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Selecting the Foundation

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For all but the smallest structures, the design of foundations consists of three essential operations:

1. calculating the loads that must be transferred from the structure to the strata supporting it;
2. determining the exact character of subsurface conditions, including groundwater conditions, to a depth of at least twice the width of the structure; and
3. designing a foundation structure that will safely transfer the loads from the structure to the foundation beds that have been found at the site.

The very small buildings excluded from this general statement may be taken to be one and two-storey residences and equivalent structures, the loads from which are so small in relation to the size of the area they cover that empirical methods of foundation design will usually, though not always, suffice. This Digest will present an outline of the way in which the type of foundation structure best suited to a particular site can be selected.

There is a wide choice of types of foundation structure. If the loads from building columns can be transmitted directly to the ground beneath, the column base can be enlarged in some suitable way - by a concrete slab, a concrete-encased grillage of steel beams or even heavy timbers. The result is a *spread footing*. If it is necessary to have many spread footings beneath a structure, it may be economical to join all of them together into one large concrete slab on which the columns bear. This is then a *raft foundation* (or continuous footing) . The name is a good one, since it implies that the structure is "floating" on the ground beneath. The actual principle, of flotation is sometimes used when the foundation structure is located well below the ground surface. The whole basement of a building then acts as a *box foundation* or, if specially designed, as will be explained below, a *floating foundation*.

The types so far described are all used very close to, or at the surface of, the ground. If the building loads have to be transferred to strata well below the surface, it must be done through sub-surface columns. If these consist of cylindrical holes filled with concrete, they will be called caissons, which are generally used for very heavy loads. More usually the columns can be more slender units and may be driven into the ground or formed of concrete in smaller diameter holes that are specially formed. These are*piles* and may be of concrete, steel or wood.

Whatever type of foundation structure is used, its object is to transfer the load from the building to the ground safely. The *bearing capacity* of the soil or rock clearly must not be exceeded. Very few cases are on record where this has happened and an actual failure has taken place, the tilting of the Transcona Elevator near Winnipeg being one of the few major examples and one that is world famous. Much more frequent is the development of *excessive settlement* when the full load is applied. With modern soil mechanics techniques and adequate subsurface investigation, there is today no reason why building settlements cannot be predicted with accuracy and the foundation design so proportioned that the inevitable settlement will be within allowable limits.

Such design is the work of an expert in foundations. Every designer, however, whether architect or engineer, must have a broad appreciation of the principles of foundation design so that he may select, from the various types available, that best suited to his structure. The design of foundations is not something that, as one designer was heard to say, "can be left to the piling company." The following notes suggest the main determinants that govern the solution of the type of foundation to be used.

Variations in Site Conditions

Subsurface conditions at any building site can be grouped into three main types:

1. solid rock - may exist either at ground surface or so close to it that buildings may be founded directly upon it;
2. bedrock - may exist beneath the surface but at such a depth that building loads may, if necessary, be transferred indirectly to it; and
3. bedrock - may be so far beneath the ground surface that it is neither practicable nor economical to transfer building loads to it, the loads having to be carried by the superincumbent soil.

The direct influence of local geology upon the conditions that may be expected in any locality will be obvious. There are few major examples of the first condition met with in normal Canadian building practice, although many of the major buildings in the city of New York are founded directly upon the Manhattan schist that constitutes so much of Manhattan Island. In many Canadian cities, such as Montreal, Toronto, Ottawa and Vancouver, there are some locations where rock is close enough to the surface to be used directly as the foundation bed, but only in some northern locations is this condition a general determinant of foundation design. The second condition is very widely experienced. in Canadian cities, Winnipeg being a typical example, and many of its buildings are supported on caissons and piles that transmit the building loads to the underlying bedrock. The third condition - bedrock so deep below the surface that it cannot be used as a bearing medium - is also encountered in Canada, notably in prairie cities such as Saskatoon.

This variety of subsurface conditions is, in itself, an indication of the varied geology to be found in Canada. The fact that almost all of its surface has been glaciated is of unusual significance, since the form of the underlying bedrock may bear no resemblance to the contours of the ground surface above. Canada may not yet, like Oslo in Norway, have such a remarkable example as one in that city where one corner of a building, now famous, rests directly upon solid rock-while the opposite corner is supported by steel piles that go down over 160 feet to bear on the same rock surface. There are, however, in many Canadian cities, buildings that have had to be founded on quite uneven rock, the Besserer Street Postal Building in Ottawa being a particularly good example. Even with bedrock close to the surface at one corner of a building site, therefore, no assumptions can be made that this condition will persist over the site. Test borings *must*be put down at intervals such that there can be no doubt as to where rock will be found when excavation commences. The Building Physics part of the Division's own building in Ottawa was originally planned as an extension of the main Building Centre. Test borings showed, however, that in a distance of 75 feet from the rear corner of the existing building, the level of the bedrock dropped over 90 feet. The extension was therefore built as a separate unit at a location where bedrock could readily be used. The fact that such great variations in rock level can be encountered must always be kept in mind in all Canadian building foundation design work.

Buildings Founded Directly in Rock

When bedrock is conveniently and economically available at a depth that can be used as direct bearing for the building to be erected, foundation design is greatly simplified. The solidity and continuity of the rock must naturally be thoroughly tested by diamond drilling over the whole site, especially with sedimentary rocks in which seams may be encountered. Only if very heavy concentrated loads have to be transmitted to the rock will loading, or strength tests be necessary, as a general rule; but groundwater conditions will be of special importance, not only in connection with construction operations but also in relation to the design of the permanent drainage arrangements.

Buildings Founded Indirectly on Rock

It is impossible to specify the limiting depth to which building loads can be economically transferred to bedrock well below ground surface, since subsurface conditions as well as the size of the building and the nature of its loads will all be determinants. It is believed that the foundations for the Cleveland Union Terminal Tower in Cleveland, Ohio, still constitute the record for depth, caissons transferring the Tower loads to bedrock at a depth of 250 feet. At least one Canadian bridge is founded on piles that go somewhat beyond this depth, but these are extremes. With the advance of modern Soil Mechanics studies, solutions can now usually be found for problems of building foundation design where bedrock is very deep that do not necessitate such unusually long supporting columns. For whether piles or caissons are used, their function is to act as columns in transferring the loads from the foundation of the building to the bedrock beneath.

Piles used in this way are, therefore, *end-bearing piles* as distinct from *friction piles*, to be mentioned in the next section. As columns supported by the surrounding soil, they are subject to compressive stress. Wood, steel, or concrete piles can be used. The loads involved with modern buildings usually dictate the use of steel or concrete but many older buildings are still supported by timber piles. If any changes in the level of groundwater occur in the vicinity of such buildings, rotting of the wood may result and cause trouble. Settlement of the Boston Public Library was found to be due to this cause. Steel piles are easy to handle and to chive; their use will be dictated by economic factors if ground conditions are suitable and if it is known that no adverse groundwater conditions are present that might cause deterioration of the exposed steel. Concrete piles may be pre-cast or cast-in-place, the former requiring accurate knowledge of depths if curing is to be avoided; the latter requiring that ground conditions be quite suitable for their use even if they are of the type utilizing a steel shell that is driven first and then filled with concrete.

If unusually heavy and concentrated loads have to be transferred from building, to rock, then the maximum practicable size of pile may not be adequate and larger columns in the form of caissons must be used. Correspondingly, if preliminary investigations have indicated the presence of boulders or any other condition that will make pile driving difficult or impossible, caissons must be considered unless an altogether different type of foundation design is possible. Ingenious machines are now available for excavating the circular holes for caissons. With good soil conditions and lined holes, the shafts can be inspected down to bedrock before Concrete is placed in position. The well known "Chicago well" is a widely used type of foundation caisson, many thousands having been used to carry building loads through the blue clay upon which Chicago is founded. Belling out the bottom of the caisson to obtain extra bearing area on bedrock is common practice if soil conditions are suitable.

It will be evident that for all these methods most accurate knowledge of subsurface conditions - and especially of bedrock levels - is essential. With such information, it is possible to estimate costs accurately, so that they can then be compared with the cost of the alternatives now available for founding structures directly upon soil.

Buildings Founded on Soil

Soils are solid materials not dissimilar to rock except that, they are not so strong and may consist, as does sand, of small fragments of rock that have to be confined if they are to carry load. A stiff clay can be almost identical with a soft shale - to such an extent that one cannot draw a hard-and-fast dividing line between what is rock and what is soil. Accordingly, soils will be susceptible to stress and strain in exactly the same way as rock or any other solid material. It is, therefore, possible to calculate in advance the stress from superimposed building loads that will be in any soil. If the strength characteristics of the soil are known, it is also possible to calculate in advance of construction how the soil will behave when the loads are applied. The strength characteristics of soils can be determined by laboratory tests carried out on carefully obtained samples. These must be in a condition as close as possible to that of the soil in place. Since most soils contain water, this means that most soil samples must be very carefully protected as soon as they are taken from the ground, usually by the waxing of the containers, so that the water content or the samples when tested will be the same as that of the soil in the ground.

These procedures and associated theoretical considerations of soil action constitute the modern science of Soil Mechanics. The proper application of the results of such scientific studies now enables the foundation engineer to design a foundation for any given combination of loads on even the most unpromising soil, as also upon soils that have not caused problems when utilized in more pragmatic ways. If, for example, loads are relatively light and the bearing strata of soil are correspondingly strong, with no weak buried strata that might cause settlement at the surface when loaded, then spread footings or the common type of foundation raft of reinforced concrete may prove to be practicable foundation designs.

If there is a stratum of strong soil at some appreciable distance below the surface, as revealed by soil sampling and testing, then the use of piles may again be suitable and economical for transferring the loads from the structure to the good bearing material. Such piles may gain a part of their bearing capacity from the friction developed between their exposed sides and the soil with which they are in contact in penetrating the soils that overlie the strong bearing material. Alternatively, soil studies may show that merely by driving piles into the upper layers of soil, without any firm bearing stratum for the points of the piles, enough resistance can be mobilized from the "skin friction" (as it is called) between the sides of the piles and the surrounding soil to provide the necessary support for the calculated building loads. It is usual to conduct loading tests on one or more full-scale driven piles to check on such calculations. Standards methods for such loading tests are available, and means for transforming the results of a single pile test into a reasonable estimate of the bearing capacity of a complete pile group.

Before any decision can be made as to the use of piles however, the most accurate subsurface information for the whole building site must be available. Not only must the presence of boulders be checked for, but also the possible existence of weak buried strata. This is particularly important if uncased cast-in-place concrete piles are to be used. These are versatile units and are quite widely used when piles have been called for, but their success depends upon the adequacy of the soils through which they are driven. Subsurface information is also necessary in order to enable alternative foundation types to be investigated.

Some types of clay soils, although they have good strength properties, are so constituted that when loaded they will easily compress as water is "squeezed out" of them. This feature will cause undue settlement of any structure founded upon them. If, however, the water is squeezed out of such clay over the whole site in advance of building, the clay will provide quite adequate bearing capacity with no detrimental settlement of the structure. This can be achieved by preloading the whole site with a load that can readily be removed when erection of the building is to proceed - a heavy material such as sand may be handled easily. Preloading has now been quite successfully applied to a wide variety of building sites. The economics of the method naturally limit its application to rather special cases, but it is probable that its use will increase appreciably.

A far older method, but one now coming into prominence, is readily described as the use of a *floating foundation*. The word "floating" is used in its literal sense. When a body floats in water, it displaces a volume of water the weight of which is equal to the weight of the floating body. In just the same way a building can be floated on soil, the weight of the building and its loads being equal to the weight of the "displaced" soil, i.e., the soil that must be excavated to provide for the foundation structure of the building.

Before any soil has been removed, the stress at the level of the bottom of the necessary foundation (due to the weight of the soil that is to be removed) can readily be seen to be exactly the same as the stress that will be present when the building and its loads have been substituted for the excavated soil. Theoretically, no further settlement of the underlying soil will take place. Construction requirements may modify this desirable state slightly, but the basic idea is sound. It has already been applied to many large buildings.

It is not a new idea. The great Sir John Rennie quite clearly used it for the design of a warehouse in the West Indian Docks of London, England, in the early nineteenth century. Like many other ideas of those inspired early pioneer engineers, floating foundations had to wait until the twentieth century was well on its way before they were recognized again as one of the soundest of all types of foundation design when anything other than direct bearing on soil strata at or near the surface of the ground must be used. The Post Office Building in Albany, New York, was one of the pioneer North American buildings to be so founded. There are now some Canadian buildings floating on the soil beneath them, notably a fine multi-storey building in Ottawa founded on Leda clay. It seems certain, with steady advance in the art of foundation engineering, and especially since Canada has so many locations where the soils are actually weakened by the operation of pile driving, that floating foundations will be used to an increasing degree in this country when the combination of soil conditions and building loads warrants this type of design.

Expert engineering assistance is naturally necessary for the design of all major building foundations as it is also for the conduct of all preliminary subsurface investigations. At the same time, building designers, architects and engineers should have a broad appreciation of the main types of foundation structure that can be used, and of the correlation of such designs with with the over-all pattern of local sub-surface conditions. A finished foundation design should be an integral part of the design of all buildings; it is not something that can, or should, be left to be worked out after construction has started.

Foundations for Small Buildings

The foundations for small buildings were excluded from the preceding discussion because they are rarely "designed" in the engineering sense, usually being based on common local practice. Simple calculations will show that the loads to be carried by the foundation bed beneath a single-family dwelling, for example, are small indeed. Factors other than loads and consequent bearing stresses accordingly influence such foundations. Amongst the most important of these, especially in some parts of western Canada, is the existence at ground surface of clay soils having well developed properties of swelling and shrinking with changes in water content. In such areas special measures are called for to avoid serious troubles with movements of the superstructure. More attention is now being given, therefore, to the foundations of smaller buildings. Long accepted practices, such as the inevitability of house basements, are being questioned. A future Digest will be devoted to this subject, with special reference to the potential for economy in building provided by the use of concrete slabs-on-ground for house foundations.