Settlement of the Foundation Structures: Types, Signs, Causes, Prevention & Correction Methods

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What is Foundation Settlement?

Inevitably, soils deform under the load of foundation structures. The total vertical displacement that occur at foundation level is termed as settlement. The cause of foundation settlement is the reduction of volume air void ratio in the soil. Moreover, the magnitude of foundation settlement is controlled by many factors type of soil and foundation structure. Foundations on bedrock settle a negligible amount. In contrary, Foundations in other types of soil such as clay may settle much more. An example of this is Mexico City palace of fine arts has settled more than 15 feet (4.5m) into the clay soil on which it is founded since it was constructed in the early 1930s. However, building foundation settlement is normally limited to amounts measured in millimeter or fractions of an inch. Structures will suffer damages due to settlement of its foundation specifically when the settlement occur in quick manner. In this article, different types of foundation settlement along with their cases and expected effects on the structure will be discussed.

Types of Foundation Settlement

Settlement of the foundation structures is a problem that people have faced ever since they first started constructing. The size of a foundation structure settlement is primarily dependent on the weight of the structure and the deformation characteristics of foundation soil. When analyzing this problem, it is necessary to distinguish between the concepts of uniform and differential settlements.

Uniform Foundation Settlement

- When foundation settlement occurs at nearly the same rate throughout all portions of a building, it is called uniform settlement.
- If all parts of a building rest on the same kind of soil, then uniform settlement the most probable type to take place.
- Similarly, when loads on the building and the design of its structural system are uniform throughout, the anticipated settlement would be uniform type.
- Commonly, uniform settlement has small detrimental influence on the building safety.
- However, it influences utility of the building for example damaging sewer; water supply; and mains and jamming doors and windows.

When there is a uniform settlement of the foundations, we have no major issue if the whole structure settles with the ground floor similarly. However, when the settlement of the structure is significant though it is uniform, there will be issues such as damage to the connections with other structures, formation level difference at the connection to the outside, etc.

Uniform Foundation Settlement

- Settlement that occurs at differing rates between different portions of a building is termed differential settlement.
- Differential settlement occurs if there is difference in soils, loads, or structural systems between parts of a building. in this case, different parts of the building structure could settle by substantially different amounts.
- Consequently, the frame of the building may become distorted, floors may slope, walls and glass may crack, and doors and windows may not work properly.
- Uneven foundation settlement may force buildings to shift out of plumb which lead to crack initiation in foundation, structure, or finish.
- Majority of foundation failures are attributable to severe differential settlement.
- Lastly, for conventional buildings with isolated foundations, 20mm differential settlement is acceptable. And 50mm total settlement is tolerable for the same structures.

Figure 1. Differential Foundation Settlement

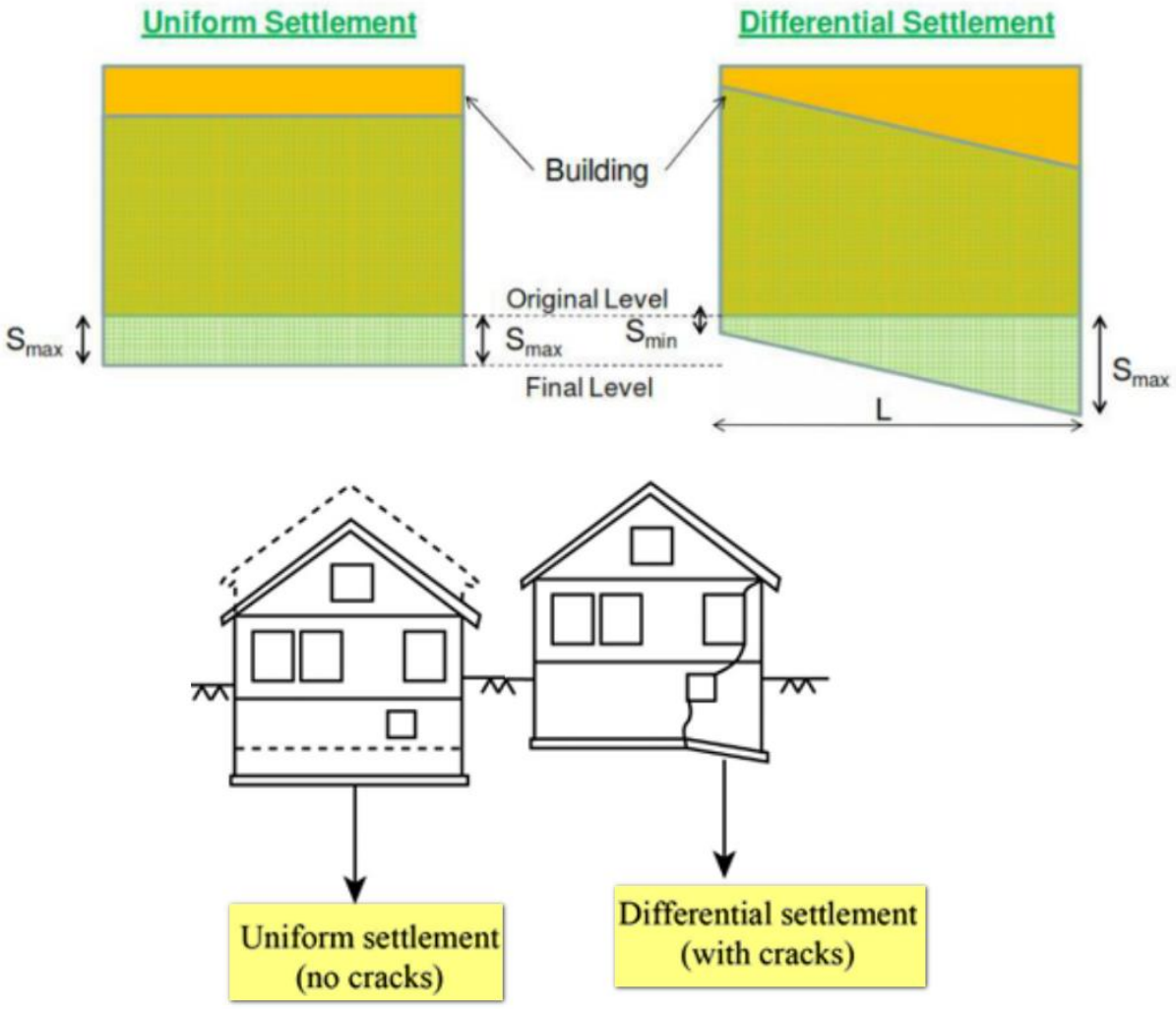

Figure 2. Uniform vs Differential settlement

Signs of Differential Settlement

How to Identify Differential Settlements? , the formation of cracks in the structure and damage to the non-structural elements such as brick walls is the issue that can be identified as indicators of the differential settlement of foundations. Some following defects can be highlighted.

1. Sticking Windows and Doors

Difficulty in the opening of the doors and the windows

Figure 3. Sticking Windows and Doors

2. Wall & Floor Damage

Noticeable cracks in the floors and the walls

Figure 4. Wall & Floor Damage

3. Drywall cracks

Figure 5. Drywall cracks

4. Foundation Cracks & Deterioration of Slabs

Figure 6. Foundation cracks & deterioration of slabs

5. Structural Instability

Figure 7. Structural instability

6. **Sloping or unevenness of the floors and cracking of tiles.**

Causes of Differential Settlement

1. **Incorrect sizing of foundation**

Sizing of the shallow foundations is done based on the allowable bearing capacity.

Area of Foundation = Column Load (SLS) / Allowable Bearing Capacity

The column load at the serviceability limit state (SLS) will be divided by the allowable bearing capacity of the soil to obtain the area of the footings. This is the initiation of the foundation design. In this manner, we maintain the pressure under the foundation at the same level.

When the pressure under all the foundations is similar, there is a high possibility of having a similar settlement of footings if the condition of the ground remains the same for all the footings.

However, if we mistakenly or intentionally, changed the pressure under the footings, there will be different settlements in foundations.

2. **Expansive Clay**

This type of soil change is properties with the change in the moisture levels.

When the moisture content of the soil increases, the clay starts increasing its volume. If there are foundations in these soils, they will be subjected to upward movement if the movement resisting mechanism is not established.

The movement of the soil can lift buildings and it will start to shrink when the soil moisture content is lowered. Mostly this movement can be observed in different areas where the expansive soil exists.

Especial attention shall be made when shallow foundations are designed in these types of soils.

3. Poorly Compacted Soil

When it is required, during the construction, there may be soil filling in the area where the foundation is constructed. This may be done as an improvement of the ground. It is required to maintain the uniformed compaction and adequate compaction of soil under the foundation.

If the compaction of the soil is different from one place to another, it could lead to a differential settlement. To avoid the differential settlement of foundations, it is required to the testing the compaction on a random basis.

4. Soil with Weak Bearing Capacity

Soils with weak bearing capacity and having variations of their allowable limit could cause settlement of the foundations when different loads are applied.

5. Change in the Soil Profile

Soil profile could change from one place to another. It could be vertically or horizontally. Having different ground conditions is the initiation for the differential settlements.

It is required to correct assessment of the condition of the ground before proceeding with the design.

6. Change in the Soil Pour Water Pressure / Water Table

Changes in the soil water level could lead to the settlement of the foundations. This issue could arise when there are deep excavations for the construction of foundations in the adjoining land.

Continuous dewatering close to its structure could cause settlement of the foundations if the groundwater recharged is not done adequately or dewatering shall be controlled by continuous shoring up to the rock or impervious layer.

7. Vibration

Vibrations induced by the surrounding could affect the part of the structure. If it is felt to the part of the structure, there could be a settlement of the foundation.

8. Trees and vegetation

Having vegetation in the soil where the foundations are constructed could lead to the settlement of the foundations when they decomposed with time.

In addition, if there are trees close by, their roots could lift the foundations and damage them. Therefore, special attention shall be made if those kinds of trees are there.

Figure 8. Trees and Vegetation

How to Prevent Differential Settlement

Prevention is better than cure. Therefore, necessary action shall be taken at the initial stage rather than doing the repairs or any modifications to the structure/ground.

1. Awareness of ground condition before design and construction

The designer and the construction team shall be well aware of the condition of the ground.

As designers, whether to do geotechnical investigation, at which degree we should do the investigation, what are the required parameters, etc. can be decided only if the designer is having certain knowledge of the condition of the ground.

On the other hand, the construction team shall be aware of the condition of the ground to plan the construction according. Poor knowledge of the soil types, etc. will end up in many construction issues.

2. Geotechnical Investigation before the design

The most common practice is to do a geotechnical investigation before proceeding with the design. The design shall be carried out as per the actual condition of the ground rather than designing for hypothetical values assumed.

3. Correct Estimation of Bearing Capacity

Based on the data obtained during the geotechnical investigation, the calculation of the bearing capacity of the soil is done. Due to the incorrect interpretation of the investigation date, finally, we may end up with the wrong bearing capacity.

The designer shall be aware of the type of soil and possible value for the bearing capacity. Otherwise, if we design the foundation with the wrong values and there may be a different settlement of foundations.

4. Appropriate design of the foundation must be done

5. Tie beams

It is common practice to provide a tie beam to control the settlement of the structure.

It is recommended to provide tie beams when there are expansive soils. Upward movement of the foundation could be controlled by these beams up to a certain level.

Tie beams shall be designed for bending and shear stresses induced due to the upward movement.

Figure 9. Tie Beams

6. Eccentric loading must be avoided as far as possible.

7. Ground Improvement

Where it is required, ground improvement shall be done to control the settlement of foundations. Wear areas of the ground could be treated or replaced as required.

8. Control Groundwater Level During Construction

When there is construction near a structure and if they are doing dewatering continuously, it will cause settlement of foundations. Further, it could lead to different settlements depending on the length of the structure and it could generate different groundwater levels.

When continuous dewatering is done, the groundwater level is lowered. As a result of that, pouring water pressure under the foundation will reduce. This may cause settlement of the foundations. This could have a differential settlement of foundation on sandy soil.

Continuation of the shoring till the hard layer or rock surface, correct assessment of the influence of the groundwater table lowering, ground water recharging, etc. could be done to avoid issues of this nature. These methods and assessments shall be done under the guidance of good experienced and qualified engineers on this subject.

Allowable Foundation Settlement for Different Structures

The allowable settlement is defined as the acceptable amount of settlement of the structure and it usually includes a factor of safety. The allowable settlement depends on many factors, including the following:

1. The Type of Construction

For example, wood-frame buildings with wood siding would be much more tolerant than unreinforced brick buildings.

2. The Use of the Structure

Even small cracks in a house might be considered unacceptable, whereas much larger cracks in an industrial building might not even be noticed.

3. The Presence of Sensitive Finishes

Tile or other sensitive finishes are much less tolerant of movements. **The Rigidity of the Structure** If a footing beneath part of a very rigid structure settles more than the others, the structure will transfer some of the load away from the footing. However, footings beneath flexible structures must settle much more before any significant load transfer occurs. Therefore, a rigid structure will have less differential settlement than a flexible one.

4. Aesthetic and Serviceability Requirements

The allowable settlement for most structures, especially buildings, will be governed by aesthetic and serviceability requirements, not structural requirements. Unsightly cracks, jamming doors

and windows, and other similar problems will develop long before the integrity of the structure is in danger.

Table below shows the allowable foundation displacement into three categories: total settlement, tilting, and differential settlement. It indicates that those structures that are more flexible (such as simple steel frame buildings) or have more rigid foundations (such as mat foundations) can sustain larger values of total settlement and differential movement.

Table 1. Allowable foundation displacement into three categories

Type of Settlement	**Limiting factor**	**Maximum Settlement**
Total settlement	Drainage	15 – 30 cm
	Access	30 – 60 cm
	Probability of non-uniform settlement:	
	1. Masonry walled structures	2.5 – 5 cm
	2. Framed structures	5 – 10 cm
	3. Chimneys, silos, mats	8 – 30 cm
Tilting	Stability against overturning	Depends on H and L
	Tilting of chimneys, towers	0.004L
	Rolling of trucks etc.	0.01L
	Stacking of goods	0.01L
	Crane rails	0.003L
	Drainage of floors	0.01 – 0.02 L
Differential settlement	High continuous brick walls	0.0005 – 0.001 L
	One-storey brick mill building, wall cracking	0.001 – 0.002 L

	Plaster cracking	0.001 L
	Reinforced concrete building frame	0.0025 – 0.004 L
	Reinforced concrete building curtain walls	0.003 L
	Steel frame, continuous	0.002 L
	Simple steel frame	0.005 L

Where, L = distance between adjacent columns that settle to different amounts, or between two points that settle differently. Higher values are for regular settlements and more tolerant structures. Lower values are for irregular settlement and critical structures. H = Height and W = width of structure.

Foundation Failure Due to Settlements

The most important causes of foundation failure are as follows:

1. **Unequal Settlement of Soil**

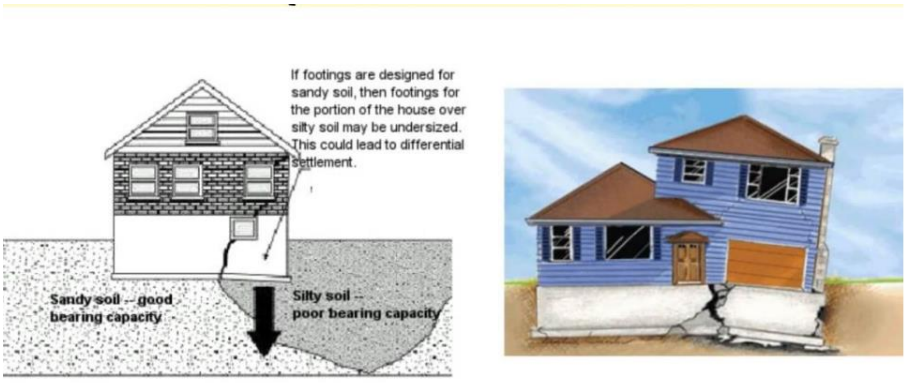

Figure 10. Unequal settlement of soil

It is the first common causes of foundation failure. In this foundation failure, The cracks are developed in a foundation or buildings due to the Uneven settlement of soil. Due to that, the durability of building is reduced. Also due to cracks, the reinforcement of foundation are corroded.

Causes of Unequal settlement of soil:

- Uneven distribution of load
- Change in soil Bearing capacity
- Eccentric loading etc.

Remedies measures:

- The foundation should be supported on a rock or hard surface.
- The foundation should be designed keeping in mind the type of soil.
- The pressure on the soil should not exceed permissible bearing pressure on it.

2. Unequal Settlement of Masonry

Figure 11. Unequal settlement of masonry

The mortar used in masonry is compressed or shrink by applying **a heavy load** on it before it hard properly due to that, the masonry settles unevenly.

Due to the Uneven settlement of masonry, cracks are developed in foundation which causing failure of the foundation.

Remedies measures:

- The mortar used in masonry should be exactly stiff and have the required workability.
- The masonry work should be lifted slowly together.
- If cement mortar is used in one day, the height of the wall should not exceed 1.5 m.

- The masonry should be cured properly for 10 days.

Correction Methods for Foundation Settlement

The settlement of the foundation due to external reasons can be prevented and controlled. Also, the settled foundations can be corrected and prevented from further settlement.
The choice of method for correction majorly depends upon the structure, soil type, reason for settlement, and the cost of application.

1. Site Inspection & Correction of External Reasons for Settlement

The site should be thoroughly inspected and the following points should be checked-

- Drainage.
- Possibility of Waterlogging.
- Trees and bushes very close to the structure.
- Leakage in underground sewer lines, water lines, HVAC lines, etc.
- Termite or ant burrows, rat holes, etc., near the foundation.

2. Underpinning

Underpinning is a method to prevent the foundations from further settlement. The method involves the strengthening of the foundation by transferring the load to deeper strata.
The foundation is clubbed with pins embedded in the deeper ground. Underpinning is often done in conjugation with the shoring.

Figure 12. Underpinning

3. Grouting

Grouting is a process of injecting a liquid into the soil to protect the soil from erosion, improve load-carrying capacity and reduce water seepage. The grouting can be done in two ways- chemical grouting and jet grouting.

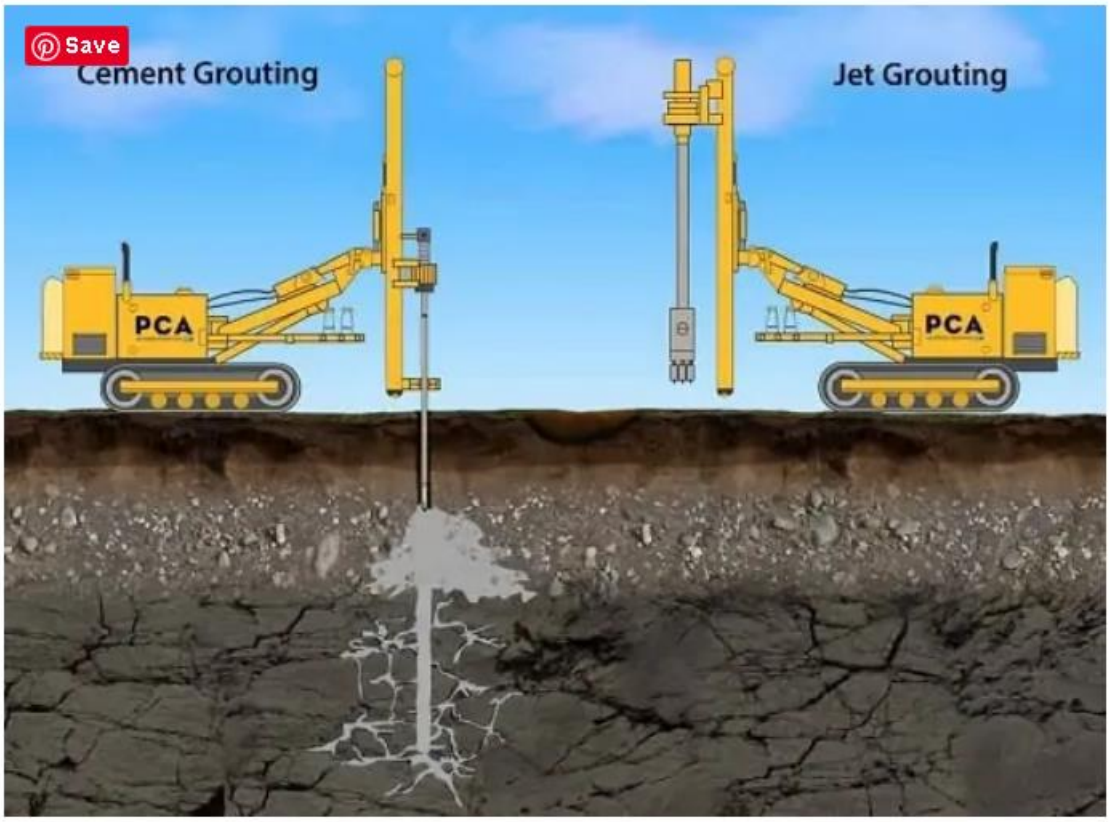

Figure 13. Grouting

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