

THE ENGINEERING EQUIPMENT AND MATERIALS USERS' ASSOCIATION

Prevention of tank bottom leakage

**A guide for the design and repair of
foundations and bottoms of vertical,
cylindrical, steel storage tanks**

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Foreword

The prevention of ground and ground water pollution from leaking storage tanks containing oil or chemical feedstocks or products is of primary importance, particularly in areas with a large number of storage facilities. Where such facilities are near to rivers and other waterways there is an additional risk of pollution being spread and affecting a wider natural environment. Also, leakage is a financial loss to the owner.

National and local authorities are becoming increasingly environmentally conscious, and various countries have introduced, or are introducing, statutory regulations aimed at minimising the risk of such pollution.

The EEMUA Storage Tanks Technical Committee considered that there was a lack of guidance in this area and has therefore developed this Publication to meet that need. This Guide addresses the problem of leakage from vertical cylindrical tanks constructed of plain carbon steels and caused by loss of integrity. Such loss is almost always caused by deterioration of the tank bottom, which itself may be caused by corrosion or by deterioration of the foundation. Therefore, the guidance given is aimed exclusively at preserving the integrity of tank bottoms.

Tanks of special design and those built of stainless steel or non-ferrous materials are not covered in this Guide, although many of the recommendations contained herein would be applicable to those types. Neither does the Guide cover spillages due to mal-operation.

A list of standards and other publications referred to in the text is given in the References at the back of the Publication.

Note on Terminology

The terms 'tank system' and stored 'product' are used in the text. **Tank system** means the entire tank and its foundation. Stored **product** refers to whatever oil or chemical is stored in the tank, including feedstocks.

1. Introduction and Scope

1.1 Background

Experience has shown that the bottoms of vertical cylindrical steel storage tanks used for oil and chemical products are the most vulnerable part of the structure. It is obvious that the risk of bottom leakage increases with the age of a tank. Statistical correlation between age and risk of leakage, based on data from BP and the American Petroleum Institute (API), is illustrated in Figure 1.

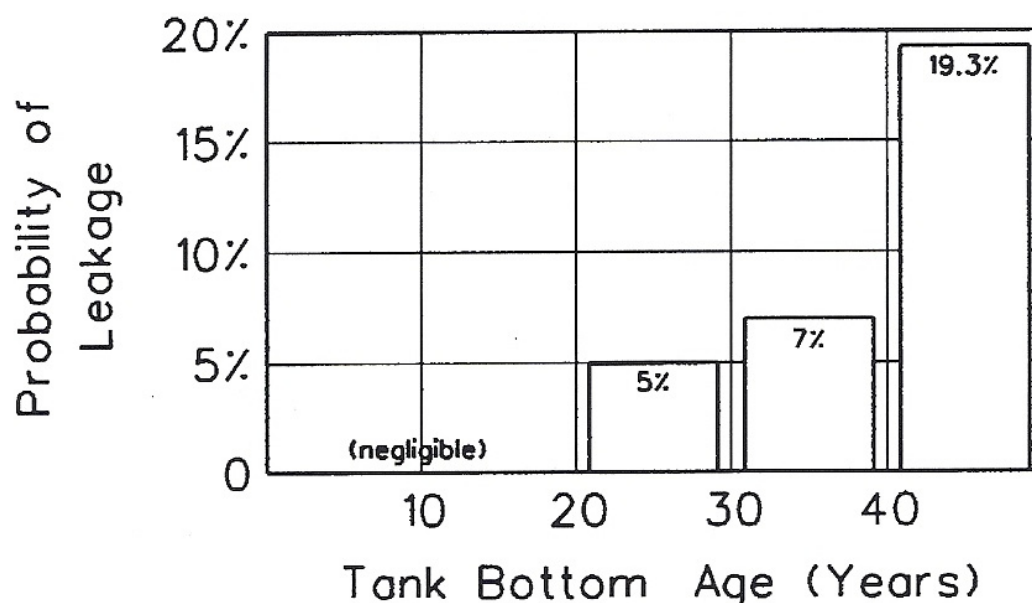


Figure 1 Probability of leakage from tank bottoms plotted against age

Leaking tank bottoms may allow the stored product to penetrate into the tank foundation, the subsoil or even into ground water. If leaks are not detected at an early stage and remedial action taken, serious environmental pollution may result. The prevention and detection of leaks are therefore of high importance, and greater attention is being given to this area by industry and regulatory authorities.

Various methods for under-tank leak detection and ground/ground water protection are increasingly being employed, and in some countries may even be mandatory under certain conditions. However, it is generally considered that the provision of special under-tank leak detection systems should be limited to tanks containing hazardous products. Products such as wax, bitumen, sulphur, etc., that would solidify outside of a heated tank and thus not permeate into the subsoil, are classified as non-environmentally hazardous.

1.2 Legislation and Available Standards Pertaining to Ground/Ground Water Pollution

Examples of legal and/or regulatory developments in Europe, Japan and the United States are:

- **UK.** Highly Flammable Liquids and Liquefied Petroleum Gases Regulations (SI 1972 No. 917); The Storage of Flammable Liquids in Tanks (HSG 176).
- **Belgium.** Non-statutory regulations - 'Vlaem II' document.

- **Germany.** Legislation governs inspection intervals and requirements for double bottom tanks.
- **The Netherlands.** Regulatory (non-statutory) NRB: 2001 “Nederlandse Richtlijn Bodembescherming” developed by Deltalinqs (a body concerned with, among other things, safety and environmental matters in the Rotterdam Europoort area).
- **Japan.** Legislation governs inspection intervals and the mean thickness of bottom plates (with retirement/replacement criteria).
- **USA.** American Petroleum Institute Publication 340⁽¹⁾.

The trend in legislative requirements for minimising the risk of leakage from tank bottoms makes it convenient to divide storage tanks into four categories or classes with respect to the integrity of the tank bottoms, as set out in Table 1.

Table 1 Tank bottom integrity classification

Class	Remarks	Sketch
1	‘Traditional’ (as defined in 2.2). No ‘second line of defence’ (see 7.2.1).	Labels: Shell, Grade level, Tank bottom, Granular soil pad
2	Improved traditional. No well defined second line of defence; integrity not quantified.	Labels: Free draining layer, Lower permeability soil
3	Engineered containment. Integrity cannot be checked in service.	Labels: Free draining layer, Geomembrane (or double bottom)
4	Monitored containment. Integrity can be checked in service.	Labels: To vacuum system, Vacuum gauge, Double steel bottom and void space

Figure 2 consists of two plots of tank bottom integrity class against the consequence of failure. In the left hand graph the legal limits imposed on integrity class in Germany and Switzerland (which have similar requirements) and in the US are shown as bold horizontal lines. Integrity classes below these lines are not permitted for new tanks for oil and chemical products in the countries concerned. The right hand graph is a conventional plot of integrity against consequence of failure. This may be used as a guide where the legislative requirements do not dictate otherwise.

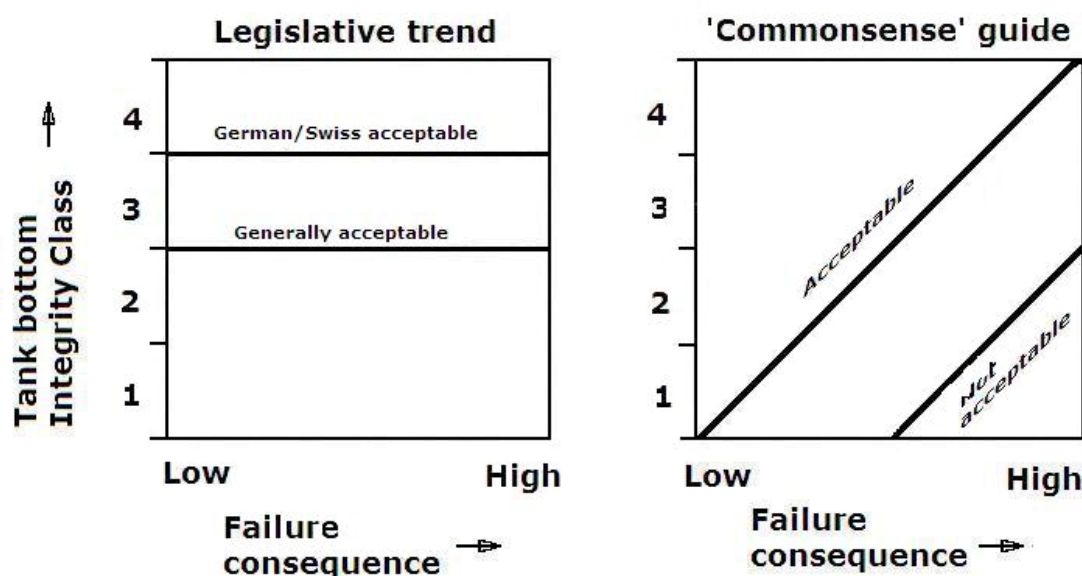


Figure 2 Acceptability of Tank Bottom Integrity Class with respect to Consequence of Failure

The effects of globalisation on both industry and legislative bodies have led to a growth of interest in environmental protective measures. This in turn has influenced the establishment of regional (European) and global guidance documents on safeguarding the environment when affected by industrial growth. Some of these guidelines covering protection of soil and ground water can be found in the References⁽²⁾⁽³⁾.

1.3 Scope

This Publication gives guidance on a range of topics affecting tank bottom integrity including:

- Types of tank foundations (including guidelines for required soil investigations, design and installation of tank foundations and specifications of suitable materials) and bottoms (single and double) — selection, advantages, disadvantages.
- Main causes of bottom leakage — settlement, corrosion.
- Records.
- Inspection techniques.
- Corrosion protection — coatings, linings, cathodic protection.
- Repair methods.
- Leak detection systems.
- Membranes as soil barriers.

Appendices are included covering typical foundation details, tank records flow chart, comparison of systems for preventing leakage, and flow charts to assist in the repair decision process.

2. Tank Foundations: General Design Considerations

2.1 General

Because of the wide variety of surface, sub-surface and climatic conditions at tank locations it is not possible to prescribe a single type of foundation design. However, it is common practice to build tanks on the following foundation types:

- sand pad;
- sand pad with annular ring of coarse granular material;
- concrete ring wall;
- concrete raft under the entire tank; and
- piled concrete raft.

Irrespective of the type of foundation chosen for a particular tank, all tank foundations should be designed based on the principal functions and requirements listed below.

The functions of a tank foundation are:

- To spread and transfer the load from the tank and its contents via the tank foundation and shoulder to the sub-grade so that the resulting ultimately expected settlements, both total and differential, remain within allowable limits.
- To raise the tank bottom above ground water, capillary water, surface water and minor spillages.
- To provide a smooth surface with sufficient bearing capacity and stability for tank construction and operation.
- To channel rain water away from the tank shell and tank bottom quickly.
- To provide a raised elevation to the tank base in order to enhance the net positive suction head of pumps.

The requirements of the shoulder to the tank foundations are:

- To provide sufficient lateral support to the tank foundation under all conditions. The shoulder should be capable of providing sufficient lateral support during construction, operating and maintenance activities.
- To resist edge settlement beneath the tank shell.
- To resist wash-out of the tank foundation as a result of tank bottom leakages and possible ingress of water.
- To resist erosion by wind and/or water.

2.2 Sand Pads

Traditionally, most storage tanks were erected on a sand pad, a typical example of which is shown in Figure 3 overleaf. A description of this type of foundation is given in BS 2654: 1989 Appendix I.3⁽⁴⁾ (also see Section 2.3 below).

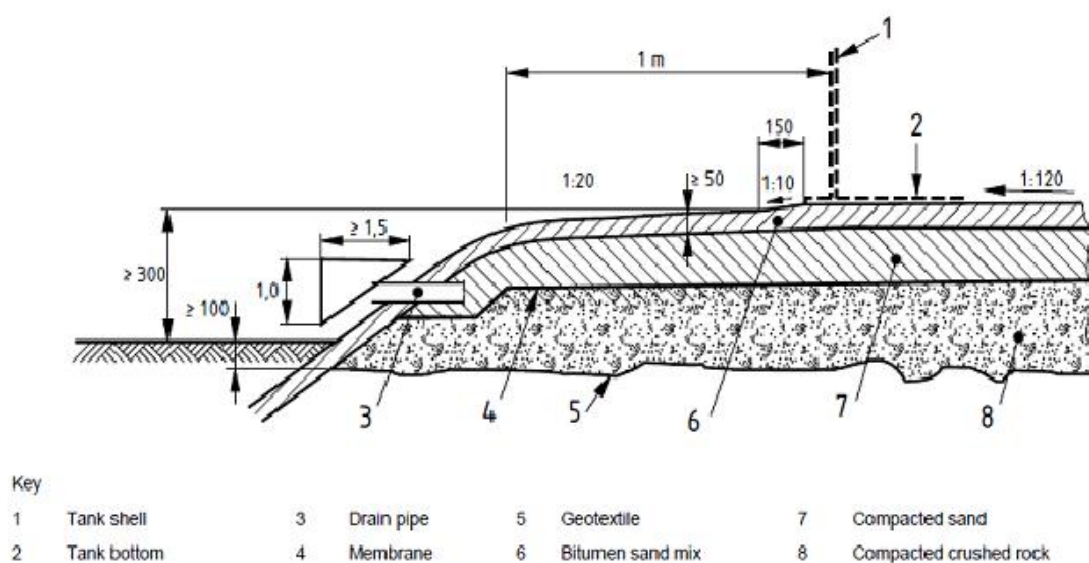


Figure 3 Typical sand pad foundation

Reproduced from EN 14105: 2004 courtesy of British Standards Institution

The EN 14015⁽⁵⁾ standard of 2004 and successor of BS 2654 indicates a similar foundation pad in Appendix VII, Figure I-1.

2.3 Sand Pad with Annular Ring of Coarse Material

Annular rings in coarse materials such as crushed rock or gravel were described in BS 2654, A.3.2 and subsequently repeated in its successor EN 14015, I.4.2 and in API Standard 650⁽⁶⁾, B.4.3. As stated in the former reference, such annular rings may be required to provide high edge-load resistance: when locally available material has insufficient strength if unconfined; to prevent wash-out of fine soils in the event of a bottom leak; and to protect against erosion around the tank perimeter. This design is preferred to ordinary sand pads.

2.4 Concrete Ring Wall

For medium and high pressure tanks as well as for small diameter tanks with relatively large height to diameter ratios, it may be necessary to prevent uplift of the shell due to the combined effects of internal pressure and wind movement, or to earthquake. As stated in BS 2654, A.4.3, or its successor EN 14015, I.4.3, this can be achieved by means of anchoring the shell to a concrete ring wall (or to a raft - see Section 2.5 below). A typical ring wall foundation is shown in Figure 4. For further guidance see also API 650, B.4.2.

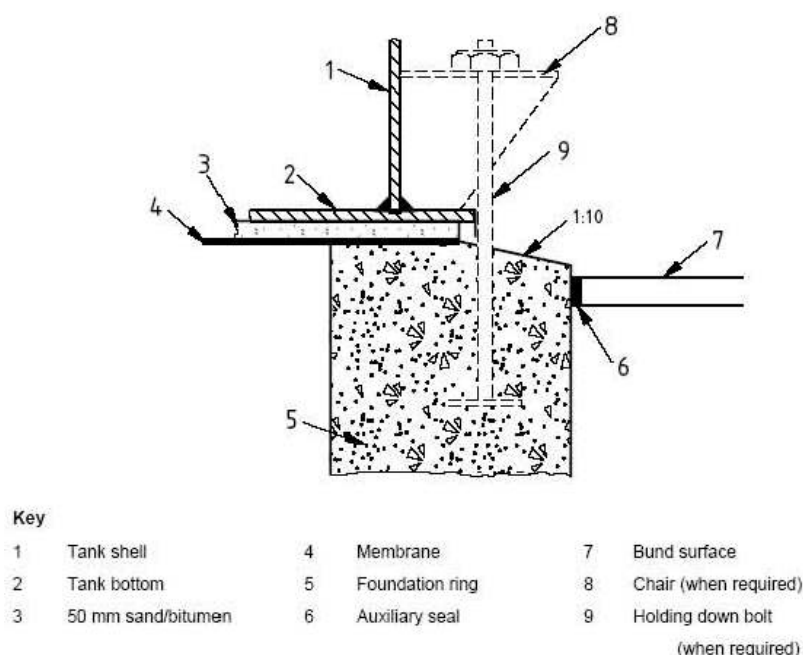


Figure 4 Typical detail of anchorage to concrete ring wall

2.5 Concrete Raft: Plain and Piled Slab

Where poor soil conditions exist, concrete raft foundations may be constructed. Piled foundations will give increased resistance to settlement. Typical designs (with and without piles) are shown in Figure 5.

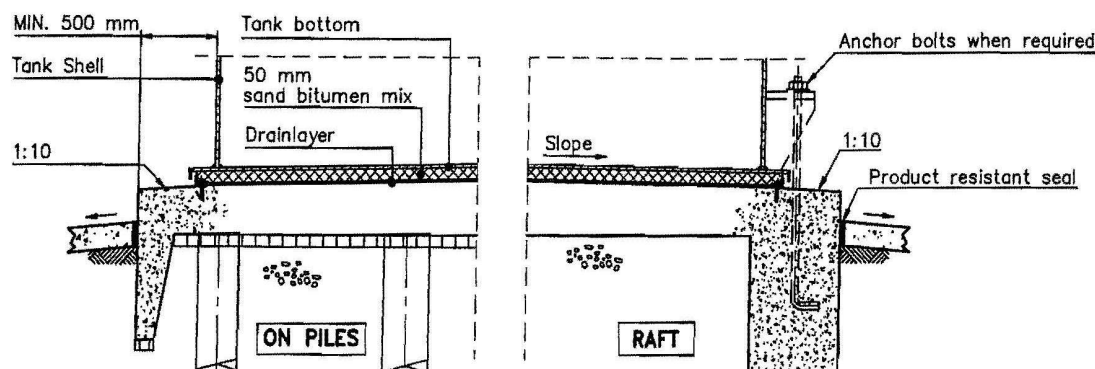


Figure 5 Concrete raft foundations, plain and piled

A concrete raft structure with or without piling, though more costly to build than other foundation types, may be justified in certain circumstances on the basis of very low maintenance costs (both for the foundation and tank structure and fittings). This is due to the inherent resistance of this foundation type to settlement, tilting and alleviating out-of-roundness of the shell (which affects floating roofs and seals), and the protection it gives against underside corrosion. Where long periods in service are required (e.g. airport fuel tanks) such an investment may be justified. This type of foundation could also be a cheaper solution where crushed rock is not available. For more information see the EN 14015, I.4.4.

2.6 Sand Pad Foundation with Crushed Stone 'Piles'

To counter poor sub-soil conditions, sand pad foundations have been built with crushed stone 'piles', that is holes drilled in the sub-soil and filled with crushed rock, with vertical drains incorporated to improve subsoil quality by allowing drainage of surface water deeper into the soil. Stone piles with their high voidage and vertical drains will increase the risk of ground/ground water pollution from leaking tanks by providing good leakage paths deep into the soil. Such designs are not therefore recommended for oil/chemicals storage tanks.

2.7 Design of Tank Foundations

2.7.1 Soil Investigations

The tank foundation profile (e.g. cone up, cone down, flat, dimensions and shoulder) should be chosen in accordance with the stiffness and homogeneity of the underlying soils and the results of settlement and stability calculations. These calculations should be based on the results of a soil investigation. The properties of the existing sub-soil should be thoroughly investigated. These investigations should include a study to establish the history of the site and identify any natural processes or previous development that may influence the characteristics of the ground.

The techniques employed for the soil investigations depend on the characteristics of the site to be investigated. Common methods of investigation include: Cone Penetration Tests (CPT's); bore holes; and *in-situ* and laboratory testing. The purpose of the investigation is to determine the physical, mechanical and chemical properties of the underlying strata.

The required number of CPT's and borings depend on the diameter of the tank and the variation of the sub soil layers. The minimum required number of CPT's and borings is:

- 5 for tanks up to 12.5 m diameter;
- 9 for tanks between 12.5 and 40 m diameter; and
- 13 for tanks with diameters exceeding 40 metre.

The CPT's should be carried out on the tank foundation circumference at interval lengths of approximately 10 m (centre to centre) and one near the centre of the tank, together with one or more borings. The required depth of CPT's and borings normally depends on the tank diameter but should always include the compressible or weak sub-soil layers. As a minimum, the depth of the exploratory holes should be the greater of either the diameter of the tank or 25 m depth. In some instances, further penetration may be prevented before the minimum depth due to increased strength or density of the ground, or due to encountering rock or an obstruction. In such instances the reason for refusal should be determined and this should be reported as reason to terminate the investigation at the reduced depth.

The type and number of laboratory tests should be agreed upon between tank owner and the qualified and accredited geotechnical contractor which has experience with local soils and with tank foundations. This contractor should establish a report that, as a minimum, includes advices on the following:

- Whether it is possible to build the tank according to the required standard or codes at the proposed location.
- Requirements for soil improvements, including the type and extent of soil improvements (see Section 2.7.2).
- The influence of the excavations (if required) and the load of the new tanks on adjacent tanks or structures.
- The influence of wind and earthquakes on the tank, the tank contents, tank foundation and the sub-soil in relation to the possible liquefaction of the sub-soil.
- The time-settlement behaviour of the tank foundation and the tank.
- The required compaction of tank foundation and shoulder.
- The maximum tank height or filling height.
- A proposal for a hydrostatic test scheme, including any restrictions on the filling rate during the hydrostatic test to ensure the stability of the tank and its foundation.

The analysis should take into account the possible effects of increases in pore water pressure, settlement and creep. Details should be given of a monitoring programme to be carried out during the test and the validation exercise to confirm that the performance of the ground is in line with predictions. The monitoring programme should also state the actions that should be taken to ensure the stability of the tank and its foundation system, if limits are exceeded.

2.7.2 Soil Improvements

If calculations show that the ground conditions may produce unacceptable settlements, many well established methods are available to improve the situation. In principle, consideration should be given to the simplest and most cost effective methods of improving the ground conditions. However, where time constraints preclude the least expensive solution, more sophisticated and expensive methods may be required. The design of ground improvement works is a specialist area that requires a thorough understanding of the ground conditions and capabilities of appropriate improvement techniques to ensure the correct solution is adopted. In some instances, ground conditions and/or time constraints will result in a piled foundation.

Preloading of compressible areas through the construction of temporary embankments is a simple and cost effective method of achieving consolidation. Further economies can be achieved if the material used to form the preload embankment comprises of suitable materials that can be re-used in construction upon removal. During construction of the preload embankment and the subsequent settlement period, a monitoring system should be installed. At least three settlement beacons should be installed along the future axis of each foundation. Survey data should be recorded on a regular basis in accordance with a predefined programme to determine settlements. For more sensitive soils, or at proposed locations of critical structures, other parameters may require measurement including pore water pressures, settlements at depth and surface settlement profiles.

The recorded data should be analysed and reference should be made to the predicted consolidation rate. If results indicate the consolidation rate is slower, or the settlements are larger than predicted, measures should be taken to gain a better understanding of the ground condition and settlement characteristics so that modifications can be implemented if necessary. The foundation design can

be verified by monitoring settlements and other specified parameters during the construction and preload period.

The duration of the preload period depends on the sub-soil condition that will dictate the duration of the hydrodynamic period. In some cases, where the calculated preload period is too long, methods of accelerating the settlements by installing vertical drains may be considered. However, this is only permitted at locations where there is no risk of groundwater and soil contaminations with the vertical drain providing a preferential drainage path.

Other alternative solutions to treat poor grounds include the use of special fills e.g. lime or cement stabilisation, ground replacement (excavation of poor material and replacement with compacted suitable materials (see Appendix I)), soil mixing, dynamic compaction, vibro compaction, vibro replacement and pressure grouting. In all cases, the main principles should apply:

- Design of ground improvement system.
- Production of detailed method statement.
- Controlled work including construction trials with quality records produced.
- Monitoring and post treatment compliance testing to verify design.

2.7.3 Design Parameters

2.7.3.1 Tank Foundation

The tank foundation should be designed as a flexible foundation with sufficient strength to ensure that it is capable of:

- Absorbing sub-soil deformations to ensure deformations in the tank base remain within allowable limits.
- Distributing the possible unequal foundation pressures.

The relative rigidity of the tank shell with respect to the bottom slab and the sub-soil should be taken into consideration. Total rigidity of the tank foundation (i.e. a concrete slab or rigid elements in, around and under the tank) should be avoided.

In case anchoring systems would be required to prevent uplift of the tank bottom from its foundation, when tanks are operated under increased internal pressures or when tanks are subject to overturning induced by wind and/or seismic loads, concrete ring wall foundations should substitute the crushed rock foundation type. Guidelines exist for the design of concrete ring wall foundations and the design to be used to assess the structural integrity of these structures⁽⁷⁾.

Under certain circumstances, soil improvements (see Section 2.7.2) under the tank foundation should be considered in order to:

- Provide a foundation with sufficient strength.
- Reduce large differential settlements and total settlements.
- Avoid or reduce earthquake induced liquefaction potential.

The minimum elevation of the tank foundation at the base of the tank should be 0.6 m above the adjacent terrain. The predicted long-term settlement should be added to this value.

Drain pipes should be placed around the circumference of the foundation (if completely closed) as shown in

Figure 6 in order to: (i) allow enclosed water to be withdrawn from the foundation during its compression from loads from the tank; (ii) detect leakages; and (iii) to prevent the build up of pore pressure due to liquid accumulating in the tank pad.

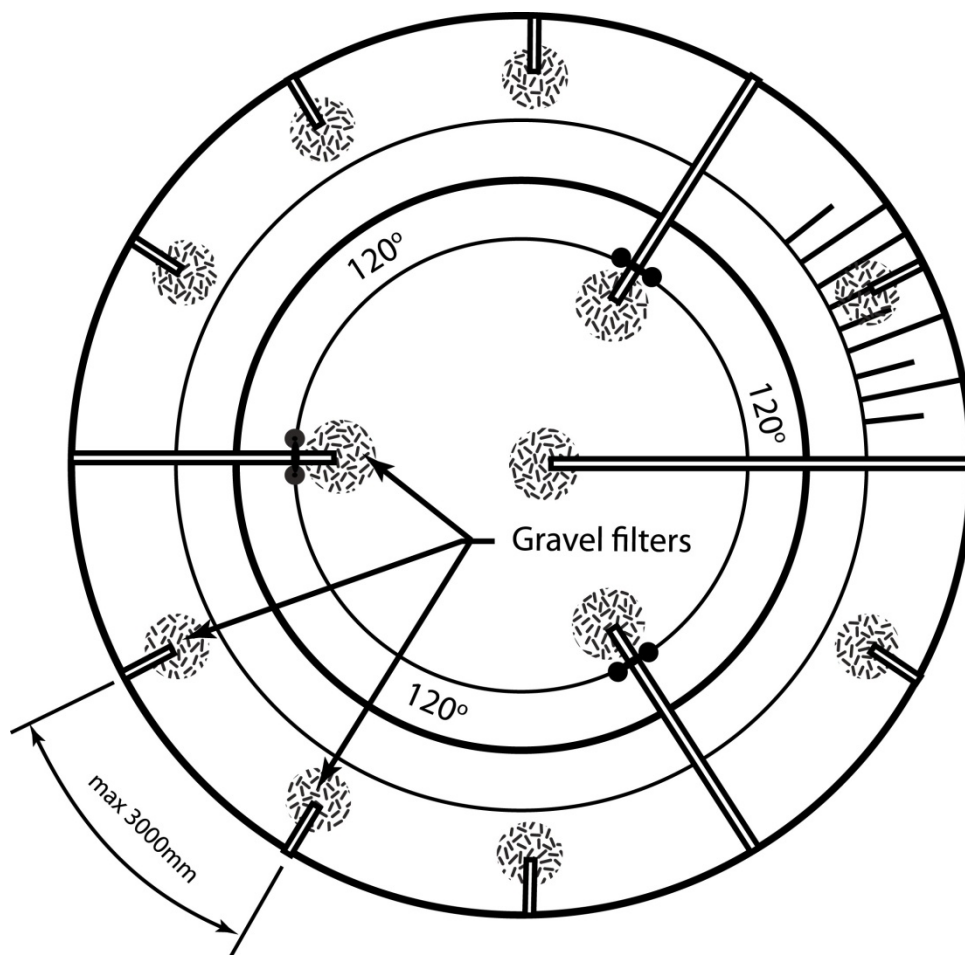


Figure 6 Top view showing drain positions

Geo-textile should be installed under the surface finishing to the shoulder if there is a possibility to wash out of fine materials.

A stability analysis of the shoulder and the tank foundation should take into account the following aspects:

- Wind loads.
- Earthquake loads.
- Blast waves (if so required by local laws).
- Initial height above adjacent ground level.
- Highest possible ground water level.
- Angle of slope of shoulder.
- Geotechnical properties of the tank foundation materials and sub-soil.
- Load provided by the tank and its content during hydrostatic testing, normal operation and maintenance.

The liquefaction potential of the sub-soil due to earthquake or other dynamic load source should be investigated.

2.7.3.2 Foundation Shoulder

The foundation width should be selected so that the stability of the foundation, shoulder and sub-soil should be ensured. The minimum width of the foundation shoulder (S) depends on several aspects:

- Height of the tank (H).
- Diameter of the tank (D).
- Density of the product stored in the tank (for oil products, water filling in hydrostatic test is normative).
- The type of foundation (no crushed stone ring, crushed stone ring or piled etc.).
- Slope of the shoulder edge.
- Height of tank foundation above grade (T).

The following limiting values for the shoulder width and height should be adopted for tanks with various heights:

A) Tank foundations without an annular ring of coarse material (see Table 2).

Table 2 Dimensions of tank with respect to width of shoulder and height of tank foundation (without annular ring)

H[m]	D[m]	S _{Minimum} [m]	T _{Maximum} [m]
10	<15	1.0	1.0
10	>15	1.5	0.9
20	<15	1.5	0.9
20	>15	1.5	0.9

B) Tank foundation with an annular ring of coarse material (see Table 3).

Table 3 Dimensions of tank with respect to width of shoulder and height of tank foundation (with annular ring)

H[m]	D[m]	S _{Minimum} [m]	T _{Maximum} [m]
10	<15	1.0	1.2
10	>15	1.5	1.0
20	<15	1.5	1.0
20	>15	1.5	1.0

The shoulder should have a gradient of 1:20 over the dimension S. Beyond this dimension the slope should not exceed a gradient of 1:1.5 (see also Figure 3).

To properly compact a foundation comprising entirely of sand for a tank with a diameter (D), the width of the foundation during initial construction of the tank and the foundation should be larger than the final dimensions. The minimum dimension during compaction should be: $D + 6 \cdot S$. The tank foundation can be trimmed back to the correct size on completion of the construction of the tank.

For a tank foundation with a crushed stone ring such enlargement is not necessary.

The wide compacted shoulder provides lateral support to the concentrations of stresses in the soil below the tank, see Figure 7:

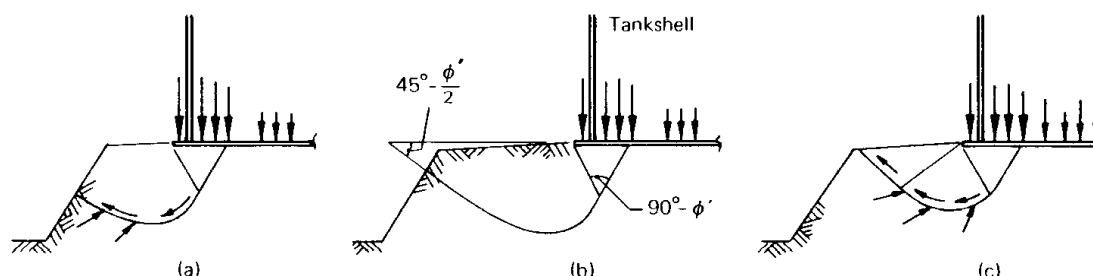


Figure 7 Tank foundation shoulders

- Figure 7(a) illustrates a shoulder that is too narrow, where soil movement under the shell or even a slip failure is likely to occur.
- Figure 7(b) illustrates a shoulder that is wide enough, but not sufficiently compacted. Consequently, the angle of internal friction (ϕ) of the shoulder material is low and a slip failure could occur. Settlements and differential settlements will also be experienced.
- Figure 7(c) illustrates a wide, sufficiently compacted shoulder with no risk of soil movement or a slip failure of the shoulder.

In general, a slope stability failure occurs when the resisting forces are lower than the forces generating the failure (i.e. the factor of safety falls below unity). To reduce the probability of failure, a number of actions can be taken. The shoulder can be widened and thereby the rupture path will be lengthened and more resistance to failure will be achieved. Alternatively, crushed stone that has a high angle of internal friction that results in a higher resistance to slip failure could be used. However, it is possible that a failure may result through the underlying soil, where, although the failure path is longer, the resistance is lower due to the lower angle of internal friction of the soils. Care should be taken in the analysis to ensure that the potential rupture path with the lowest factor of safety is identified and that this meets the minimum design requirements.

Foundation shoulders should be wide enough and properly compacted. In particular, a high density should be achieved through compaction for the material under the annular plate and under the tank shell, as well as a short distance outside the tank footprint to ensure the high concentrations of loads are evenly distributed at a shallow angle through the shoulder and into the underlying soil. This will result in spreading the loads from the tank and its contents and minimising the bearing pressure on the sub-soil. This is especially important on soft silts or clays.

2.7.4 Foundation Materials

2.7.4.1 General

Since the foundation type as described in Section 2.3, above, is the most commonly used and the preferred foundation type, the following additional information is presented with respect to the parameters of the materials to be used in such foundations.

2.7.4.2 Tank Foundation Body

The tank foundation body should be constructed from clean granular materials which meet the following requirements:

- not crushable;
- low compressibility ($C^4_{10} > 500$);
- high friction properties ($\psi' > 35^\circ$, $c' = 0$);
- low silt content ($\leq 10\%$ mass/mass);
- free draining ($k \geq 1 \times 10^{-4}$ m/s);
- insensitive to weathering, oxidation, chemical changes, changes in mechanical properties;
- easy to compact; and
- not sensitive to liquefaction (especially when constructed in earthquake zones).

Well-compacted sand, especially coarse sand, amply meets these requirements providing the chemical and mechanical stability of the minerals is guaranteed. In order to prevent capillary rise of the groundwater the upper 200 mm of the tank foundation should comprise coarse sand.

2.7.4.3 Gravel Backfill under Tank Shell and Annular Plate

A 'foundation ring' for the tank foundation shoulder and a zone under the tank shell and tank bottom constructed from hard crushed rock is preferable to sand. This material is stronger and has a greater resistance to edge settlement and damage during construction and erosion. The specification for crushed stone to be used in tank foundation construction is given in Appendix II-3.

The tank foundation body inside this ring may comprise finer granular materials such as sand. However, a filter cloth (geo-textile) should be installed between the sand body and shoulder material in order to prevent washout.

Granular material as specified for the tank foundation body (see Section 2.7.4.2) may also be used for the 'foundation ring' provided special attention is given to compaction and protection from damage during tank construction. In addition, measures should be taken to ensure the material under the tank shell is not disturbed, as this could result in edge settlement and possible tank deformation or failure.

The use of a concrete ring, in order to prevent edge cutting or to accommodate anchor bolts, requires special attention because poor construction may damage the tank bottom and influence the settlement behaviour of the shell.

2.7.4.4 Tank Foundation Finishes

The purpose of the surface finishing layer under the tank bottom plates is:

- To act as a barrier to corrosion promoted by water or water vapour, together with chemicals which may be present in the tank foundation or subsoil.
- To promote a uniform distribution of stress from the tank bottom to the tank foundation.
- To protect the tank foundation during construction.
- To allow thermal expansion of the tank bottom.

The function of the surface finishes of the tank foundation shoulder is to protect the foundation from damage caused by weathering, erosion and construction, operation and maintenance activities. The tank foundation and covering comprising loose elements or tiles directly on a tank foundation shoulder should be in an optimum condition during hydrostatic testing.

The surface finish layer under the tank should be a mixture of sand and bitumen, or oiled sand for hot ($> 70\text{ }^{\circ}\text{C}$) tanks. The sand of this mixture should be clean and have a low silt content. The exact composition of the dry sand/bitumen mix should be based on the assessment of field trial results. Guidelines for the design and placement of dry sand mixtures are given in Appendix III. Where a sand and bitumen mixture is used, the layer should protrude slightly (approximately 150 mm) beyond the bottom plates of the tank and, after completion of the tank construction and testing, this ring should be filled carefully with bitumen to minimize corrosion of the bottom plates.

The final levels of the placed and compacted surface finishes under the tank edge between any two points 10 m apart around the periphery of the tank should not be greater than $\pm 6\text{ mm}$ and the envelope of peripheral surface levels should lie within 12 mm above to 12 mm below the design levels.

The tank foundation shoulder may, like bund walls, be covered by a mixture of sand, bitumen and cement or lime (i.e. a wet sand mix), a (hot) micro-asphalt mix or, if a light hydrocarbon or chemical spill is likely, a concrete geo-textile.

The surface finish to the shoulder should have a gradient slope of 1 vertical in 10 horizontal from the underside of the annular plate of the tank, to avoid ingress of water under the tank after some tank settlement has occurred. The exact composition, which depends on the sand grain size distribution, particle shape, etc., should be based on the assessment of field trial results. Guidelines for the design and placing of wet sand mixtures are presented in Appendices IV and V.

2.7.5 Construction

Soil investigations should be carried out in accordance with Section 2.7.1.

Soil improvements, if necessary, as well as the placement and compaction of foundation materials should be in accordance with Section 2.7.2. Typical processes for construction of tank foundations are presented in (Appendix VI). During construction of the tank foundation, compliance testing should be performed on each 0.3 m thick layer of placed and compacted material by means of one of the following test methods:

- The Nuclear Density Gauge method. (ASTM D5195⁽⁸⁾ for detailed information and required procedures).
- The core-cutter method⁽⁹⁾.
- Sand replacement method⁽⁹⁾.

The number of compliance tests to be taken **per layer** should be the same as given for the number of CPT's to be taken on completion of the tank foundation outlined in the following table:

- 3 for tanks up to 5 m diameter;
- 5 for tanks between 5 and 25 m diameter;
- 9 for tanks between 25 and 50 m diameter; and
- 13 for tanks with diameters exceeding 50 metres.

When the construction of the tank foundation is completed, verification testing should be carried out to confirm the total tank foundation meets the requirements of the design. The CPT should be used for this verification exercise and should as a minimum extend through the tank foundation material and any underlying strata which may have been subject to ground improvement.

The penetration depth for the verification testing should extend, as a minimum, to the larger of the following values:

- 5 m below the surface of the tank foundation.
- The full extent of the substrata which has been subject to ground improvement.

This is to ensure the engineering properties of the subsoil beneath the tank foundation meet the minimum values adopted in the design. Should the verification test fail to meet the required investigation depth, the reason for refusal should be determined and proposals for corrective action should be established.

Should the recorded results of the verifications tests fail to meet the minimum design values adopted for the tank foundation and the substrata, the reason for the reduced values should be determined and proposals for corrective action should be established.

3. Tank Bottoms: Designs

3.1 General

Materials used for the construction of tanks, including bottoms, should be in accordance with recognised national standards such as BS EN 14015, API 650 or DIN 4119-1⁽¹⁰⁾. The standards also show typical arrangements of tank bottoms which may be with or without annular plates, the latter being typical of small tanks only.

3.2 Tank Bottoms with Annular Plates

Tank bottoms are constructed from rectangular plates surrounded by 'sketch' plates (plates with one end rectangular). In the larger tank sizes (> ca. 12.5 m diameter) there is normally an outer annular ring of segmental plates to which the shell is welded. This type of tank bottom is illustrated in Figure 8 and Figure 9.

However, lap-welded bottom plates directly under the tank shell, albeit accepted by existing design and construction codes (EN 14015 or API 650), may cause weak, vulnerable areas leading to premature failure of the shell-to-bottom connection. It is therefore recommended that bottom plates under the shell be of 8 mm minimum thickness and be butt-welded with or without a backing strip. In the first case the welds should be welded from both sides (top and bottom) and subsequent adequate non-destructive testing, as provided for in the design and construction codes, should be used to assess the structural integrity of these welds.

The use of a completely butt-welded bottom structure for smaller diameter tanks has the cost-effective advantage of allowing good quality-control of welding and of paint/coating application. However, for these small tanks, the thickness of all bottom plates should be at least 8 mm.

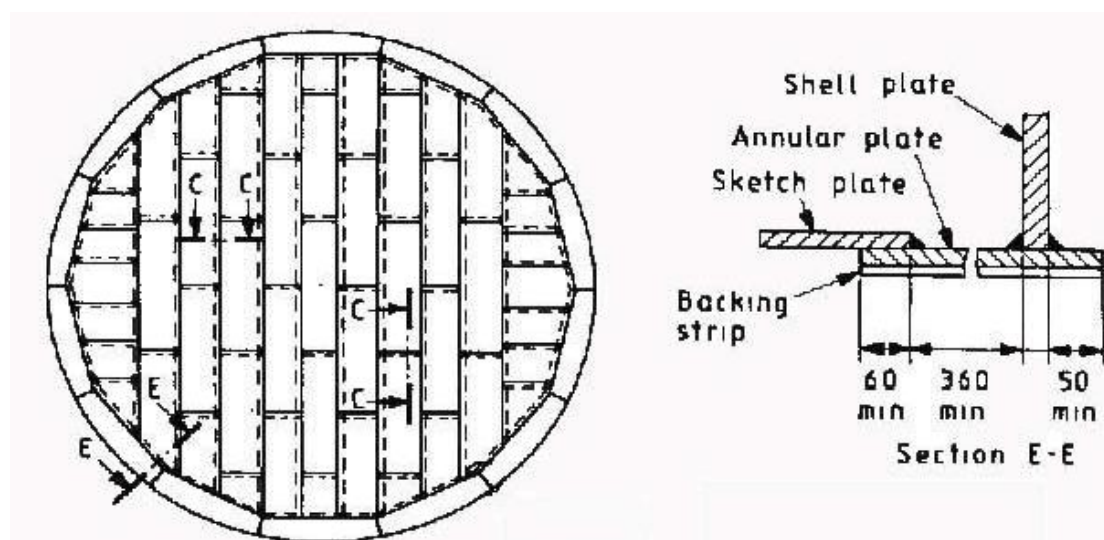
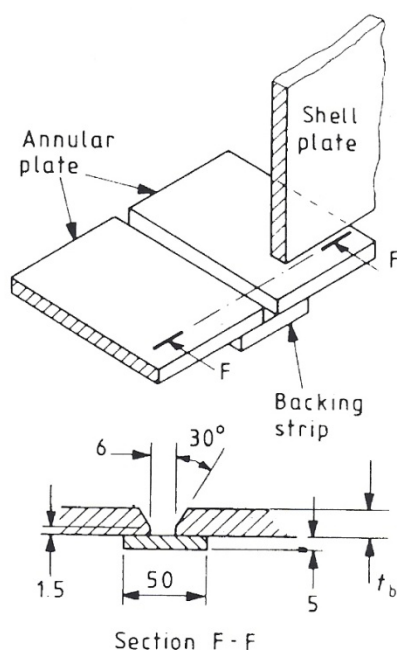
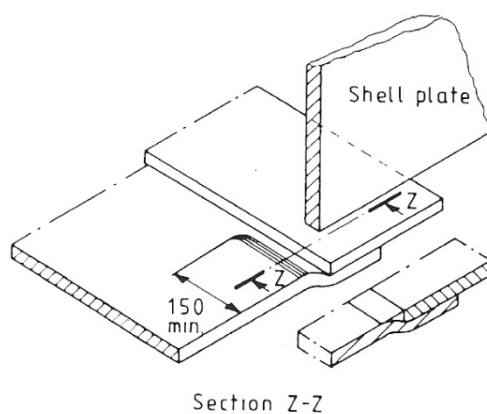


Figure 8 Typical lap jointed bottom layout with annular plates
Reproduced from BS 2654: 1989 courtesy of British Standards Institution



All dimensions are in mm

Figure 9 Butt-welded annular bottom plates



All dimensions are in mm

Figure 10 Lap-welded annular bottom plates

Reproduced from BS 2654: 1989 courtesy of British Standards Institution

3.3 Tank Bottoms without Annular Plates

A typical layout of this type of tank bottom is shown in Figure 11. This design is suitable for smaller tanks (up to ca. 12.5 m dia.) not subject to the risk of internal explosion. Where there is such a risk, bottom plates should be butt-welded (see EEMUA Publication 180: 2007, Edition 2, Section 7.2.4⁽¹¹⁾).

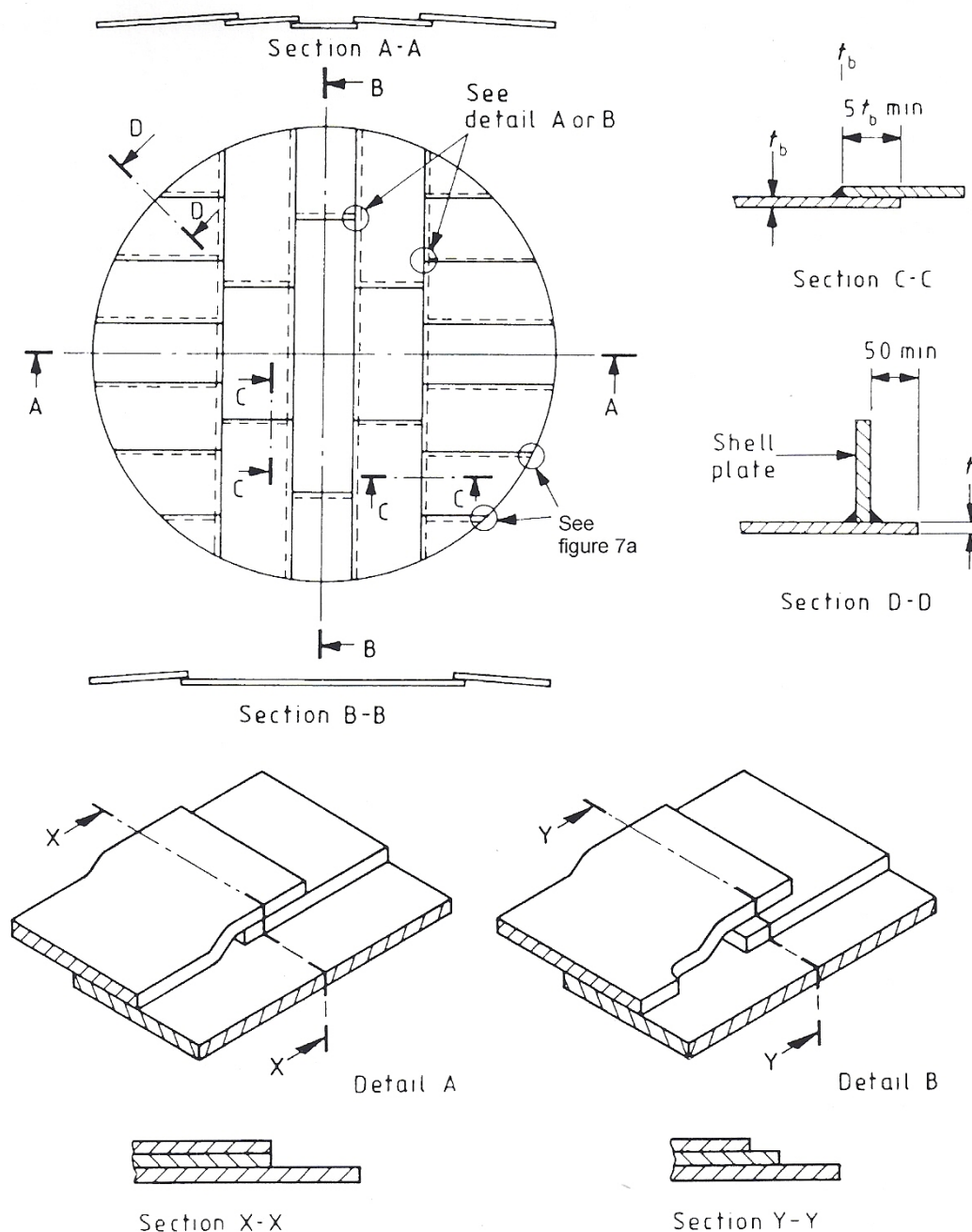


Figure 11 Typical lap jointed bottom layout without annular plates
 Reproduced from BS 2654: 1989 courtesy of British Standards Institution

3.4 Double Bottoms

3.4.1 Double Bottoms in New Tanks

The bottoms of above ground storage tanks can leak as a result of either topside or underside corrosion or a combination of both. Topside corrosion can be detected by standard inspection techniques, but underside corrosion is more difficult to detect. The provision of a double bottom, as described for example in API Standard 650 is one method of achieving under-tank leak detection.

In some European countries the use of double bottom systems is mandatory, but – especially when settlements are to be expected – the use of double bottoms will lead to problems and additional stresses in tank components that are not intended to take up these additional stresses.

In Appendix XI of this document two versions of a double bottom system, as frequently used in some European countries, are shown. In these cases the double bottom is divided in separate compartments and either a leak detection plug is installed that can be taken out to check leakage (see Drawing 1 in Appendix XI) or, in each compartment, a vacuum can be induced. When – due to leakage – the vacuum is reduced or drops out, an alarm system could alert operational staff and the reason for the breakdown of the vacuum can be inspected (see Drawing 2 in Appendix XI).

The committees that propose new tank design and construction codes and standards have based the theory behind the design of tank bottoms on the assumption that tank bottoms do not take up the hydrostatic loads from the stored product. The bottom plates convey these loads immediately to the tank foundation.

At the bottom of the tank shell the radial expansion of the shell, due to liquid pressure, is restrained by the tank bottom. The radial elongation of the bottom itself is very small and can be neglected - mainly due to the friction between the bottom plates and the top layer of the foundation. The restraint of the radial expansion of the shell causes the lowest shell course to rotate. Because the shell forms a rigid unit with the bottom plate directly under the shell, the bottom plate will rotate an equal amount as the lowest shell portion. The rotation of the bottom plate will cause the bottom plate to lift-off from the foundation, as shown in Figure 12. This lift-off continues for some distance inside the tank, until the liquid pressure on the bottom plate balances the rotational moment introduced into the bottom by the rotation of the shell.

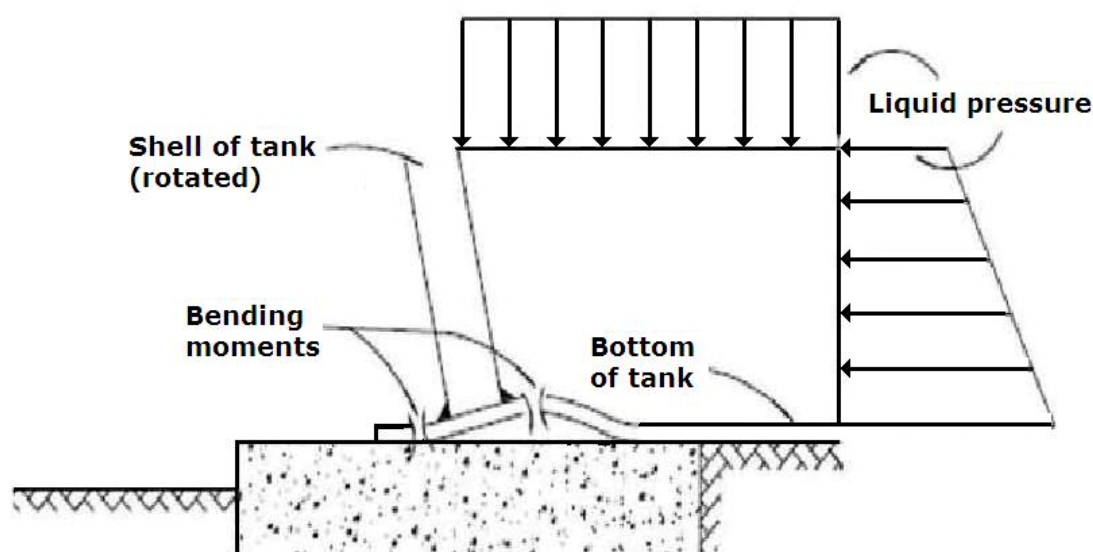


Figure 12 Deflection of tank bottom on a concrete foundation

This rotation of the inner bottom plates just near the shell-to-bottom connection weld should be allowed for within the design of the additional (double) bottom connection. The drawings in Appendix XI indicate that the upper bottom should not be welded straight to the tank shell but an angle bar acts as a flexible tool that allows the tank shell to rotate without introducing additional stresses into the connecting detail of the upper bottom. For this reason each different bottom has different functions. The lowest bottom acts as the main tank component that conveys all loads to the foundation and that rotates near the shell-to-bottom connection. Thus this component is designed to safeguard the structural integrity of the tank. The upper bottom is not taking up any loads or does not convey loads to the foundation. Therefore it can be regarded as a tank component that is safeguarding the operational integrity and acts as a primary leak barrier but-structural wise – it is just of minor importance.

3.4.2 Double Bottoms in Existing Tanks

Figure 13 shows two designs of double bottoms for steel storage tanks reproduced from the API standard (Figs I-4 and I-5).

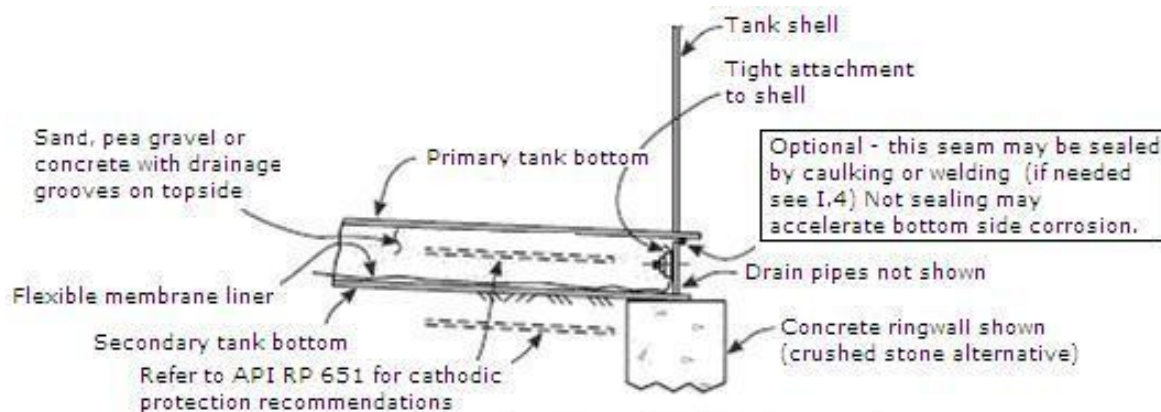


Figure I.4 -Double Steel Bottom with Leak Detection at the Tank Perimeter (Typical Arrangement)

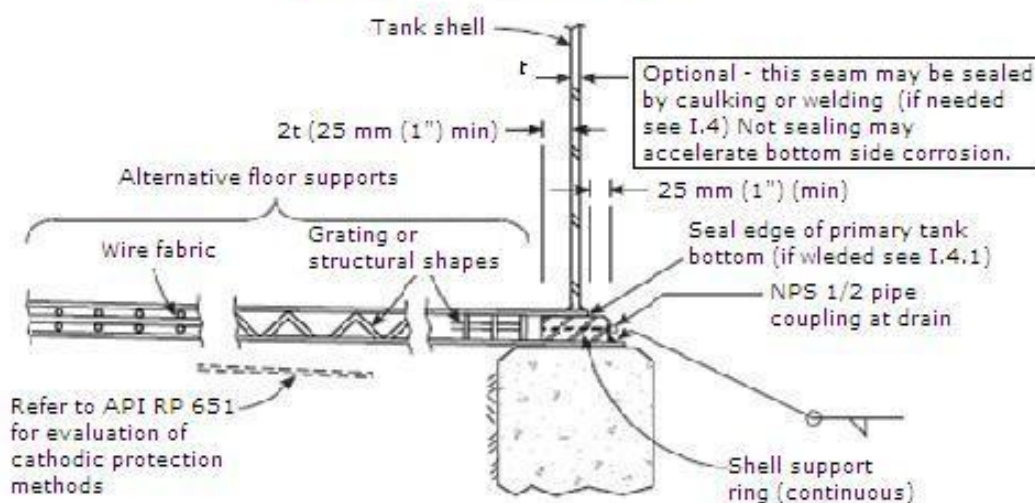


Figure I.5 Double Steel Bottom with Leak Detection at the Tank Perimeter (Typical Arrangement)

Figure 13 Two types of double skin bottoms

Reprinted from API Std. 650 *Welded Steel Tanks for Oil Storage*, 10th Ed., Addendum 3, 2003. Courtesy of the American Petroleum Institute

The double bottom design shown in I-4 of Figure 13 has evolved from what is generally known as the 'letter box' repair method for installing a new bottom in an existing tank. In the past before the advent of leak detection requirements, if a tank bottom was found to be leaking a new bottom was installed about 100 mm above the old bottom by slotting the tank shell progressively around its circumference and sliding in new bottom plates. The space between the old and new bottoms was filled with sand, gravel or concrete. The new bottom was welded to the tank shell with two fillet welds in the same way as the original bottom (see Figure 14).

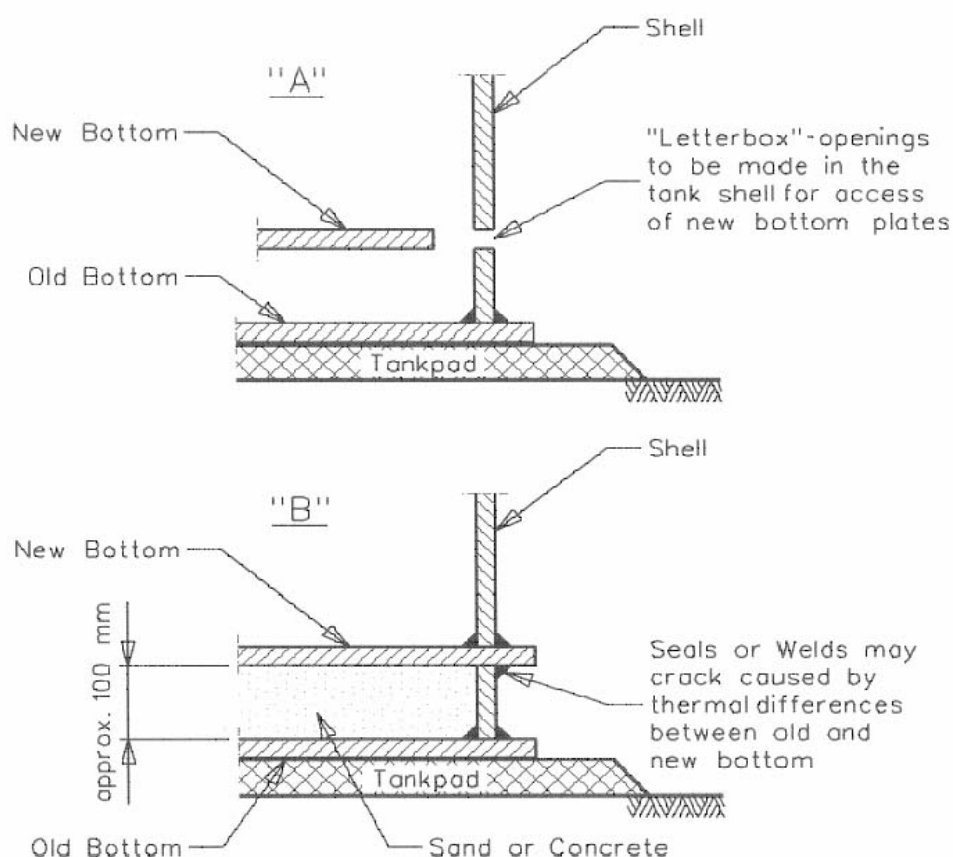


Figure 14 The 'letter box' method

The 'letter box' method of installing a new bottom in a single bottom tank has been in use for small and medium sized tanks constructed from carbon steels in order to cut costs and time for removal of a deteriorated old bottom and installing a new one instead. This method allows the old bottom to stay in place and a new bottom is welded into the tank that should take up both functions:

- the structural integrity part (it should take up and convey all loads to the foundation, and it should deal with the tank shell rotation as explained above); and
- it must safeguard the operational integrity (it must act as a primary leak barrier).

When the new primary bottom is installed, support for it has to be re-established both outside and inside the tank (see API 650 on how to avoid weld cracks) such that the old bottom and intermediate shell section are effectively redundant.

Although API 650 does not specify any requirement to provide support for the new bottom outside the shell, paragraph I.4.1 (API 650) requires proper support of the new bottom and evaluation of the design to verify that the primary bottom and shell are not over-stressed under the specified loading conditions including tank settlement.

I-4 of Figure 13 also shows a flexible membrane liner laid on the secondary bottom before the interspace is filled. This is intended to minimize galvanic coupling between the two bottoms, since corrosion, and therefore leakage, from

the topside of the primary bottom or from the underside of the secondary will be accelerated if galvanic coupling occurs. However it should be noted that when the upper bottom would deteriorate to such an extent that this may also start leaking, the void space between the two bottoms is now filled with a product-contaminated filler material and removal should now be executed in a confined space, making such remedial work even more difficult or dangerous.

I-5 of Figure 13 shows a relatively new type of double steel bottom used in new tanks in some countries. Structural shapes or wire fabrics are installed between the two bottoms to support the primary bottom. These systems need to be applied with caution if significant tank bottom settlement is predicted.

Where not a mandatory requirement, the installation of double bottoms should be carefully evaluated, taking into account the relatively high costs of the design and of the rectification work required when tanks undergo progressive settlement. It may be possible to jack up double bottom tanks in the smaller size range in order to re-level, but this is very costly. Also the lowest bottom cannot be inspected even when the tank is out of service, and consequently its integrity is always questionable.

Leaving the old tank floor even if there is no contact with the newly replaced bottom and constructing a new foundation should not be encouraged. Some users have constructed a >500mm thick crushed stone level. However, if there are any settlement problems, re-levelling will become very difficult.

4. Main Causes of Tank Bottom Leakage

4.1 General

Internal and external corrosion in combination with excessive settlement are often the main causes of bottom leakage. The interface between the tank structure and the foundation as well as the design and construction of the foundation itself are important factors. However, short cuts, cost cutting exercises and inadequate, budget-driven repairs (the consequences of which may be underestimated) are often the culprits identified in tank bottom / foundation failure reports.

Observance of the guidelines set out below, which are based on extensive international experience, will contribute significantly towards achieving safe operation of storage tanks.

4.2 Foundations

The top of the tank foundation should be finished at a level above grade sufficient to avoid any contact between the tank bottom (cone-down) structure and the water table at its maximum level.

A minimum foundation height of 600 mm above grade level of the tank compound or bunded area, measured after the tank hydrotest, is recommended for sand pads and similar foundation types to allow for a maximum cone down height of 300 mm and for future even settlement of the tank. For concrete raft foundations a minimum height of 100 mm is recommended.

Rainwater collecting within the bunded area should be drained off within six hours of each rainstorm or should not be allowed to exceed 5% of the bunded volume. Sand pads and foundations made with a coarse granular fill should be constructed with drains or tell-tale pipes to ensure drainage of water trapped within the foundation.

Note. Cone-up type bottoms/foundations are normally recommended for 'hot' tanks storing products at raised temperatures. Accelerated corrosion of annular plates may occur in this type of tank.

4.3 Settlement

Storage tank/foundation settlement should be monitored and/or inspected on a regular basis as required by Chapter 7 and Appendix B3 of EEMUA Publication 159 Edition 3: 2009⁽¹²⁾. Recommended limits for soil settlement and shell tilt are given in Sections 7.2 to 7.4 of the aforementioned publication.

4.4 Corrosion of Bottom Plates

4.4.1 General

Bottom plate corrosion can occur in various forms of which **general corrosion** and **pitting corrosion** are the most important. These can appear on either side of the bottom plates (internal and external tank corrosion). General underside corrosion should be slight where there is a well prepared and maintained

foundation, e.g. 0.125 mm/year for carbon steel (see EEMUA Publication 159: Edition 3, 2009, Section 4.3.1).

General corrosion, appearing over large areas, causes a regular, slow reduction in bottom plate thickness. Tank standards generally allow a reduction in the thickness of bottom plates (usually made from 6 mm thick plate) to a minimum of 2.5 mm before requiring repairs. With annular ring plates the allowable reduction is half the original plate thickness.

The main causes of internal and external corrosion are listed below.

a) Internal Corrosion

- Presence of aggressive substances or contaminants in the stored product including Sulphate Reducing Bacteria.
- Ingress and accumulation of (rain) water in the tank due to:
 - breathing of the tank due to temperature differences (with the ambient) and condensation of water vapour;
 - presence of water in the stored medium;
 - leakage of rain-water through the floating roof seal, etc.; and
 - poor welding of annular and bottom plates allowing moisture to sit in the weld and corrode the weld locally to the weld imperfection.

b) External Corrosion

- Sub-standard quality of the top layer of the foundation pad.
- Ingress of rain-water by permeation and capillary action due to unevenness in the top of the foundation pad (see Figure 15).
- Corrosion at a water trap formed by mounding of the tank foundation and/or edge settlement (see Figure 16).
- Edge lamination of the annular plates particularly in areas where water and debris collect around the base of the tank.
- Poor welding of annular and bottom plates.
- Inadequate removal of mill scale from bottom plates.

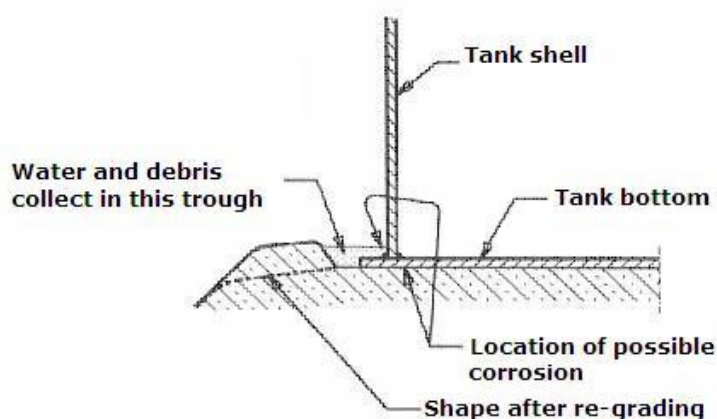


Figure 15 Ingress of water by permeation and capillary action