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Crawford, C. B.

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Foundation Movements

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C. B. Crawford

Please note

In designing a structure it is commonly assumed that the foundation will not move. Correspondingly, if cracks appear in the structure it is assumed that the foundation did move and that this is the sole cause of cracking. Neither assumption is correct. To assess the influence of the foundation on cracking it is necessary to take into account the nature and magnitude of foundation movements and to understand why and how they occur.

Within reason, there is less concern for the total settlement of a building than for differential settlement. The Palace of Fine Arts in Mexico City, for example, has sunk more than 10 feet into the ground since it was built 60 years ago and the most noticeable effect is that the grand stone stairway has disappeared and the entrance is now at street level. Classical failures like this seldom occur today. Foundation failures are now quite rare, due largely to improved understanding of the properties of soil and rock materials. Nevertheless, detrimental movements do occur occasionally and it is the purpose of this Digest to explore the possible causes.

Soils and bedrock are similar to other building materials in that they deform under load, but unlike them they must be used as they appear in nature; they cannot be controlled by a manufacturing process. Except for special cases bedrock can be excluded from consideration because it is normally an adequate foundation material. Soils, on the other hand, are often stressed to their limit by foundation loads.

Foundation Stresses

The prediction of foundation movement is based on knowledge of how foundation loads are transferred to the ground and how earth or rock materials respond to resulting increases in stress. There are too many variables for these predictions to be precise, but for most situations they are adequate.

Consider first how stresses are transferred to the ground under a large and a small footing, each carrying the same unit pressure (Figure 1). The curved lines under the footings are lines of equal increase in stress due to footing load. This is often called the "bulb of pressure." Note that the deepest line, indicating a stress increase equal to 10 per cent of the applied load, extends to a depth twice the width of the footing. If a series of narrow footings is installed close together the bulbs of pressure intersect and the influence on the ground is deeper than for an isolated footing. When piles are used, foundation loads are carried to deeper strata. If the piles are long in relation to the width of the building, the effect is much greater than if the piles are relatively short. The bulb of pressure concept is used to determine the depth to which foundation soils must be explored.

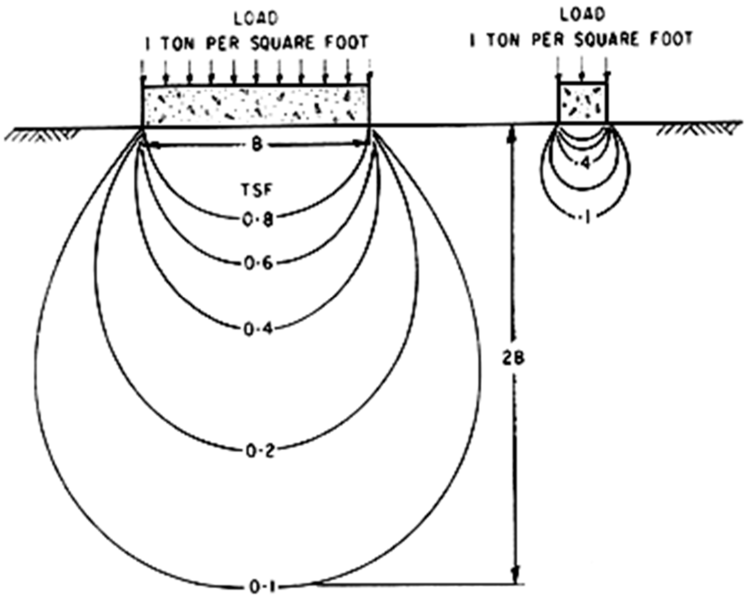

Figure 1. Lines of equal vertical stress caused by surface loads.

Examples of Settlement

As building loads are applied to the ground an "immediate" settlement occurs as a result of instantaneous compression of the soil. Most immediate settlement may be accommodated within the structure as it is built, and fortunately much of the differential movement occurs at this stage. Under certain conditions, however, fine-grained soils will continue to compress under constant load for many years. This long-term compression is called "consolidation" settlement and is caused by the squeezing out of water from the pores in the clay.

Differential settlement occurs for a number of reasons:

- local variations in soil compressibility,
- variation in thickness of compressible soil,
- differences in footing sizes and pressures,
- variation in applied loads,
- overlapping stresses,
- differences in depth of embedment of footings.

A classic example of consolidation settlement is occurring under the Empress Hotel in Victoria, B.C. This building is founded on 50-foot piles which rest on gravel at one end but penetrate only to the middle of a compressible clay layer at the other. Although the maximum settlement at the deep clay end is more than 30 inches, the damage is not especially serious because the building has tended to tilt on a plane. Fortunately, level observations have been taken annually since 1912, shortly after the Empress Hotel was built, so that it has been possible to reconstruct the loading and settlement history from the beginning of construction. This shows that settlement occurred rapidly during the first five years and continues slowly 65 years after construction.

If foundation loads vary, the differential settlement can be more serious even when sub-soils are relatively uniform. The National Museum Building in Ottawa is an example of such a situation. This massive structure has a complex footing system on two levels, with bearing pressures varying from less than 1 ton per sq ft to more than 4 tons per sq ft. The differential settlement became so serious five years after the building was opened that the tower structure over the main entrance had to be removed in 1915 to prevent collapse. The estimated total settlement varied from zero where the bearing pressures are small to 1.6 feet under the tower. A few years ago a section of original flooring was removed, revealing that as much as ½ foot of settlement had occurred during construction so that the total differential settlement at footing level is probably more than 2 feet. This has caused considerable damage to some interior partitions, but owing to the nature of the framing the basic structure is sound.

Another example will illustrate how modern foundation practice permits successful building on even very poor subsoils. An industrial plant on the south shore of the St. Lawrence River at Varennes, 20 miles downstream from Montreal, rests on a 2.5-foot thick reinforced concrete mat over 100 feet of compressible clay. The mat foundation was integrated with pile foundations for special machinery. Mat pressure varies from 700 to 1,700 psf over the 100- by 300-ft building area. Settlement varies from more than 6 inches under the heavily loaded area to about 2 inches under the lightly loaded area. Most of the settlement occurred during the one-year construction period ending in 1957, but another 2 inches occurred in the six years following construction. This degree of differential settlement was perfectly acceptable to the owners on an economic basis and an extension begun in 1961 was built in the same way. The buildings were designed with sufficient flexibility to allow the differential settlement to pass virtually unnoticed.

A second example from the same general soil area has not turned out so happily. In this case a large warehouse connected to a special facility on piles was founded on a 3-foot sand fill over compressible clay. The designers did not realize that the sand fill added more load to the ground than did the structure. The result has been more than 1 ½ feet of unanticipated differential settlement, accompanied by considerable damage and operating difficulties.

In most areas of Canada the differential settlement of an important building can be limited to a fraction of an inch. The 26-storey CN Tower in Edmonton is a good example of the foundation performance that can be expected when modern technology is applied. This reinforced concrete structure, founded on spread footings resting on a sandy or silty clay till at depths of 22 to 26 feet, had a maximum settlement after 6 years of just over 1 inch, with a differential of less than ½ inch; 80 per cent of the settlement occurred during construction. The risk of detrimental settlements appears to be much greater in more modest structures such as 10- or 15-storey apartment blocks where owners may often be inclined to skimp on foundation investigation and design.

Types of Settlement

There are three basic types of settlement: uniform settlement, tilt, and non-uniform settlement (Figure 2). Uniform settlement and tilt (within reason) do not greatly affect a structure, but resulting movements may cause serious problems with services and appendages such as water mains and connecting tunnels. Non-uniform settlement is characterized by angular distortion and may cause cracks or even structural failure. The degree of angular distortion is indicated by the ratio of differential settlement to distance between supports, Δ/L. Laboratory tests and field experience have given reasonable correlations between angular distortion and damage for various kinds of construction ranging from 1/750, where difficulties with sensitive machinery may occur, to 1/150 where structural damage is to be feared.

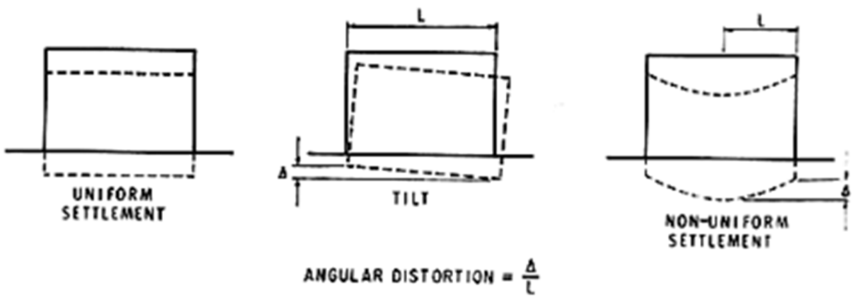

Figure 2. Types of settlement.

The amount of settlement that a building can tolerate, the "allowable" settlement, depends on its size, type and intended use. The allowable settlement for the plant at Varennes, for example, would not be permitted in a city hall. For practical reasons, the amount of settlement that would be tolerated under the difficult conditions of Mexico City is greater than would be tolerated in any Canadian city.

Swelling and Shrinking Soils

So far the discussion has been confined to foundation movements caused by compression of subsoil due to loading. Large movements can also occur from shrinking or swelling of clay subsoil resulting from stresses unrelated to foundation pressure.

Fine grained clay soils may be subjected to extremely high stresses due to air drying or vegetation. Shrinkage may take place throughout the full depth of rooting and the depth of the active layer depends on both climatic conditions and vegetation. Drought-resistant vegetation growing in semi-arid climates may have roots extending deeper than 20 feet. Because tree roots are extremely efficient in extracting soil moisture, both the depth and rate of shrinkage can be greatly accelerated in soils supporting such vegetation. Some soils will swell back to their original volume when they are rewetted. The movement of a footing up and down, therefore, depends on the condition of the soil at the time of construction and on subsequent wetting and drying. Usually the worst heaving conditions develop in soils that have been previously desiccated by heavy vegetation or extreme aridity and then subjected to greatly increased moisture conditions as a result of construction and irrigation practices.

Although shrinking and swelling usually affect only shallow, lightly loaded footings they can cause considerable damage even to large buildings. Swelling soils are common on the Prairies. In Winnipeg, an extension to a church was built over an area in which the trees were cut down immediately before construction. The floor slab for the addition, which rested directly on the ground, was heaved 6 inches in two years, giving an annoying discontinuity between the old and new sections. Although the main structure was supported on piles, there was severe damage to partitions and finish in the basement, with some distortion transmitted to the superstructure above grade.

It is common in many of the heavy clay regions of Canada for shallow foundations to move up or down by several inches. In these regions the problem can be overcome by designing a rigid structure to reduce differential movement or by providing a deeper foundation (usually short piles) to carry the structure and allowing space under floors for soil movements.

Other Causes

There are several other causes of foundation movement worthy of mention. Freezing of the ground is a problem in most parts of Canada. When fine-grained soils such as silts and clays or even dirty sands and gravels freeze, water is drawn up from the water table to freeze into discrete lenses and cause a volume expansion. Usually the normal winter heating keeps frost away from footings, but the possibility of frost heaving under attached garages or depressed driveways is often forgotten and results in considerable damage to light structures. Frost action is also a hazard during construction. A large building under construction in Ottawa was badly damaged during a cold winter period. Basement floor slabs were heaved and cracked and the movements extended up through the structure, causing distortion and cracks in partition walls. In Northern Canada there are many cases of serious distortions of heated buildings due to the thawing of ice in the permafrost under them.

Even bedrock is not always reliable. The basement floor of a downtown building in Ottawa began to heave mysteriously several years after construction. Research revealed that the pyrite in the shale bedrock was being converted by oxidation and bacterial action to gypsum and other sulphate materials to cause swelling. Parts of the floor heaved as much as 4 inches in five or six years, although only minor structural distortion was caused before the swelling was arrested by chemical treatment.

It may be concluded from this review that foundation movements always occur. The important point to remember is that foundation performance can be satisfactorily predicted. For simple foundations on good sites this can be done with a modest expenditure. At poor sites, or where foundations are complex, an extensive and possibly expensive investigation is required. The designer has to compromise between his desire for zero movement and the owner's desire for the cheapest foundation. On the one hand it may be advantageous to accept rather large differential movements and to design joints to accommodate them. On the other hand he may be able to demand a foundation sufficiently stable to allow deflections to be ignored for purposes of joint design, permitting joints provided for other purposes to accommodate small deflections due to foundation movement. Because of the interaction of the soil and the structure, the advantages of having the foundation engineer and structural engineer work together are very clear.