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Numerical investigation of bund overtopping under storage tank failure events

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ABSTRACT

In this paper computational fluid dynamics simulations (CFD) were carried out in order to investigate the efficiency of bund designs and top wall deflectors (breakwaters) under several tank failure modes. Investigation was performed over laboratory scale configurations, some of them were also experimentally studied. Simulations were performed using the Volume of Fluid (VOF) method and literature data were used for assessing the solver prior to investigate the different bund designs. Numerical and experimental results agreed, showing the suitability of numerical methods to predict overtopping. The amount of liquid lost showed a low dependency with the containment shape (square, circular or rectangular), but a high one with the bund height. On the contrary, the use of breakwaters showed to be a suitable and very efficient way to reduce liquid loss, although inducing significant extra mechanical efforts over the bund walls.

1. Introduction

The tanks to store hazardous liquids are usually surrounded by a retaining wall or bund generally made of sloped earth or concrete high-collar bunds. The purpose of their is to retain any spillage of the stored liquid which may occur. These secondary containments may have a variety of configurations (square, circular, rectangular), capacities and shapes of bunds. In its guidance on the storage of flammable liquids in tanks, the Health Safety Executive (Great Britain) states that “a bund capacity of 110% of the largest storage vessel will normally be sufficient” and that “the bund should have sufficient strength to contain any spillage” (Thyer et al., 2002).

Although the bunds that surround the storage tanks are commonly over-dimensioned to contain up to 110% of the tank capacity, it is well established that they will not totally avoid liquid loss under severe tank failures (Clark et al., 2001). It has been corroborated by experimental tests as well as real vessel failures. Experiments carried out with a model storage tank inside a 110% bund capacity have shown that, even for slow tank draining (over a period of 30s), the bund is overtopped in almost every case (ref: in HSE Contract Research Report 405/2002). Atherton (Atherton and Ash, 2007) has reported that under severe failures a significant amount of liquid could still overtop bunds designed to retain 200% of the tank total capacity.

Failures can be attributed to a number of causes including human error, inappropriate or poor maintenance, loss of wall thickness by corrosion, vapor ignition, differential settlement, earthquakes, lightening strikes, hurricanes, flood damage and over-pressurization. Such incidents have highlighted the need for the proper assessment of potential risks and the requirement for suitable methods of mitigation. Chang and Lin (2006) reviewed more than 240 accidents along the world and found that 74% of accidents occurred in petroleum refineries and oil storage terminals, and 85% of the accidents involved fire and explosions. The main failure causes were by lightning (33%) and human errors including poor operations and maintenance (30%). The rest was consequence of equipment failure, sabotage, crack and rupture, leak and line rupture, static electricity and open flames. The structural collapse of oil storage tanks is frequently the result of combined and synergistic interaction of mechanical stress and corrosion reactions. Cracks are generally initiated by corrosion, although failure is consequence of the propagation of the cracks caused by stresses concentration (Kim et al., 2009).

Evidently, the more severe the failure the more the overtopping. These catastrophic tank failures are unusual and consequently the risk related to such events is estimated to be lower than 5×10^{-6} per tank

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List of symbols

γ	Phase fraction []
$\mathbf{U}$	Velocity [m/s]
p	Pressure [Pa]
t	Time [s]
ρ	Density [kg/m^3]
μ	Dynamic viscosity [Pa s]
τ	Stress tensor [N/m^2]
I	Identity matrix []
k	Turbulent kinetic energy [m^2/s^2]
ε	Turbulent dissipation rate [m^2/s^3]
σ	Surface tension coefficient [N/m]
$\mathbf{g}$	Gravitational acceleration [m/s^2]
$\mathbf{S}$	Mean rate stress tensor [1/s]
$\mathbf{x}$	Position vector [m]
V_c	Containment volume capacity [m^3]
V_t	Initial stored tank Volume [m^3]
V_l	Volume of the liquid leaving the containment [m^3]
R_v	Containment capacity ratio. $R_v = V_c/V_t$ []
Q	Overtopping fraction ($Q = 100[V_t - V_l]/V_t$) [%]
D_s	Characteristic grid size [m]
N_t	Amount of grid elements []
y	Distance from the tank center to the bund [m]
z	Minimum distance from the tank wall to the bund [m]
d	Distance from the tank wall to the bund corner [m]
H	Liquid column height [m]
h	bund height [m]
θ	Containment slope angle [°]
R	Tank radius [m]
r_{eq}	Equivalent tank to bund distance [m]
M	Momentum [Nm]
F	Force [N]

Subscripts:

l	Liquid phase
g	Gas phase
r	Relative value
t	Turbulent
eff	Effective

Acronyms:

BW	Breakwater
CFD	Computational Fluid Dynamics
GAMG	Geometric Algebraic Multi-Grid
MULES	Multid. Univ. Limiter with Explicit Sol
RANS	Reynolds-averaged Navier-Stokes
SGS	Symmetric Gauss-Seidel
VOF	Volume Of Fluid

year (Thyer et al., 2002). Despite this, the consequences for workers and the environment can be very severe.

Although total tank failure is a very unlikely event, the probability for that scenarios grows with the lack of control and maintenance. Such failures have occurred in the USA, Greece, Lithuania and Argentina, among others. There have been more than 100 major incidents involving storage facilities globally in the last 20 years and the worst that has ever befallen took place at the Buncefield Oils Storage Deposit in Hertfordshire in 2005. It has been regarded as the largest explosion in Europe since the Second World War (Atherton and Ash, 2007). In 1988 a tank spilled more than 14.000 m^3 of oil in the USA. The tank failed during filling because of a crack developed near the tank base, which rapidly propagated vertically to the top in less than a second (Mesloh et al., 1988). More recently, in 2015 in Argentina, an oil wash tank failed in similar conditions spilling 1.700 m^3 of oil and water.

Modelling of asymmetric modes of failure or ”jetting failures” has been undertaken over a number of tanks and bunds geometries, and the results to date indicate that the levels of overtopping and the magnitudes of the dynamic pressures are significantly high enough to cause concern.

The structural integrity of the bund as a result of the dynamic pressures involved is of possible greater significance. Failures, which can occur as a result of a damaged pipe or valve connection, or even the partial remotion of a small section of a tank wall, can be particularly problematic. The issue here is the magnitude of the dynamic pressure of the fluid hitting the wall combined with the duration of the impact, which will be more powerful than any normal static pressure. In the instance of earthen dykes, there is a high probability that the earth would be eroded, resulting in the total loss of secondary containment. On the other hand, in the case of concrete walls, the impact could result in the loss of integrity of the structure, removing part of the bund or the breakwaters. Precursor studies (Cuperus, 1980, Rouzsky, 1983; Baldwin, 1983; Bombard and Vehlin, 1983) on high-collar bunds indicated that the hydrodynamic loading near the base of a bund could be between three and six times higher than the expected from hydrostatic loads (Thyer et al., 2002).

Catastrophic tank failures could become worse if more than one tank is housed in the secondary containment. In this case, the hydrodynamic load could easily produce dents or even demolish the adjacent tanks (Thyer et al., 2002).

Assuming that the bund remains intact in the event of a tank failure, a fraction of the stored liquid will inevitably be lost due to the energy of fluid wave or jet impacting against the secondary containment. Estimations made from actual incidents have shown that between 25% and 50% of the original contents were lost. Furthermore, the losses over vertical bund walls without breakwaters, earthen dykes or constructed embankments can be even higher. The more important factor is not the volume of the liquid spill, but the rate at which it is spilled: fast spills can pass over the top of most containment dykes.

To date, few researchers have dedicated to perform experimental tests, mostly reporting the overtopping and sometimes also the mechanical efforts over the bund. Some tests have been related to total failures (Atherton and Ash, 2007), (Atherton et al., 2004) whereas others focused on particular leakage scenarios based on real accidents (Pettitt and Waite, 2003).

The influence of the bund shape and the slope angle of embankments was firstly experimentally investigated by Greenspan et al. (Greenspan and Young, 1978), and subsequently by Clark and Savery (1993) and Law and Johnskareng (1994) in the Imperial College. They found that the lower overtopping was obtained with concave curved bunds followed by vertical bunds (90°) and finally by 60° and 40° inclined bunds. They also found that there is a linear dependency among the overtopping factor and the bund to tank distance.

Perhaps the pioneer works combining numerical and experimental tests were from the Imperial College of London in the 80‘s. These precursor researchers showed the dependence of the overtopping with the bund height and bund distance from the tank. Nonetheless, they only considered complete failures with vertical bunds without breakwaters.

Much of the numerical investigation has been made using the shallow water method. The most relevant work is from Ivings and Webber (2007), Ivings and Webber (Webber and Ivings, 2010) and SreeRaj (2008). The first ones investigated the response of square containments made of vertical bunds under complete failure, partial leakage from the tank bottom side, and small and big holes. SreeRaj