Foundations for Cylindrical Storage Tanks

Les fondations des réservoirs cylindriques

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Summary

The foundation requirements and other characteristics of cylindrical storage tanks are reviewed in general terms. A discussion is presented of the permissible settlement behavior for tanks and other distinguishing features. The types of foundations used for a variety of soil conditions are reviewed. These foundation solutions include the use of a sand pad, a concrete or crushed rock ring wall, an interlocking sheet pile ring wall, and a pile foundation with a crushed rock pile cap.

Sommaire

Après des généralités concernant les conditions que doivent remplir les fondations des réservoirs cylindriques et certaines de leurs autres caractéristiques, cet article étudie le comportement des réservoirs soumis à des tassements admissibles.

Les différentes sortes de fondations utilisées pour les différentes propriétés du sol sont examinées. Les solutions adoptées comprennent des couches de sable, murs annulaires de béton ou de pierres, rideaux de palplanches en forme d'anneau et une fondation sur pieux avec un casque constitué de grosses pierres.

Introduction

In selecting building foundations, it is quite important to consider the unique characteristics of the planned structure in addition to evaluating the behavior of the soils upon which the structure will rest. This is particularly true with cylindrical storage tanks, which form a familiar part of petroleum refineries, chemical plants, and many other manufacturing industries.

A cylindrical storage tank is a simple structure. It consists of a nearly flat metal bottom, a thin cylindrical shell, and either a fixed or floating roof. Despite the apparent simplicity of storage tanks, there is relatively little information available concerning the permissible soil behavior for these structures and the types of foundations which can be used.

The purpose of this paper is to discuss the following :

(1) The unusual characteristics of cylindrical storage tanks in common use.

(2) The types of tank foundations which have been used or considered in common practice.

(3) The major uncertainties which exist in predicting the foundation behavior of tanks.

Structural Considerations

It is possible to obtain cylindrical storage tanks with diameters ranging from 15 feet to 250 feet. The tank heights normally range from 16 feet to a maximum of 56 feet. The tank bottom is normally one-fourth inch in thickness and is generally fabricated by lap-welding. The tank bottom normally extends a minimum of one inch beyond the tank shell; this permits field erection by means of welding both the inside and outside of the shell to the tank bottom. The tank shell may be considered as a series of welded rings; each ring is normally eight feet in height. The shell rings increase in thickness from top to bottom; a maximum thickness of one and one-half inches is used for tanks over 48 feet in height.

Two types of roofs are in common use : a cone roof and a floating roof. The cone roof is permanently attached to the tank shell and is supported by a series of rafters, girders and columns. A floating roof is free to rise and fall with the variation in level in the tank contents. The floating roof is kept in the center of the tank by special devices.

A critical feature of a floating roof tank is that the clearance between the roof and the tank shell is fairly small. The floating roof will not function if the tank shell becomes distorted. Malfunctioning of a floating roof can result in serious explosions or roof-collapse should a vacuum be created between the tank contents and roof. Typically, the difference between the maximum and minimum tank diameters cannot exceed eight inches. This is an important factor when selecting tank foundations, since a small amount of differential settlement around the base of the tank can produce a magnified distortion along the top of the tank shell.

Typical Tank Foundations

General—The selection and design of tank foundations must consider factors which are quite different than for other types of structures. These factors are as follows :

(1) A cylindrical storage tank is an inexpensive structure *for its size*. As an illustration, a 48-foot-high tank with a diameter of 140 feet will hold more than 130,000 barrels; yet the cost of such a tank may be only $200,000. *Unlike most structures, the cost of a tank foundation can exceed the cost of the tank itself.*

(2) A tank is very light in comparison with its contents. The average load imposed on the subsoils can be increased from a negligible amount to more than 3,000 pounds per square foot in a very short period of time during hydrostatic testing. By contrast, there is a gradual increase in the foundation loads during construction for most buildings. Thus, unlike other buildings, almost all of the tank loading is applied suddenly *after* completion of the structure. With the rapid application of loads, it is often possible to separate "elastic" deflections from movements resulting from consolidation.

(3) A cylindrical storage tank can withstand large settlements. Uniform settlements of six inches to a foot are not

uncommon. Many tanks are still in use even following settlements as large as three feet. A tank bottom is quite flexible; relatively large deflections can occur between the center and edge of the tank without harm. However, differential settlement around the perimeter of the tank can be very critical—since this can cause serious distortions of the tank shell or malfunctioning of a floating roof.

(4) The bottom of a storage tank is quite thin and will remain in contact with the subsoils during settlement. Thus, a storage tank is unique in that the loads are uniformly applied to the subsoils. Since most theories of applied soil mechanics assume a uniform application of pressures at the foundation level, the subsurface stress conditions and deflections can be predicted more accurately with storage tanks than with many other types of structures.

(5) If adverse differential settlements occur, a tank can be releveled for a relatively modest cost. Where it is permissible to risk re-leveling tanks, it is possible to use a tank design with an exceedingly low margin of safety. However, the economics of tank re-releveling will depend on the effects of taking a tank temporarily out of operation. Thus, a low margin of safety is permissible only where the tank contents could be pumped elsewhere in the event of failure or during re-leveling.

Ideal Soil Conditions—A typical tank foundation for ideal soil conditions is illustrated on Fig. 1. The site should

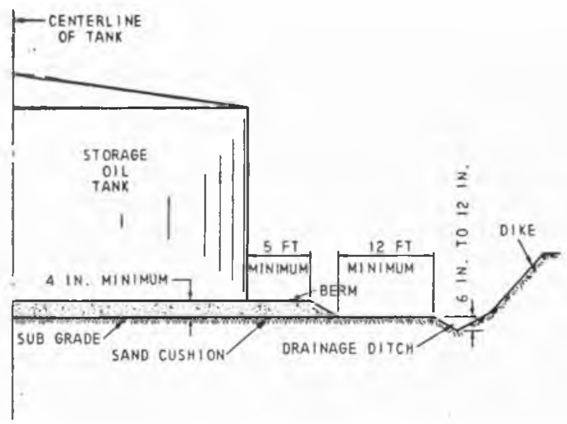

Fig. 1 Typical foundation treatment for good soil conditions.
Solution type pour des fondations sur sols de bonne qualité.

be stripped of all topsoils and organic material. Following site stripping, it is necessary to re-compact the exposed subgrade and to place the tank bottom on a pad of sand or gravel. This pad is usually a minimum of four inches in thickness and is normally elevated over the surrounding grade to provide satisfactory drainage. The center of the tanks is generally crowned or elevated above the tank edge. A slope of one inch per ten feet of tank radius is often used; the crown is sometimes limited to a maximum of six inches for large storage tanks. The purpose of elevating the center of the tank bottom is to permit adequate drainage within the tank bottom following settlement.

It is generally preferable to place the tank on a layer of oiled sand; however, pouring oil directly on the sand pad is rarely permissible, since too much oil could result in a fire when the bottom of the tank is welded.

The weight of the tank shell and roof can result in concentrated loads as high as 1 400 pounds per lineal foot along the base of the tank shell. Since the shell is attached to a flexible tank bottom, abrupt " edge cutting " can result,

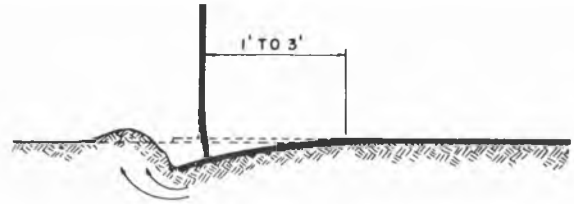

Fig. 2 Edge failure.
Affaissement du bord d'un réservoir.

as illustrated on Fig. 2. Such "edge cutting" may result in abrupt deflections of from three to four inches where the tank is constructed directly over clean sand. To reduce the amount of edge deflection, a ring of angular crushed rock or a shallow concrete ring wall can be installed as illustrated on Fig. 3. A concrete ring wall is seldom designed for complete

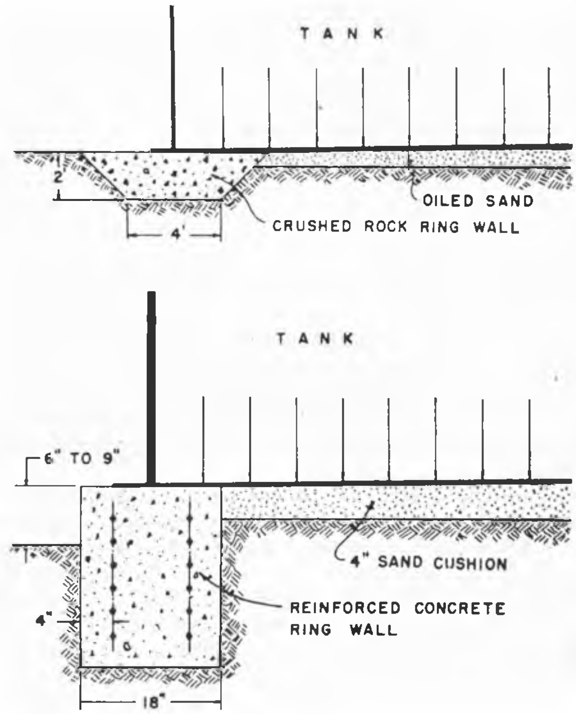

Fig. 3 Ring walls of crushed rock and reinforced concrete.
Murs annulaires de pierre et de béton armé.

rigidity along the entire perimeter of the tank; it normally serves the purpose of spanning local zones of more compressible soils. The ring wall may require continous reinforcing to resist " hoop tension" if there is danger that the subsoils may move laterally under the applied tank loads.

When concrete ring walls were first employed, it was felt that the wall should be placed immediately outside the tank perimeter. However, from experimentation, it was concluded that the placement of the shell directly on the ring wall is preferred, since this aids in tank erection and maintenance. Heavy asphaltic roofing paper is often placed between the tank bottom and the concrete ring wall in order to form a seal and to provide a more uniform contact surface.

At the present time, the use of a ring of crushed rock or concrete is fairly controversial. Some designers feel that "edge cutting" is rarely detrimental to the tank structure and that the cost of special edge treatment cannot be normally justified. By contrast, other designers believe that the use of a concrete ring wall, in particular, facilitates tank erection and reduces maintenance costs. In addition, it has been argued that abrupt distortions at the edge of a tank can produce dangerously high stresses within the welded connection of the tank bottom and the tank shell.

Areas Underlain by Thin Layers of Weak Soils—Frequently the foundation engineer is faced with tank sites underlain by from five to 20 feet of extremely weak and compressible cohesive soils. Since the operating pressures imposed by storage tanks may be as high as ten to 20 times the undrained strength of the subsoils, the " obvious" solution for such sites might be to use a pile foundation. However, the cost of pile foundations may equal or exceed the tank cost; thus, the designer may have to use considerable ingenuity in order to develop alternate solutions.

Where the thickness of the weak deposits is relatively thin, it is often possible to remove these materials and replace them with fills which have better physical properties than the natural soils. However, the presence of a high ground water level can make the excavation of weak soils hazardous and difficult. Fig. 4 illustrates a typical design

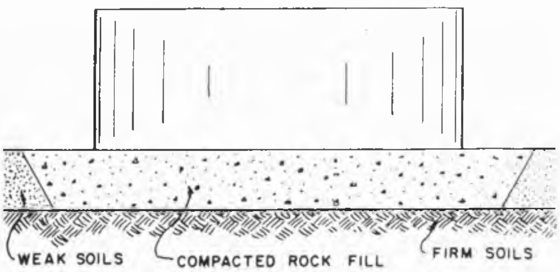

Fig. 4 Tank on layer of compacted fill.
Réservoir fondé sur une couche de terre compactée.

where the weak subsoils were removed and replaced with fill. It is generally advisable to extend the fill layer beyond the tank perimeter in order to reduce differential deflections.

The preloading or surcharging of tank sites is often considered to reduce tank settlements and to develop the necessary soil strength. The surcharging may be accelerated by use of sand drains, wellpoints or deep pumping. Unfortunately, a surcharging period of months or even years may be needed prior to tank erection. It is sometimes possible to use the tank itself as a surcharging device. Thus, after the tank is erected, water loads are imposed in small increments; each loading increment is maintained for a sufficient period of time to achieve the desired consolidation and required increase in subsoil strength. In several instances, a controlled loading program of more than a year's duration has prooved to be more economical than alternate solutions, such as removing the weak subsoils or using a pile foundation.

Where the weak subsoils are less than about 20 feet thick, it is often possible to "float" the tanks on a layer of fill placed over the weak deposits. The fill layer must have a sufficient thickness and strength to prevent the rupturing of the subsoils; the fill layer must also extend far enough beyond the tank perimeter to prevent lateral plastic flow of the weak layer. The problem of lateral flow of a thin layer of soil beneath a firm layer of fill is analogous to stepping lightly on a tube of toothpaste. Even if the walls of the tube are strong enough to resist rupturing, the contents will squeeze out laterally if the cap is left off the tube. Where a large enough Fill "cap" is used, the lateral plastic flow will be resisted by the shearing strength developed along the upper and lower boundaries of the weak soil layer.

It is possible to prevent tank failure by restraining the ateral movement of the weak subsoils by other structural means. This restraint can be provided by means of a concrete ring wall, interlocking sheet piling, or by a ring of gravel which extends through the weak soil layer. Such installations are illustrated on Figure 5. The use of such ring

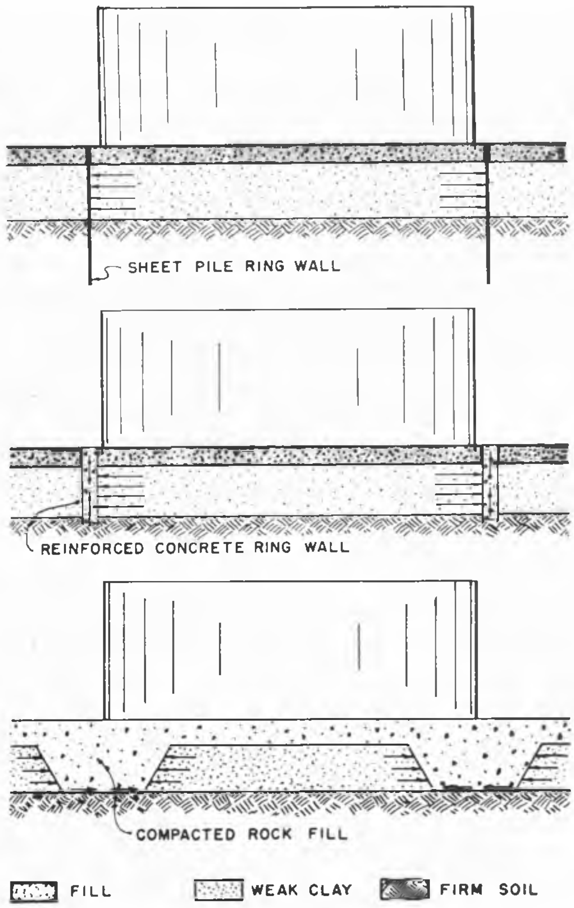

Fig. 5 Ring walls to prevent lateral movement of weak soils.
Murs en forme d'anneau pour éviter le déplacement latéral des sols de faible portance.

walls, however, can result in very large differential settlements between the center and edge of the tank.

An interlocking sheet pile wall or a deep concrete wall is quite expensive and is rarely used. (Such solutions have been used, however, as a corrective measure following a tank failure.) The use of a deep ring of crushed rock or sand has been used successfully on at least ten occasions for areas underlain by up to 15 feet of weak clays. The dimensions of the crushed rock ring are selected in such a way that the passive soil resistance outside the ring wall and the base "friction" of the ring will exceed the outward thrust of the confined zone of weak soil.

Whenever tanks are placed directly above weak deposits without the use of piling, there is considerable risk that the tank deflections may exceed the permissible limits. The owner should be informed of the risk involved in trying to reduce the foundation costs. It is sometimes possible to obtain significant savings even if a tank must be re-leveled several times during its useful life. Storage tanks may be re-leveled by both hydraulic jacking of the tank skell and "mud-jacking" of the tank bottom. Assuming that it is necessary to re-level a floating roof tank, the roof is lowered to within a few feet of the bottom of the tank and is then supported at the center, edge and intermediate points.

Brackets are welded around the outside of the tank shell. The tank shell is then lifted by means of hydraulic or mechanical jacks. The tank shell may be raised in this manner by as much as 18 to 24 inches. An asphaltic concrete berm is then constructed beneath the edge of the tank and the jacks are removed. Hoses are then attached to openings in the tank bottom and grout is injected to raise the tank bottom to the desired level. The asphaltic concrete berm around the tank perimeter forms a pressure seal. In two recent installations, tanks as large as 120 feet in diameter were completely re-leveled for a cost of less than $10,000. In both cases the re-leveling proved satisfactory and saved over $75,000 as compared to a conventional pile foundation.

Pile Foundations—The cost of the conventional pile foundation with a reinforced concrete cap can be extremely high in relation to the cost of the tank. As an alternate to a concrete cap, a layer of crushed rock of other granular soils is sometimes placed directly above the piles. With this system, the loads are transmitted to the piles as the result of arching within the granular cap. Granular pile caps have been successfully used for nearly 50 years. However, the design of the crushed rock pile cap is still more or less empirical. A typical design which has been used successfully in many installations is illustrated on Fig. 6.

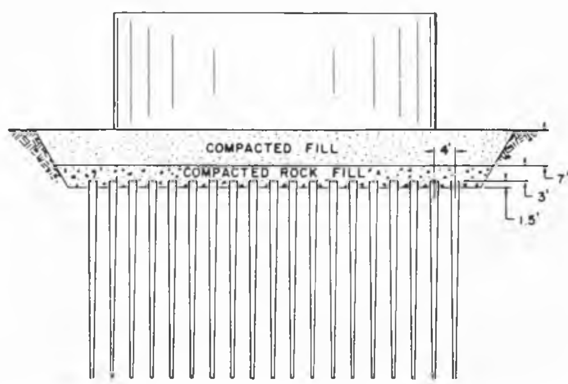

Fig. 6 Typical design using crushed rock pile cap.
Plan type d'une fondation sur un casque de pieux recouverts de pierre broyée.

Conclusion

While this article provides a general review of the types of tank foundations which can be employed, it seems important to mention that there are several uncertainties which remain concerning tank foundation design and behavior. These uncertainties include the following :

(1) Edge treatment : Very little information exists as to the amount of differential distortion which can occur around the base of a tank without producing sufficient warping of the tank shell to impair the action of a floating roof. Information is also needed concerning the amount of distortion which can take place at the base of a tank shell without resulting in failure of the welded joints.

(2) Mechanics of tank failure : There seems to be a considerable uncertainty as to mechanics of soil rupture where a tank is located above a weak soil layer. This is particularly true in analyzing the behavior of a layer of very weak cohesive soils under a layer of firm fill. In this case, it may be unsafe to consider the strength of the fill layer outside the tank perimeter, since the fill layer may be subjected to tensile stresses.

(3) Tank settlement : At the present, little information exists concerning the ways of predicting the magnitude and rate of deflection resulting from lateral plastic flow of highly stressed clays beneath a flexible tank.

(4) Pile foundations. More information is needed concerning the design of a crushed rock pile cap. As an illustration, the behavior of a granular pile cap is uncertain during conditions of an earthquake or other vibrations.

References

[1] Aldrich, H. P., Jr. (1957). Site Preloading Eliminates Piles for Two Oil Storage Tanks. *Journal of the Boston Society of Civil Engineers*, vol. XLIV, No. 1, January 1957, pp. 1-35.

[2] Boberg, Irving E., (1951). Oil Storage Tank Foundations. The Water Tower, March, 1951.

[3] Braswell, Andrew M., Jr. (1958). Settlement of Oil Storage Tanks. *Journal of the Soil Mechanics and Foundations Div., Proceedings of the American Society of Civil Engineers*, vol. 85, S.M.S., pp. 1863-1 through 1863-20.

[4] Byrne, Ralph E. (1948). Plastic Flow in Overstressed Soils. *Unpublished Research Report.*

[5] Jurgenson, L. (1934) The Application of Theories of Elasticity and Plasticity to Foundation Problems. *Journal of the Boston Society of Civil Engineers*, vol. 21, p. 206.

[6] Meyerhof, G. G. (1951). The Tilting of a Large Tank on Soft Clay. *Proceedings of the South Wales Institute of Engineers*, 1951, vol. LXVII, No. 2, pp. 53-71.

[7] Nadai, A. (1931). Plasticity. McGraw-Hill, New York, (New Edition 1950).

[8] Roberts, D. V. (1951). These Floating Roof Tanks Were Built on 'Floating Foundations'. *Petroleum World & Oil*, April 25, 1957.

[9] Skempton, A. W. & Bjerrum, L. (1957). A Contribution to the Settlement Analysis of Foundations on Clay. *Geotechnique*, vol. VII, No. 4, 1958, pp. 168-178.