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Ministry of Railways

FOUNDATION SETTLEMENT
IN
BUILDINGS
[CAUSES & PREVENTION]

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Maharajpur, Gwalior - 474 005

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Preface

The natural opponents of any earth retaining structures are 'water and soil', which may be harmful to any structure if not properly taken into account the various physical properties of soil, most of which are not constant. This tendency of soils to fluctuate in their physical properties is in contradistinction to the behaviour of artificially manufactured materials (*viz.* iron and steel), the properties of which are relatively constant.

Since the civilisation begins, the soil is being extensively used as foundation material which supports the structures, and also as construction material in case of earth dams, highway and other fills, ingredients in mortars etc. When the foundation settlement occurs, the structure suffers heavy losses due to sudden collapse resulting in un-count casualties. The adequate preventive measures have to be adopted at the initial level by way of investigating the soil strata carefully as to ensure the complete safety against such failures. The design of foundation in any earth retaining structure should be done by taking into account the ultimate bearing capacity of soil. Also the earth-quake affected areas need to be investigated well before the design of foundations to be finalised.

Indian Railway is a big organisation having large assets of civil engineering structures and buildings through out the country covering almost all the regions, where soil properties (physical as well as engineering) change and such behaviour should be investigated and analysed well before final lay-out of foundation.

This handbook is prepared with the objective to provide informative technical details on '***Foundation Settlement in Buildings - Causes and Prevention***' for the guidance of civil engineering personnel involved in planning, designing, construction and maintenance of buildings & other structures. It covers the basic nature of soil, behaviour of soil underneath the foundation, effects of under-ground water on foundations, causes of foundation settlement and their preventive as well as protective measures with brief description of codal provisions.

This handbook does not supersede any existing instructions from Railway Board, RDSO & Zonal Railways and the provisions of IRWM, BIS codes & reports on the subject. *This handbook is not statutory and contents are only for the purpose of guidance.* Most of the data & information mentioned herein are available in some form or the other in various books and other printed matter.

I am grateful for the assistance given by Shri K.C.Shakya, CTA/Civil, who went through the complete text, collected information, data etc. and did text-editing work. Nice data entry has been done by Shri Ramesh Bhojwani, Console Operator, CAMTECH.

We welcome any suggestions from our readers for further improvement.

CAMTECH/Gwalior
Date : 29.03.07

A.K. Dadarya
Director/Civil

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Chapter – 1

Introduction

Foundation design and construction are two basic requirements of any earth retaining structure, which transfers its load to the underlying earth's crust. The materials that constitute the earth's crust are arbitrarily divided into two types, i.e. soil and rock, which are the main structural materials and in reality, there is no clear distinction between them. Soils and sites are so variable that it is not practicable to formulate any hard and fast rules.

The mechanical properties of soils are far more complex and difficult to determine. No material has greater variation of properties than soil, probably because it is not a manufactured standard product like steel. This is because the soil with which the engineer must work was placed by nature in a great variety of kinds and conditions. The selection of soils for foundation of any structure is not entirely within the engineer's control. The stability and function of a structure will largely depend upon the behaviour of the soil upon which and/ or of which it is built.

In the subsequent chapters, the basic technical information on the subject has been covered in details, covering (i) '*general behaviour of soil*' i.e. nature of soil, its profile, stability and properties alongwith its behaviour under foundation (ii) '*effect of groundwater*' i.e. ground water level, importance of water level and effect of under-ground water on foundation (iii) '*foundation settlement*' i.e. foundation failures, causes of foundation settlement, time-dependant settlement (iv) '*settlement in shallow and deep foundation*' i.e. brief description of the relevant Indian Standards (v) '*preventive measures*' i.e. improvement of bearing capacity of soil through soil stabilising methods, protection of excavation, safety of existing structures.

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Chapter – 2

General Behaviour of Soil

2.1 Nature of Soil

Soil is considered by the engineer as a complex material produced by the weathering of the solid rock. The formation of soil is as a result of the geologic cycle continually taking place on the face of earth.

- **Soil is a natural aggregate of mineral grains** with or without organic matters, that can be separated by gentle mechanical means, such as agitation of water, wind, frost, etc. Soil may be defined as that which comprises accumulations of solid particles, loose or cohesive deposits, such as gravel, sand, silt, clay or any combination there of which is loose enough to be removed with a spade or shovel in a dry or saturated state.
- **Rock is a natural aggregate of mineral grains** connected by strong and permanent cohesive forces. The term 'rock' may be applied to materials, which are natural beds or large hard fragments or original igneous, sedimentary or metamorphic formations.

Since soils are the natural substance and some of their characteristics are briefly described as below:

- ◆ **Elasticity:** A soil is said to be elastic when it suffers a reduction in volume while the load is applied, but recovers its initial volume immediately when the load is removed. Peat possesses such type of elastic behaviour.
- ◆ **Capillarity:** It is the ability of the soil to transmit moisture in all directions regardless of any gravitational force. The maximum theoretical height of capillary rise depends upon the pressure which tends to force the water into the soil, and this force increases as the size of the soil particles decreases. The capillary rise in a soil when wet may be equal as much as 4 to 5 times the height of capillary rise in the same soil when dry.
- ◆ **Cohesion:** Cohesion is the internal molecular attraction which resists the rupture or shear of a material and is derived in fine grained soils from the water films which bind together the individual particles in the soil mass. Cohesion of a soil which decreases as the moisture content increases, is the characteristic of the fine materials with particle size below 0.002 mm (clay).
- ◆ **Internal Friction:** Internal friction is due to the resistance of grains to sliding over each other and is the characteristic of the coarse materials of particle size larger than about 0.002 mm. The strength of a non-cohesive soil depends entirely on internal friction. The resistance in sliding of grain particles of a soil mass depends upon the angle of internal friction which, in case of clay, is seldom zero and may be as much as 26° .
- ◆ **Permeability:** Permeability of a soil is the rate at which water flows through it under the action of (unit) hydraulic gradient. In the majority of materials the rate of flow is directly proportional to the head of water, and the permeability is therefore a constant for the

particular material. The permeability of cohesive soils is, in general, very small. Sands drain readily whilst silts and clays are difficult or impossible to drain.

Note: A knowledge of permeability is required not only for seepage, drainage and ground water problems but also for the rate of settlement of structures on saturated soils.

- ◆ **Compressibility:** The decrease in volume per unit increase of pressure is defined as the compressibility which in case of sand and silt, varies with density, and in case of clay, varies directly with water content and inversely with cohesive strength.

Note: Gravels, sands and silts are incompressible soils which suffer no significant volume change when subjected to compression. Clays are compressible soils which swell when overburden pressure is removed.

2.1.1 Soil Profile

The soil profile is a vertical cross section of the actual soil strata at a given site showing a natural sequence and thickness of soil layers below the ground surface. A good graphical representation of a soil profile, showing also the position of the groundwater table as well as engineering classification is very instructive and helpful in various geo-technical designs such as structural foundations, highways, and other kinds of earthworks.

- ◆ **Properties of Soil:** Basic soil properties and parameters can be sub-divided into physical, index, and engineering categories. Physical soil properties include density, in-situ density, particle size distribution, specific gravity, and water content. Index parameters of cohesive soils include liquid limit, plastic limit, shrinkage limit, and activity. Such parameters are useful for classifying cohesive soils and providing correlations with engineering soil properties.

Engineering soil properties and parameters describe the behaviour of soil under induced stress and environmental changes. Of interest to most geo-technical applications are the strength, deformability, and permeability of in-situ and compacted soils.

- ◆ **Stability of Soil:** The most important factor which is to be realised before planning, designing, constructing and maintaining any earth retaining structure, is the soil stability. The un-braced or even braced soil masses may become unstable after a soil stability failure occurs and the damage becomes apparent. There have been many infamous situations that underline the importance of proper design, construction, and maintenance methods in achieving soil stability.

2.2 Engineer's view

Soil as an engineering material is extremely complex. Each of the constituent parts of a soil has different physical properties, and the presence of them in varying proportions affects the different properties of the whole composite considerably. The term soil includes all regolith (the layer of loose rock particles that covers the bedrock of most land on earth) material, or the entire soil profile down to, and some times even into, the underlying consolidated rock, referred to also as bedrock generally taken as granted for borings, wells, tunnelling for sub-surface exploration, shelters, storage tanks. Soil is a material by means of which and upon which civil structures are built.

Note: More accurate information for the characterization of the physical and mechanical properties of soils can be obtained only from laboratory tests.

2.3 Behaviour of Soil under Foundation

The most important part of a fully loaded structure is the foundation through which the total load of the structure is transmitted to the soil underneath. It is the main concern of a foundation engineer who should take into consideration the various properties of soil before designing a structure.

The behaviour of soil underneath the foundation should be studied for safe functioning of building. A rational design of the foundation is based upon the bearing capacity, which may be defined as the largest intensity of pressure that may be applied by a structure or a structural member to the soil which supports it without causing excessive settlement or danger of failure of the soil in shear.

If the shear stress in a mass of soil underneath a foundation exceeds the shear strength of the soil, the soil may then fail in shear, causing large settlements and resulting in a tilting or collapse of the structure. Shear failure takes place quickly as soon as the bearing capacity of the soil is exceeded, whereas consolidation settlements continue over a long period of years after the structure has been completed. As consolidation proceeds, more water is expelled from the soil. Thus, consolidation increases the shear strength of the soil with time.

While designing foundation of a structure, the safe bearing capacity of soil is taken into calculations. This value may be obtained by dividing ultimate bearing capacity (i.e. the minimum gross pressure intensity at the base of the foundation at which the soil fails in shear) with a suitable value of factor of safety that may range from 2 to 5 or even more.

2.4 Behaviour of Soil due to fully loaded structure

Soils behave in a complex manner when loaded. Soil when stressed due to loading tends to deform. The resistance to deformation of the soil depends upon factors like water content, bulk density, angle of internal friction and the manner in which load is applied on the soil. When excessive load is transmitted to the soil by a structural foundation, the settlement of the foundation takes place, which can endanger the stability of the structure. The settlement due to load is caused basically on account of two factors, namely,

- *the soil below footing gets compressed by certain amount, and*
- *since the foundations cover only a limited area, there is a possibility that the concentrated stresses developed are so high as to cause actual rupture (shear failure) and displacement of soil below.*

Some soils and rocks have layers of harder material between thin layers of softer material, which may not be detected unless thorough investigation is carried out. The softer layers may undergo marked changes in properties if the loading on them is increased or decreased by the proposed construction or affected by related changes in ground water conditions. These should be taken into account.

2.5 Behaviour of Soil due to Ground Subsidence

In certain areas, mass movements of the ground are liable to occur from causes independent of the loads applied by the foundations of structures. These include *mining subsidence*, *landslips on unstable slopes* and *creep on clay slopes*. The most troublesome subsidence events are small in scale and generally related to human activity that is primarily because of liquid and solid extraction from the soil or rock in the immediate vicinity of the foundation of the structure.

2.5.1 Mining Subsidence

In mining areas, subsidence of the ground beneath a building or any other structure is liable to occur. The magnitude of the movement and its distribution over the area are likely to be uncertain and attention should, therefore, be directed to make the foundations and structures sufficiently rigid and strong to withstand the probable worst loading condition. Mining subsidence is liable to occur in mining areas. The magnitude of the movement and its distribution over the area of the workings and their vicinity can be roughly estimated.

- Where future subsidence is likely to occur, care should be taken to design the superstructure and foundation sufficiently strong or sufficiently flexible to cater for probable ground movements.
- Long continuous buildings should be avoided and large building should be divided into independent sections of suitable size, each with its own foundations.
- Expert advice from appropriate mining authority should be sought.

2.5.2 Landslip on Unstable Slopes

- The construction of structures on slopes which are suspected of being unstable and are subject to landslip should be avoided.
- On sloping ground on clay soils, there is always a tendency for the upper layers of soil to move downhill, depending on type of soil, angle of slope, climatic conditions, etc. In some cases, the uneven surface of the slope on a virgin ground will indicate that the area is subject to small land slips and, therefore, if used for foundation, will obviously necessitate special design consideration.
- Where there may be creep of the surface layer of the soil, protection against creep may be obtained by following special design considerations.
- On sloping sites, spread foundations should be on a horizontal bearing and stepped. At all changes of levels, they should be lapped at the steps for a distance at least equal to the thickness of the foundation or twice the height of the step, whichever is greater. The steps should not be of greater height than the thickness of the foundation, unless special precautions are taken.
- Cuttings, excavations or sloping ground near and below foundation level may increase the possibility of shear failure of the soil. The foundation should be well beyond the zone of such shear failure.

- If the probable failure surface intersects a retaining wall or other revetment, the latter should be made strong enough to resist any unbalanced thrust. In case of doubt, as to the suitability of the natural slopes or cuttings, the structure should be kept well away from the top of the slopes, or, the slopes should be stabilized.
- Cuttings and excavations adjoining foundations reduce stability and increase the likelihood of differential settlement. Their effect should be investigated not only when they exist but also when there is possibility that they are made subsequently.

2.5.3 Creep on Clay Slopes

Where a structure is to be placed on sloping ground, additional complications are introduced. The ground itself, particularly if of clay, may be subject to creep or other forms of instability, which may be enhanced if the strata dip in the same direction as the ground surface. If the slope of the ground is large, the overall stability of the slope and sub-structure may be affected. These aspects should be carefully investigated.

2.6 Behaviour of Soil due to Seasonal Weather changes

During periods of hot, dry weather a deficiency of water develops near the ground surface and in clay soils, this is associated with a decrease of volume or ground shrinkage and the development of cracks.

- The shrinkage of clay will be increased by drying effect produced by fast growing and water seeking trees. The range of influence depends on size and number of trees and it increases during dry periods. In general, it is desirable that there should be a distance of at least 8 m between such trees.
- Boiler installations, furnaces, kilns, underground cables and refrigeration installations and other artificial sources of heat may also cause increased volume changes of clay by drying out the ground beneath them, the drying out can be to a substantial depth. Special precautions either in the form of insulation or otherwise should be taken.

In periods of wet weather, clay soils swell and the cracks tend to close, the water deficiency developed in the previous dry periods may be partially replenished and a sub-surface zone or zones deficient in water may persist for many years. Leakage from water mains and underground sewers may also result in large volume changes. Therefore, special care must be taken to prevent such leakages.

2.7 Behaviour of Soil due to Depth of Foundation

A foundation in any type of soil should be below the zone significantly weakened by root holes or cavities produced by burrowing animals or works. All foundations should extend to a depth of at least 50 cm below natural ground level. The depth should also be enough to prevent the rainwater scouring below the footings.

Where there is excavation, ditch, pond, water course, filled up ground or similar condition adjoining or adjacent to the sub-soil on which the structure is to be erected and which is likely to impair the stability of structure, either the foundation of such structure should be

carried down to a depth beyond the detrimental influence of such conditions, or retaining walls or similar works should be constructed for the purpose of shielding from their effects.

Clay soils, like black cotton soils, are seasonally affected by drying, shrinkage and cracking in dry and hot weather, and by swelling in the following wet weather to a depth which will vary according to the nature of the clay and the climatic condition of the region.

□ Depth of foundation to which foundations should be carried depends upon the following principal factors:

- The securing of adequate allowable bearing capacity.
- In case of clayey soils, penetration below the zone where shrinkage and swelling due to seasonal weather changes, and due to trees and shrubs are likely to cause appreciable movements.
- In fine sands and silts, penetration below the zone in which trouble may be expected from frost.
- The maximum depth of scour, wherever relevant, should also be considered and the foundation should be located sufficiently below this depth.
- Other factors such as ground movements and heat transmitted from the building to the supporting ground may be important.

□ Where footings are adjacent to sloping ground or where the bottoms of the footings of a structure are at different levels or at levels different from those of the footings of adjoining structures, the depth of the footings should be such that the difference in footing elevations should be subject to the following limitations:

- When the ground surface slopes downward adjacent to a footing, the sloping surface should not intersect a frustum of bearing material under the footing having sides which make an angle of 30° with the horizontal for soil and horizontal distance from the lower edge of the footing to the sloping surface should be at least 60 cm for rock and 90 cm for soil (see Fig. 1).

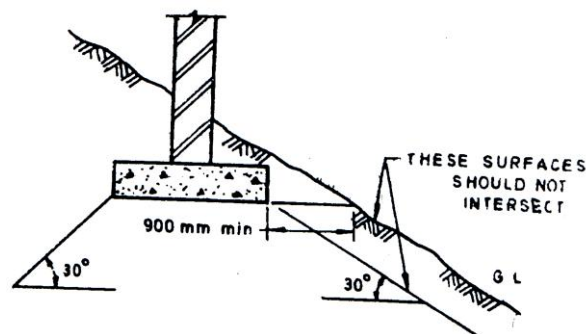


Figure – 1

- In case of footings in granular soil, a line drawn between the lower adjacent edges of adjacent footings should not have a steeper slope than one vertical to two horizontal (see Fig. 2).

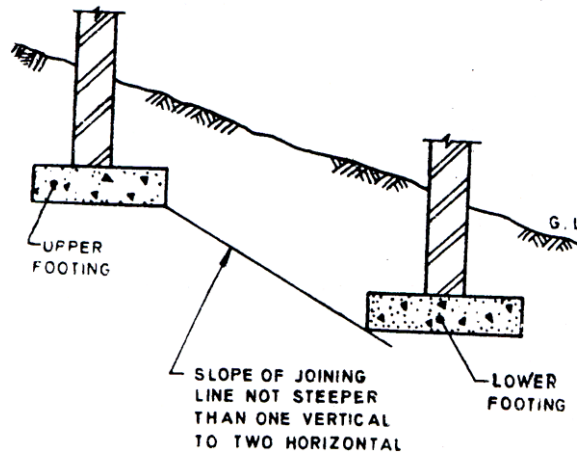


Figure – 2

- In case of footing in clayey soils, a line drawn between the lower adjacent edge of the upper footing and the upper adjacent edge of lower footing should not have a steeper slope than one vertical to two horizontal (see Fig. 2).

Note: The requirement given above should not apply under the following conditions:

- Where adequate provision is made for the lateral support (such as with retaining walls) of the material supporting the higher footing.
- When the factor of safety of the foundation soil against shearing is not less than four.

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Chapter – 3

Effect of Groundwater

3.1 Groundwater Level

It fluctuates, and will depend upon the permeability of the strata and the head causing the water to flow. The water level in streams and water courses, if any in the neighbourhood, should be noted, but it may be misleading to take this as an indication of the depth of the water table in the ground. Wells at the site or in the vicinity give useful indications of the ground-water conditions. Flood marks of rivers may indicate former highest water levels. Tidal fluctuations may be of importance. There is also a possibility of several water tables at different levels, separated by impermeable strata, and some of this water may be subject to artesian head. Fluctuations in the elevation of the groundwater table are due to

- normal natural fluctuation and drought;
- artificial lowering of the groundwater table as, for example, for providing a dry foundation pit, river regulation or operations for drainage of an area, through radiation of heat from blast and other furnaces (drying, shrinking of soil);
- raising the groundwater table artificially by impounding water in a reservoir, by tides, floods (may cause heave of soil), breaks in water mains;
- subsidence of soil caused by mining and tunnelling operation (subways and vibrations).

3.2 Importance of Groundwater Tables

- For most types of construction, water-logged ground is undesirable because of its low bearing capacity. On sites liable to be water-logged in wet weather, it is desirable to determine the fluctuation of the water table in order to ascertain the directions of the natural drainage, and to obtain a clue to the design of intercepting drains to prevent the influx of groundwater on to the site from higher ground. The seasonal variation in the level of water table should also be noted.
- If in the earlier stages of investigations, dewatering problems are anticipated, a detailed study should be carried out to ascertain the rate of flow and seepage.
- For deep excavation, the location of water-bearing strata should be determined and the water pressure observed in each, so that necessary precautions may be taken during excavation, for example, artesian water in deep strata may give rise to considerable difficulties unless precautions are taken. An idea of the steady level of water should be obtained. Bore holes, which have been driven, may be used for this purpose, but since water levels in bore holes may not reach equilibrium for some time

after boring, these should be measured 12 to 24 hours after boring and compared with water levels in wells that may be available in the area.

Note: It is seldom necessary to make detailed groundwater observations in each one of a group of closely spaced bore holes but sufficient observations should be made to establish the general shape of the groundwater table; however, observations should always be made in the first boring of the group. The minimum and maximum groundwater levels should be obtained from local sources and wells in the area would also give useful information in this regard.

- In making groundwater observations, it should be remembered that in some localities there may be one or more isolated bodies of water or perched groundwater tables above the main groundwater table. The formation of perched groundwater tables is caused by impervious strata, which prevent the water from seeping down to the main body of groundwater. The difference in water levels in bore holes spaced reasonably close to one another would indicate a perched water table.

3.3 Effects of Under-ground Water on Foundations

Increase in moisture extent results in substantial loss of bearing capacity in case of certain types of soils, which may lead to differential settlements. On sites liable to be water-logged in wet weather, it is desirable to determine the contour of the water table surface in order to indicate the directions of the natural drainage and to obtain the basis of the design of intercepting drains to prevent the influx of groundwater into the site from higher ground. The seasonal variation in the level of the water table is of importance in some cases.

- ***In case of soils with low permeability***, the water levels in boreholes or observation wells may take a considerable time to reach equilibrium with groundwater. Spot readings of water level in boreholes may, therefore, give an erroneous impression of the true groundwater level. It is generally determined by measuring the water level in the borehole after a suitable time lapse for which a period of 14 hours or more be used as the case may be.
- ***In case of soils with high permeability***, such as sand and gravels, lapse of some time is usually sufficient, unless the hole has been sealed with drilling mud. In these cases it may be necessary to resort to indirect means to establish the approximate location of the water table. Where deep excavation is required, the location of water bearing strata should be determined with particular care and the water pressure in each should be observed so that necessary precautions may be taken during excavation.

In certain localities where considerable quantities of soluble salts are contained in ground water and soil, portland cement concrete, especially thin members or buried metals are subjected to deterioration and corrosion. Certain soils have a corrosive action on metals, particularly on cast iron, due to either chemical or bacteriological agency. In industrial areas, corrosive action may arise from industrial wastes that have been dumped on the site. Chemical analysis of samples of groundwater or soil (or sometimes both) should be done to assess the necessity of special precautions.

The following are some of suggested methods:

- Dense cement concrete M20 mix or richer may be used to reduce permeability and increase resistance to attack from sulphates.

- Portland pozzolana cement may be used to control and reduce the activities of the sulphates.
- Special cements like high alumina cement, super sulphated cement, which are sulphate resistant, may be used.
- A thick coating of bitumen may be given over the exposed surfaces of foundation below the water table to prevent infiltration of water into the foundation.
- A thick layer of cement concrete (with sulphate resistant cement) and coated with bitumen be laid before laying of foundation concrete to prevent infiltration of water from sulphate bearing soil.

Note: The soluble salts are usually sulphates of calcium, magnesium and sodium. Water containing these salts gets into the concrete and reacts with the set cement or hydraulic lime. This reaction is accompanied by considerable expansion which leads to the deterioration and cracking of the concrete. The amount of soluble sulphates may be considered excessive from the point of attack on concrete if it is more than 30 parts of SO_3 per 100 000 parts of sub-soil water or in the case of clays if more than 0.2 percent SO_3 by weight of clay in air-dry condition, which should be determined by proper analysis.

3.3.1 Groundwater Lowering

Specially repeated lowering and raising of water level in loose granular soils tend to compact the soil and cause settlement of the foundations. Prolonged lowering of the water table in fine-grained soils may introduce settlements because of the extrusion of water from the voids. Pumping water or draining water by wells or pipes from granular soils without adequate filter material as protection may, in a period of time, carry a sufficient amount of fine particles away from the soil and cause settlement.

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Chapter – 4

Foundation Settlement

All foundations settle under load and the general tendency is for some parts of a structure to settle more than others causing relative movement. The critical factor in the settlement of a structure is not the amount of settlement but the differential settlement between the different parts of a structure itself. Excessive pressure is comparatively uncommon cause of settlement. Investigation of all layers under a foundation should be made as even thin layers, which are weak in shear, can cause settlement.

With structures built on sands and gravels the settlement is likely to be partially completed at the end of construction, but when the site is undertaken by clays or silts, settlement is likely to continue for a long time after construction and cracks may appear many years after completion. Due allowance shall, therefore, need to be made for this slow consolidation settlement. In strata of organic soils, settlement may continue almost indefinitely.

4.1 Settlement of Foundation

As the soil settles, so does the foundation. The settlement of a foundation of a building or a structure may be defined as the vertical movement (change in elevation) of the base of the footing under the influence of their over-weight or due to other causes. In other words, settlement is the sinking of a structure due to a compressive deformation of the underlying soil. The effect of settlement depends upon many factors such as its magnitude, uniformity and the type of structure.

If the contact pressure at the base of the footing on the soil is uniform, and uniformly distributed, settlements may be tolerable if the type of structure and/or its exploitation can withstand such settlements. However, a uniform, tolerable settlement should not be construed as a failure because settlement of a soil as a function of load is a normal physical phenomenon.

Settlement is not always a bad characteristic of structure provided it is uniform throughout and does not reach excessive limit. The magnitude of the settlement that should occur, when foundation loads are applied to the ground, depends on the rigidity of sub-structure and compressibility of the underlying strata. For the safety of foundations, the engineer-in-charge should be well familiar with all causes of settlement.

4.1.1 Uniform Settlement

Uniform settlement is settlement, which is brought about when the entire structure, under uniform pressure distribution on a uniform, homogeneous soil material, settles evenly without causing additional stresses in the structure.

Uniform Consolidation Settlement

- ***In case of cohesive soil:*** *Clays, shales and silts are classified as cohesive soils (true silt has little cohesion). The settlement in cohesive soils is usually more and full settlement of a structure founded on a cohesive soil is attained after a very long time. This is due to the long time needed for the expulsion and draining of water out of the voids of the cohesive soil at a certain load intensity (contact pressure) transmitted to the soil by the foundation of the structure.*
- ***In case of non-cohesive soil:*** *Sands and gravels are classified as non-cohesive or cohesionless soils as they possess no plasticity and tend to lack cohesion especially when in the dry state. The settlement in non-cohesive soil (sandy soil) is usually less and almost ceases during and at the end of the time of construction.*

4.1.2 Non-uniform or Differential Settlement

The foundations of different elements of a structure may have un-equal settlements and the difference between such settlements will cause non-uniform or differential settlement, which may be disastrous, leading to cracking of the structural members, impairment of the structural rigidity of the building, and eventually to the collapse of the structure.

This is particularly true with statically indeterminate structures such as continuous beams on more than two supports, frames, arches, vaults, and others. In these structures, settlement of a support induces supplement moments, and if these additional bending moments are not taken into account in proportioning the structural members, the structure may turn out to be too weak to resist the additional moments, and may start to crack.

Note: A tall building may lean because of unequal, or differential settlements of the soil, and so would two adjacent structures as for example, two oil storage tanks or two towers built next to each other; these tanks would lean toward each other because of the pressure distribution overlap in soil from these two tanks. In case of piers, abutments etc. the consequence may be disastrous for the bridge.

Non-uniform Consolidation Settlement

It is known that the magnitude of the settlement depends not only on the compressibility of the soil, but also upon the size and shape of the footings of foundations, upon the stresses in the soil underneath the foundations, water regimen in the soil, and other factors. Compression of soil is manifested in settlement of foundations.

Differential Settlement that is required for designing of a foundation is more difficult to estimate because of the magnitude of the differential settlement is affected greatly by the non-homogeneity of natural deposits and also the ability of the structures to bridge over soft spots in the foundation.

- On a very important job, a detailed study should be made of the sub-soil profile and the relation between foundation movement and forces in the structure should be investigated.
- Ordinarily, it is sufficient to state the design criteria in terms of allowable total settlements and design accordingly.

4.1.3 Permissible Settlement

The foundation design is a very complex problem, in the solution of which one must consider many factors involved and also some 'possible impossible conditions'. Every important structure designed on compressible clay should be accompanied by an estimate of the possible settlements, which may occur at various points under the foundations, the *rate of settlement*, and the magnitude of the final settlement.

4.2 Foundation Failure

When a structure collapses, it happens not only due to soil failure, but also due to the following factors, which may be responsible for the total structural failure:

- Inaccuracy in the values of the superimposed loads carried by the structure throughout its service life.
- Inaccuracy in the basic assumptions for analysis and in the design calculations.
- The degree of imagination and effort put into design.
- Inaccuracy in design engineer's assumptions as to the basic properties of the concrete and steel or the failure of these materials to comply with those properties.
- The degree with which the materials are checked and, the quality of execution of the work supervised.
- The possible deterioration of the structure in course of time, due to environmental effects.
- Insufficient data available for bearing capacity and other geo-technical properties of soils.
- The stability of loaded soil against shear failure not checked.
- Lack of information on ground water-carrying layers, their numbers, depth; position of the ground water table and its fluctuation that may cause structure to settle; ground water flow (direction and velocity), and aggressiveness with regard to soil and foundation material.

4.2.1 Structural Failures

Another important design-related cause of failure is under-estimation or lack of recognition of extreme loads associated with natural events, such as earthquakes, hurricanes, floods, and prolonged precipitation. Related failures include soil liquefaction during earthquakes, hydrostatic uplift or water damage to structures because of a rise in groundwater level, undermining of foundations by scour and overtopping, or wave erosion of earth dikes and dams. *An equally important constraint that must be appreciated by both engineers and clients is the limitations of the current state of geo-technical engineering practice.*

Since these factors, which make a structure unsafe, are of a random character, it appears rational to introduce the *concept of probability* in establishing methods for the determination of structural safety.

A structure recognizes various disturbances like cracking and deflection which can cause a structure to become unfit for use during its service life. When a structure is loaded heavily or becomes eccentric in loading, uneven distribution of load, much more than the load calculated for design, may cause a structure to collapse. It is evident that the failure of structure can be due to design criteria too.

4.2.2 Constructional Failures

The structures during construction are usually related to undesirable subsurface conditions not detected before or during construction, faulty design, or poor quality of work. Examples are:

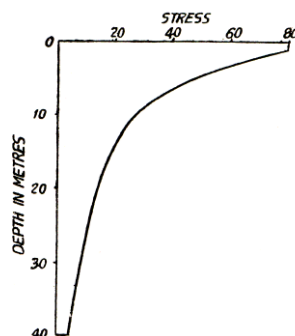
- Foundations supported on expansive or collapsing soils, on solutioned rock, or over undetected weak or compressible sub-soils.
- Deficient construction techniques or materials.
- Foundation designs too difficult to construct properly.
- Foundations that do not perform as anticipated.

4.3 Causes of Settlement

Some of the main factors contributing to settlement of soils are as follows:

4.3.1 Settlement due to Static Loads on Soil

The weight of the building or structure causes reduction in the volume of soil due to expulsion of water from the voids of the soil. The void ratio decreases while the volume of solid particles remains unchanged. The effect of this decrease in volume is the vertical downward movement of the structure, viz., settlement or a compressive deformation of the soil structure. The compressive soil layer under the foundation of structure is stressed upto to large depth due to the weight of the structure.



Stress distribution with increasing depth

As shown in figure, the stress due to surface load is maximum at the foundation level and decreases as one goes down and down to various depths. In general it may be said that any compressible stratum lying within three times the width (shorter dimension) of footing would certainly contribute towards the settlement of the structure.

4.3.2 Settlement due to Dynamic Forces from Vibrations

Dynamic forces from vibrations or impulses are excited by machinery like turbo-generators, turbines etc.; traffic, pile driving operations, explosions, earthquakes, and various impacts on soil due to collapse of structures and/or earthworks. These factors loosen the structural strength of the soil, particularly the strength of non-cohesive soils. The effect of the operation of the machines on settlement is quite large.

If a building or structure is founded on a non-cohesive soil and if it is subjected to vibrations from any source then there will be extra settlement. But the settlement caused by the vibration of clayey soil is usually so small that it does not cause any damage to the structure. In case of sandy soils the greatest settlements occur within a range of about 500 to 2500 impulses per minute which is known as optimum range of vibrations.

4.3.3 Settlement due to Excavation of Soil

If an excavation is made in a sandy soil the structure founded near the excavation will be affected and it will cause extra settlement but the settlement due to excavating the cut does not extend beyond a distance equal to the depth of the cut. So, if the depth of cut is 5 metres then the building at a distance within 5 metres from the excavation will only be affected. If the cut is properly braced then the amount of settlement gets reduced and is not likely to exceed about 0.5 percent of the depth of the cut.

When any cut is made in soft clay; the structure loaded at the sides of the cut acts like a surcharge. Hence clay near the bottom of the cut yields laterally towards the excavation under this surcharge. Therefore the ground surface above the yielding clay starts settling. If the cut is very narrow the lateral yield spreads only a short distance from the sides of the cut but if the cut is wide then the lateral yield spreads to a long distance and may be much longer than the depth of the cut.

4.3.4 Settlement due to Lowering of Water table

Whenever a deep excavation is made upto a large depth, the water table is encountered invariably. The water has to be pumped out so that workmen can work in dry condition in the excavated area. The lowering of water table by pumping seriously affects the structure founded in the vicinity. The effective pressure on the sub-soil increases due to lowering of water table. The increase of the effective pressure causes extra settlement of the nearby structures. In case of sandy soil the lowering of water table does not affect the structure so badly as in case of clayey soil. In case of clayey soil the lowering of water table may cause settlements.

4.3.5 Settlement due to Deterioration of Foundation Concrete

Sometimes the deterioration of concrete of foundation starts due to sulphates, carbon dioxide, chemically contaminated water and other chemicals. Due to this, large cracks develop in the structure as the deterioration of concrete leads to extra settlement of the structure.

Note: In certain localities, ground water and soil may contain constituents in amounts sufficient to cause damage to foundations of structures. Cement concrete is liable to be attacked by water containing sulphates. Some soils have a corrosive action on metals, particularly on cast iron due to either chemical or bacterial-agency, and enquiry should be made in the locality to find if such corrosion has previously occurred. In such cases, a chemical analysis of the soil should be made to assess the necessity of special precautions. Ground water may be tested for its salt content, alkalinity or acidity, etc, for its effect on foundations.

4.3.6 Settlement due to Increasing Load on Surrounding of Soil

When any portion of the ground surface has been loaded, it causes the adjacent surface to tilt and settle. The amount of tilt will depend upon a number of factors. If the sub-soil consists of soft clay the effect of the weight of a new structure on the neighbouring structure can be quite high and it may cause extra settlement to old structure. It is not necessary that such tilts are always detrimental.

4.3.7 Settlement due to Other possible factors

- Unequal distribution of the weight of the structure on the foundations.
- Earthquake, etc.
- Horizontal movement of the earth adjoining the structure.
- Atmospheric action.
- Transpiration of trees and shrubs.
- Settlement from frost-heaved soils; natural (from thawing) and artificial (under refrigeration houses).

4.4 Effect of Permeability on Settlement

The expulsion of water from the voids of the saturated clay soil by an externally applied load in the consolidation process, and the change in volume associated with such a process, are essentially a problem of permeability of a soil to water. The permeability, besides compressibility, is one of the principal factors relative to settlement of a soil, viz., settlement of structure. The magnitude of settlement depends upon the compressibility of the soil, whereas the rate of consolidation depends on both permeability and compressibility.

Permeability of soil is a very important physical property of soil because some of the major problems of soil and foundation engineering are connected with it. We are already aware that every soil mass has some voids and water tends to travel from one place to another through these voids. This phenomena is known as permeability. In other words, permeability can be defined as the property of soil mass which permits the passage of water through its interconnecting voids. Some soils are more permeable and some are less. For example, gravels are more permeable while clay is least permeable.

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Chapter – 5

Settlement in Shallow & Deep Foundation

5.1 General

The design and construction of deep foundations for the purpose of transferring the weight of surface loads down through unsuitable soils to underlying firm bearing strata is an exciting and fascinating aspect of foundation engineering.

As the code specifies, the *shallow foundations* (width > depth) neglecting the shearing resistance of soil above the base level of the foundation and the *deep foundations* (width < depth) having the shearing resistance of soil adjacent to the deep foundation, subjected to symmetrical static vertical loads undergo the settlement, which may be the result of one or combination of the following causes:

- Static loading
- Deterioration of foundation
- Mining subsidence
- Shrinkage of soil (in case of shallow foundation)
- Vibration subsidence due to underground erosion and other causes.

A) In case of Shallow Foundation: When the load is not excessive, the resulting settlement may consist of the following components:

- Elastic deformation or immediate settlement of foundation soil
- Primary consolidation of foundation soil resulting from the expulsion of pore water
- Secondary compression of foundation soil
- Creep of the foundation soil

When considering a *shallow foundation* for a given loading system, the design engineer must take into account three areas. They are the following:

- Footing placement, which involves its proper sitting as to location and depth.
- Safety against bearing capacity failure, which involves the proper footing design as well as the strength of the foundation materials beneath the footing.
- Tolerable foundation settlements, which involves calculating the anticipated settlement and comparing it to the allowable settlement that the structure will stand.

B) In case of Deep Foundation: When the load is not excessive, the resulting settlement may consist of the following components:

- Elastic compression of the foundation structure
- Slip of the foundation structure relative to the soil
- Elastic deformation or immediate settlement of the surrounding soil and soil below the foundation structure

- Primary consolidation settlement of the surrounding soil
- Primary consolidation settlement of the soil below the foundation structure
- Creep of the foundation structure under the constant axial load
- Secondary compression of the surrounding soil and soil below the foundation structure

When considering a *deep foundation* for a given loading system, the design engineer must take into account the following areas:

- Site exploration and deep foundation system's design.
- Serious consideration must be given to unusual, and potentially dangerous, circumstances which may interfere with the system as finally designed and constructed.
- No deep foundation project should ever be initiated without previous soil borings at the site and the identification of the various strata to be found there.

5.1.1 Limitations

- If the static load is excessive, the catastrophic settlement may occur. The catastrophic settlement is not covered as the foundations are expected to be loaded only upto the safe bearing capacity.
- Settlement due to deterioration of foundations, mining and other causes cannot, in the present state of knowledge, be estimated.
- Satisfactory theoretical methods are not available for the estimation of secondary compression. However, it is known that in organic clays and plastic silts, the secondary compression may be important and, therefore, should be taken into account.
- Such methods are not also available for computation of settlement due to the slip of foundation structure to the surrounding soils and creeping of foundation structure.

Note: If a structure settles uniformly, it will not theoretically suffer damage irrespective of the amount of settlement. In practice, settlement is generally non-uniform, which induces the secondary stress in the structure. If the estimated settlements exceed the allowable limits, the foundation dimensions or the design may have to be suitably modified.

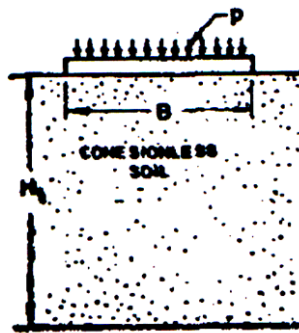
5.2 Soil Profile

5.2.1 In case of Shallow Foundation

Where there are both cohesionless and cohesive soil layers, unless the cohesive layer is thin or the cohesive soil is stiff or the cohesionless soil is very loose, the settlement contribution by the cohesionless soil layers will be small compared to that due to the cohesive soil layers; and the former may be neglected. Rock is incompressible compared to soil and therefore, the settlement of the rock stratum is neglected.

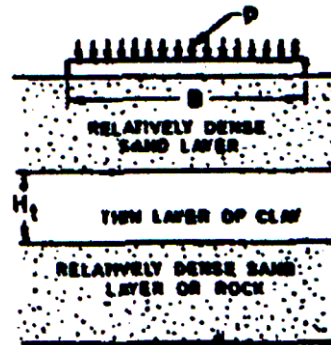
The method of computation for cohesionless deposit differs from that for a cohesive deposit. Therefore, the different types of soil formations require different methods of settlement computation.

The following are the possible types of soil formations, in which the settlement at any point is computed as the sum of the settlements of all the layers (average compressibility of each layer is estimated) below this point, which are affected by the superimposed loads.

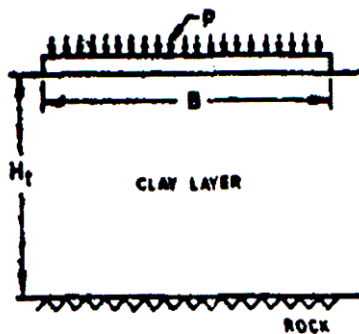


No limitation for H_t

Deposit of cohesionless soil resulting on rock

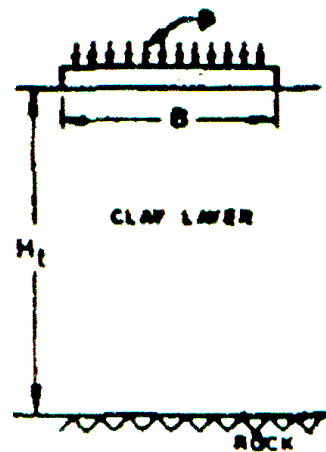


Thin clay layer sandwiched between cohesionless soil layers or between a cohesionless soil layer at top and rock at bottom



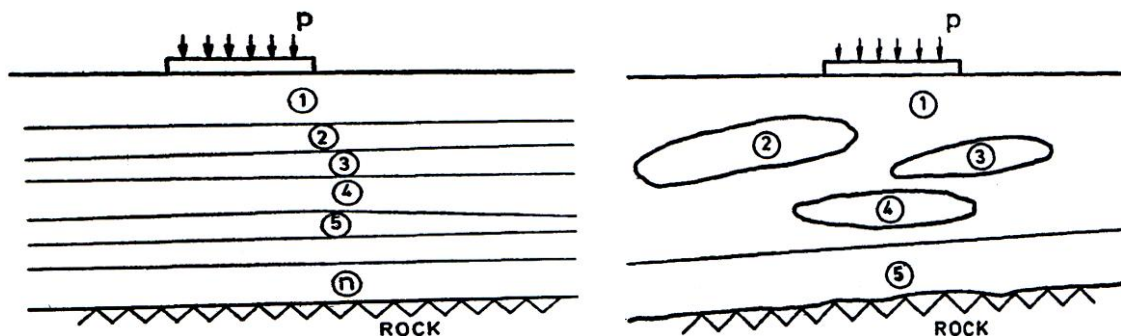
$B > H_t$

Thin clay layer extending to ground surface and resting on cohesionless soil layer or rock



$B < H_t$

Thick clay layer resting on cohesionless layer or rock



1, 2, 3..... n are independent layers

1,2,3..... are independent layers

Deposit of several regular soil layers

Erratic soil deposit

Where, P = Concentrated load, kg
 Ht = Thickness of soil layer, m
 B = Width of footing, m

5.2.2 In case of Deep Foundation

The soil profile may be simplified into one or more layer depending upon the extent of uniformity. The settlement is computed as the sum of the settlements of all layers which are affected by the superimposed loads. Rock is incompressible compared to soil and therefore, if the foundation rests on soil, the settlement of rock stratum is neglected.

Sands and other cohesionless soils undergo settlement immediately; whereas clays undergo immediate and consolidation settlements. The immediate settlement can be estimated by pile load tests and by theoretical methods, using elastic constants obtained from un-drained tests. The consolidation settlements are estimated by approximate methods using the consolidation test results. The total settlements can be estimated as the sum of immediate and consolidation settlements or by theoretical methods using the elastic constants obtained from drained tests.

The following are the possible types of soil formations for purposes of computing the settlements of deep foundations:

- Homogeneous cohesionless deposit,
- Homogeneous cohesive soil deposit,
- Deposit of two or more regular soil layers,
- Erratic soil deposit, and
- The soil deposit resting on rock.

5.3 General Considerations

- **Requirements:** The following information is necessary for a satisfactory estimate of the settlement of foundations.
 - Details of soil layers including the position of water table.
 - The effective stress-void ratio relationship of the soil in each layer.

- State of stresses in the soil medium before the construction of the structure and the extend of over consolidation of the foundation soil.

□ **Assumptions:** The following assumptions are made in settlement analysis.

- The total stresses induced in the soil by the construction of the structure are not changed by the settlement.
- Induced stresses on soil layers due to imposed loads can be estimated.
- The load transmitted by the structure to the foundation is static and vertical.

□ **Limitations:**

- The thickness and location of compressible layers may be estimated with reasonable accuracy.
- The settlement computation is highly sensitive to the estimation of the effective stresses and pore pressures existing before loading and the stress history of the soil layer in question.
- Unequal settlement may cause a redistribution of loads on columns.
- The soil layers experience stresses due to the imposed loads. It is customary to compute stresses induced in soil by simple formulae based on theory of elasticity or by approximate methods.

5.4 General observations as adopted in Deep Foundation

The methods of estimating the settlement of deep foundations depend upon the type of deep foundation and the manner of transfer of loads from the foundation structure to the foundation soil apart from the type of soil profile. The theoretical estimation of settlement is done by integrating the vertical strain for the entire depth of soil or rock formation. In general the theoretical method is tedious, other procedures are adopted.

Note: In the present state of knowledge, even the methods available for estimating total settlements are in a developing stage and therefore no reference is made to differential settlements as mentioned in relevant Indian Standard.

5.5 Steps involved in Settlement computations

5.5.1 Collection of Relevant Information

The following details pertaining to the proposed structure are required for a satisfactory estimation of settlements:

- Site plan showing the location of proposed as well as neighbouring structures,
- Building plan giving the detailed layout of load bearing walls and columns and the dead and live loads to be transmitted to the foundation.
- Other relevant details of the structure, such as rigidity of structure, and
- A review of the performance of structures, if any, in the locality and collection of data from actual settlement observation on structures in the locality.

Note: As the settlement behaviour of the soil profile is affected by the drainage and possible flooding conditions adjacent to the site and presence or absence of fast growing and water seeking trees, these information may also be collected.

5.5.2 Determination of a Sub-soil Profile

- Generally, it will be sufficient, if two exploratory holes are located diagonally on opposite corners, unless the proposed structure is small, in which case one bore hole at the centre may be sufficient. For large structures, additional bore holes may be driven suitably.
- In favourable cases, all borings may be sufficiently alike to allow the choosing of an idealised profile, which differs only slightly from any individual borings and which is a close presentation of average strata characteristics.
- Adequate boring data and good judgement in the interpretation of the data are prime requisites in the calculation of settlements. In the case of cohesionless soils, the data should include the results on undisturbed samples. In general, in the case of clay layers, for each one of the clay layers within the zone of stress influence at least one undisturbed sample should be tested for consolidation characteristics. In the case of thick clay layers consolidation test should be done on samples collected at 2 m or lesser intervals.

5.5.3 Stress Analysis

- **Initial Pore Pressure and Effective Stress:** The total vertical pressure at any depth below ground surface is dependent only on the weight of the overlying material. To obtain initial effective pressure, neutral pressure values should be subtracted from the total pressure. The possible major types of preloading conditions that can exist are the following.
 - In *simple static* case and the *over-consolidated* case, the neutral pressure at any depth is equal to the unit weight of water multiplied by the depth below the free water surface.
 - In *residual hydrostatic* case, a condition of partial consolidation under the overburden exists, if part of the overburden has been recently placed as for example in made up lands and delta deposits. In this case, the neutral pressure is greater than that in the previous case, since it includes hydrostatic excess pressure. If allowed sufficient time, this case could merge with the static case.
 - In *artesian* case, there is upward percolation of water through the clay layer due to natural or artificial causes. In this case, in addition to the hydrostatic pressure a seepage pressure acts upwards and reduces the effective pressure in the soil.
 - In the pre-compressed or *over-consolidated* case, the clay might have been subjected to a higher effective pressure in the past than exists at present. This may be due to the water table having been lower in the past than at present or due to the erosion or removal of some depth of material at the top.

Note: The identification of one of the four cases listed above for the given site conditions is essential for the satisfactory evaluation of magnitude of settlements.

□ **Pressure Increment:** The pressure increment is defined as the difference between the initial inter-granular pressures as existed in the field prior to application of load and the final inter-granular pressure after application of load. The following may contribute to the pressure increment:

- Pressure transmitted to the clay by construction of buildings or by other imposed loads,
- Residual hydrostatic excess pressures,
- Pressure changes caused by changes in the elevation of the water table above the compressible stratum, and
- Pressure changes caused by changes in the artesian pressure below the compressible stratum.

In case of Deep Foundation: The stresses induced by the superimposed loads on the lower strata can be determined by elastic theory or by approximate methods. The pressure increments due to the loads from deep foundations are not usually calculated using elastic theory due to the following reasons:

- The distribution of friction along the length of the pile or other deep foundation and the bearing load are not known;
- The influence of the method and process of installation of the foundation structure are not known; and
- Variation in the distribution of the loads due to time dependent effects such as thixotropy (to change by touch), varying loads, change in ground water, consolidation is not known.

5.5.4 Settlements in Shallow Foundation

If the soil consists of several regular soil layers, the settlement of each layer below foundation should be computed and summed to obtain the total settlement. The settlement contribution by cohesionless soil layers and cohesive soil layers should be estimated. In variable erratic soil deposits, if the variation occurs over distances greater than half the width of foundation, settlement analysis should be based on the worst and the best conditions and if the variation occurs over distances lesser than half the width of the foundation, the settlement analysis should be based on worst and average condition.

Note: The worst properties should be assumed under the heavily loaded region and the best and average properties under the lightly loaded regions.

□ **On cohesionless soils:** Settlements of structures on cohesionless soils such as sand take place immediately as the foundation loading is imposed on them. Because of the difficulty of sampling these soils, there are no practicable laboratory procedures for determining their compressibility characteristics. Consequently, settlement of cohesionless soil deposits may be estimated by a semi empirical method based on the results of static cone or dynamic penetration test or plate load tests. The relevant Indian Standards may be followed.

- **On cohesive soils:** In the case of clay layers, the total settlement should be computed by adding the immediate and consolidation settlements together. The two cases as given below are considered for estimation of settlements of foundation on cohesive soils.
 - Clay layer sandwiched between cohesionless soil layers or between a cohesionless soil layer at top and rock at bottom.
 - Clay layer resting on cohesionless soil layer or rock.

5.5.5 Settlements in Deep Foundation

□ End Bearing Piles

- ◆ **On Rock:** If piles are well seated in rock, the settlement may consist of elastic compression of foundation structure and the immediate settlement of rock. The immediate settlement may be computed for the equivalent raft which would have dimensions just sufficient to enclose or circumscribe the pile group as if it is located at shallow depths and thereafter the calculated value is corrected for depth. The settlement may also be estimated from load tests.

Note: In this case, the point resistance may normally be equal to the load on the pile, as practically there may not be any development of skin friction. However, the point resistance could be more than the load on pile due to development of negative skin friction, in which case, the negative skin friction should be estimated and added to the load on pile to get the point resistance.

Negative Skin Friction: Negative skin friction is a downward force acting on piles and other deep foundations, due to the surrounding soil moving downwards relative to the foundation structure. This can happen in the case of deep foundations passing through compressible strata into a bearing stratum if there is a recent fill or if it is proposed to fill up the site or if it is proposed to lower the ground water table. In such situations, the friction developed will be acting downward and therefore should be added to the point load.

- ◆ **On De-composed Rock:** The compressibility of de-composed rock can not be reliably estimated in the present state of knowledge. Settlement in this situation can be estimated largely on local experience.
- ◆ **Through Compressible Strata into Sand:** The settlement of piles and pile groups through compressible strata into sand depends upon the ratio between point resistance and total load. The separation of the point resistance and skin friction may be effected by conducting cyclic load test (Two pile test & Instrumented pile test). After separating the skin friction and point resistance, the settlement of the upper strata due to skin friction and the settlement of the sand stratum should be computed and added to obtain total settlement.
- ◆ **Through Compressible Strata into Stiff Clay:** In this case, initially, unless the compressible strata is very soft the load would be mostly carried by skin friction but ultimately all the load would be taken by end bearing on the stiff clay. The settlement of the stiff clay may be computed by assuming that the foundation is replaced by an equivalent raft.

- ◆ **Embedded in Firm Stratum underlain by Soft Clay Layer:** If the bearing stratum is underlain by a soft clay layer, the settlement of the foundation may be computed as the case may be.

□ **Friction Piles**

- ◆ **In Cohesionless Soils:** The settlement of a single pile in cohesionless soils can be reliably estimated by pile load test. The settlement of a friction pile group in cohesionless soils is expected to be less than the observed settlement of a test pile (driven alone, not a pile in the group) as the soil between the piles is compacted by displacement due to pile driving. It can reasonably be assumed that the settlement of a pile group in cohesionless soils will be equal to the settlement of a well foundation having a depth and base equal to the overall dimensions of the pile group estimated.
- ◆ **In Cohesive Soils:** The pile group may be replaced by an equivalent foundation for which the settlement may be computed.

- **Pile Foundation in Erratic Deposits:** In variable erratic soil deposits, if the variation occurs over distances greater than half the width of foundation, settlement analysis should be based on the worst and the best conditions and if the variation occurs over distances lesser than half the width of the foundation, the settlement analysis should be based on worst and average condition.

Note: The worst properties should be assumed under the heavily loaded region and the best and average properties under the lightly loaded regions.

5.5.6 Time rate of Settlements

The settlement at any time may be estimated by the application of the principles of Terzaghi's one dimensional consolidation theory. When considering the drainage of clay layer, concrete of foundation may be assumed as permeable. The coefficient of consolidation should be evaluated from the one dimensional consolidation tests using suitable fitting methods. In the case of evaluation of time rate of settlement of structures constructed with certain construction time, the procedure as adopted in relevant Indian Standards may be followed.

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Chapter – 6

Preventive Measures

Preventive measures against failures of structures should be adopted to ensure the safety of a fully loaded structure during its planning. The possible reasons of failure due to foundation settlement should be kept in mind while designing and executing the proposed structure. As far as soil strata is concerned, it should be well studied and the findings should be applied before the actual construction is started. The soil, if found weak or its bearing capacity is low, should be improved by adopting suitable methods.

6.1 Improving the bearing capacity of soil

If foundations are left open for one rainy season it will enable the soil to settle down, and it will also be known whether the natural movements of the soil below due to increment of moisture are likely to cause any damage. Foundations in bad soils can be improved by:

- Increasing the depth of the foundation except when the material grows wetter as the depth increases.
- Compacting the soil by ramming.
- Ramming in sand, gravel, moorum, broken stone or brick bats in-situ between the foundation concrete and soil. This is useful for silt or black cotton soils and clayey soils.
- Cement grouting of the rammed materials will make the foundations much harder.
- Draining out water from wet foundations.
- Driving piles, either of wood or concrete, or driving and withdrawing piles and filling the holes with sand or concrete. This will increase the density of the soil.
- Artificial stabilisation can be used to seal off permeable strata for deep foundations, or to give soft soils additional strength if they are likely to flow.

6.2 Protection of excavation

- The protection of excavation during construction of timbering and dewatering operations, where necessary, should be done.
- After excavation, the bottom of the excavation should be cleared of all loose soil and rubbish and should be levelled, where necessary. The bed should be wetted and compacted by heavy rammers to an even surface.
- Excavation in clay or other soils that are liable to be affected by exposure to atmosphere should, wherever possible, be concreted as soon as they are dug.

- The bottom of the excavation should be protected immediately by 8 cm thick layer of cement concrete not leaner than mix 1: 5: 10.
- The refilling of the excavation should be done with care so as not to disturb the constructed foundation, and should be compacted in layers not exceeding 15 cm thick with sprinkling of minimum quantity of water necessary for proper compaction..

6.3 Remedial measures against harmful settlements

In general, settlements of soil, since they are natural phenomena, are unavoidable. However, the engineer should make provision for keeping down large, intolerable and non-uniform settlements.

To attain uniform settlements it is not necessary to achieve the same contact pressure intensities under all footings of the foundations of one structure. However, it is necessary to bring into accord the shape and the size of the footings so that all foundations of one and the same structure attain one and the same amount of settlement. Every non-uniform load distribution leads to unequal, or differential settlement.

- ◆ **To make intolerable settlements harmless**, the following constructive measures are applied:
 - structures are supported on foundations designed as statically determined structural systems;
 - structures and their foundations are designed as a rigid, stereometric unit (for example silos on continuous slab);
 - long structures are subdivided and built as separate units;
 - a structure, the parts of which are non-uniformly loaded, is subdivided.
- ◆ **To achieve uniform settlements**, one would
 - design foundations by observing the ‘area law’ of the loaded footings;
 - use artificial cushions of soil underneath the less settling foundation parts of the structure;
 - build different parts of foundations of different weight and on different soil at different depths;
 - build the heavier parts of the structure first (such as towers and spires, for example) and the lighter parts later.
- ◆ **Some remedial measure against large settlements**
 - removal of soft layers of soil, such as peat, muck, or other material, consistent with economy;

- the use of properly designed and constructed pile foundations;
- provision for lateral restraint or counterweight against lateral expulsion of a soil mass from underneath the base of an earth fill;
- reduction of the contact pressure on the soil in some instances; the problem here is more that of the proper adjustment between pressure, shape, and size of the foundation in order to attain uniform settlements underneath the structure;
- pre-consolidation of a building site long enough for the envisioned load and tolerable settlements (dams, bridges, highway or airfields fills);
- building slowly on cohesive soils to avoid lateral expulsion of a soil mass, and to give time for the pore water to be expelled by the surcharge load and drained away;
- chemical or mechanical stabilisation of soil at a building site.

Note: To accomplish these objectives, the need for thorough soil exploration and soil testing comes to the fore.

6.4 Soil Stabilisation Methods

Soil stabilization is the chemical or mechanical treatment designed to increase or maintain the stability of mass of soil or otherwise to improve its engineering properties. It may increase strength, increase or decrease permeability, reduce compressibility, improve stability, or decrease heave due to frost or swelling. The classification of the methods of stabilization is based on the treatment given to the soil (for example, dewatering, compaction, etc), process involved (for example, thermal, electrical, etc), and on additives employed (for example, asphalt, cement, lime, etc). The choice of a particular method depends on the characteristics of the problem on hand.

The main techniques used are constructed fills, replacement of unsuitable soils, surcharges, reinforcement, mechanical stabilization, thermal stabilization, and chemical stabilization. Some of the methods are briefly summarised as below:

- **Mechanical stabilisation**

It comprises a variety of techniques for rearranging, adding, or removing soil particles. The objective usually is to increase soil density, decrease water content, or improve gradation. Particles may be rearranged by blending the layers of a stratified soil, remoulding an undisturbed soil, or densifying a soil. Sometimes, the desired improvement can be obtained by drainage alone.

The process of compacting (densifying) soil is the oldest and most important method of soil stabilisation. Most of the time, compaction alone solves a particular soil problem and is generally the most economical of the techniques available. In addition to being used alone, compaction procedure is an essential part of a number of the other methods of stabilisation. Compaction improves interlocking, increases apparent cohesion and reduces pore dimensions. Due to this phenomena shear strength of the soil mass increases.

- **Electrical stabilisation**

When a direct electric current passes through a saturated soil, water flows towards the cathode. In case water is pumped at the cathode and not replaced at the anode, the soil decreases in volume; thus consolidating the soil. The strength of the soil is increased by this type of consolidation known as electro-osmotic consolidation. The electric current may cause (a) ion exchange (b) deposition of solids from the electro-chemical decomposition of the electrodes, and (c) alteration of the arrangements of soil particles.

- **Thermal stabilisation**

Thermal stabilisation has been used successfully in many large projects, including foundation for buildings and machinery. Heating or cooling of a soil changes its properties. Even a slight increase in temperature cause a slight strengthening in a clay by decreasing the electric repulsion force between clay particles, a flow of pore water because of the imposed thermal gradients, and a reduction in water content due to increased evaporation rate. Heat may change an expansive clay into a non-expansive material.

Thermal stabilisation can also be obtained by freezing the pore water in soil. As soon as soil water freezes, the strength increases rapidly with decreasing temperature. Freezing is generally a temporary stabilisation and it must be used with proper caution. Soil has been stabilised by this method for various purposes, which are

- ice piles
- ice cofferdams
- freezing to permit the advancing of mine shafts or tunnels
- freezing of soil samples in order to obtain reasonably undisturbed sample, and
- underpinning of buildings.

- **Cement stabilisation**

Cement has been used successfully to stabilise granular soil, sands, silts and upto medium plastic clays all over the world. Major constituents of cement which have a distinct effect on the strength aspect of soil-cement mix are

- *Calcium di-silicate*, which is responsible for long term strength due to hydration reaction.
- *Calcium tri-silicate*, which sets fast and is responsible for immediate strength gain.
- *Free lime*, which may bring about base exchange capacity and change the texture of the soil. This may also contribute to long term Pozzolan reaction.

Adequate amount of cement, proper amount of moisture, high compaction and good curing are important for obtaining a good compacted strong soil-cement mix. Strength of soil-cement increases with increasing amount of cement. If a soil contains too much organic matter or sulphate, cement would not produce proper strength.

- **Lime stabilisation**

Soil generally contains sand, silt and clay fractions. The clay minerals carry a negative charge on the surface and to a large extent responsible for imparting plasticity to the soil sample. Such types of soils have been successfully stabilised by lime, decreasing the plasticity of the soils. Generally the use of lime is restricted to warm or moderate climates, because lime-stabilised soils breakup under freezing and thawing. The degree to which lime will react with soil depends on quantity of lime, soil type and the period of curing for soil-lime mixture.

The method is not applicable to soils containing a large or variable amount of calcium or magnesium salts or to soils which also contain cement, and in such cases it may not be possible to determine the lime content by chemical means.

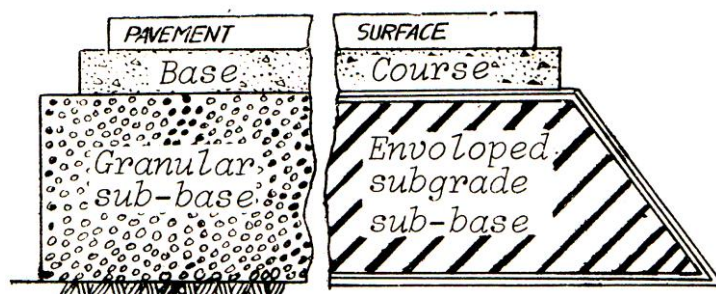
- **Bituminous stabilisation**

Stabilisation of soil with bituminous materials obtained either as natural materials or as by-product from petroleum industry is satisfactory for coarse-grained or granular soils. Its use for stabilising plastic soils is limited. It is not suitable for use in climatic conditions where the ambient temperature exceeds 30°C.

While treating cohesive soils with bituminous admixtures, special attention should be paid to all factors which might contribute to the structural integrity of the stabilised material. Drainage is considered to keep the surface infiltration and adverse ground water conditions within limits.

- **Membrane stabilisation**

If soils which are not satisfactory for sub-base construction are isolated from external sources of water, it can be used successfully as a sub-base. If an enveloped sub-grade is to be used as a sub-base, the material is compacted to a high density at a low possible moisture content. Enveloped sub-grade soil does not function satisfactorily as base courses under high traffic pavements, because it is impossible to compact most of the clay soils to densities which will result in strengths approaching to that of crushed stone or soil aggregate mixtures.



Comparison of ordinary and enveloped sections

- **Chemical stabilisation**

There are a number of chemicals which are used as primary additive for soil stabilisation. Some of them are listed below:

- Stabilisation with calcium and sodium chlorides.
- Lignin and chrome-lignin
- Sodium silicate
- Water proofers
- Natural and Synthetic Polymers

6.5 Safety of existing structures

There may be some possible reasons by which the *safety of existing structures* may be affected:

- Excavations in the immediate vicinity which may cause a reduction in support to the structure.
- Mining or tunnelling operations in the neighbourhood.
- Adjacent structures which may impose additional loads on the foundation strata or additional stresses in earthwork and supporting structures.
- Vibrations and ground movements resulting from traffic, piling or explosions in the immediate vicinity.
- Shrinkage of clay soils due to weather, transpiration of plants.
- Lowering of the ground-water level by pumping from wells may cause settlement of the ground surface over a wide area.
- A rise in the ground-water level may cause movement of the foundation strata.

6.6 General Considerations

- The construction of access roads, main sewers and drains should preferably be completed before commencing the work of foundations.
- Sufficient precautions should be taken to protect the already constructed foundations during subsequent work.
- Any obstacles, including the stump of trees, likely to interfere with the work should be removed.
- Holes left by digging, such as those due to removal of old foundation, uprooted trees, burrowing by animals, etc, should be back-filled with soil and well compacted.

- Generally the site should be levelled before the layout of foundations are set out. In case of sloping terrain, care should be taken to ensure that the dimensions on plans are set out correctly in one or more horizontal planes.
- The layout of foundations should be set out with steel tapes.

OUR OBJECTIVE

To upgrade Maintenance Technologies and Methodologies and achieve improvement in productivity and performance of all Railway assets and manpower which inter-alia would cover Reliability, Availability, and Utilisation.

*The contents of this handbook are for guidance only & are **not statutory**. It also does not supersede any instructions from Railway Board, RDSO, and Zonal Railways & the provisions of IRWM, BIS Codes/Reports on the subject. If you have any suggestion & any specific comments, please write to us :*

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