

BUND DESIGN TO PREVENT OVERTOPPING

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Most bunds are designed to contain 110% of the contents of the largest tank in the bund. However, it is now well established through a number of incidents and experimental work that stored materials may overtop the bund wall due to the momentum of the release following catastrophic tank failure. This paper is concerned with experimental work conducted to investigate whether bund walls could be retrofitted to prevent overtopping, avoiding the necessity to extend the bund height by several metres. Such a measure could be used where a risk assessment has shown that the residual risk to various receptors, both people and environmental, is not tolerable, after the effect of preventative measures has been analysed, i.e. bund redesign would only be used in an extreme case. The paper shows the results of the experimental work and demonstrates that the new design successfully prevented overtopping at a 1:30 scale.

KEYWORDS: Atmospheric storage tanks, catastrophic tank failure, bund overtopping, risk assessment, prevention, control.

INTRODUCTION

Modern design standards for bunds surrounding atmospheric storage tanks should ensure that the bunds are able to contain at least 110% of the maximum volume of the largest tank in a bund. This capacity is intended to contain the hazardous liquid, e.g. crude oil, kerosene, should there be a failure of the tank wall or the adjoining pipework. However, in the event of a catastrophic tank failure, or even a large connection failure there is the potential for the released liquid to surge over a bund wall due to the momentum of release. Several incidents have occurred in the past where liquid has been released over the secondary containment[1,2] and theoretical models have been developed to characterise such a release, e.g[3,4,5].

The experiments of Greenspan and Young[3] show that conventional bund walls would need to be almost as high as the initial liquid level to eliminate overtopping due the projection of a 'plume' of liquid with enough kinetic energy (derived from the initial potential energy of the static liquid) to rise over conventional walls.

Bund overtopping is a particular problem when there is a sloping bund wall or dike of low height. Some dikes have a shallow slope of only about 30° from the horizontal and total height of 1.5 m above grade. Following failure from the primary containment overtopping may result in about 50% or more of the contained material being released outside the secondary containment (Greenspan and Young[3]). This may be catastrophic if it affects an environmentally-sensitive area.

A series of experiments has been carried out to investigate the effects of placing a vertical section of wall on top of an existing sloping bund wall to mitigate the effects of overtopping. It was recognised that a vertical wall alone would be unlikely to achieve the desired effect of eliminating overtopping. The second author had observed sea wall tests where overtopping from waves was reduced by the shape of the sea wall, designed to deflect the high velocity wave run-up and any 'splash' back into the sea. Therefore, the experiments included experiments with a horizontal 'lip' at the top of the vertical section on the inside of the wall. The experiments showed that while there was significant overtopping when using a typical bund wall design, overtopping was virtually eliminated when using the horizontal 'lip'.

This paper describes the experimental work carried out, the results and the significance in terms of inherently safer design of bund walls, particularly where the environmental risk may be high.

OBJECTIVE OF EXPERIMENTAL WORK

Bund overtopping has been shown to be a problem in a number of historical incidents. On several occasions, the design of the bund wall or dike was not sufficient to retain the spilled liquid following catastrophic failure of the primary containment; generally, the bund wall or dike was insufficient in height and was sloped so that the escaped liquid could run-up and easily flow over the top. This was particularly illustrated in the Floreffe incident of 1988 when it was estimated that between 40 and 71% of diesel oil from the primary containment overtopped the dike and 750,000 gallons flowed into the adjacent river causing serious disruption to water supplies and the environment[2].

Experimental work has been carried out on a number of occasions[3,4,6–9] to examine the flow of liquids overtopping bund walls following failure of the primary containment. Often the focus has been placed upon how much overtopping may be expected.

The objective of this series of experiments was to investigate if there was the potential to retrofit typical existing bund designs (with sloping walls) with a mechanism to alleviate the overtopping potential. It was not the intention to simply investigate how the height of the bund wall would need to be increased to retain all the liquid, rather if a specific design could be used, i.e. by use of an internal 'lip' on top of the bund wall, similar to a sea wall.

APPARATUS

A model of the bund was constructed in polypropylene to 1:30 scale for typical storage tanks and bunding arrangements. As with other experiments (e.g. Greenspan and Young[3] provide the justification) to study these effects a linear scale was chosen. The "base model" had sloping walls with the top of the wall 57 mm (to model 1.7 m) above the base of the bund. The angle from the horizontal plane was about 35°. The capacity of the bund was about 170% of the maximum scale tank capacity of a prototype tank (27.5 or 35 metres diameter, maximum fill height 11 metres). Alternative bund walls could be fitted to the model along one side to test the effects of different wall profiles:

1. An increased height of 77 mm (to model 2.3 m) above the base of the bund,
2. 77 mm (2.3 m) high sloping wall with an additional vertical section at the top of height 47 mm (1.41 m) with a 'lip' similar to a sea wall of width 19 mm (0.57 m).

A storage tank was represented by a moveable vessel approximately 700 mm (to model 21 m) in diameter, which although not typical of a crude oil or petroleum product storage tank (which have a lower height to diameter ratio) was more convenient to move and was large enough to give more than the maximum head for a liquid release from a typical tank (>10 m).

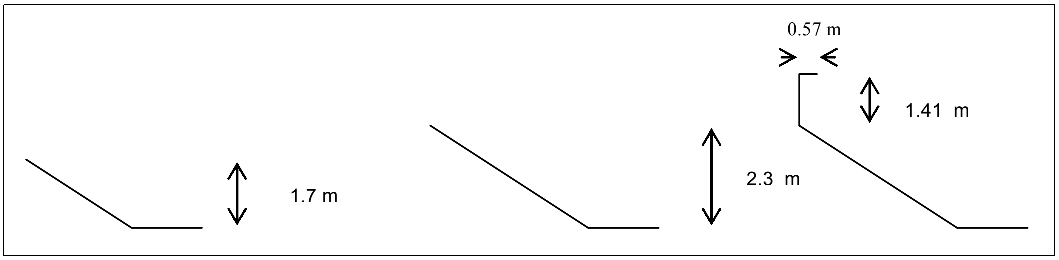


Figure 1. Bund wall arrangements

The release mechanism consisted of a sliding plate behind a polypropylene block with the required hole cut into it. On the inside of the sliding plate was another polypropylene block with a larger hole than all the test holes. This is shown in Figure 2.

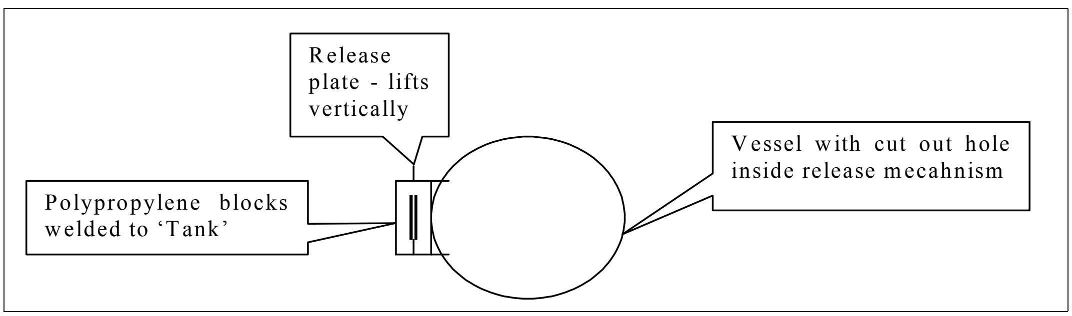
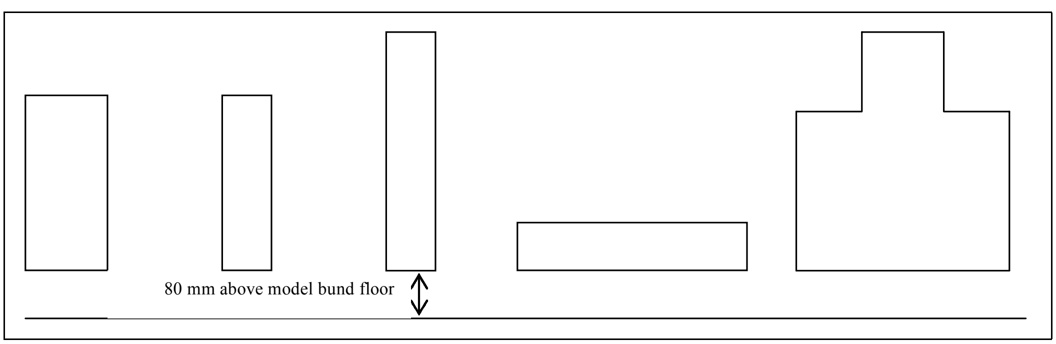


Figure 2. Test vessel

The design of the release mechanism allowed different holes to be used, in order to model different failure types in the tank wall. Five hole sizes and shapes were used in the tests, as shown in Figure 3.



Hole 1	Hole 2	Hole 2 (modified)	Hole 3	Unrestricted
100 × 50 mm	100 × 40 mm	130 × 40 mm	40 × 130 mm	130 × 50 + 2 × 100 × 40 mm

Figure 3. Holes sizes and shapes

After each test there was some residual fluid remaining in the vessel, below the lower edge of the hole (80 mm above the model bund floor).

The test fluid was water (SG 1 rather than the SG of 0.83 for a typical hydrocarbon fuel) and the flow over the bund wall was collected in rectangular vessels and weighed.

EXPERIMENTAL METHOD

The test runs were arranged to investigate the effects of the different bund walls, different distances between the release point and the bund wall, different heads of liquid and different orientation/shape/size of failure. The combinations are listed in the results.

The tests were performed in order to model a release of kerosene from tanks with various liquid heights. As indicated above in Figure 3, it was not possible to construct the apparatus to demonstrate a failure at the base of the tank.

The tests were filmed on a video recorder and example tests photographed.

The amount of water released was calculated from the geometry of the test vessel. The amount spilling over the bund wall was found by weighing the catch vessels and subtracting the empty weights. Most of the water was released within about 10 to 20 seconds.

Observations on the tests were recorded using the following nomenclature:

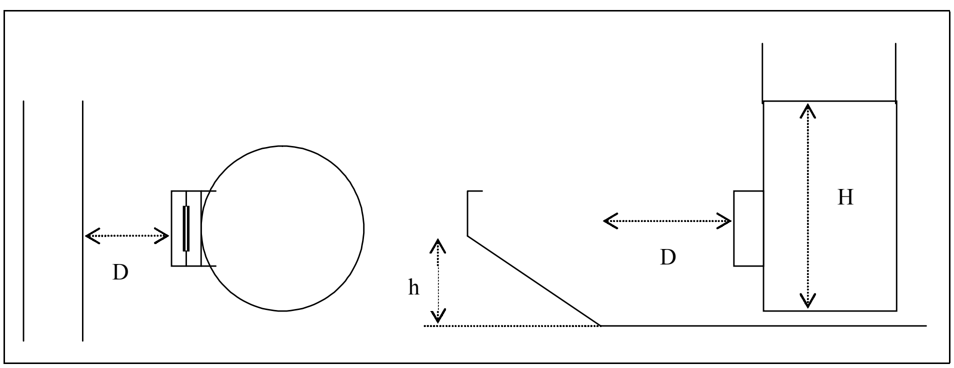


Figure 4. Nomenclature

RESULTS

Records are presented in Table 1 at prototype scale, derived from the model results.

Only two pairs of tests are directly comparable but serve to demonstrate that the two runs which gave the highest proportion of overtopping (0.342 and 0247) with the sloping bund of height 2.3 metres, Tests 2 and 3A showed virtual elimination of overtopping when repeated with the sea wall section in place (Tests 9 and 7 respectively resulted in 0.001 and 0.002 of the release overtopping the bund. This corresponds to less than 10 m^3 at full scale, compared with up to around 1000 m^3 without the sea wall. The tests were designed to demonstrate the effectiveness of the arrangement rather than to compare the results with and without the additional structure.

Table 1. Summary of results

Test no.	Liquid head, H, above bottom of hole (m of water)	Distance from bund, D (m)	Hole	Bund wall height, h (m)	Proportion of release overtoppin g bund
1	6.6	9	1	1.7	0.62
2	8.58	3	1	2.3	0.342
3A	8.58	13.5	1	2.3	0.247
4	6.6	20	1	2.3	0.019
4A	11.4	20	1	2.3	0.103
6	6.6	20	1	2.3 + sea wall	0.001
6A	9	20	1	2.3 + sea wall	0.000
7	8.58	13.5	1	2.3 + sea wall	0.002
7A	9.9	13.5	1	2.3 + sea wall	0.002
8	8.58	9	1	2.3 + sea wall	0.000
8A	9.9	9	1	2.3 + sea wall	0.000
9	8.58	3	1	2.3 + sea wall	0.001
9A	9.9	13.5	1	2.3 + sea wall	0.002
10	6.6	20	2	2.3 + sea wall	0.001
10A	7.5	20	2	2.3 + sea wall	0.002
11	8.58	13.5	2	2.3 + sea wall	0.009
11 Repeat	8.58	13.5	2	2.3 + sea wall	0.000
11A	9.9	13.5	2	2.3 + sea wall	0.000
12	8.58	9	2	2.3 + sea wall	0.006
12 Repeat	8.58	9	2	2.3 + sea wall	0.000
12A	9.9	9	2	2.3 + sea wall	0.000
13	8.58	3	2	2.3 + sea wall	0.018
13A	9.9	3	2	2.3 + sea wall	0.043
14	8.58	3	2 modified	2.3 + sea wall	0.014
15	6.6	20	3	2.3 + sea wall	0.000
16	8.58	23.5	3	2.3 + sea wall	0.000
17	8.58	9	3	2.3 + sea wall	0.000
17A	9.9	9	3	2.3 + sea wall	0.000
18	8.58	3	3	2.3 + sea wall	0.000
18A	9.9	3	3	2.3 + sea wall	0.000
19	8.58	3	Unrestricted	2.3 + sea wall	0.000

Only two pairs of tests are directly comparable but serve to demonstrate that the two runs which gave the highest proportion of overtopping (0.342 and 0247) with the sloping bund of height 2.3 metres, Tests 2 and 3A showed virtual elimination of overtopping when repeated with the sea wall section in place (Tests 9 and 7 respectively resulted in 0.001 and 0.002 of the release overtopping the bund. This corresponds to less than 10 m^3 at full scale, compared with up to around 1000 m^3 without the sea wall. The tests were designed to demonstrate the effectiveness of the arrangement rather than to compare the results with and without the additional structure.

OBSERVATIONS

1. Although the volume of liquid released does not scale to the full contents of a typical tank, the liquid head used is similar to the maximum liquid head in a storage tank when scaled up. The effect of a greater volume (larger tank diameter) would be to reduce the rate at which the head decreased following the start of the release and so increase the duration of the release, the proportion of liquid overtopping the bund would be similar.
2. In Test 6A, only 1 or 2 small drops of liquid splashed over the bund wall.
3. In run 7A, there was initially no overtopping of the bund but after about 10 seconds one large 'splash-over' occurred.
4. For Tests 8 and 8A there was no overflow.
5. For Tests 9 and 9A there was very small overflow, the smallest amount detectable.
6. For Tests 11 and 12, there was a long delay to overflow.
7. It was observed that the silicone sealant (between the floor and the bottom of the bund wall) was being moved by the liquid flow during the test and that this was a possible cause of disruption to the flow causing the delayed splash, i.e. if there is an obstruction on the sloping face of the bund, this may cause some splash over the raised bund wall. The sealant was removed and replaced with a polypropylene weld that solved this problem.
8. The repeat of Tests 11 and 12 then showed no overflow and in Test 12A a small drop splashed over but was not detectable by weighing.
9. Tests 13 and 13A resulted in part of the release jetting directly over the top of the bund and sea wall extension, demonstrating that spigot flow could overtop the bund for a tank close to the bund wall.
10. Tests 11 and 11A were repeated and Test 11 resulted in no overspill but in 11A a small amount splashed over and was just detectable by weighing.
11. Tests 15, 16, 17A and 18A resulted in no overflow. For Tests 17 and 18, there were small drops of overflow but this was not detectable by weighing.
12. The hole restriction was removed for Test 19 to give the maximum possible hole size, but no overflow was observed or measured.

Still photographs from the tests are shown in Figures 5 and 6.

Figure 5. Bund wall (2.3 m) without 'Sea Wall'

Figure 6. Bund wall with 'Sea Wall'

COMPARISON WITH OTHER MODELS

The experiments showed that when using a typical bund wall design, the results were compared with the model of Michels et al.[4] and shown in Table 2.

Table 2. Comparison of tests 1 to 4A with the Michels model

	Overtopping proportion	Michels et al. prediction
Test 1	0.62	0.25
Test 2	0.34	0.25
Test 3A	0.25	0.12
Test 4	0.02	0.04
Test 4A	0.10	0.04

Thus, it can be seen that the actual amount of overtopping was generally greater than that predicted by the model of Michels et al. This could be due to the fact that the slope in the test runs was shallow and thus it provided a smooth trajectory for the liquid to run up. (Other causes could be the experimental arrangement not allowing complete release to the tank bottom, and the smaller than normal diameter to height ratio). Such a result was expected and, in fact, important, as such an arrangement was seen as a control where it was felt necessary to be in agreement with previous research. However, overtopping was virtually eliminated when using the horizontal 'lip', and this is evident from the videos of the experiments. The work of Greenspan et al.[3] used similar set-ups to investigate the effects of overtopping. Greenspan, however, found that overtopping still occurred. The likely reason for the difference in results here is that Greenspan's experiments were one-dimensional, i.e. the liquid was released down a channel to a wall and spreading across the bund was not modeled. The experimental apparatus used in this work is more realistic as it allows for spreading across the bund two-dimensionally.

The fluid mechanics of the tests have not been investigated theoretically, but it was found experimentally that smooth flow across the bund is important. When there was a disturbance created by the silicone rubber seal between the bund floor and the wall, this caused turbulence in the flow, resulting in water being projected over the sea wall. When the seal was replaced by a polypropylene weld, the flow was more laminar in nature and overtopping did not occur for the majority of the tests. Thus it is likely to be importance not to have such obstacles in actual bunds. The fluid mechanics would need to be investigated further both experimentally and theoretically.

COMPARISON WITH HISTORICAL DATA

Several incidents have occurred in the past where there has been a catastrophic failure of an atmosphere storage tank containing crude oil or petroleum products. Such incidents are well documented by Wilkinson[1]. Following such a failure the tank contents have been released and in some instances the material has been lost outside of the secondary containment due to the momentum from the initial surge. The best example of this was the Floreffe incident[2] of 1988, which is mentioned above. The experimental work conducted here has supported the evidence from past incidents and other experimental work[3,4,6–9] that the effects of overtopping can be catastrophic for typical bund wall arrangements, particularly if the tankage is situated adjacent to vulnerable receptors.

The effects of retrofitting the bund wall with the design discussed in this paper have not been tested in reality. However, it is expected that the effects would be significant and possibly with sufficient design that overtopping would be alleviated altogether. For specific designs, further designs would be desirable, possibly with a larger scale to test the effects up scale-up.

CIVIL ENGINEERING ISSUES

As discussed in a paper by Davies et al.[10] there may be structural failure of a bund wall by the surging of the released liquid. For many current bund walls, where the wall is simply of a vertical construction, the wall would likely collapse, due to the dynamic forces as the released liquid impacted the wall. Hence, even if the wall could prevent overtopping, it may well collapse completely, resulting in a catastrophic release from the secondary containment.

Hence, the bund wall must be designed to withstand the dynamic forces of the surging liquid over a period of many seconds. A retrofit of the design discussed in the experimental point would be pointless if this were to collapse.

DISCUSSION - PREVENTION OR CONTROL?

It should be pointed out that the bund wall design investigated in this experimental work is only to control the effects of catastrophic failures. Its use is only mooted in extreme circumstances where it may be necessary to retrofit existing bunding arrangements for the protection of vulnerable receptors, e.g. Sites of Special Scientific Interest (SSSIs) or populated areas. A risk assessment should be conducted to determine whether it may be necessary to include such a design. In any case, mechanisms of prevention should first be explored to ensure that the risk is as low as reasonably practicable. Such mechanisms may include corrosion prevention, Non Destructive Testing (NDT), hydrostatic testing, etc., where these are set out under robust safety and environmental management systems. Only if the residual risk still deemed as not tolerable and further cost-effective mechanisms for prevention have been exhausted, then mechanisms for control such as retrofitting the bund walls should be considered.

The lessons learnt from previous accidents should be considered in preventing catastrophic tank failures. For example, the Floreffe tank underwent brittle fracture causing it to fail catastrophically. The tank was 40 years old and had been dismantled, transported and then reassembled. It failed on its first refill. The lessons from this and other such failures cited by Wilkinson are important to prevent a reoccurrence.

Davies et al.[10] cite the following reasons for catastrophic releases from storage vessels after inspection of incidents recorded on the MHIDAS database (Major Hazardous Incidents Database):

- brittle failure of primary containment, sometimes caused by rapid changes in ambient temperature,
- failure of tank seams due to fire impingement,

- failure of the tank during the initial filling process,
- boilover of tank contents,
- acts of vandalism or sabotage.

For the construction of new tanks, effective use of land-use planning, together with modern design standards and state-of-the-art methods for accident prevention, should ensure that standard bunds walls that retain 110% of the tank contents should be sufficient.

CONCLUSIONS

1. The experimental work described in this paper has shown that it is possible to design bund walls to prevent overtopping following catastrophic failure, without having to build the walls to extreme heights. By incorporating a design similar to that used for sea walls, i.e. the use of a horizontal 'lip', the surging liquid can be directed back into the bund even for 'unzipping' type releases.
2. Such a bund wall design would need to be of sufficient strength to withstand the dynamic forces of a surging liquid following a catastrophic release. Such forces would likely cause many simple vertical walls to fail and thus the design would require significant reinforcement. The fluid mechanics of the catastrophic release would need to be investigated in detail as it was observed that obstacles in the bund may cause turbulence that may, in turn, cause overtopping to occur.
3. The bund wall design should only be used for retrofitting bund walls after a risk assessment has been carried out. The risk assessment should first explore all mechanisms of prevention and only if the residual risk is still not tolerable should retrofitting then be considered. Such a bund design should not be need for new tanks, where effective use of land-use planning, together with modern design standards and state-of-the-art methods for accident prevention should ensure that the risk of catastrophic failure and overtopping is broadly acceptable or as low as reasonably practicable.

REFERENCES

1. Wilkinson, A, Bund Overtopping - the consequences following catastrophic failure of large volume liquid storage vessels, AEA Technology, SRD/HSE R530, 1991.
2. Prokop, J., The Ashland Tank Collapse, *Hydrocarbon Processing*, 67(5), 105, May, 1988.
3. Greenspan, H.P., Johansson, A.V., An Experimental Study of Flow Over an Impounding Dyke, *Studies in Applied Mathematics*, Vol.64, p.211, 1981.
4. Michels, H.J., Richardson, S.M., Sharifi, T., Catastrophic Failure of Large Storage Tanks, IChemE Symposium Series No.110, 1989.
5. Trbojevic, V.M., Slater, D.H., "Tank Failure Modes and Their Consequences", *Plant/Operations Progress*, 8, 84, 1989.
6. Clark, N. and Savery, J., The Catastrophic Failure of Containment Vessels, 3rd Year Link Project, Dept. of Chem. Eng. and Chem. Technology, Imperial College, London, and the Health and Safety Executive, Buxton, December, 1984.

7. Law, G.D., and Johnskareng, G.R., Containment Provisions and Overflow of 2-Dimensional Catastrophic Tank Failure, 3rd Year Link Project, Dept. of Chem. Eng. and Chem. Technology, Imperial College, London, and the Health and Safety Executive, Buxton, December, 1984.
8. Cleaver, R.P., Cronin, P.S., Evans, J.A., Hirst, I.L., An experimental Study of Spreading Liquid Pools, IChemE, Hazards XVI, Manchester, November 7th–9th, 2001.
9. Thyer, A.M., Hirst, I.L., Jagger, S.F., Bund Overtopping – The Consequences of Catastrophic Tank Failure, J. Loss Prev. Process Ind., 2002.
10. Davies, T., Harding, A.B., McKay, I.P., Robinson, R.G.J., Wilkinson, A., "Bund Effectiveness in Preventing Escalation of Tank Farm Fires", Trans IChemE, Vol. 74, Part B, May 1996.