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TECHNICAL PAPER

INSPECTION AND REPAIR OF STORAGE TANK BOTTOMS AND FOUNDATIONS USING AIRBAG LIFTING

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Abstract

Within the past five years the environmental impact on the operation of petro-chemical product storage tanks containing hydrocarbon or other dangerous goods, constructed to standards such as API 650, has taken on critical implications for refineries, distribution centres and other storers of Dangerous Goods. Pollution of the supporting foundation and possible widespread effects on ground water has resulted in moves to require the installation of secondary containment. That is not to say, necessarily, a tank with two steel bottoms, but alternative means of reducing the failure probability to an acceptable public or statutory level. Compliance with statutory codes such as Dangerous Goods Regulations 2007 dictate that 'impervious' secondary containment is now required. The USA have enacted a raft of legislation with regard to secondary containment this 'mirrored' in EC and other part of the world.

The ongoing quest by engineers is to establish corrosion trends in tanks through inspection by various means however the underfloor has always provided a challenge to ascertain a clear evaluation of deterioration hence, assurance of the integrity of the primary containment.

Clearly, increased inspection of the tank bottom has merit and visual examination of the bottom from inside the tank can be supplemented by ultrasonic methods, acoustic leak detection and magnetic flux scanning. Tank lifting now offers a very cost-effective method for underfloor inspection, combined with the opportunity to undertake repairs to the bottom and underside painting, together with improvements and repairs to the Bit-sand surface of the tank pad. An impervious membrane can also be installed with a leak detection trough formed around the tank edge so rendering the tank compliant and extending its useful life.

In fact, tank lifting using discrete airbags offers the most cost-effective method for lifting tanks off their foundations. When compared with the more conventional system of hydraulic jacking, the airbag method results in some very distinct advantages, apart from a most significant reduction in cost. It is not necessary to weld any attachments to the shell or dig deep pits beneath the annular plate. Site preparation is an absolute minimum, and only requires excavations extending 400mm, under the tank shell by 800mm wide and

30mm deep, at a number of discrete locations. In the case of smaller tanks, say up to 46M (150 feet) diameter, the annular plate can be well clear of the pad within six hours of the lifting crew arriving at site.

Introduction

Due to a small number of accidents resulting in the release of petro-chemical liquids, not necessarily associated with storage tanks, there has been a public outcry by the environmental lobby the results of which could have serious cost implications for operators. Those not fully understanding the subject matter has resulted in hurried legislation which could result in requirements that would virtually be inoperable in the short term if fully enforced by regulatory bodies. Clearly, the industry must respond positively to assuage public concern and regulatory compliance, but in a manner that will clearly be seen as meaningful and positive.

Regular programmed inspection is the obvious first task and this should be based on past historical records to ensure that all aspects of the examination are pertinent to potential sources of product leakage. Past experience has demonstrated quite conclusively that catastrophic shell failure as a consequence of long-term service is most improbable. While corrosion will reduce the shell thickness, any failure will be pre-empted by localised pin hole leaks and provide an adequate safety margin.

However, the tank bottom plates present an entirely different picture since underfloor corrosion has, to date represented a major problem for operators and maintenance engineers with the risks of a leak being present for extended periods without anyone being aware of a problem. Table 9.1 in AS 1940 [3] shows typical inspection schedules required, actual inspection checklists can be based upon API 653 requirements however, care should be excised as some Australian Code requirements differ from the acceptance/rejection criteria from those laid out in API 653 especially with assessment of floor thickness remaining limitations.

It is not unknown for a leaking tank bottom to wash away the foundation to the extent that the static head of liquid can no longer be supported. The bottom plate lap welds will rupture leading to the complete discharge of the contents, almost invariable when the tank is at or close to its maximum capacity. Fears of bottom failure have led to a number of proposals such as building in a double bottom to the tank or installing some form of leak detection membrane beneath the tank. Such actions are not without their own problems such as setting up a galvanic cell or trapping rain water beneath the tank should settlement in the shape of dishing take place.

**Whilst internal inspection of the bottom plates can give a clear picture of what is happening to the upper surface, it requires the use of ultrasonic or magnetic flux methods of examination to assess what may be happening to the bottom surface. Magnetic flux scanning can provide a great deal of useful information in a relatively short period of time, but does nevertheless fall short in a number of critical areas. The greatest by far of these is the inability to address the 'root cause' of the corrosion but only to detect that it is there.
The 'root cause' is invariably the basecourse foundation and in particular debris left on the foundation cap such as welding rod stubs, wood blocks or stones projecting through the cushion layer atop the foundations all of which result in corrosion cells being set up. Lifting the tank clear or its foundation offers what must be the most definitive method of**

underside inspection. Moreover, once the tank has been raised it is then possible to grit blast and paint the bottom and install an impervious membrane if necessary included in the remake of the foundation of the tank.

In what follows the airbag method of tank lifting is described together with recent experiences on a range of tank sizes. The approach is radically different to what some consider as the 'conventional' method, that is, hydraulic jacking. The lifting has been supported by analytical and experimental studies to develop safe procedures for lifting, lowering and restoring tanks and their foundations to a renewed level of integrity compatible with rising environmental requirements and standards adopted in other parts of the world as regulatory requirements currently.

Practical Considerations

Lifting tanks using hydraulic jacks has been looked upon as the conventional method, but requires a great deal of preparatory work, digging either numerous deep pits beneath the tank annular or welding on brackets at about 5-6 m (15-18 ft) intervals around the tank shell to install the hydraulic jacks. In contrast, using airbags it is only necessary to excavate a minimum number of slots extending 400mm (20 inches) under the tank shell by 1m (40 ins) wide and 75-100mm (3-4 ins) deep, at a number of discrete locations. The number of airbags to be used for initial lifting and final lowering requires consideration because of the local increase in compressive stress in the shell. Once the tank is clear of the ground, many more bags can be used to speed up the lifting process.

The variation in the lifting capacity of an airbag is a function of height verses weight; The standard airbag is 850mm (approx 32 ins) square by 25mm (1 in) thick, with a maximum operating air pressure of 9 Barg (125 psi) and an effective lifting height of 150mm (6 ins). As the bag is inflated and the air pressure increases, the lifting capacity also increases; however, a point is reached where the lifting capacity begins to decrease because the bag begins to balloon excessively, thus reducing the total lifting area (i.e, Force = Pressure X Area). Figure 1 shows an inflated airbag in position beneath an elevated tank.

The lifting procedure must follow a set sequence to minimise sideways or rotational movement of the tank as it is raised. This follows from the fact that the airbag is quite flexible. If the tank were simply raised on all the airbags at the same time it would lack rigidity and not maintain position. However, by the same token should the tank move or need to be moved relative to its original position, it is a simple task to pull it to the desired position whilst sitting on the airbags or use the airbags 'differentially' to reposition the tank both laterally and rotationally.

The normal method of lifting is to jack the tank sector by sector, always keeping part of the annular in contact with the wooden stiles that are erected under the tank at it rises. This provides resistance against movement. The lowering sequence is the reverse of the lifting sequence so ensuring that should any movement have occurred, the process is reversed as the tank is lowered.

As stated earlier, it is necessary to cut into the tank pad. Thus, during the final stages of lowering, any area of damage to the tank pad surface or ring beam are made good before the tank is settled to its normal position. The last action is to remove the remaining airbags and make good the small excavations by filling and ramming with Bitsand.

Obviously, where tanks are erected on a concrete ring beam an alternative technique must be used to install the airbag. A method has been developed which allows the tank to be raised the initial 60-75mm (2.5-3ins) locally, to permit installation and removal of a small number of airbags following which additional airbags can be installed. However, it should be noted that lifting over a concrete ring beam is contingent upon the beam having sufficient strength to withstand the increased local loads. This method of initial lifting can also be applied to small and medium sized tanks where the lifting force is less than 240,000 kg (500,000 lbs) providing the shell plate has sufficient local thickness to avoid buckling and so avoid the need to excavate beneath the tank shell.

In addition to the airbags, the only equipment required is:

- **an air compressor**
- **30mm diameter main airlines to feed groups of local regulators and small lines to the airbags,**
- **rectangular timbers to build the support stiles.**

For an isolated and disconnected tank, raising can commence within a few hours of arrival at site.

In spite of having visually inspected the floor welds and discussed past operating history and inspection records with the owner prior to lifting the tank, it is a requirement of API 653 and very strongly recommended that the tank bottom should be vacuum box tested and the annular fillet welds tested after the tank is lowered and before it is returned to service.

Theoretical Considerations of Bottom Deflection and Shell Compression

From classical theory of elasticity, Timoshenko [1], it is possible to predict the deflection of a circular plate subject to a uniform load normal to the surface. This is given by:

$$w = pa^4 / 64K \quad \text{at the centre of the floor} \qquad [1]$$

$$\text{Where } K = Et^3 / 12\,(1 - v^2)$$

In the case of an empty tank, the pressure on the bottom can be equated to the weight per unit area. The predicted deflection and related stresses are many orders of magnitude in excess of what occurs in reality.

Two factors which influence these differences are:

(a) The bottom plates are lap welded and the joints form a series of narrow stiffeners running in both directions across the tank floor.
(b) It is difficult to model the bottom deflection accurately due to the stiffening of the lap weld filler material having a different Young's modulus than the surrounding plate.
(c) There is a stress stiffening effect as the bottom deflects (the bottom can be likened to a drum skin as it is tensioned.

The important point to note in equation [1] is that the deflection is proportional to the radius raised to the power 4. This has implications when considering the response of a floating roof to tank lifting. When the tank bottom is unsupported during lifting, the roof will lose the benefit of support from many of its poles.

With practical information on the deflection of tank bottoms during lifting it is possible to modify the theory to predict the behaviour of the other tanks and thus establish limits for the stresses in the bottom as it deflects.

In addition, one can consider the bottom, when freely suspended from the shell as deflecting into essentially, a saucer shape representing a small element of a very large sphere. From simple algebraic considerations it can be shown that the length of arc is given by :

$$1 = \left\{ \frac{2\pi \sin^{-1}}{180} \left(\frac{D}{D^2/4w + w} \right) \right\} \left(\frac{D^2}{8w} + \frac{w}{2} \right) \qquad [2]$$

where D is the tank diameter. It is a simple matter to calculate the strain and hence the stress in the tank bottom as it is raised. Clearly, the maximum deflection will be influenced by the degree of initial cone-up or down of the bottom. The relationship between stress and deflection can be used in the lifting process to govern the need to install an airbag under the tank bottom if the deflection appears to be going beyond acceptable limits. It should be noted however, that the bottom deflection would also be affected by the extent of slack

plate present due to thermal expansion and throat contraction of the lap welds locked in at the fabrication stage. This can result in predicted theoretical stresses being greater than measured values and which cannot be accounted for reliably.

In addition to the mid-plain stretching of the bottom there will be a bending stress, which is a maximum of the shell to annular joint. Having established from practical lifting cases, the relationship between the true deflection and the theoretical predictions it is possible to modify the theoretical value of edge being movement to calculate the maximum bending stress in the annular or bottom plate. Since the shell to annular joint will have some flexibility, the assumption of a rigid connection will provide an element of conservatism in the predicted maximum stress value.

Under normal operating conditions, the compressive stress in the tank shell is proportional to the height. Once the shell is raised by the airbags, the compressive stress also becomes proportional to the unsupported length resulting in much bigger localised values. These peak stress areas do exhibit increased local radial deflection and could result in local elastic or plastic buckling.

In order to avoid problems with localised stress peaks, the number of lift points must be designed with care. API 650 Appendix E [2] provides design limits for avoiding damage due to earthquake loading. The rocking motion induced in a tank due to seismic activity results in concentrated compressive loading of the shell not unlike that due to lifting. As a safeguard against damage at the lifting locations, analysis is undertaken based on the allowable compressive stresses in API 650 Appendix E to design for a number of airbags to be used in a lift.

Practical Applications

In what follows a number of cases are described together with some of the lessons learned during the activities. The operation of floating roof tanks frequently results in accelerated general corrosion of the mid range strakes, that is to say, strakes ‘washed’ between low and high inventories in normal operations. As the roof rises and falls the rim seals scrape the plate surface and continuously expose a new surface to the corrosion mechanism. This is particularly so in light refined products which do not deposit a protective coating or waxy surface on the shell plate. Once the mid range strakes have corroded to a thickness which is no longer acceptable replacement of the plates rather than demolition and re-building the tank is financially attractive. However, there is little to be achieved if the shell life is extended by many years and the bottom plates cannot be assured to give the same life expectancy. Tank lifting can offer that assurance given that the underside can be inspected, painted, a membrane installed and/or cathodic protected if desired

When tank bottoms have failed or shown extensive deterioration, it has been quite common to install a complete new bottom over the existing plates. This second bottom extends either to the annular plate or is jointed to the shell. The plates may be laid in direct contact with the existing bottom or separated by 75-150mm (3-6 ins) of sand or Bitsand. In either case, subsequent lifting can increase additional problems related to supporting the tank floor. The new inner floor could be braced to avoid deflection but there is not means of supporting the original floor against deflection.

Figure 6 is an example of a 53m (174 ft) diameter by 19m (62 ft) high tank with a column supported roof. The floor had suffered significant corrosion damage and been completely over-plated as a means of repair. Similarly, the roof had severe general corrosion and lost extensive areas of roof plate. This was all indicative of the roof structure also being less than sound although no members had failed. The roof was supported by a total of 31 columns. In the original design, the live load was some four times greater per unit area than the weight of the floor. On this occasion while it may have been possible to brace the floor and roof, the need to lift the old bottom meant that there was no alternative to the use of airbags to raise the tank and support the original floor and roof columns from beneath the tank. To this end airbags were worked under the tank as it lifted from the perimeter and lifting was completed with the floor supported at a number of points such that at no time did the difference in levels between roof support columns exceed 300mm (12 ins).

Experimental Evidence

As a matter of course, when any tank is lifted, the deflection of the bottom is recorded together with its initial position. The same records are taken for the floating roof when this is appropriate together with details of the rolling ladder tracks and any stiffening that the roof may have. Strain gauge testing is also carried out on tank sizes for which no previous results are available. The results are used to confirm the accuracy of the modified theoretical predictions and so enhance the safety associated with lifting using the airbag method.

All of the aforementioned considerations and calculations together with the strain gauging results conducted by Nanyang University of Singapore have cumulated in our ability to develop a computer program to ensure that any size tank whether floating or fixed roof can be lifted without exceeding acceptable stress limitations.

Summary

The application of the airbag method for lifting bulk liquid storage tanks has been described, together with some of the background theory and experimental measurements that have been made to develop a safe and very economical means of raising tanks so that their bottom underside can be examined or foundation pad repaired or complete secondary containment inserted under the tank.

NDT methods are always a ‘compromise’ and address the evaluation of a defect but not the ‘root cause’ or seek to remediate the cause, this can lead to defects caused by foundation debris continuing to manifest themselves in the corrosion of repaired plates on a floor.

Other considerations are those causing settlement problems in storage tanks where the ground bearing capacities have not resisted the forces applied by the tank. Planar tilt and diffential settlement render the tank unusable if this exceeds the limitations in Appendix B of API 653. The lifting of the tank either partially or wholly to insert a ring beam (FIG 1) is required to remediate the settlement.

The merits of this method compared with hydraulic jacking are considerable not least of which are the speed of operation and the reduction in cost. Because the airbags can be used under the floor as well as around the shell there would appear to be no technical limit the size of tank that could be lifted.

BEFORE

AFTER

FIG 1

FIG

FIG 2

FIG 3 – Grit Blast prior to inspection and coating of underfloor

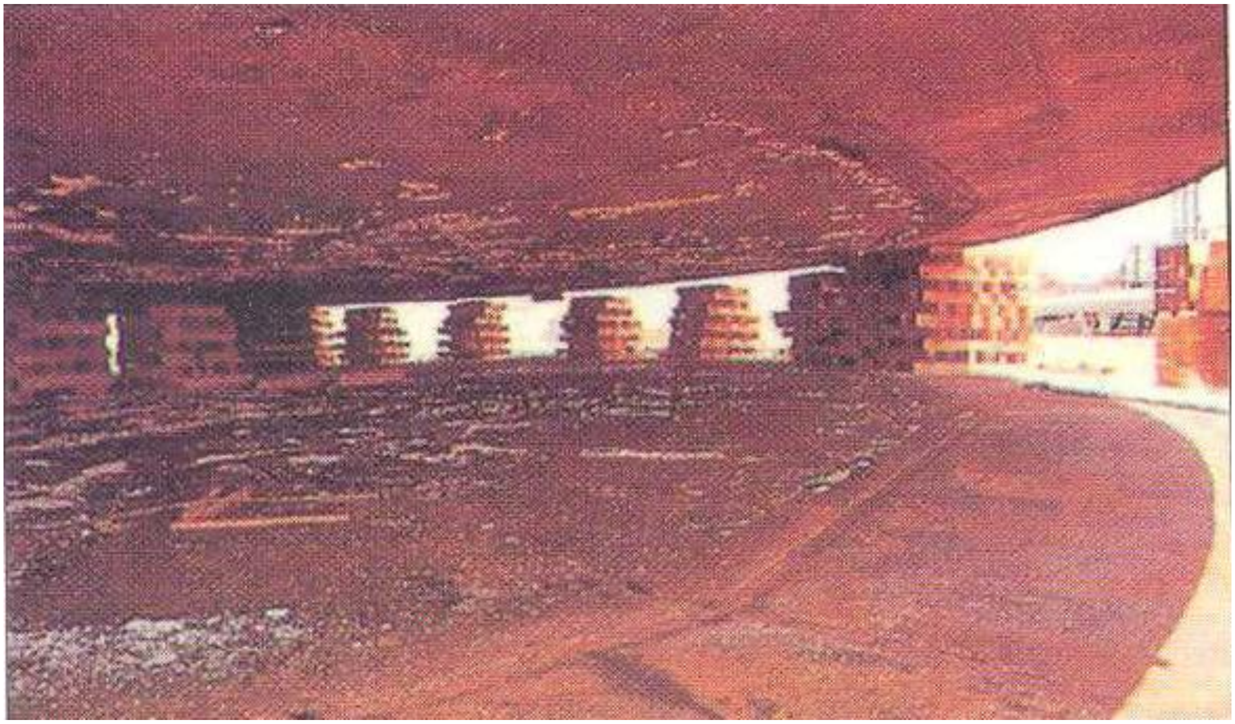

FIG 4 - 23M X 17M Tank Singapore Refining Co. Lifted 2M

FIG 5 Profiling Foundation BP Kewdale

FIG 6 Installation of Leak Detection Sump HMAS STIRLING

FIG 7 HMAS STIRLING

References

1. S Timoshenko, Theory of Plates and Shells, McGraw Hill.

2. API 650

3. NACE 2nd World Tank Conference Paper Wildin/Adams