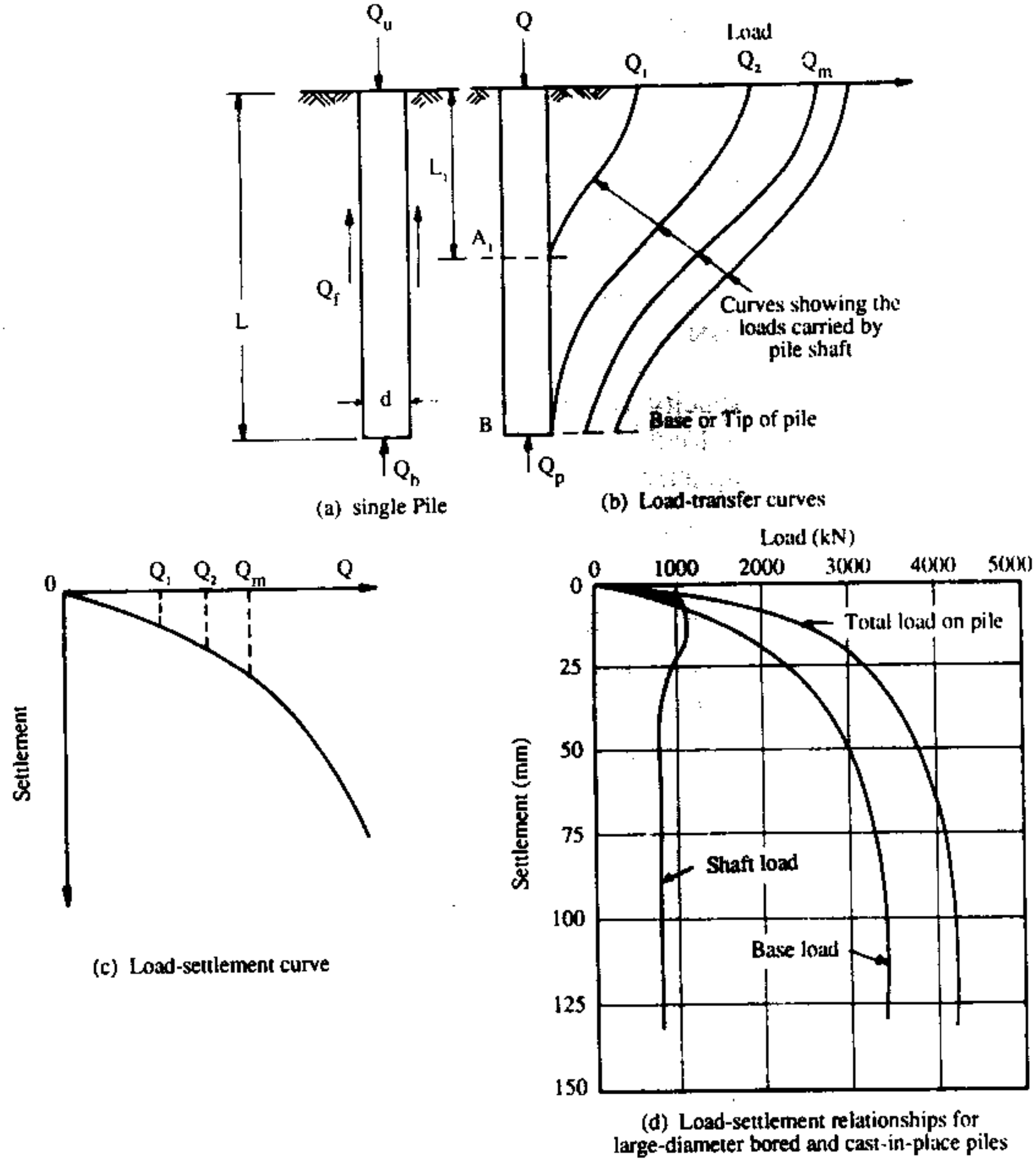

Fig. 9.1 Load Transfer Mechanism

When the ultimate load applied on the top is Q_u, a part of the load is transmitted to the soil along the length of the pile and the balance is transmitted to the pile base. The load transmitted to the soil along the length of the pile is called as the ultimate friction load or skin load Q_f and that transmitted to the base is called as the base or point load Q_b. The total ultimate load Q_u is expressed as the sum of there two, that is,

$$Q_u = Q_b + Q_f = q_b A_b + f_s A_s \,, \tag{9.1}$$

where, Q_u = ultimate load applied on the top of the pile,

q_b = ultimate unit bearing capacity of pile at the base,

A_b = bearing area of the base of the pile,

A_s = total surface area of pile embedded below ground surface,

f_s = unit skin friction (ultimate).

9.2.2 Load Transfer Mechanism

Consider the pile shown in Fig 9.1*b* is loaded to failure by gradually increasing the load on the top. If settlement of the top of the pile is measured at every stage of loading after equilibrium condition is attained, a load settlement curve as shown in Fig. 9.1*c* can be obtained.

If the pile is instrumented, the load distribution along the pile can be determined at different stages of loading and plotted as shown in Fig. 9.1*b*.

When a load Q_1 acts on the pile head, the axial load at ground level is also Q_1, but at level A_1 (Fig. 9.1*b*), the axial load is zero. The total load Q_1 is distributed as friction load within a length of pile L_1. The lower section A_1B of pile will not be affected by this load. As the load at the top is increased to Q_2, the axial load at the bottom of pile is just zero. The total load Q_2 is distributed as friction load along the whole length of pile L. The friction load distribution curves along the pile shaft may be as shown in the figure. If the load put on the pile is greater than Q_2, a part of this load is transferred to the soil at the base as point load and the rest is transferred to the soil surrounding the pile. With the increase of load Q on the top, both the friction and point loads go on increasing. The friction load attains an ultimate value Q_f at a particular load level, say Q_m, at the top, and any further increment of load added to Q_m, will not increase the value of Q_f. However, the point load, Q_p, still goes on increasing till the soil fails by punching shear failure. It has been investigated by Van Wheele (1957) that the point load Q_p increases linearly with the elastic compression of the soil at the base.

The relative proportions of load carried by skin load and point load depend on the shear strength and elasticity of the soil. Generally the vertical movement of the pile which is required to mobilise full end resistance is much greater than that required to mobilise full skin friction. Experience indicates that in bored *cast-in-situ* piles full frictional load is normally mobilised at a settlement equal to 0·5 to 1 per cent of pile diameter and the full base load Q_b at 10 to 20 percent of the diameter. But, if this ultimate load criterion is applied to piles of large diameter in clay, the settlement at the working load (with a factor of safety of 2 on the ultimate load) may be excessive. A typical load-settlement relationship of friction load and base load is shown in Fig. 9.1*d* (Tomlinson, 1986) for a large diameter bored and *cast-in-situ* pile in clay. It may be seen from this figure that the full shaft resistance is mobilised at a settlement of only 15 mm whereas the full base resistance, and the ultimate resistance of the entire pile is mobilised at a settlement of 120 mm. The shaft load at a settlement of 15 mm is only 1000 kN which is about 25 percent of the base resistance. If a working load of 2000 kN at a settlement of 15 mm is used for the design, at this working load, the full shaft resistance will have been mobilised whereas only about 50 percent of the base resistance has been mobilised. This means if piles are designed to carry a working load equal to 1/3 to 1/2 the total failure load, there is every likelihood of the shaft resistance being fully mobilised at the working load. This has an important bearing on the design.

The type of load-settlement curve for a pile depends on the relative strength values of the surrounding and underlying soil. Fig. 9.2 gives four types of failure. They are as follows:

Fig 9.2*a* represents a driven pile (wooden or reinforced concrete), whose tip bears on a very hard stratum (rock). The soil around the shaft is too weak to exert any confining pressure or lateral resistance. In such cases, the pile fails like a compressed, slender column of the same material; after a more or less elastic compression buckling occurs. The curve shows a definite failure load.

Fig. 9.2*b* is the type normally met in practice. The pile penetrates through layers of soil having low shear strength down to a layer having a high strength and the layer extending sufficiently below the tip of the pile. At ultimate load Q_u, there will be a base general shear failure at the tip of the pile, since the upper layer does not prevent the formation of failure surface. The effect of the shaft friction is rather less, since the lower dense layer prevents the occurence of excessive settlements. Therefore, the degree of the mobilisation of shear stresses along the shaft will be low. The load settlement diagram is of the shape typical for a shallow footing on dense soil.

Fig. 9.2*c* shows the case where the shear strength of the surrounding soil is fairly uniform; therefore, a punching failure is likely to occur. The load-settlement diagram does not have a vertical tangent, and there is no definite failure load. The load will be carried by point resistance as well as by skin friction.

Fig 9.2*d* is a rare case where the lower layer is weaker. In such cases, the load will be carried mainly by shaft friction, and the point resistance is almost zero. The load-settlement curve shows a vertical

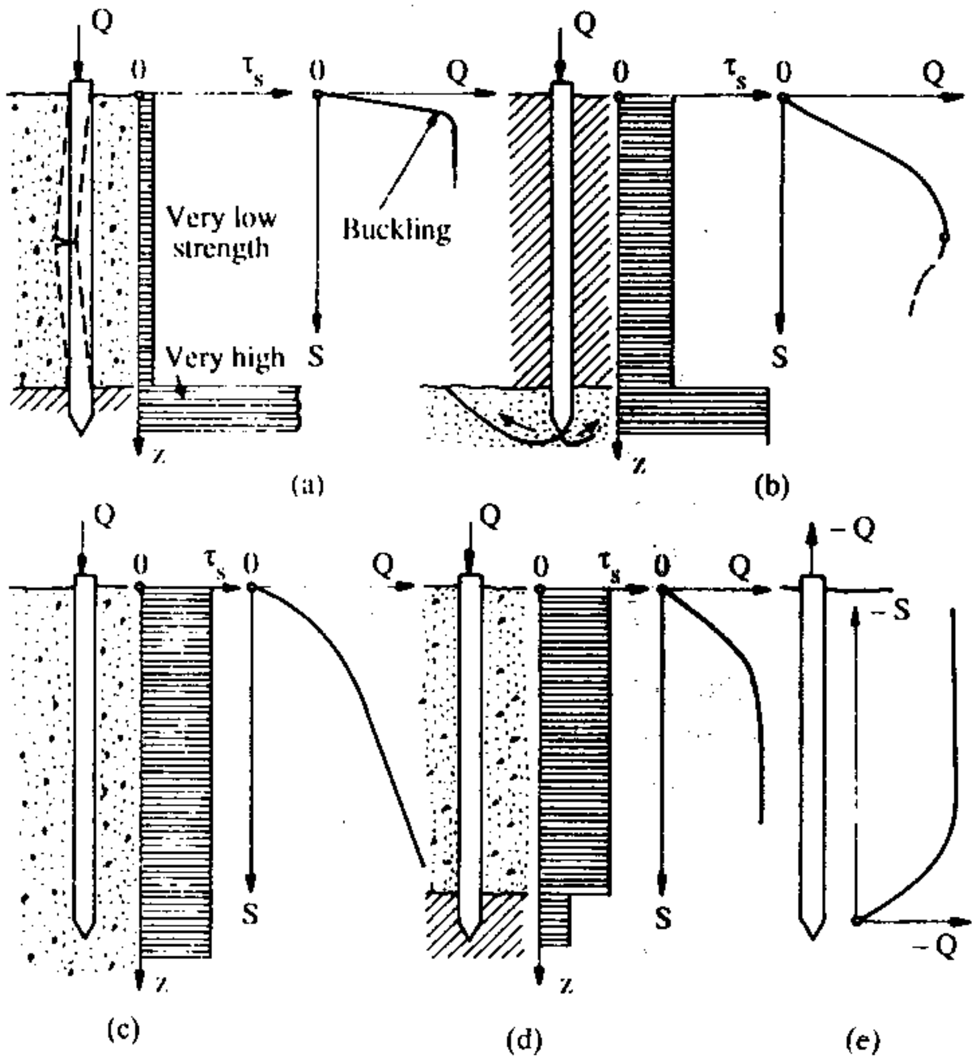

Fig. 9.2 Types of failure of pile. Figures (*a*) to (*e*) indicate how strength of soil determines the type of failure: (*a*) buckling in very weak surrounding soil; (*b*) general shear failure in the strong lower soil; (*c*) soil of uniform strength (*d*) low strength soil in the lower layer, skin friction predominant; (*e*) skin friction in pull.

tangent, which represents the load when the shaft friction has been fully mobilised.

Fig 9.2*e* is a case when a pull, $-Q$ acts on the pile. Since the point resistance is again zero the same diagram, as in Fig. 9.2*d*, will characterise the behaviour, but heaving occurs.

9.2.3 Definition of Failure Load

The methods of determining failure loads based on load-settlement curves are described in Section 9.12. However, in the absence of a load settlement curve, a failure load may be defined as that which causes a settlement equal to 10 percent of the pile diameter or width (as per the suggestion of Terzaghi) which is widely accepted by the engineers. However, if this criterion is applied to piles of large diameter in clay and a nominal factor of safety of 2 is used to obtain the working load, then the settlement at the working load may be excessive.

9.3 FACTOR OF SAFETY

In almost all cases where piles are acting as structural foundations, the allowable load is governed soley from considerations of tolerable settlement at the working load.

The working load for all pile types in all types of soil may be taken as equal to the sum of the base resistance and shaft friction divided by a suitable factor of safety. A safety factor of 2·5 is normally used. Therefore we may write

$$Q_a = \frac{Q_b + Q_f}{2{\cdot}5}. \tag{9.2}$$

In case the values of Q_b and Q_f can be obtained independently, the allowable load can be written as

$$Q_a = \frac{Q_b}{3} + \frac{Q_f}{1{\cdot}5}. \tag{9.3}$$

It is permissible to take a safety factor equal to 1·5 for the skin friction because the peak value of skin friction on a pile occurs at a settlement of only 3–8 mm (relatively independent of shaft diameter and embedded length but may depend on soil parameters) whereas the base resistance requires a greater settlement for full mobilisation.

The least of the allowable loads given by Eqs. (9.2) and (9.3) is taken as the design working load.

9.4 METHODS OF DETERMINING ULTIMATE LOAD BEARING CAPACITY OF A SINGLE VERTICLE PILE

The ultimate bearing capacity Q_u of a single vertical pile may be determined by any of the following methods.

1. By the use of static bearing capacity equations.
2. By the use of of the values of SPT, CPT and PMT.
3. By field load tests.
4. By dynamic method.

The determination of the point bearing capacity, q_b, of a deep foundation on the basis of theory is a very complex one since there are many factors which cannot be accounted for in the theory. The theory assumes that the soil is homogeneous and isotropic which is normally not the case. All the theoretical equations are obtained based on plane strain conditions. Only shape factors are applied to take care of the three-dimensional nature of the problem. Compressibility characteristics of the soil complicates the problem further. Experience and judgement are therefore very essential in applying any theory to a specific problem. The skin load Q_f depends on the nature of the surface of the pile, the method of installation of the pile and the type of soil. An exact evaluation of Q_f is a difficult job even if the soil is homogeneous over the whole length of the pile. The problem becomes all the more complicated if the pile passes through soil of variable characteristics.

9.5 GENERAL THEORY FOR ULTIMATE BEARING CAPACITY

According to Vesic (1967), only punching shear failure occurs in deep foundations irrespective of the density of the soil so long the depth-width ratio D/B is greater than 4. The types of failure surfaces assumed by different investigators are shown in Fig. 9.3 for general shear failure condition. The detailed experimental study of Vesic indicate that the failure surfaces do not revert back to the shaft as shown in Fig 9.3*b*.

The total failure load $\bar{Q}_u$ may be written as follows

$$\bar{Q}_u = Q_u + W_p = Q_b + Q_f + W_p , \tag{9.4}$$

where, Q_u = load at failure applied to the pile,
Q_b = base resistance,
Q_f = shaft resistance,
W_p = weight of the pile.

The general equation for the base resistance may be written as

$$Q_b = (cN_c + q_oN_q + 1/2\gamma BN_\gamma)A_b , \tag{9.5}$$

where, B = width or diameter of the shaft ,
q_o = effective overburden pressure at the base level of pile,
A_b = base area of pile,
c = cohesion of soil,
γ = unit weight of soil,
N_c, N_q & N_γ = bearing capacity factors which take into account the shape factors.

Cohesionless soils

For cohesionless soils, $c = 0$ and the term $\frac{1}{2}\gamma BN_\gamma$ becomes

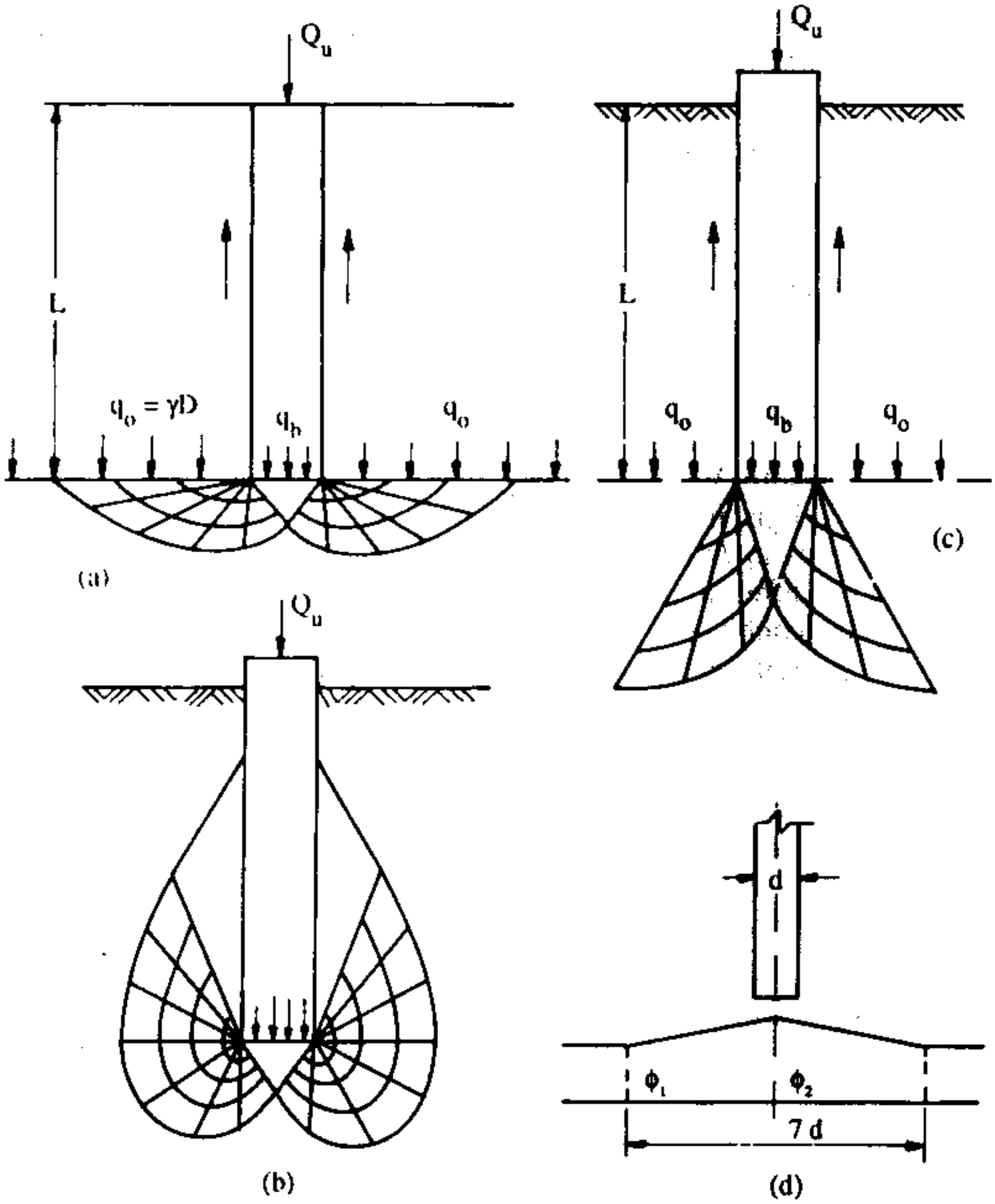

Fig. 9.3 The shapes of failure surfaces at the tips of piles as assumed by (*a*) Terzaghi, (*b*) Meyerhof, and (*c*) Vesic, (*d*) The effect of driving of pile on ϕ.

insignificant in comparison with the term $q_o N_q$ for deep foundations. Therefore (Eq 9.5), reduces to

$$Q_b = q_o N_q A_b\ . \tag{9.6}$$

Eq. (9.4) may now be written as

$$\bar{Q}_u = Q_u + W_p = q_o \mathrm{N}_q A_b + W_p + \mathrm{Q}_f\ . \tag{9.7}$$

The net ultimate load in excess of the overburden pressure load $q_0 A_b$ is

$$Q_u + W_p - q_o A_b = q_o N_q A_b + W_p - q_o A_b + Q_f \,. \tag{9.8}$$

If we assume for all practical purposes, W_p and $q_o A_b$ are roughly equal for straight sided or moderately tapered piles, Eq. (9.8) reduces to

$Q_u = Q_b + Q_f$

$$Q_u = q_o N_q A_b + Q_f$$

or

$$Q_u = q_o N_q A_b + A_s \bar{q}_o \bar{K}_s \tan \delta \tag{9.9}$$

where, A_s = surface area of the embedded length of pile,

$\bar{q}_o$ = average effective overburden pressure over embedded, depth of pile,

$\bar{K}_s$ = lateral earth pressure coefficient,

δ = angle of wall friction.

Cohesive soils

For cohesive soils such as saturated clays (normally consolidated), we have for $\phi = 0$, $N_q = 1$ and $N_\gamma = 0$. The ultimate base load from Eq. (9.5) is

$$Q_b = (c_b N_c + q_o)\, A_b \,. \tag{9.10}$$

The net ultimate base load is

$$(Q_b - q_o A_b) = c_b N_c A_b \,. \tag{9.11}$$

Therefore, the net ultimate load capacity of pile, Q_u, is

$$Q_u = c_b N_c A_b + Q_f$$

or

$$Q_u = c_b N_c A_b + A_s\, \alpha\, \bar{c}_u \,, \tag{9.12}$$

where, α = adhesion factor,

$\bar{c}_u$ = average undrained shear strength of clay along the shaft,

c_b = undrained shear strength of clay at the base level,

N_c = bearing capacity factor

Eqs. (9.9) and (9.12) are used for analysing the net ultimate load capacity of piles in cohesionless and cohesive soils respectively. In each case the following types of piles are considered.

1. Driven piles. 2. Driven and *cast-in-situ* piles. 3. Bored piles.