5th Annual Symposium, Mary Kay O'Connor Process Safety Center
"Beyond Regulatory Compliance: Making Safety Second Nature"
Reed Arena, Texas A&M University, College Station, Texas
October 29-30, 2002

Inherent Safety of Dikes Against Catastrophic Failure of Storage Tanks

Mike Moosemiller and Tracy Whipple
Det Norske Veritas (USA), Inc.
16340 Park Ten Place, Suite 100
Houston, TX 77084
Phone: 281-721-6780 · 281-721-6756
Email: mike.moosemiller@dnv.com · tracy.whipple@dnv.com

Abstract

It is industry practice to provide passive containment (dikes) of storage tank equivalent to 110% of the capacity of the tank. This standard is sufficient for containment of small to moderate leaks. However, it is generally inadequate to contain a catastrophic failure, which can form a wave that simply washes over the side of (or through) a dike wall. The 110% standard has generally served industry well, since the likelihood of a catastrophic tank failure is very low historically. However, concerns over terrorist attacks, and adoption of principles such as "inherent safety", have brought the catastrophic tank failure case back onto the "radar screen" of chemical risk management.

It is possible to analyze the potential for tank dike spillover using both "classic" correlations and more modern techniques such as computational fluid dynamics (CFD). In recent work, the two methods have been shown to provide similar results, with the classic approach providing some insights not immediately apparent from CFD outputs alone. Spillover correlations and mitigation strategies are described.

1.0 TANK AND DIKE ISSUES

Several factors are relevant when discussing the potential for and risks of a catastrophic tank failure that escapes containment. Some of these relate to the tank itself, such as:

- Volume/liquid level stored in the tank
- Hazardous properties of the material stored in the tank
- Mechanical integrity of the tank
- Security of the tank against sabotage/attack
- Presence and usage of dike rainwater drainage valves

Other issues relate to the dike:

- Volumetric capacity
- Dike mechanical integrity
- Proximity of the dike wall to the tank
- Proximity to sensitive populations, environments or other equipment

This paper focuses on the variables that impact the potential for dike breech once a catastrophic tank failure has occurred. This has not been a great concern among facilities historically, since tanks have had a small frequency of catastrophic failure. However, the nation's tank population is aging, and a sabotage/terrorist attack on a tank no longer seems as incredible as perhaps it once did. Having tank containment that is robust in all circumstances also follows the principle of "*inherent safety*". Now is a good time to reevaluate those installations where the risks may be higher than previously understood.

2.0 HISTORICAL APPROACH

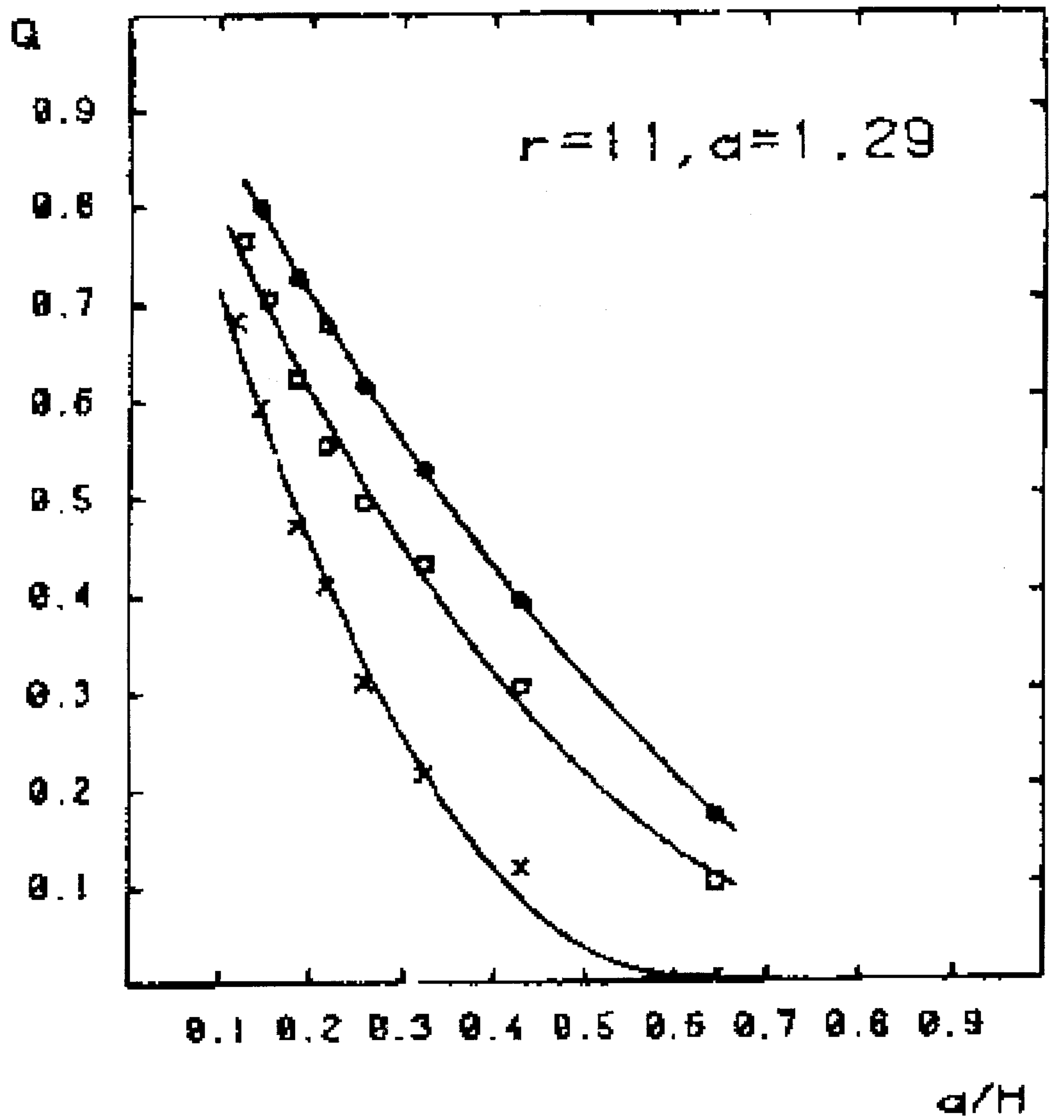
Most facilities design their dike walls based on API or related standards. These typically require that the diked area be capable of containing 100-110% of the volume of the tank within. This approach is generally suitable, although it can be compromised through a variety of factors such as dike degradation, leaving rainwater drain lines open, etc.

In a pair of seminal papers about 20 years ago [1, 2], Greenspan et al. conducted bench-scale tests of fluid flow over barriers. Their work showed that a substantial fraction of liquid released as the result of a catastrophic tank failure would wash over the top of a barrier such as a dike. The spillage fraction was found to be primarily a function of initial liquid height, dike height and dike wall angle of inclination. Figure 1 is an example of the types of results obtained.

These studies were enlightening in many ways. Aside from providing an estimate of overflow potential, the data were presented in a way that allows the analyst to gauge the sensitivity of the results to variations in the critical inputs. The researchers also evaluated a wide variety of dike shapes – some practical, some not – that greatly lowered spillover. Portions of one of the figures from the original papers illustrating the effect of dike shape is reproduced as Figure 2.

Unfortunately, rigorous means of verifying the scaling properties of these bench tests (computer modeling or large-scale tests) were not readily available at the time, although Greenspan did lay out in some detail the mathematical foundations of waves and shock waves in this situation. Also, the studies were, by necessity, limited in range of variables and dealt with idealized tank and dike configurations. So it was difficult to apply these lessons in practice with confidence.

Figure 1: Dike Spillover Fraction
(from Greenspan and Johanssen [2])

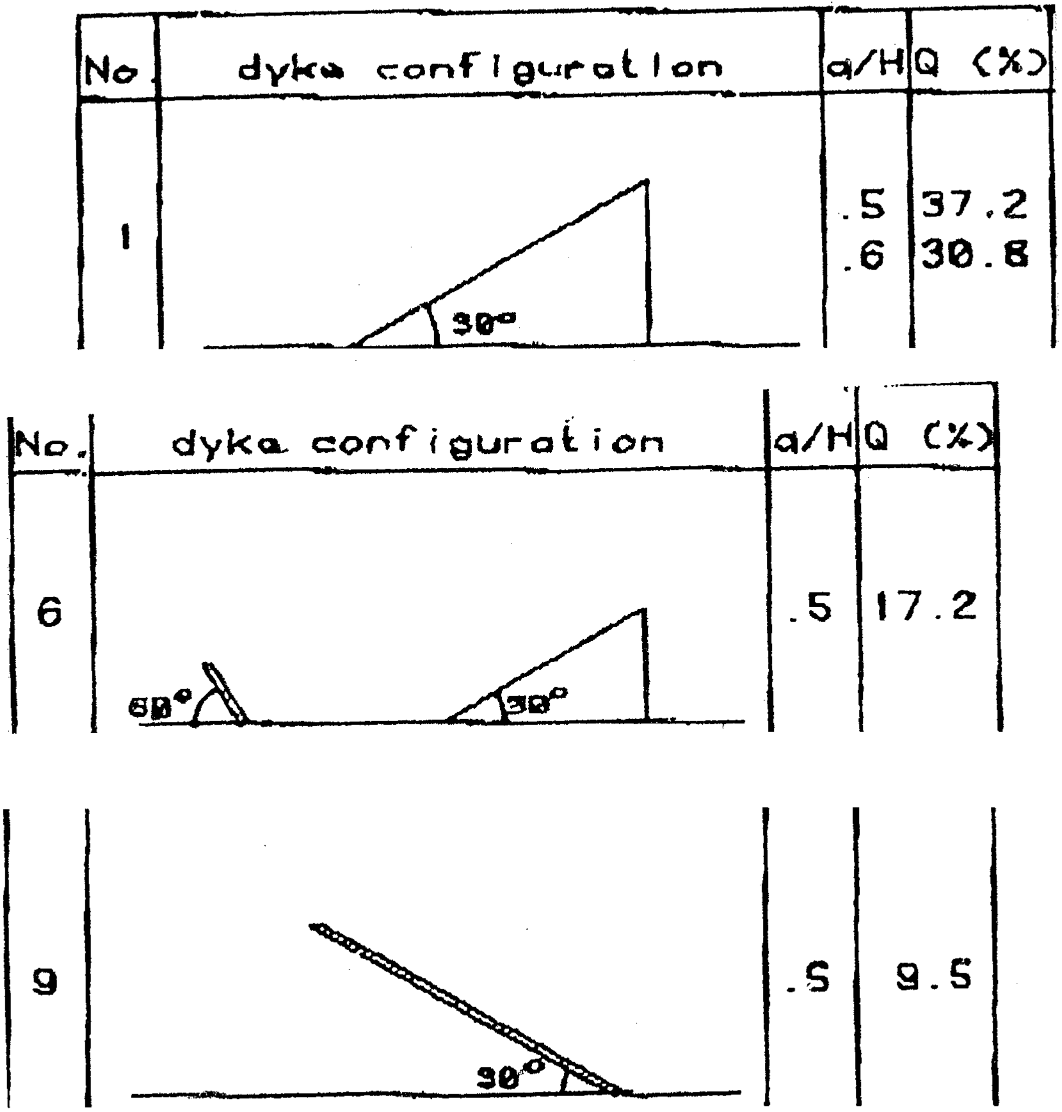


In this figure, the following symbols are used:

Q = fraction of tank contents that overflow the dike wall.
r = radius of the dike
a = height of dike
H = height of tank

● = 30 degree dike angle
□ = 60 degree dike angle
x = 90 degree dike angle

Figure 2: Dike Overflow Fraction for Various Dike Shapes
(from Greenspan and Johanssen [2])



Example:

Tank height “H” = 12 feet, 100% full
Dike height “a” = 6 feet (a/H = 0.5).

In Case No. 1, 37.2% of the tank contents would spill over the dike. In Case 6, with an internal reverse baffle, 17.2% would spill over. And in Case 9, with a 30-degree reverse angle dike wall, only 9.5% of the tank contents would spill over the dike wall.

3.0 COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS

More recently, CFD models have been introduced that can be used to simulate tank failure releases at actual scale. Results for such tests were published previously by Trbojevic and Slater[3]. One of the figures from this paper that illustrates the spillover phenomenon is reproduced below.

Figure 3: Modeling of Fluid Movement Resulting From a Tank Failure

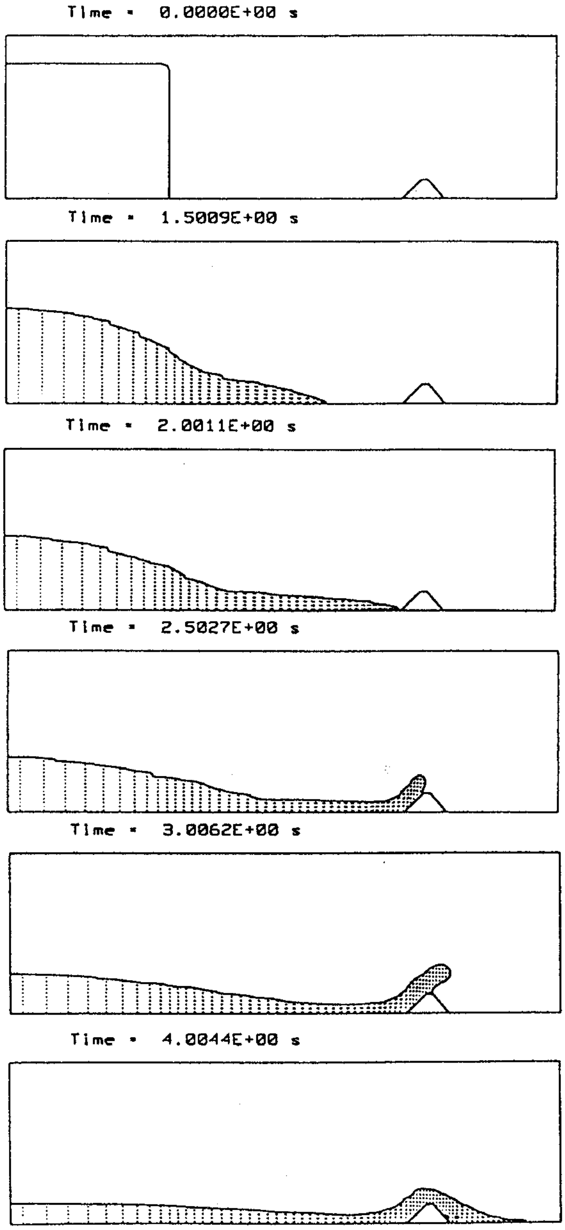


Figure 3. Tank with a dike—free surface at different times.

Plant/Operations Progress (Vol. 8, No. 2)

Several unpublished project reports also assessed dike overflow issues. In general these studies demonstrated that it was necessary to substantially lower the operating level in tanks to guarantee that dike overflow or breakthrough would never occur.

CFD models, once validated against laboratory or other tests, provide a tremendous new tool that:

(a) can be applied to any shape tank and dike
(b) can handle a wider range of design variables

The disadvantages of CFD analysis are that:

(a) initializing the analysis can be expensive,
(b) it can be difficult to assess the sensitivity of input variables without repeating the analysis many times, and
(c) the results of an analysis are very detailed, but the physical phenomena driving the results are not always clear

4.0 COMPARISONS AND LESSONS LEARNED

As part of recent (confidential) analyses, the two approaches were compared. The results of the "historical" bench tests were largely confirmed by the CFD models, for the limited number of cases that it was possible to review.

Furthermore, the earlier works provided insights as to the reasons for the results that were not apparent to the CFD analysts. In one particularly interesting case, a CFD model was used to evaluate the benefit of placing a short wall between a tank and the dike wall. The goal was to "knock down" the momentum of the release so that it would not spill over the dike.

The strategy worked – the model showed that no liquid would flow over the dike. But it was not until the Greenspan work was reviewed years later that the reason *why* was clearly understood. For this case, the intermediate wall propelled the liquid into the air such that it fell onto the dike wall face at an incident angle of near 90 degrees. This was fortuitous – moving the wall a few feet closer to or farther away from the tank would have largely negated the benefit. The Greenspan analyses explained this phenomenon.

This experience illustrates that while CFD modeling can provide answers to dike overflow problems, it may not be sufficient in *understanding* dike overflow problems.

5.0 ANOTHER ISSUE – DIKE INTEGRITY

In the "standard" angled dike, the wave largely retains its momentum (which is why there is spillover). With small amount of momentum imparted to the dike walls, they may handle the force of a catastrophic failure. However, vertical walls, or reverse angled walls, have a considerable force placed on them.

The Trbojevic and Slater paper quantified these forces for two examples, and CFD models generally provide this information as well. It is not uncommon for the forces applied to the bottom of a vertical wall in a catastrophic failure to be 4 times the hydrostatic pressure. This may or may not be an issue to consider in a tank farm setting. However, these forces are often sufficient to cause smaller, more vertical, barriers to topple, slide or fail.

6.0 RISK EVALUATION STRATEGIES

Both the "historical" and CFD approaches to dike analysis are time-consuming. Therefore the first step in any assessment of tank overflow risk is to identify those candidates worthy of further analysis. This risk-ranking exercise would primarily include those factors listed in Section 1.

Once a candidate list of high-risk tanks is developed, the "historical" approach can be used relatively easily to screen those having no overflow potential (unfortunately, there are probably few of these). Of those that do overflow, this approach can provide a rough estimate of the amount that will overflow. This can then be used to evaluate containment external to the dikes such as adjoining dikes, drainage systems and topographical features.

If there are tanks/dikes that fail these tests, some detailed evaluation of risk mitigation strategies may be necessary. Potential strategies include:

(a) installing an intermediate barrier between the tank and the dike wall (a recent study used readily-available concrete traffic barriers coupled together)
(b) utilizing higher/steeper dike walls, or more unconventional dike wall shapes (although these may introduce fire hazard issues)
(c) providing secondary containment or spill channeling
(d) reducing tank inventories
(e) increasing internal tank inspections and/or increasing security, to lower the likelihood of the initial tank failure

In any case, companies need to overcome the complacency that comes with meeting the "110% capacity" standard for dike design, since this approach is *not necessarily* "inherently safe". The technologies and strategies are available for assessing the "worst case". And where the "worst case" is credible, these tools should be used.

REFERENCES

(1) Greenspan, H.P. and R.E. Young, "Flow Over a Containment Dyke", J. Fluid Dynamics, 87:179-192 (1978).

(2) Greenspan, H.P. and A.V. Johansson, "An Experimental Study of Flow Over an Impounding Dike", Studies in Applied Mathematics, 64:211-223 (1981).

(3) Trbojevic, V.M. and D.H. Slater, "Tank Failure Modes and Their Consequences", Plant/Operations Progress, Vol. 8, No. 2, April 1989.