

EXXON EXXON ENGINEERING	CIVIL WORKS TANK FOUNDATIONS PROPRIETARY INFORMATION - For Authorized Company Use Only	DESIGN PRACTICES	
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EXXON RESEARCH AND ENGINEERING COMPANY - FLORHAM PARK, N.J.

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SCOPE

This practice covers the design and construction of foundations for atmospheric storage tanks, as specified in [IP 4-8-1](#). Foundations for refrigerated tanks, tanks containing acid, tanks supported on piles, and pressurized spheres are beyond the scope of this practice, and are only briefly discussed.

REFERENCES

1. Duncan, James M. and D'Orazi, Timothy B., *Stability of Steel Oil Storage Tanks*, ASCE Journal of Geotechnical Engineering, Vol. 10, No. 9, September, 1984.
2. Darragh, Robert D., *Controlled Water Tests to Preload Tank Foundations*, AS Journal of Soil Mechanics and Foundations, September, 1964.
3. [IP 4-8-1](#), *Tank Foundations*.
4. [IP 9-4-1](#), *Atmospheric Storage Tanks*.
5. [IP 9-6-1](#), *Refrigerated Storage Tanks*.
6. ER&E Tank Maintenance Guide, ER&E Report No. EETD 50.
7. *Civil Design Considerations for Elevated Foundations and Secondary Containment Walls for Refrigerated Tanks*, ER&E Report EE.90E.82

BACKGROUND

Storage tanks are unique structures due to their flexibility and their lightness in comparison with the weight of their contents. Because of its flexibility, a tank can tolerate large settlements in comparison with other heavy structures, and a thin, flexible foundation can normally be used. Exxon's preferred tank foundation has been developed over the years through research projects and experience with numerous tanks.

Because they can tolerate large settlements in comparison with most other structures, tanks are often sited in areas where the underlying soils are weak and compressible. In such cases, either:

- Tank height must be restricted to what can be safely supported by the subsoil.
- Soil improvement must be undertaken.
- Tank weight must be transferred to a competent soil layer using piles.

Pile support for tanks is to be avoided whenever possible because of the cost involved. Further, pile design and installation must be carefully done to ensure that differential stiffness between adjacent piles is minimized. Differential pile stiffness can cause failure of the pile cap as it attempts to redistribute loads between the piles.

Whatever foundation is chosen, it is recommended to eliminate the potential for contaminating the underlying ground by leaks from the tank bottom. Thus, special attention to minimizing corrosion, and installation of an impermeable membrane in the pad to control any leakage which does develop, are now routine.

DESIGN AND CONSTRUCTION CONSIDERATIONS

Tank foundation design requires consideration of the subsoils (from grade elevation down) and the tank pad (from grade elevation up). The type, quality, and uniformity of the subsoils will govern bearing capacity and settlement magnitude and pattern, and will dictate things like:

- Height of tank that can safely be built.
- Soil improvement requirements.
- Expected settlements.
- Rate of settlements.

Tank pad design is covered by [IP 4-8-1](#), and there is normally little need to make major modifications to the IP design. This design has been developed to provide:

- Adequate support for the concentrated tank shell weight.
- Permeability within the pad so that leakage can escape without building up pressures that might cause a major washout.
- Materials which will retain their strength in the event of a leak.
- Materials which will assist in preventing tank bottom corrosion.
- Tank bottom leak detection, and collection of any leakage which does occur.

DESIGN AND CONSTRUCTION CONSIDERATIONS (Cont)

Pad construction, and records pertaining to pad construction, are very important as well. Specifically, materials and material placement must be as specified, and tolerances of material placement must be respected. Further, it is imperative that appropriate tests be performed to verify material types and compaction, and that surveys be performed to verify that specified tolerances were met.

Special considerations sometimes govern tank foundation design in high wind or earthquake areas. In such areas, tank sliding or overturning due to the wind or earthquake loads could dictate the need to anchor the tank. Normally sliding or overturning are only a problem with high, small diameter tanks.

SOIL INFORMATION

Good engineering practice requires that a soils investigation be carried out for all new tanks in order to assess the safe soil bearing capacity and settlement characteristics. This investigation, and subsequent analyses using data from the investigation, should be handled by a geotechnical engineer experienced with tank foundations. The investigation is normally done with soil borings, perhaps in combination with cone penetration tests. The number of borings and the extent of subsequent testing and analysis will vary with the number and size of the tanks, the complexity of the soil profile, and prior experience in the area. For a normal new development area, the recommended number of borings would be:

TANK DIAMETER	NUMBER OF BORINGS
Up to 50 ft (15 m)	1 per 1-2 tanks
50 to 100 ft (15 to 30 m)	1 per tank
100 to 150 ft (30 to 45 m)	2 or 3 per tank
> 150 ft (> 45 m)	3 or more per tank

On existing plant sites with a long history of trouble-free operations, the number of borings may be reduced to about half this number. On poor sites, the number of borings required might double.

The amount and type of soil sampling and laboratory testing are also variables which should be adjusted in accordance with conditions encountered. The end product of the soils investigation is a reliable evaluation of foundation stability and estimates of settlement at various stages of the tank service life. As such, the main engineering parameters required for the soils are shear strength and compressibility. These parameters can be assessed in a number of ways, depending on the types of soils present.

TANK INFORMATION

In order to progress tank foundation design, certain tank information is required. Obviously the tank location must be known in order to investigate the soils present, but in addition to this:

- Tank height and diameter.
- Service.
- Roof type (floating or fixed).
- Tank bottom elevation.

In addition, unusual features of the tank, such as elevated temperatures, can be important and should be made known.

FOUNDATION DESIGN

The tank foundation must be designed to adequately support the tank and prevent failure. Tanks can fail in a number of ways. These include:

- Exceeding the strength of the soil (bearing capacity or stability failure).
- Excessive settlement (causes unacceptable tank distortion or bottom plate weld failure).
- Loss of support (soil eroded from beneath the tank, or soil liquefies due to vibrational forces).

These modes of failure are covered in more detail below.

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FOUNDATION DESIGN (Cont)

BEARING CAPACITY

A bearing capacity failure occurs when the soil strength is exceeded, and a mass of soil shears from beneath the tank. This is illustrated in **Figure 1**. With the exception of loose, fine granular soils which are subject to potential liquefaction during strong earthquakes, granular soils rarely present bearing capacity problems. The majority of tank stability problems are associated with silty or clayey soils. Due to the relatively large diameter of most tanks in comparison to the thickness of such layers, a general shear failure is rarely of concern. The main concerns are either a local shear failure at some point around the shell, or plastic flow or creep of soil from under the tank. Common and relatively simple methods for assessing the factor of safety against shear failure are shown in **Figure 2**. The analysis is a "search for the minimum factor of safety" exercise involving calculation of shearing resistance for a number of circular areas with their centroids located along the tank shell. Somewhat more complex methods involving bearing capacity theory are covered in **Reference 1**. Computer methods for slope stability analysis can also be used.

A minimum factor of safety against bearing capacity failure of 1.5 is desirable under hydrotest conditions. The geotechnical engineer, however, may permit a lower factor of safety depending on the quality of the soils investigation done, experience with soil behavior at the site, controls on loading rate and foundation behavior monitoring during hydrotest, and other factors.

In some cases, plastic flow of soil may be the limiting design condition. This normally is the case when a relatively thin (in comparison with the tank diameter) soft cohesive layer underlies a firm soil layer. Plastic flow is a time-dependent lateral movement of soil from beneath the tank, which can occur if the soft layer is overstressed. Methods for assessing plastic flow are covered in **Reference 2**.

TANK SETTLEMENT

It is important to keep in mind that tanks can tolerate more settlement than most structures and refinery process equipment. Also, it is very important to distinguish between shell settlements and bottom settlements.

Uniform soil conditions result in uniform settlement around the tank shell, and a uniform pattern of settlement across the tank bottom. Assuming uniform soil conditions, tanks can accommodate large settlements without distress. Also assuming uniform soil conditions, and an adequate factor of safety on bearing capacity, the center of a tank will settle more than the shell, and thus there is a differential settlement between the center and the shell. This particular differential settlement, however, is relatively unimportant to tank behavior as long as settlements are less than 12 in. (300 mm) at the shell.

While shell and center settlements are relatively easy to calculate, differential settlements around the shell and across the bottom are not. This is because the soils investigation normally does not provide sufficient data, and it would be uneconomical to drill the large number of borings required. It is this differential settlement, however, which is of primary importance in tank performance. Research done at Exxon Research & Engineering Company has resulted in development of criteria for total shell settlement, which if respected, will generally ensure that differential settlements are within acceptable limits. These criteria, along with corresponding tank design requirements, are provided in **IP 9-4-1**. A more thorough discussion of tank settlement patterns and their effect on the tank is provided in the Exxon TANK MAINTENANCE GUIDE. In general, however, shell settlements can be categorized into three groups.

- **Uniform Shell Settlement** - the shell settles evenly so that the structure remains level. This type of settlement does not stress the shell and does not require correction as long as the tank pad and piping connections are not adversely affected.
- **Planar Tilt** - the shell settles differentially, but remains in a plane. This planar tilt does not normally have a serious affect on the integrity or operation of the tank, and consequently is seldom a problem.
- **Differential Shell Settlement** - the shell settles but does not remain in either a level or tilted planar condition. This type of settlement is not normally detrimental from a structural standpoint as long as the foundation is adequate, but does have the effect of distorting the tank. In a floating roof tank, this distortion can cause roof binding or a loss of seal around the roof.

These types of settlement are illustrated on **Figures 3** through **5**.

Regarding bottom settlements, as indicated above these are normally not a problem if soil conditions are uniform, as a uniform pattern of settlement across the bottom then develops. Deviations from this uniform pattern of settlement, however, can cause excessive bottom stresses to develop. The pattern of settlement across the tank bottom is not usually predicted during the foundation design stage, due to limitations on the amount of data that can practically be acquired. However, steps should be taken during foundation preparation to minimize the potential for non-uniform bottom settlements (see next section), and the pattern of bottom settlements should be checked periodically when the tank is out of service. Again, the TANK MAINTENANCE GUIDE covers this subject in detail.



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FOUNDATION DESIGN (Cont)

If excessive settlements are expected, ER&E's practice is to perform soil improvement such that settlement estimates are reduced to an acceptable level. Currently, settlements are considered excessive if:

- They are expected to exceed 12 in. (300 mm) at the shell.
- They are expected to distort the tank sufficiently to necessitate tank releveing.

This practice evolved from research work done in response to some tank failures which occurred in the late 1960s.

LOSS OF SUPPORT

Loss of support for the tank normally means loss of pad or subsurface soil due to erosion. Ways in which erosion can occur include:

- Storm action, where water flows down the tank shell and over the pad, or flows stream-fashion adjacent to the pad.
- Tank leakage, where fluid escaping from the tank (usually through the bottom) exits the pad and carries pad material with it.
- Sewer leakage, where a sewer line under the tank allows infiltration of soil which is carried away by the sewer flow.

Of these, the first two are accommodated reasonably well by the tank pad provided in [IP 4-8-1](#). Erosion by storm action is protected against by a paving material on the exposed pad surfaces. Erosion by tank leakage is protected against by providing a pervious layer [4 in. (100 mm) of crushed stone] and a leak detection system. The pervious layer can accept leakage and conduct it to the leak detection sump, and the impervious material below this layer (often a synthetic membrane) can prevent leakage from reaching lower materials in the pad or subsoil. Further, tank leakage is rare, and hopefully will be noticed in routine inspections. Erosion due to storm action usually occurs rather slowly, and can be noticed and repaired before it becomes a problem.

Erosion due to sewer leakage can be catastrophic, as a large amount of material can be removed quickly. Fortunately this is rare, as active sewers beneath tanks are rare. A recent case, however, would have resulted in failure of a new tank during hydrotest had the problem not been noticed and corrected. A sewer line was known to exist beneath the tank site, and decommissioning and grouting were planned. Before this work was done, however, hidden sewer damage initiated infiltration and loss of material beneath the tank, and a large void developed. To guard against such occurrences, sewer lines should be identified and decommissioned or rerouted early in the foundation preparation stage of the project. In addition, decommissioned sewer lines should be grouted.

Another way in which support for the tank can be lost is through soil liquefaction. Liquefaction is the loss of strength of soil under earthquake vibrations. Susceptible soils are generally saturated sands and silty/clayey sands in the loose to medium dense range of relative density. A liquefaction assessment is a specialized task which should be carried out by a geotechnical engineer. The need for such an assessment should be considered in earthquake prone areas.

FOUNDATION CONSTRUCTION

Foundation construction as considered herein includes any improvement of subsoils, as well as construction of the tank pad itself.

Regarding improvement of subsoils, the need for general subsoil improvement should be identified via the geotechnical investigation at the site, and from assessments of settlement and bearing capacity. If excessive settlement is predicted, or the bearing capacity factor of safety is too low, then subsoil improvement must be designed to overcome these shortcomings. The two most common methods of subsoil improvement are excavation of poor soil and backfilling with structural fill, and preloading the tank site with soil to remove settlement and strengthen subsoils before the tank itself is built.

Some consultants promote the use of slow hydrotesting of the tank to accomplish soil improvement. In essence, this is using the tank and the water in it as a substitute for a soil preload. ER&E does not recommend this practice due to the stresses and distortions which can be imparted on the tank. Also, soil improvement by installation of stone columns is sometimes suggested. Numerous uncertainties exist with stone columns under tanks, and their use should be avoided in favor of other improvement methods.

Regardless of whether or not general subsoil improvement is required, the need for local subsoil improvement should be checked at all tank sites during early construction activities. As indicated earlier, the geotechnical investigation could easily miss localized pockets of poor soil which could be important to tank performance. Such pockets, if existing near ground surface, can often be detected by observation during any clearing and grubbing activities required, and by proofrolling the tank site once such stripping work is done. Proofrolling involves driving a heavy piece of construction equipment (such as a loaded dump truck or a heavy compactor) over the full tank area, and observing the soil action under this weight. Wave action or walking of the soil normally means a soft spot exists, and these should be excavated and replaced with structural fill. Observation of subsoil action during proofrolling should be done by a geotechnical engineer or some other person experienced with earthwork and soil behavior.

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FOUNDATION CONSTRUCTION (Cont)

Tank pad construction involves placement of a number of different materials, each of which has a specific function. It is important that:

- Materials specified in [IP 4-8-1](#) be used. Any material substitutions contemplated should be approved by ER&E or a geotechnical engineer experienced with tank pad function and construction.
- Materials be placed using controlled lifts, and compacted to specified levels using compaction equipment appropriate for the particular material at hand.
- Specified pad tolerances be met.
- Detailed construction records be kept. This will be covered in more depth in the next section.

Figure 6 shows a typical tank pad, along with information on the function of various materials.

Regarding pad tolerances, of particular importance is the area of the pad which will support the tank shell. If this area is out of tolerance, then shell plate fit-up problems and tank distortion during construction can result. While the specified tolerances ([IP 4-8-1](#)) are tight, they can definitely be achieved with a diligent effort from the pad constructor. A simple procedure which has proven effective in the past is:

- Place the 4 in. (10 cm) crushed stone layer (**Figure 6**) nearly to design elevation.
- Choke voids in this layer with finer crushed material, such as ASTM 448 Size No. 9, and overbuild somewhat using this finer material. (Use of this finer material also helps guard against point contacts of coarse stone against steel, which are undesirable from a corrosion viewpoint.)
- Trim down to design elevation.

Another technique which can be used involves finishing the pad at the shell with a layer of mortar. In this case, the 4 in. crushed stone layer would be placed to approximately design elevation, then partially excavated to accept a mortar layer centered at the shell. Maximum dimensions of the mortar layer should be 1 ft wide x 2 in. (30 cm x 5 cm) thick. It should be either unreinforced or fiber reinforced, but not mesh or bar reinforced.

Another material in the pad which sometimes causes construction difficulty is the oiled sand layer. This material can be prepared by premixing the oil and sand, and then transporting to the pad for placement, but this sometimes requires special mixing and handling equipment. Alternatively, it is sometimes easier to place the sand first, and then spray-apply the oil. Test patches should be used to ensure that the oil will penetrate the sand to a 2 in. (5 cm) depth, and to determine the amount of oil required for this penetration.

CONSTRUCTION MONITORING AND RECORDS

Construction monitoring and records are extremely important during all phases of foundation construction. Monitoring and records not only tend to ensure compliance with specifications, but they can be invaluable in troubleshooting if tank problems arise, or in dealing with contractual disputes if different parties are involved with foundation construction and tank construction. Examples of types of records which have proven valuable in the past include:

- Excavation locations, depths, volume estimate, dates, weather conditions, inspector involved, and any relevant comments/observations.
- Compaction test information, including test results, lift number, lift thickness, soil type, specification requirements, dates, inspector, weather conditions, type of compactor, maximum Proctor density and optimum moisture content for the fill material being used, comments/observations. For materials being placed and compacted which aren't easily tested for compaction, such as some crushed stone ringwall materials, record number of compactor passes as well.
- Elevation data for the finished pad, including dates, surveyor, reference datum, elevation point locations, and sketches. Of particular importance is the pad at the tank shell. A careful survey by a licensed surveyor should always be conducted around the shell at completion of pad construction (before accepting the pad from the pad builder) and just prior to the start of tank construction. These surveys ensure that the pad builder has met the specification tolerances, and set the basis for future settlement surveys. Further, they can be invaluable in settling contractual disputes. Serious problems have arisen in the past when pad and tank construction was done by different contractors, and the condition/configuration of the pad was not properly determined at turnover of the pad to the tank erector.

Regarding elevation surveys, it is emphasized that surveys should always be referenced to a permanent datum, and not to some arbitrary datum set up for the particular survey being done. There are numerous examples of successive surveys being referenced to different arbitrary datums, thus resulting in elevations which are not comparable and are relatively useless.