Failure of Above-ground Storage Tanks (AST): A New Methodology for Assessing Consequences

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The Energy Institute has recently carried out projects to better understand the risks due to failures of Above-ground Storage Tanks (AST) and to develop methodologies for quantifying consequences as a result of AST failures.

ASTs are used widely in the process industries and in mid-to-downstream oil & gas, to store liquid chemical, agricultural and food industry products, as well as liquid hydrocarbons. Individual tanks vary in size from small tanks of around 100 m3 to large tanks which may be of the order 10,000 m3. Smaller works may have just one or two smaller sized tanks; however, large "tank farms" at refineries and fuel oil (petrol, diesel, kerosene) distribution centres may have tens of large tanks on one site.

AST inventories commonly include chemicals and hydrocarbons that are flammable, toxic, or potentially damaging to the environment; and these are typically regulated in Europe by the Seveso III Directive and land use planning regulations. Uncontrolled releases of these inventories would present a range of personnel, business continuity and environmental hazards and proper design, operation and maintenance is required. This includes attention to the secondary and tertiary containment systems, which are required to hold any inventory leaked from the AST due to failure of the primary containment (the structure of the AST itself) or operational shortcomings.

The Energy Institute has carried out a programme of work to provide AST operators and duty holders with tools to determine the consequences of a range of AST failures. In an earlier phase of the work, an FMECA assessment was used to define typical failure modes for ASTs, along with frequencies of failure. These included failures of the ground connection; failures to the vertical sides; and catastrophic failures.

In the current phase of the work (described in this paper) a methodology has been developed based around the FMECA outcomes, to quantify the consequences of AST failures. This determines the force loading on the secondary containment bund wall due to the fluid wave released from a failed AST. It determines whether there is sufficient structural capacity in the bund to withstand the loading, or whether the fluid wave can cause failure of the bund wall. If the loading exceeds the structural capacity of the wall it is assumed that 100% of the AST contents is lost from the secondary containment. The methodology also determines the volume of fluid which can over-top the wall following AST failure, if the bund wall itself remains intact.

The methodology is coded in a simple-to-use Excel spreadsheet and is based on standard (“text book”) equations and empirical models for fluid motion and structural strength. The methodology has been validated with empirical data and computational fluid dynamics model data for a range of typical AST arrangements.

Together, the FMECA and the methodology provide a frequency of failure and indication of the consequence of the failure. These will enable duty holders to make better-informed decisions for AST design and operation; and provide data for risk assessments of these assets.

Keywords: Above-ground storage tank; failure; collapse; secondary containment; bund; overtopping

Introduction

Background

The Energy Institute’s (EI) Containment Systems Working Group (CSWG) has commissioned a project to “Develop failure mode analysis assessment tool for above ground storage tanks – effects of catastrophic failure on secondary containment”. The objective of the project has been to improve the predictive risk assessments for catastrophic Above-ground Storage Tanks (AST) failure, which is required as part of COMAH safety regulations in the UK and other national legislation worldwide. This work aims to provide consistency in the predictive risk assessments and clarity in the required risk reduction measures, which will benefit both operating company and regulator risk analysts. The work has been defined in a number of phases defined by the EI.

Phase 1 of the project focused on catastrophic primary containment failure modes and the factors that affect vulnerability to failure. This work was completed by Arcadis Consulting (Owen, 2017) who developed a guidance document and Microsoft Excel based tool and user guide from the results of a Failure Modes, Events & Criticality Analysis (FMECA) for catastrophic tank collapse. This work is due to be published by the Energy Institute in mid-2019.

Phases 2-4 of the project have recently been completed by the authors of this paper and is described herein. The work has built on the total incident frequency output from the work in Phase 1 and developed a methodology for assessing the consequences of AST failure. The consequences assessed in the methodology are developed from the seven potential AST failure modes determined in Phase 1. Each of these failure modes can result in a hydrodynamic load being applied on the secondary containment wall by the stored fluid escaping the AST. The methodology assesses whether the secondary containment bund is capable of resisting these loads, and whether for specific failure modes, there will be any overtopping.

This paper describes the work undertaken to develop the methodology – this includes the literature search; development of source terms for the hydrodynamic loads; development of the structural model; the methodology tool itself, which is coded in Microsoft Excel; and verification of the tool. The methodology has been reviewed and tested by the Energy Institute's Containment Systems Working Group (CSWG) which comprises owners, operators, consultants and representatives from COMAH Competent Authority. It has also been reviewed by a wider group of similar stakeholders.

Literature Review

Description

A literature review has been carried out which has focused on standards, guidance, regulations and incident reports pertinent to the operation of above-ground storage tanks. Over forty separate documents have been reviewed and the full description of these, together with a ranking for relevance and importance will be included in the final publication of this work by the Energy Institute. The most directly relevant documents for AST operation, AST failures and bund overtopping are summarised here.

Foremost amongst industry documents relevant to this work are the Control of Major Accident Hazards (COMAH) documents, including: the COMAH Competent Authority Workstream – Secondary and Tertiary Containment of Bulk Hazardous Liquids at COMAH Establishments (COMAH Competent Authority, 2010). This sets out the legislative requirements to duty holders at AST sites, as well as design requirement and references for secondary and tertiary containment; bund materials; and applicable British Standards. Also significant in setting out requirements for design and operation of AST sites is the Health & Safety Executive (HSE) Process Safety Leadership Group (PSLG) final report – Safety and Environmental Standards for Fuel Storage Sites (HSE, 2009). This report sets out the implementation of the Buncefield Major Incident Investigation Board final report recommendations including engineering against loss of secondary containment.

To change the focus to understanding consequences of AST failures, and catastrophic loss of containment in particular, HSE Research Report RR333 (Atherton, 2005) provides detailed experimental data from a study carried out at Liverpool John Moore's University (LJMU). In this study laboratory-scale experiments were carried out to test a range of tank catastrophic collapse scenarios and develop data for secondary containment overtopping and bund wall dynamic loading (pressure) data. Thyer et al. (2002) provide a similarly important paper which incorporates a review of experimental studies for tank collapse, theoretical studies and predictive models. The data from this can be used for comparison and verification of other models. However, the studies are based on and provide information for overtopping only, and do not include structural design and potential for structural collapse. A similar but much earlier study to the HSE Research Report RR333 is the work by Greenspan (1981). This contains details of experiments carried out for bund overtopping fractions. This looks at bunds with 90, 60 and 30 degree wall angles and so enhances the RR333 report with data for containment systems with earth bunds.

In more recent years, a number of groups have applied Computational Fluid Dynamics (CFD) modelling to studies of AST failures and catastrophic collapses. Nair (2008) used a CFD model for tank failures looking at three failure modes and compared the results with the RR333 / LJMU data (Atherton, 2005). However, only a single bund arrangement was studied. Trebojevic (1989) carried out a CFD model study for LFG and crude oil spills looking at different bund designs and attempting to define a design load for these. The CFD models Trebojevic used are coarse by today's capabilities, but this shows a willingness to adopt this form of modelling as the best available technology to assess AST failures and design mitigation.

In HSE Research Report RR755, Webber et al (2009) recognised that using full three-dimensional CFD models for AST collapse modelling can be time-consuming and difficult to apply. They developed the SPLOT (Spreading Liquid Over Terrain) model based on the shallow water equations and carried out validation work to understand the limits of the model. The HSL SPLOT model aims to achieve many of the same goals as the proposed EI methodology which we have developed in the current project. However, the SPLOT model relies on a numerical solution of the shallow water equations which makes it less practicable to implement in a simple spreadsheet-type format which can be distributed to third parties. Also, it does not include structural loading issues on the bund wall and the potential for the bund to collapse.

In addition to the published work reviewed in the literature search, MMI Thornton Tomasetti has carried out a range of studies for different clients who operate ASTs and similar storage. Most of these have required CFD modelling to understand the overtopping fraction of the volume of fluid escaping from an AST, and the hydrodynamic force this imparts on the secondary containment bund wall. These studies have covered a range of small to large tanks; with single or multiple tanks within a bound. Although these studies cannot be put into the public domain, they have provided background and understanding to AST failure modelling.

Development of the Methodology

Methodology Principles

An important principle for developing this new methodology to assess AST failures and consequences has been that it should be easily issued to and used by third parties. This has meant that specialist software could not be used and the methodology has been coded in a set of Microsoft Excel spreadsheets. Using Excel also places constraints on the model, in that numerical models with iterative solutions are not straightforward to operate. Instead, empirical models, first-principles and text-book approaches have been used to develop the source term models.

The methodology calculation itself follows these key stages: (i) the user defines the physical parameters for their case (AST dimensions, bund dimensions, stored fluid properties; (ii) the user defines the failure mode; (iii) the users defines the bund structure; (iv) the methodology calculates the hydrodynamic loading on the bund wall due to the escaping fluid; and the volume overtopping the wall (v) the methodology compares the hydrodynamic load with the structural resistance of the bund's foundation and the wall itself. Where the hydrodynamic load exceeds the structural resistance it is assumed that the bund wall fails and there is potential for the completed stored volume of the bund to escape the secondary containment bund.

Failure Modes

Owen (2017) identified seven failure modes for ASTs and calculated a failure frequency for each mode. The seven failure modes that were defined are summarised in Table 1.

Table 1. Definition of failure modes

ID Number	Failure Mode	Failure Definition
1	Rocketing shell	This mode of failure occurs due to a fault in relieving a rapid increase of internal pressure within the tank. The internal pressure becomes so great that a tank uplift occurs, resulting in the tank being propelled upwards but leaving the tank contents to be spilt.
2	Shell / Bottom Failure	This is a failure of the weld between the tank shell and tank bottom. The weld failure would be located at the bottom of the tank, either near the tank wall or directly on the shell / bottom weld joint.
3	Bottom Failure	A breach of the tank bottom causing the product to seep out from underneath the tank. The breach would be located on the bottom plate of the tank, near the tank wall
4	Rapid Shell Failure / Unzipping	Sudden failure of a large proportion of the tank shell, creating large fissures, through which a large volume of product is subsequently released.
5	Medium Shell Failure	A smaller proportion of the tank shell is damaged and opened up, through which a large volume of product is subsequently released.
6	Failure of Main Pipe	Rupture of tank's inlet or outlet lines resulting in significant product loss from a single tank. The LOC can range from a pin prick to full bore rupture.
7	Scoring of the Tank Shell	The movement of a floating roof can score and weaken the tank shell at a specific point, which can result in a breach at that location.

Assumptions in Developing the Hydrodynamic Models

Secondary containment bunds are typically sized to provided adequate volume and prevent the loss of fluid following release. This assumes that the release is slow and there is no significant momentum in the fluid which would cause structural damage or waves and sloshing which might lead to overtopping. As part of the UK COMAH Competent Authority, the HSE (2015) provides guidelines on secondary containment (bund) design. This states that it is normal to limit the number of tanks in a single bund to 60,000 m^3 total capacity. However, incompatible stored materials should have separate bunds and tanks often have individual bunds. Also bunds should be sized to hold 110% of the maximum capacity of the largest tank or drum. This allows some latitude for the addition of foam during response to the emergency. There are no set rules on the ratio between wall height and floor area and design codes vary greatly with respect to recommendations of bund wall height. Low wall heights (1 - 1.5 m) are often used to facilitate firefighting but are poor defence against spigot flow (where a leak in the wall of a tank passes over the bund wall) or the "tidal wave" effect of a catastrophic tank failure.

As such, the bund may contain numerous tanks of varying sizes, spaced unevenly apart, and within a bund that is irregular in shape. It has not been possible to capture the very large variety of possible configurations in the general failure assessment methodology developed for ASTs.

A number of simplifying assumptions were made to develop the source terms for the hydrodynamic models in the methodology:

- Failure Mode 1 (Rocketing Shell) and 4 (Rapid Shell Failure / Unzipping) have been approximated as having the same initial condition. They can both be represented by a source term which is a column of fluid free to collapse and spread under the influence of gravity.
- The worst case for Failure Mode 6 (Failure of the Main Pipe) is a guillotine failure in which fluid is discharged from the full bore of the pipe. (Split flange failures are also possible, but these are likely to result in lower flow rates.)
- Failure Modes 5 (Medium Shell Failure), 6 (Failure of the Main Pipe) and 7 (Scoring of the Tank Shell) can be represented by the same hydraulic model source term and simplified as discharging fluid through an orifice.

- Failure Modes 2 (Shell / bottom failure) and 3 (Bottom failure) can be represented by the same hydraulic model source term and simplified as a circumferential discharge from the base of the tank.

There are many tank shapes and sizes in many different bund designs. There is little commonality between the bunds other than the general guidance provided by the COMAH Competent Authority described above. Therefore, the hydraulic source terms and resulting methodology have been based on simple bund layouts with a single tank inside a simple bunded area. Congestion within the bunded area from hydrocarbon flow lines, fire water mains, auxiliary equipment, stairs, walkways etc has not be included in the source terms and methodology. Most Above-ground Storage Tanks will be mounted on a small berm within the bund. These are typically < 500 mm high with diameter typically 200 mm greater than the tank itself. Berms have not been included in the source term models; as their effects are likely to be small, compared with the overall generalisations used in the models.

Hydrodynamic Source Terms Development

Source Term for Failure Modes (1) and (4)

Failure modes 1 (Rocketing Shell) and 4 (Rapid Shell Failure / Unzipping) have been approximated as a self-similar slumping column. This assumes that the initial column of fluid is relatively tall with relatively small radius. As the column collapses, the height decreases, and the radius increases while maintaining the same volume of fluid. In the development of the methodology, it is assumed that the tank is located at the centre of a circular bund. The effect of funnelling of the fluid between tanks or between a tank and the bund was not considered. The effect of a non-circular bund may also result in greater overtopping when compared to the correlation below – for example where waves of fluid spilled from the tank converge at a corner, this can lead to additional overtopping. These assumptions have been addressed in a verification exercise. In particular the radius of the circular bund required in the methodology was found to be best determined from a circle with the equivalent area to the actual bund.

The spreading velocity was evaluated using the same correlation as given in reference by Webber (2009)

$$u = \sqrt{2gH\left(1 - \left(\frac{R}{r}\right)^2\right)} \tag{1}$$

Where u is the spreading velocity [m/s], H is the initial height of the fluid column [m], R is the initial radius of the fluid column [m] and r is the radius of the bund [m]. The hydrodynamic force exerted by the fluid on the bund was evaluated from the conservation of momentum.

For vertical wall bunds, the overtopping fraction is calculated using the same correlation developed by Atherton (2005) which is:

$$\begin{aligned} \zeta = 1.0255 & \\ -0.1886\left(\frac{r}{H}\right) - 2.9951\left(\frac{h}{H}\right) + 0.3842\left(\frac{R}{H}\right) & \\ +0.014\left(\frac{r}{H}\right)^2 + 2.7535\left(\frac{h}{H}\right)^2 - 0.0637\left(\frac{R}{H}\right)^2 & \\ -0.0005\left(\frac{r}{H}\right)^3 - 0.8595\left(\frac{h}{H}\right)^3 & \end{aligned} \tag{2}$$

Where ζ (*zeta*) is the overtopping fraction; and h is the bund height [m].

Source Term for Failure Modes (5) (6) and (7)

Failure Modes 5 (Medium Shell Failure), 6 (Failure of the Main Pipe) and 7 (Scoring of the Tank Shell) have been simplified in the methodology as fluid discharging from an orifice. The rate of discharge from an orifice for a known level of fluid in the tank can be derived by application of the well-known Bernoulli's equation, Massey (1989).

The discharge from a "large" orifice differs from a small orifice. For a large orifice it is not appropriate to assume that all the flow passing through the orifice is at the same depth below the free surface of the fluid stored in the AST. Flow at the top of the orifice will have a smaller depth of fluid above it than flow at the bottom of the orifice, and therefore a lower driving pressure. (For our analysis the "orifice" is the hole in the AST primary containment due to the medium shell failure, failure of main pipe or scoring of the tank shell.) The variation in depth below the free surface leads to a variation in hydrostatic pressure driving fluid through the orifice; and non-uniform flow through the orifice. Typically, an orifice can be considered as "large" if the vertical pressure variation across the orifice is 5-10% of the pressure due to the stored fluid at the orifice. As pressure varies linearly with height, this means that a "large" orifice will have a diameter which is 5 – 10% of the head of stored fluid above the orifice itself. In order to generalise the method for both "small" and "large" orifices, we have used the "large" orifice methodology for all cases. This is appropriate as the difference between the small and large orifice methods reduces as the size of the orifice reduces.

To determine the total discharge through the orifice, the discharge rate is evaluated in the methodology by integrating the discharge with respect to height. The orifice diameter is a user input to the methodology. To account for frictional losses and contraction of the fluid jet downstream of the orifice, a discharge coefficient is included. This has been given a value of 0.63

(Massey, 1989) for Failure Modes 5 (Medium Shell Failure) and 7 (Scoring of the Tank Shell). For Failure Mode 6 (Failure of the Main Pipe) it is given the value 1.0 as there is no convergence of streamlines for flow discharging from a pipe. The rate of discharge has been defined in the Methodology as:

$$Q = \frac{2}{3} C_d B \sqrt{2g} \left(Z_2^{\frac{3}{2}} - Z_1^{\frac{3}{2}} \right) \tag{3}$$

Where Q is the rate of discharge [m^3/s], C_d is the discharge coefficient, B is the width of the square orifice [m], g is the acceleration due to gravity [m/s^2], Z is the distance from the free surface to the top (Z_1) and bottom (Z_2) of the orifice [m].

The hydrodynamic force exerted on the bund wall by the jet of fluid projected form the orifice or hole in the AST primary containment is evaluated from the principle of conservation of momentum. Two checks are carried out in the methodology: (i) to determine whether the jet of fluid passes over the bund wall – in which case the overtopping fraction is determined from the head of fluid in the AST which is capable of sustaining this condition; and (ii) to determine whether the jet of fluid falls short of the bund wall and impacts the floor of the bund – in this case the overtopping fraction is set to zero. If either of these conditions occurs (i.e. the jet does not impinge on the bund wall) then there is no following structural assessment

Source Term for Failure Modes (2) and (3)

Failure Modes 2 (Shell / bottom failure) and 3 (Bottom failure) have been simplified in the methodology as circumferential discharges from the base of the tank – i.e. this is the hypothetical case that the gap exists around the entire circumference of the tank. The rate of discharge has been approximated by the rate of discharge of fluid through a sluice gate under conditions of "free" discharge (i.e. there is no hindrance or back pressure effect). The coefficient of discharge for free discharge is given by Swamee (1992) as:

$$C_d = 0.611 \left(\frac{H - b}{H + 15b} \right)^{0.072} \tag{5}$$

Where H is the depth of fluid in the tank [m] and b is the width of the discharge [m]. In the limit, as $H \to \infty$ or $b \to 0$, $C_d \to 0.611$. This is conservative and is used as the discharge coefficient for these modes of failure. The calculation determines the force on the bund based on the principle of conservation of momentum. The velocity of the fluid striking the wall is estimated based on the fluid level in the tank and the volume of fluid that has been spilt.

Model for Bunds with Inclined Walls

A different approach has been adopted in the methodology for inclined bund walls. When a fluid wave impacts an inclined bund wall, not all of the horizontal momentum is converted to vertical momentum and the amount converted to vertical momentum will depend on the slope of the wall. This means that the hydrodynamic load imparted on the bund wall will be lower than for an equivalent vertical bund wall. It has been assumed in the methodology that the bund wall will always have sufficient structural resistance, and will not collapse. However, there will be enhanced overtopping and the experimental data of Greenspan (1981) has been used to to determine the overtopping fraction. This data is only available for bunds with 60° and 30° inclination to the horizontal and it is not appropriate to interpolate the data to other bund wall inclinations.

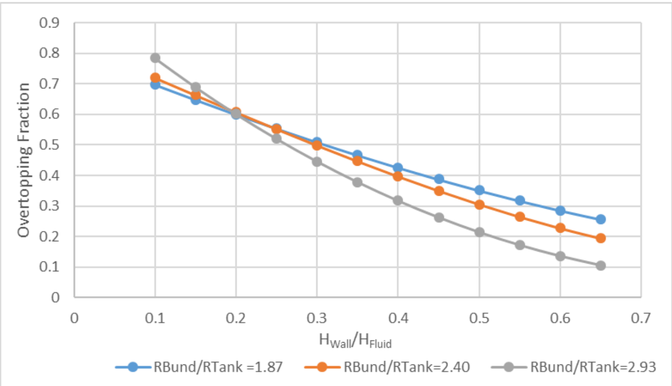

Figure 1: Experimental Data for Overtopping Fraction on a 60° Bund

For each of the 60° inclined bunds the data has three curves for different values of the ratio of the bund radius to the tank (R_{bund} / R_{Tank} = 1.87, 2.40, 2.93). For 30° inclined bunds there are just two curves (R_{bund} / R_{Tank} = 1.87, 2.40). A digitised copy of the data sets is shown in Figure 1 for 60° bunds. To determine the overtopping fraction in the methodology, bilinear interpolation has been used to interpolate between data points shown for R_{bund} / R_{Tank} and H_{wall} / H_{fluid}.

Structural Assessment

Overview

The overall methodology developed in this project takes the results of the hydraulic source term models and uses these as the force loading input values for the generic structural assessment. The structural assessment has been developed to assess whether a bund wall will provide enough resistance to prevent a structural failure when it is subject to the hydrodynamic loads.

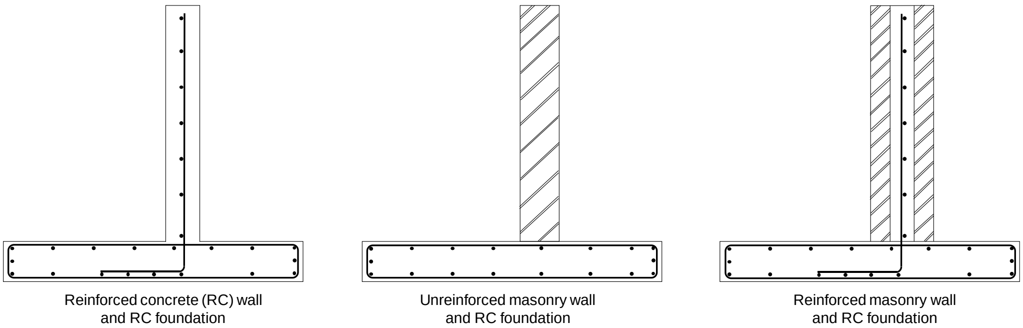

Figure 2: Three common bund wall types

The three common type of bund walls that were considered for the structural assessment: (i) Reinforced concrete (RC) wall with RC foundation – RC; (ii) Unreinforced masonry wall with RC foundation – UM; (iii) Reinforced masonry wall with RC foundation – RM. For each type of the bund wall the resistance forces and moments imparted on the foundation and bund wall itself are calculated in the methodology and compared with the peak hydrodynamic force.

Assumptions

The following assumptions have been made to simplify the structural calculations used in the methodology: (i) The duration of the hydrodynamic loading is reasonably long in comparison to the natural frequency of the walls and therefore the assessment is based on quasi-static behaviour considering the peak resultant hydrodynamic load. (ii) The resultant hydrodynamic load is simplified as a point load acting at 1/2 height of the fluid at the bund for Failure Modes 1-4. For Failure Modes 5-7, the point load is specified as acting at the height on jet impingement on the bund. (iii) The hydrodynamic load acts horizontally and normally on a vertical face of the wall. There is no "lip" or wave return profile on the top of the bund wall which would add a vertical component to the structural loading. (iv) The ground is reasonably sound for adopting spread foundations. It is also assumed that the ground water level is well below the foundation and therefore it doesn't affect the design of the foundation. (v) The calculation for reinforced masonry walls is valid for grouted cavity walls where the outer and inner skin of the brickwork is separated by a fully grouted cavity containing reinforcement. (vi) The load factor for both passive and active pressure acting on the foundation is unity for an accidental loading scenario. (vii) The partial safety factors for the bund wall materials in an accidental loading scenario are presented in Table 2. (viii) As a conservative assumption, the fluid within the bund wall does not contribute to the global stability i.e. vertical fluid pressure acting on the heel during overturning about the toe of the wall is ignored. (ix) The structural details for the RC wall comply with BS8110-1:1997 and for masonry walls comply with BS 5628-1:2005. (x) Minimum reinforcement is assumed based on the provision of BS 8110-1:1997 .

Table 2. Partial safety factors for the Bund Wall materials

Type of Bund wall construction	**Partial safety factors**	**Design Code**
Reinforced Concrete Wall	γ_{mm} = 1.3 γ_{ms} = 1.0	BS 8110-1:1997; *Cl 2.4.4.2*
Reinforced Masonry Wall	γ_{mm} = 1.15 γ_{mv} = 1.0 γ_{mb} = 1.0 γ_{ms} = 1.0	BS 5628-2:2000; *Cl. 7.5.2.2*
Unreinforced Masonry Wall	γ_{mm} = 1.5 γ_{mv} = 1.25	BS 5628-1:2005; *Cl. 23.3*

Calculation Method

The structural calculation method has a number of steps. Firstly, global stability checks are carried out on the foundation which includes: resistance to sliding due to horizontal forces acting on the wall; resistance to overturning due to moment acting about toe of the wall; and the bearing on the underlying soil due to the weight of the wall and all material contained within the footprint of the wall base compared to the allowable bearing capacity of the soil. The next step is to check the wall stem, which includes: moment resistance of the wall stem is calculated using the cross-sectional and material properties assuming bending about the base of the wall; and, the shear resistance which is calculated using the cross-sectional and material properties assuming a single shear plane perpendicular to the wall.

Factor of Safety (FoS)

The Factor of Safety (FoS) provides an indication of the likelihood of a bund wall structure failure. The FoS is determined by comparing the calculated resistance of the bund with the hydrodynamic fluid load due to the tank failure. As the FoS is calculated directly from the resistance of the bund and hydrodynamic load, it inherently accounts for the material properties, loading etc as long as these are correctly defined in the input sheet for the methodology.

A FoS of less than 1.0 indicates that the capacity is less than the demand and there is a risk of failure. In the proposed method it is simplistically assumed that a FoS<1.0 will result in bund wall collapse and a complete loss (100% overspill) of the storage tank's contents. Generally, a FoS of about 1.5 is considered acceptable and required in conventional design. However, the dynamic loading of liquid against the bund is a transient load; this type of loading condition only lasts for a short period and may not have sufficient time to cause failure. Therefore, a FoS of 1.0 is considered tolerable for extreme dynamic fluid loading scenario.

Using the Methodology

Overview

The methodology is coded in an Excel spreadsheet tool. Most of the calculations for the different hydrodynamic effects and structural calculations are contained on "hidden" sheets; the user data input and principal results for the structural resistance compared with the hydrodynamic load are contained in one simple to operate sheet. The two main stages in the Excel calculation follow these two parts to the methodology:

Hydraulic Calculations:

- Calculation of the peak hydrodynamic loading at the bund wall from the selected Failure Modes,
- Calculation of the overtopping fraction due to "sloshing" (Failure Modes 1 and 4) and projection of the leaking jet (Failure Modes 5, 6 & 7).

Structural Calculations:

- Structural assessment of the bund wall, for the type of construction specified by the user and based on the resistance of the foundation (sliding, overturning, bearing) and wall itself (moment, shearing).
- When the structural assessment demonstrates that the bund wall will fail the "overtopping fraction" (the volume of fluid which can potentially escape the secondary containment) is set to 100% of the AST's original contents. Structural failure is assumed to occur in the methodology when the hydrodynamic load in in excess of any of the structural resistances calculated for the foundation and wall.

Example

To demonstrate the user input and calculation outputs, an example is provided. The example presented here considers a catastrophic failure representing Failure Mode (4). The initial height of liquid in the AST is 15 m. The initial radius of the liquid column is 15 m representing a large storage tank with diameter 30 m. The bund height is 1.5 m with a radius of 58.1 m. The bund wall is 0.15 m thick founded on 2 m wide and 0.4 m deep pad foundation. (Note that this provides a very large storage volume in the bund, equivalent to around 180% of the stored fluid volume. This is not significant for this example which is primarily to demonstrate the structural loading on the bund wall.)

User Input

The user is required to provide AST geometrical details, failure mode, bund wall and foundation properties. Figure 3 shows examples of data in the Excel spreadsheet implementation of the methodology; these are the user input parameters required for the assessment.

Note that some options and data inputs only become valid when certain Failure Modes are selected. These are data item 8 (Figure 3), the seam gap, which is only required for Failure Mode 2 (Shell / Bottom failure) and Failure Mode 3 (Bottom failure). Also data items 9 – 11 are only required for Failure Mode 5 (Medium shell failure), 6 (Failure of main supply pipe) and 7 (Scoring of AST shell).

Results

Figure 4 presents the results for an example calculation using the input parameters shown in Figure 3. The "Hydrodynamic Calculation Results" and the peak hydrodynamic load and the fluid load height (on the secondary containment bund) for Failure Mode (4) are reported. These are: 74 kN/m and 422 mm. The "Structural Calculation Results" show the structural resistance for three failure modes for the foundation (overturning, sliding and bearing pressure); and two failure modes for the bund wall itself (moment and shear). Each of these is expressed as a fraction of the peak hydraulic load to give the Factor of Safety (FoS).

Consequences of AST Failure:

Where the minimum FoS is less than 1.0 for the foundation or bund wall, this is marked as "failed" under the "structural" section of the consequences area. If either the foundation or bund wall fails, then the overtopping fraction is set to 1.0 and the overtopping volume is set to the stored volume of fluid. If the foundation and wall both "pass", then the overtopping fraction is set to the volume which overtops due to sloshing (Failure Modes 1 and 4); or the volume which is projected over the wall in a jet (Failure Modes 5,6,7)

For the example shown in Figure 3 and Figure 4, the foundation has insufficient resistance in each of the three types of loading which are tested in the methodology. The FoS for each of these is < 1.0; they are flagged in red; and given the label “FAILED” under the consequences heading. The bund wall itself, however, has sufficient structural resistance as indicated by the moment and shear FoS which are both > 1.0 and flagged in green. The bund wall is given the label “PASSED” under the consequences heading.

Both the foundation and bund wall must have FoS > 1.0 for the system as a whole to pass; and in this example, as the foundation failed the bund system is deemed to fail. As the wall has potentially lost its integrity, the overtopping fraction id set to 1.0, to demonstrate that there is the potential for the entire fluid volume of the AST to be lost from the secondary containment.

AST and Secondary Containment (Bund) Geometry				
1	Fluid Density	ρ	870	[kg/m3]
2	Tank Radius	R_{tank}	12	[m]
3	Fluid Height	H_{fluid}	6	[m]
4	Bund Radius	R_{bund}	32	[m]
5	Bund Wall Height	H_{wall}	1.2	[m]
6	Bund Inclination from horizontal	θ_{bund}	90	[degrees]
			Vertical	
7	Failure Mode		Rapid Shell Failure/Unzipping	
			4	
8	Seam Gap			
9	Discharge Coefficient			
10	Hole Height			
11	Hole Diameter			
12	Bund Wall thickness	T_{wall}	0.12	[m]
13	Depth of foundation	D_{base}	0.4	[m]
14	Width of heel (inner)	B_{in}	2	[m]
15	Width of toe (outer)	B_{out}	1	[m]

Location of Loading				
16	Ratio of load to bund wall height	r	0.352	[-]

Soil Properties				
17	Soil selection		Strong rock	*See below*

Bund Wall and Foundation Properties				
18	Wall Type selection		Reinforced Concrete	*See below*
19	Reinforcement layout selection		Doubly-reinforced	*See below*
20	Reinforcement mesh selection		B1131	*Table A.1 below*

Figure 3. Global input parameters required for the assessment

Verification

Two layers of verification have been carried out to ensure that the methodology provides expected and reasonably accurate results. The methodology is intended as a general tool to be used for guidance for owners, operators, duty holders and regulators. It can be used to provide scenario planning and assessment in risk assessments. However, it is a general tool, and the results are intended to provide guidance, rather than absolute results. Where the methodology shows an AST and its secondary containment have marginal performance or fail, this should be the trigger for further and more detailed investigation. The two layers of verification that have been carried out are: (i) for the separate hydrodynamic source term models; and (ii) for “real” scenarios using hypothetical AST and site parameters based on a series of actual cases studied by MMI Thornton Tomasetti.

Hydrodynamic Calculation Results			
21	Peak fluid load	74	[kN/m]
22	Fluid load height	421.88	[mm]

Structural Calculation Results				
	Component	**Loading**	**Resistance [kN/m]**	**FOS**
23	Foundation	Overturning	60.03	0.81
24		Sliding	25.04	0.34
25		Bearing pressure	61.87	0.83
26	Reinforced Concrete	Moment	79.64	1.07
27	Bund Wall	Shear	81.15	1.09

Consequences of AST Failure				
28	**Structural**	Foundation	FAILED	
29		Bund Wall	PASSED	
30	**Hydraulic**	Overtopping Fraction	1.00	[-]
31		Overtopping Volume	2714	[m^3]

Figure 4: Typical output from the calculation presenting factors of safety on different structure failure modes

Verification of Hydrodynamic Source Terms

Collapsing Fluid Column – Modes (1) and (4)

The data provided by Atherton (2005) and his experiments at laboratory scale for catastrophic tank failures have been used to verify the methodology for Failure Modes 1 (Rocketing shell) and 4 (Rapid shell failure / unzipping). A case from Atherton's programme was selected in which the overtopping volume was 50%. This was anticipated to be more sensitive to the correct flow behaviour being calculated, than a case in which there was either significant or very little overtopping. The initial height and radius of the water column was 300 mm; the bund height was 30 mm with a radius of 1162 mm. For further verification of the force on the bund wall, we undertook two additional CFD model cases, one being a scaled version of the lab scale setup and the third case with a smaller bund radius. Details of the three verification cases are shown in Table 3.

Table 3. Configuration of cases assessed for verification of the force on the bund wall for modes (1) and (4).

Case No.	Initial Fluid Height (H) [m]	Initial Fluid Radius (R) [m]	Bund Radius [m]	Bund Height (h) [m]
1	0.3	0.3	1.162	0.03
2	15	15	58.1	1.5
3	15	15	30	1.5

The overall verification process proceeded in two stages. Firstly, as some of the data used for the verification is generated from CFD models, the CFD models themselves must be shown to be valid. This was carried out for the laboratory scale test in Case 1 only. Once the CFD model data for Case 1 was shown to be a reasonable and close match to the laboratory scale tests reported by Atherton (2005), then the full-scale data from Cases 2 and 3 could also be used to test the new methodology. The CFD models for the verification cases all used a 2D axis-symmetric model approach, each modelling a 5° sector of the tank and bund. All walls were specified as having smooth surfaces. Water was used with a density of 1000 kg/m^3 and a dynamic viscosity of 0.0013 kg/ms corresponding to water at 10°C. A homogenous free surface model was used where the phases of water and air share a single momentum equation.

Verification of the CFD models for Case 1: The calculated volume that overtopped the bund was ζ=0.46 compared with ζ=0.50 as measured in the experimental tests. The error in the CFD model was therefore 7% which was considered acceptable, given the possible errors in measurement of the volume of overtopped water in the experiment. The maximum pressure at the base of the bund relative to the hydrostatic pressure was calculated in the CFD model to be 6.20 and the value reported from experiments was 5.63. This gives an error of 10.1%. In the experimental work, the maximum pressure value at the base of the bund presented by Atherton was interpolated from a measured pressure profile. Atherton noted that the placement of the pressure sensors was not ideal and for identical test there was substantial variability in the measured pressure profile. The degree of variation was not reported and the maximum value at the base of the bund was said to be subject to interpretation. The value in the Atherton report is therefore not completely reliable and the error in the CFD model was considered acceptable. These results gave the confidence needed that the CFD modelling approach gave sufficiently accurate results such that the scale-up cases (Case 2 & 3) could be used in addition to the results presented by Atherton for Case 1 to verify the new methodology.

A summary of the results comparing the force from the new source term method with the maximum force that is determined in the CFD model is provided in Table 4.

Table 4. Results for force on bund for cases assessed for Failure Modes (1) and (4).

Case No.	Force [kN/m of bund] (Source Term)	Force [kN/m of bund] (CFD)	Ratio Force (Source Term) / Force (CFD)
1	0.11	0.04	2.75
2	275	130	2.11
3	828	221	3.74

The results show that the source term method is conservative with a factor of safety between around 2 and 3.75. The level of conservatism is likely to be due to the assumption of a self-similar slumping column of fluid resulting in a larger impact area and velocity than occurs in practice. Given the severity of failure modes (1) and (4) and the simplifying assumptions made, the methodology for estimating the force on the bund under these scenarios is considered reasonable. The factors of safety shown in Table 4 will help users of the methodology make reasonable judgements about their own sites and operations.

Discharges from an Orifice – Modes (5) to (7)

The rates of discharge for Failure Modes (5), (6) and (7) are based on first principles with empirical definition of coefficients developed over many years. The discharge from an orifice is well documented in fluid mechanics books e.g. Massey (1989) and Chadwick (2004). Any error in the calculation methodology is likely to be outweighed by the ability to define accurately the hole itself which results from the failure. As such, verification for these cases was not considered necessary.

Shell/Bottom Failure – Modes (2) and (3)

To provide verification data for the source term approach for Failure Modes (2) and (3) CFD analyses for three test cases were carried out. These modelled the flow under a gap at the base of an AST and calculated the resulting fluid load on the bund wall. The dimensions used for the three test cases are provided in Table 5. Typical large storage tank dimensions were used (initial fluid height and radius) and kept constant across the three cases; the gap height representing the shell or bottom failure was also kept constant. The same bund height was also used in the three cases and the only variable modified was the bund radius. (Note that the bund height is immaterial in this analysis as we are only looking to calculate the initial (peak) structural loading as the fluid impacts on the bund wall.)

Table 5. Configuration of cases assessed for verification of the force on the bund wall for modes (2) and (3).

Case No.	Initial Fluid Height (H) [m]	Initial Fluid Radius (R) [m]	Bund Radius (r) [m]	Bund Height (h) [m]	Gap (G) [m]
4	15	15	30	1.5	0.2
5	15	15	58.1	1.5	0.2
6	15	15	45	1.5	0.2

The results are shown in Table 6. These show that for cases 4 and 5 (bund radius 30 and 58.1 m) the source term method has a small but reasonable factor of safety between 1.18 and 1.33. However, case 6 (45 m bund) does not provide a factor of safety and the source term method only produces 96% of the load on the bund wall calculated by the CFD model.

Table 6. Results for force on bund for cases assessed for modes (2) and (3).

Case No.	Force [kN/m of bund] (Source Term)	Force [kN/m of bund] (CFD)	Ratio Force (Source Term) / Force (CFD)
4	6.6	5.6	1.18
5	3.2	2.4	1.33
6	4.3	4.5	0.96

Verification of Full Methodology

In this part of the verification, a number of hypothetical cases, based on real systems studied by MMI Thornton Tomasetti have been used. These have been modelled in 3D using Computational Fluid Dynamics (CFD) to provide bund wall loading and overtopping fractions. They all study Failure Mode 1 and 4 - complete structural failure and collapse of the tanks.

The first three cases studied varying tank and bund aspect ratios, for single tanks located in the centre of rectangular bunds. The fourth case is a typical layout for a large storage site; it has three large tanks and three small tanks in a single bund. One of the large tanks is subject to the failure. The four cases are defined in Table 7.

Table 7: Verification Cases

Case No.	Comment	Initial Fluid Height (H) [m]	Tank Dia (2R) [m]	Bund Width [m]	Bund Length [m]	Bund Equivalent Radius (r) [m]	Bund Height (h) [m]
7	Hypothetical tank in centre of rectangular bund	11.2	14.7	45	33	21.7	1.4
8		8	7.0	25	20	12.6	1.4
9		5	15	40	35	21.1	0.7
10	3x large; 3x small; single bund; large tank failure	11.6	37.5	125	71	53.15	2.5

The source terms for the hydrodynamic models in the methodology are based on tanks located at the centre of circular bunds. This is an idealised situation which is necessary to develop the models, but is rarely (if ever) found in practice. The radius of the bund used in the methodology can either be specified as the minimum distance from the centre of the AST to the bund wall; or the "equivalent radius" of a circle having the same area as the AST's bund. Both of these are tested in the verification study.

Table 8 compares the overtopping results from the CFD analysis with the values calculated from the new methodology. Results from the methodology which produce greater overtopping fractions are marked in green and may be considered to be conservative. For each case the result from the methodology which gives the closest value to the CFD model value is marked in bold. Basing the calculation on the bund equivalent radius (rather than an actual distance to the wall) in general gives the closest match to the CFD model results. These results show that overtopping can be calculated with a reasonable degree of accuracy for a range of cases, for scenarios in Failure Mode 1 or 4 and where the bund does not "fail".

Table 8: Overtopping Verification

Case No.	CFD Overtopping Fraction [-]	Source Term Overtopping Fraction [-]	
		Based on Equivalent Radius	Based on Distance to Wall
7	0.51	**0.60**	0.67
8	0.47	**0.47**	0.52
9	0.60	0.51	**0.58**
10	0.29	**0.34**	0.60

The force exerted on the bund wall by the fluid wave following Failure Mode 1 or 4 (total tank collapse) has also been extracted from the 3D CFD models for comparison. The CFD models calculate the variation in force around the bund wall which occur due to variable distances to the bund wall from the tank and multiple stages of impact from wave reflections and channelling). For the comparison, the peak force (averaged over 1 m^2) at the bund has been determined from the CFD models and this has been compared with the result from the methodology. The force comparisons are shown in Table 9. As with the overtopping fractions, values determined by the methodology which are in excess of the CFD model results are marked in green; the equivalent radius result giving the closest agreement with the CFD model are marked in bold.

The results tend to confirm that the basing the radius used in the methodology on the bund's equivalent radius provides the better result. For Case 7, which has a particularly tall initial fluid height, the methodology calculates the force significantly higher than the CFD model.

Table 9: Force Verification

Case No.	**CFD Force [kN]**	**Source Term Force over 1 m² [kN]**	
		Based on Equivalent Radius	**Based on Distance to Wall**
7	22.9	**132.2**	207.1
8	25.4	**47.2**	71.4
9	58.6	**57.2**	77.1
10	204.0	**243**	557

Conclusion

The work reported in this paper has been to define a new methodology for assessing the consequences of Above-ground Storage Tanks. The work has been carried out for the Containment Systems Working Group of the Energy Institute and it is intended that the Energy Institute will publish the methodology, along with supporting documents.

The methodology takes seven potential failure modes for ASTs which have been identified in a preceding piece of work. For each of these, a hydraulic source term model has been developed which determines the hydrodynamic loading force on the secondary containment bund wall due to the released wave or jet of fluid. The source term models also determine the volume of fluid which overtops or is projected over the bund wall. A structural assessment model determines the resistance of the bund wall's foundation (sliding, overtopping, bearing) and the wall itself (moment, shear). The methodology compares the structural resistances with the hydrodynamic loading and determines whether the bund will "pass" or "fail" the AST failure scenario.

Two levels of verification have been carried out on the methodology. The first of these has tested the appropriateness of the hydraulic source term models; the second has tested the performance of the methodology as a whole. Both verification studies have shown that the methodology performs well, and within a good degree of accuracy for a simple tool.

The methodology is intended to give owners, operators, duty holders and regulators better insight into the consequences of AST failure. It may be used to provide data to risk assessments. It is not intended as a design tool, and the results it provides are not sufficiently robust for that purpose. Where the methodology shows that an AST and secondary containment system fail or have marginal performance, this can be used as the trigger for a more detailed study. Conversely, a benefit of using the methodology is for cases that show that an AST and secondary containment system do not fail, as these can be screened out from a more detailed study.

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