AN EXPERIMENTAL STUDY OF SPREADING LIQUID POOLS

R.P. Cleaver, P.S. Cronin and J.A. Evans
Advantica Technologies Ltd, Ashby Road, Loughborough, Leicestershire, LE11 3GR and
I.L. Hirst HSE, St Anne's House, Stanley Precinct, Bootle, Merseyside, L20 3RA

Assessment of the hazards posed by the storage of flammable or toxic liquids in large tanks can be assisted by the used of mathematical models to calculate the consequences of leakages. These consequences may include fires or explosions from dispersion of flammable vapours, harm to persons from inhalation of toxic vapours or harm to the environment. One component of such models is a mathematical representation of the spreading of a liquid pool, and in recent years a number of pool spread models have been proposed and implemented.

However, there are a number of issues in the formulation of the spreading models that have yet to be resolved. In particular, one area of uncertainty is the boundary condition applied at the front of the spreading pool. Boundary conditions which are generally accepted as applicable to the spread of oil on water and to the dispersion of a cloud of dense gas in air may not be applicable to the spread of a liquid on land, as the balance of competing physical phenomena at the spread front is quite different. Resolution of the uncertainties this creates has been hampered by a lack of reliable experimental data at a large scale. As a result, the Health and Safety Executive have contracted Advantica to carry out a series of "liquid spread on land" experiments at their Spadeadam Test Site to provide a sufficiently detailed database to resolve this issue. This paper gives details of the experimental programme and presents selected results from it.

KEYWORDS: Liquid pool spread, Consequence assessment, release behaviour, experimental data

INTRODUCTION

Assessment of the hazards posed by the storage of flammable or toxic liquids in large tanks can be assisted by the use of mathematical models to calculate the consequences of leakages. These consequences may include fires or explosions from dispersion of flammable vapours, harm to persons from inhalation of toxic vapours or harm to the environment. One component of such models is a mathematical representation of the spreading of a liquid pool, and in recent years a number of pool spread models have been proposed and implemented [1,2.]

However, there are a number of issues in the formulation of the spreading models that have yet to be resolved. In particular, one area of uncertainty is the boundary condition applied at the front of the spreading pool; in this respect the modelling described in Webber[1] is fundamentally different to that described in Linden et al[2], for example, and in a number of other software models known to be in use. Boundary conditions which are generally accepted as applicable to the spread of oil on water and to the dispersion of a cloud of dense gas in air may not be applicable to the spread of a liquid on land, as the balance of competing physical phenomena at the spread front is quite different. Although information is available from a variety of sources[3,4,5,] resolution of the uncertainties this creates has been hampered by a lack of reliable experimental data at a large scale. As a result, the Health and Safety Executive have contracted Advantica to carry out a series of "liquid spread on land" experiments at their Spadeadam Test Site to provide a sufficiently detailed database to resolve this issue, as well as to allow more general validation.

The large scale of the test rig means that the experiments also have a direct bearing on issues of a practical nature. Most tanks used for storage of flammable or toxic liquids in the United Kingdom have capacities less than 50,000 cubic metres, although several tanks exist with capacities in excess of 100,000 cubic metres. The test tank constructed at Spadeadam replicates a tank of about 150,000 cubic metres capacity at a linear scale of one-twentieth, or, alternatively a tank of about 20,000 cubic metres capacity at a linear scale of one-tenth.

From an initial fill height of up to 1.8 m, water was released through a slot at the base of the tank and was free to spread over distances of up to 10 m on a specially constructed horizontal concrete surface. The size of the slot was such that the tank emptied completely in about thirty seconds. More rapid releases can be imagined, and indeed have occurred in practice when storage tanks have failed catastrophically. But the rate of release in these tests was judged adequate for the intended purpose of the tests. Experiments were carried out investigating not only the rate at which the pool spread, but also its interaction with a retaining bund wall of the type that is often encountered. The amount of the liquid that is able to flow over the retaining walls in this interaction is a quantity of particular interest in hazard assessment. Consequently, estimates of the proportion of the liquid that escaped from the bunded area in this way, the "overtopping fraction", were also made in the experiments.

In the following Sections, details of the experimental programme are presented and a number of the results are discussed. This includes a description of the experimental rig and associated instrumentation; an overview of the test programme; examples of the results and, finally, a discussion of the results and the implications these may have.

EXPERIMENTAL DETAILS

THE TEST RIG

The release vessel was designed to represent at 1/20th scale a quadrant of a 70m diameter storage tank. The lower section of the vessel was constructed from a section of curved mild steel with a 3.5m diameter. Elsewhere, the shape of the vessel was modified slightly in order to strengthen the vessel whilst maintaining the required cross-sectional area to represent a quadrant of a cylindrical tank, as shown on Figure 1.

For all of the tests, the vessel was filled with water at ambient temperature. A slot was cut around the circumference of the lower section of the vessel wall, and into it was fastened a quarter-circular strip of mild steel containing a slit of 25 mm height, through which the water could be released. The water was held in the vessel initially by an array of five flaps. On the outside of the tank was a pneumatically controlled mechanism that opened or closed the flaps; thereby allowing water to flow freely out of the tank for a controlled period of time.

The release mechanism was controlled by a PC based SCADA system, connected to a sequence timer system that co-ordinated the operation of the liquid release mechanism and the instrumentation.

Bund walls were fabricated from mild steel and set up on a flat 15m square concrete pad with the release vessel at one corner. Thirteen different bund configurations were used, 9 circular and 4 square. All configurations were sized to give nominally the same liquid containment volume. The two sides of the 90^{o} quadrant were enclosed with 250mm deep flat plate, and were assumed to act as walls of symmetry. Perspex sections were fitted into one of the side walls to allow video records to be made of the water flow.

For some tests, 1 circular and 2 semi circular sections were installed within the bund to represent the appropriate parts of a regular array of additional tanks. The sections were fabricated from 200mm wide flat steel strip rolled to a 3.5m diameter.

INSTRUMENTATION

A scale was marked on the inside of the vessel to show the level of water within it above the bottom of the slit. In addition, a pressure transducer was fitted in the vessel at a height that was level with the top of the slit. During the experiments, the signal from the pressure transducer was recorded on a transient recorder sampling at 200Hz, from which the rate of flow of water out of the vessel was inferred.

The movement of water across the bund floor was monitored using up to 60 resistance probes, fixed in position on the concrete bund floor using terminal block. The resistance probes consist of two electrodes separated by gap (typically 5-10 mm), which provides a high electrical resistance. The arrival of the water lowers the resistance across the gap and triggers a TTL voltage step output from a purpose-built electronic circuit. This voltage acts to terminate a computer based counting register on a counter board. Counting was started when the release was initiated, and thus, using the known count frequency, a measure of the time of arrival of the water front at a specific probe location was obtained. The accuracy of the system has been checked by comparison with cine records and has been shown to indicate arrival times with an accuracy of better than 1 millisecond.

Water that overtopped the bund was caught in a polythene sheet attached to the (outside) edge of the bund and was then pumped into calibrated containers to measure its volume.

Up to four video cameras were used in the experiments; the images being recorded on MiniDV video tape. Video timers provided a timescale for the images on the video tape. One camera was used to provide general images of the release, another provided an overhead view of the floor of the bund whilst the other two cameras were used to monitor items of specific interest, for example, the time of arrival of the water front at the bund wall, or the release of water in the vicinity of the tank.

EXPERIMENTAL PROGRAMME

In the first of two Test Phases, 37 experiments were carried out to examine liquid spread over flat uninterrupted terrain and interaction with a single, circular bund wall. Three nominal fill heights were used for these tests: 1.45m, 1.6m and 1.8m, chosen to give water volumes approximately equal to 90%, 100% and 110% of the bund capacity. Different combinations of bund location and height were investigated and bunds with face angles, relative to the oncoming water front, of either 30 degrees, 45 degrees or 90 degrees were used.

In the Phase 1 experiments, the resistance probes were positioned as shown in Figure 2. Probes deployed along two radial lines monitored the general progress of the front, and probes located along circular arcs gave information about the radial symmetry of the flow.

In Phase 2, 22 experiments investigated releases into square bunded areas, in some cases with obstructions present. Figure 3 illustrates the different configurations. In all of these cases, the bunds walls presented a vertical face to the oncoming water.

EXPERIMENTAL RESULTS

Figure 4 shows the variation of the height of water remaining in the vessel with time for three representative experiments carried out with the three initial fill levels. The experimental values were inferred from the measurements of pressure made at the base of the vessel. The data recorded by the pressure transducer inevitably contain some random, high frequency noise and, possibly, other, more physically-based oscillations, superposed on the signal recording the changing head of water as the tank empties. Such oscillations are particularly apparent in the first few seconds immediately following the opening of the flaps to release the water. As a result, some form of time averaging is required to remove this high frequency component from the data if they are to be differentiated numerically in order to infer a representative flow rate from the vessel. The curves shown in Figure 4 were produced using 0.5 second time averaging to remove the high frequency oscillations. Also shown on this Figure are predicted values obtained using the Bernoulli equation for the outflow velocity and the measured value for the area available for outflow, assuming a discharge coefficient with a value of 0.64. The agreement between the values inferred from the measurements and the predictions is very close. This gives some confidence that the measurements were made correctly and that the release mechanism worked as intended.

Figure 5 shows the time of arrival of the water front plotted against distance from the release vessel for representative tests carried out with the three initial fill levels. These measurements were made in experiments in which the bund wall located 10m from what would have been the centre of a cylindrical vessel (referred to hereafter as the 'centre of the vessel').

The time of detection of water at the resistance probes was used to infer the velocity of the front. Using the time difference between arrival of water at adjacent resistance probes along a radial line was found to give a local velocity with a significant amount of variability. Consistent with this, local variations in progress can be observed on the video records. However, a smooth polynomial curve was fitted to all of the time of arrival data collected in experiments with the same initial fill height in the vessel and this curve was differentiated to obtain an 'averaged' front velocity. A comparison of this inferred 'average' velocity with one particular set of 'local' velocity data is shown in Figure 6.

It should be noted that an examination of the video records and time of arrival records of the experiments suggests that the disruption to the flow caused by the presence of the resistance probes may have slowed the progress of the front slightly along the line of the probes. The size of the terminal block used to hold the resistance probe wires close to ground level was approximately 14mm and it was observed that there was a small wake-like region created in the lee of each probe. The video records suggest that these wake-like regions did not spread to affect the radial outflow at other locations. The maximum effect this produced appears to have occurred in the tests with the greatest initial fill level in the tank. In this case, the maximum difference in the time of arrival of the flow along the line of the probes and elsewhere at a distance of 10m (i.e arrival at the bund wall in the relevant tests) is about 0.5 secs. This suggests that the average speed of progress inferred from the resistance probe measurements systematically underestimates the true value by 0.05 m/s at most (compared with an observed value of about 0.37 m/s – corresponding to a discrepancy of about 13% in the values obtained from the resistance probe data along the 45 degree radial line). Whilst such differences should be born in mind if the data are used to compare with the predictions of mathematical models, they are of a smaller magnitude than differences in the predictions models currently in use.

The volume of water that overtopped the bund in each experiment was found to vary with the initial fill height, the profile of the bund wall and its distance from the vessel. As an example, Figure 7 shows how, in a number of the Phase 1 experiments, the amount varies with the wall angle and distance of the bund from the vessel.

DISCUSSION

As yet, only the data collected in the Phase 1 experiments have been examined in detail. This phase has provided data on the spreading of water released from the base of a tank, that at a scale of 1:20, represents a 70m diameter storage tank. The release and the surrounding geometrical arrangement are of a simple nature and this means that the flow that is produced can be simulated in a straightforward manner by mathematical models for liquid spread over land. Hence, the results from the experiments provide a dataset that can be used for the development or validation of mathematical models.

The interaction of the spreading front with a number of different bunds has been examined and the amount of water, if any, overtopping the bunds has been determined. A number of observations can be made on the data, as follows.

Firstly, as can be seen from Figure 4, the outflow from the vessel is in close agreement with expectations from theory. Also, the initial velocity of the water flowing out of the vessel is consistent as a starting value for the inferred spreading velocity data, such as that shown in Figure 5.

Within the programme, a number of experiments were carried out with the same initial head in the tank. A comparison of the spreading behaviour in these experiments gives some idea of the repeatability of the observed behaviour. It is found that there is some variation in the time of arrival at a given distance from the tank (of the order of 10 to 20%) in any one experiment. However, the results from all of the experiments, taken before interaction with the bund wall, show similar behaviour. If the time of arrival is plotted against distance from the 'centre' of the vessel, the measurements lie in a band of relatively narrow width, indicating a good degree of reproducibility in flow behaviour. Figures 5 and 6 illustrate this for the results obtained with one particular initial fill level in the vessel. Results such as those shown in Figure 5 and 6 provide the data that can be used to help investigate a number of issues. For example, the observed spreading velocity may be used to test the significance of using different boundary conditions at the front of the spreading pool within the mathematical models for pool spread on land. This should enable many of the existing uncertainties to be resolved.

The measurements of the amount of water overtopping the bund have also been examined. As Figure 7 demonstrates, if a large enough release occurs from the full perimeter of the tank, the water is capable of overtopping the bund walls, even if the bunded area has the capacity to hold all of the water that is released. Based on these results, it appears that the amount that overtops the bund decreases as the distance of the bund wall from the vessel increases (note: the bund heights were chosen to ensure that the bunded volume had nominally the same capacity in each case.). The amount also appears to be sensitive to the bund wall angle. Of the designs that were tested, the vertical bund wall was the most effective at retaining the water within the bund in this case.

It is expected that the results from the second Phase of experiments will shed further light on the release behaviour in situations that are more likely to be encountered in practice. Finally, it is noted that many of the mathematical models include the effects of parameters such as the surface tension and viscosity of the liquid within their formulation. Hence, once the existing uncertainties in the spreading behaviour have been resolved, it should be possible to use the models to define a specific, limited, programme of further experiments to provide data to confirm the influence of these parameters.

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DISCLAIMER

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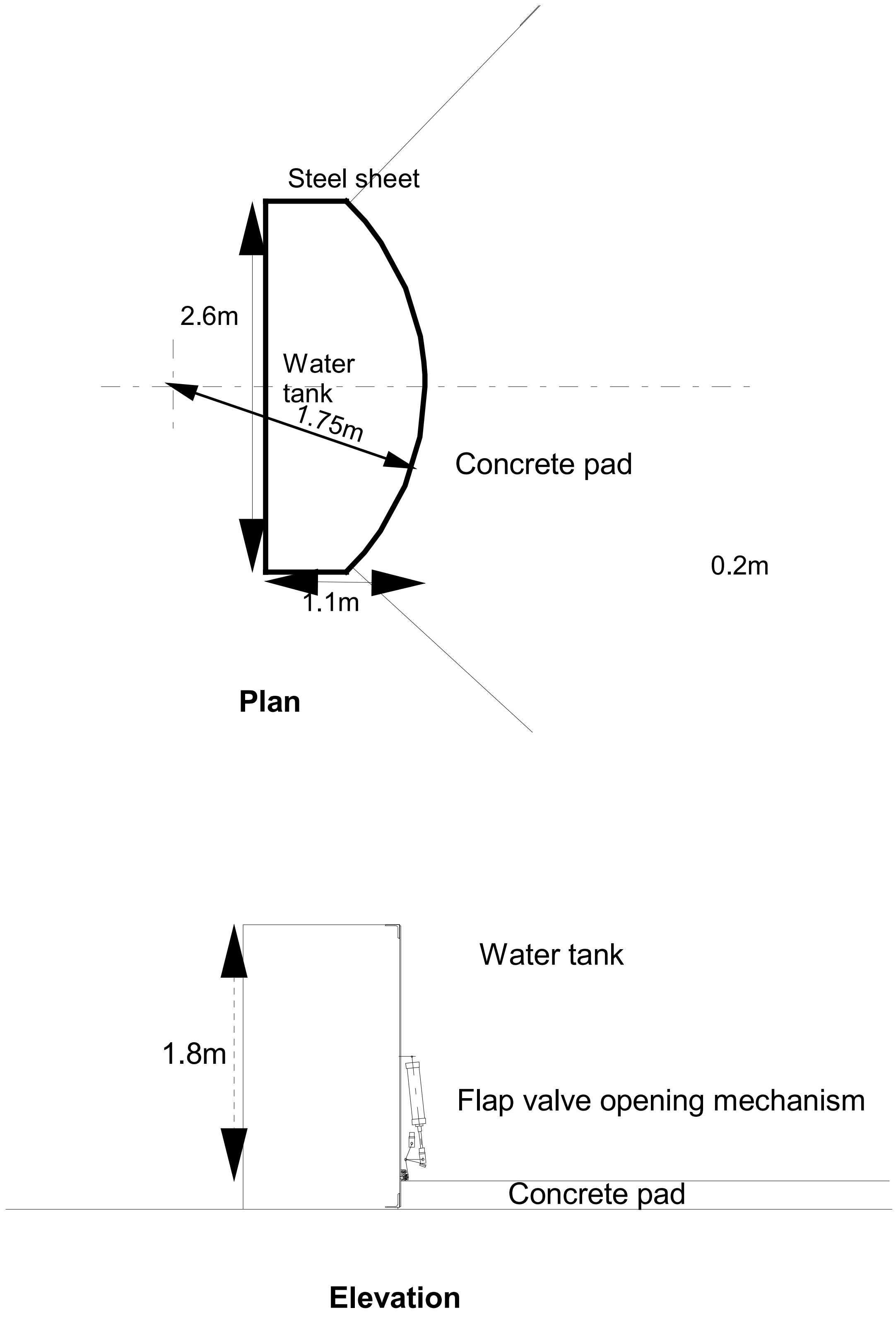

Figure 1. Diagram showing the design of the experimental rig.

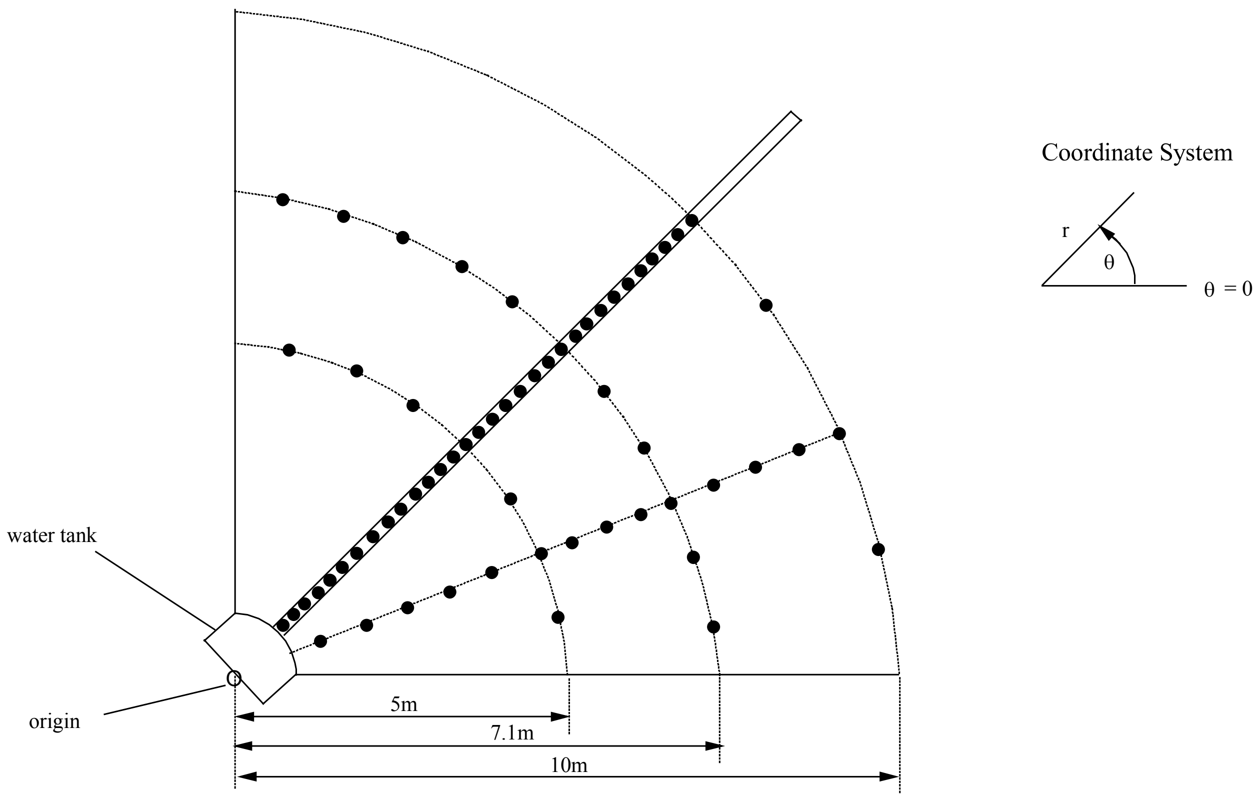

Figure 2. Location of the resistance probes used in the Phase 1 experiments.

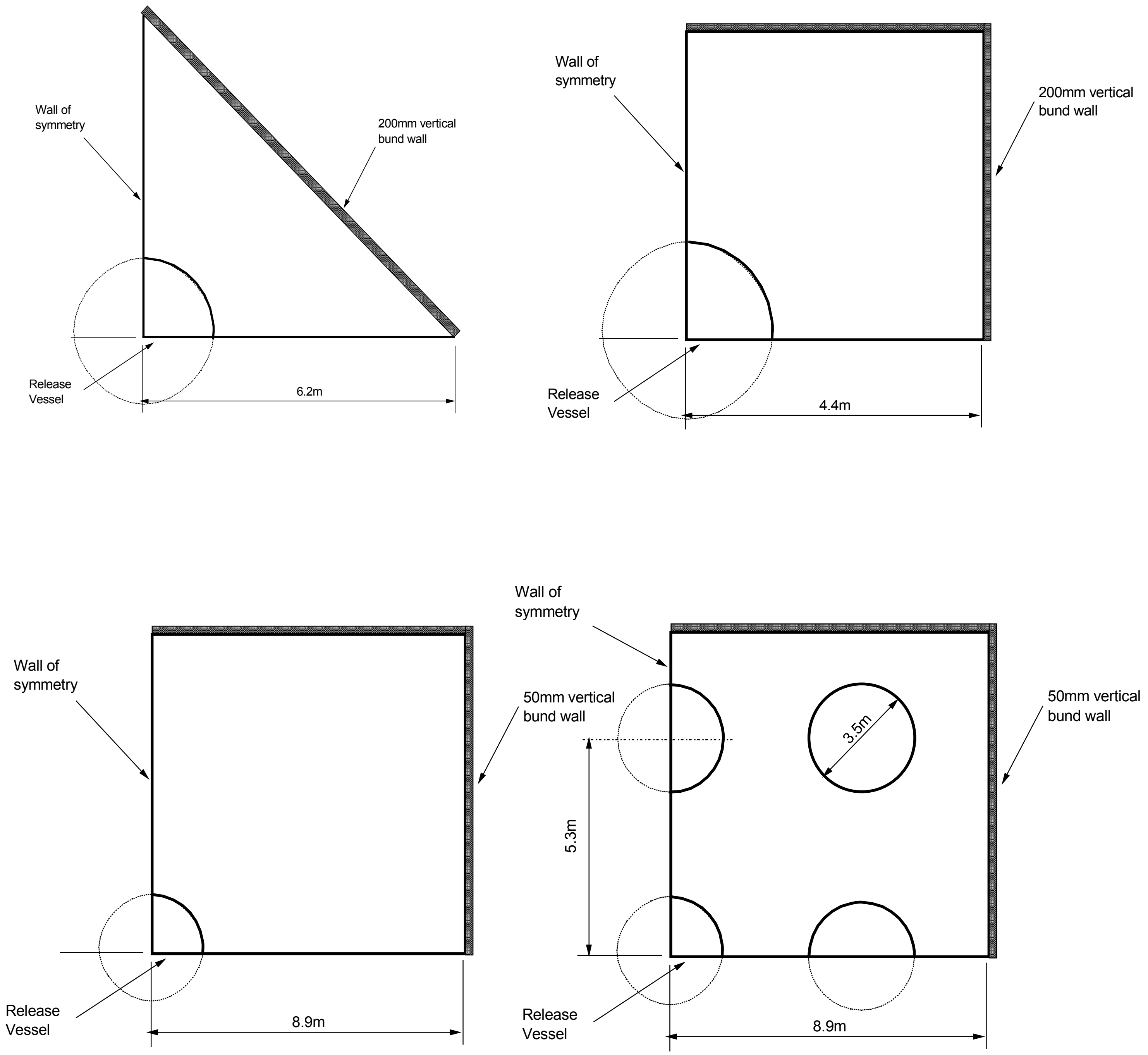

Figure 3. Four arrangements of bunding investigated in Phase 2 of the experimental programme.

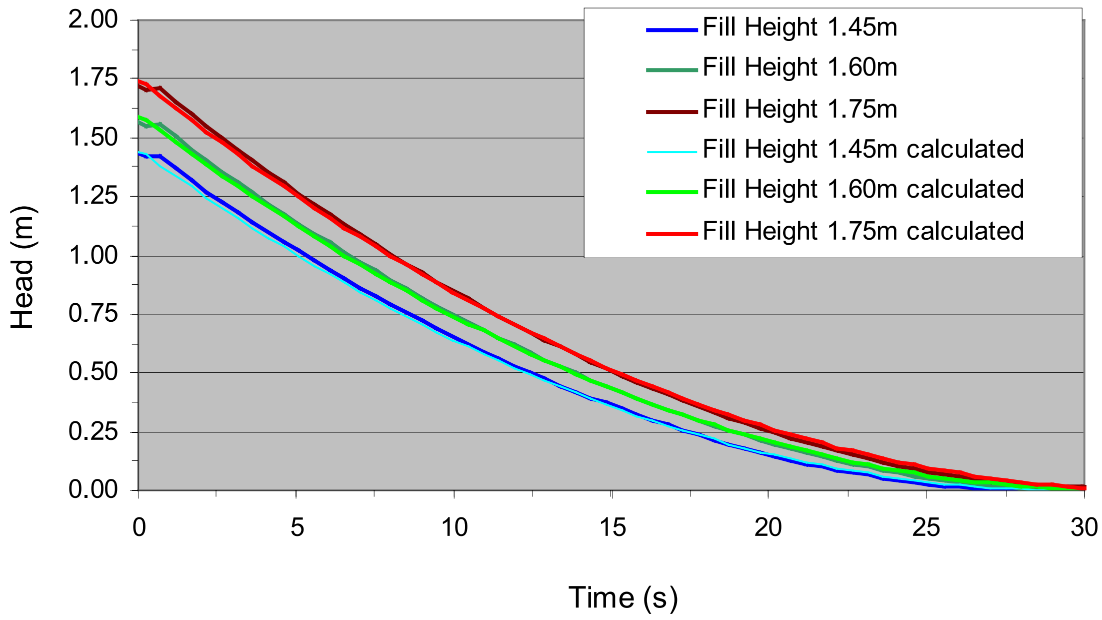

Figure 4. Comparison of flow rate of water from the tanks for three different head heights. (predictions plotted with a zero time shift, as indicated by transducer response).

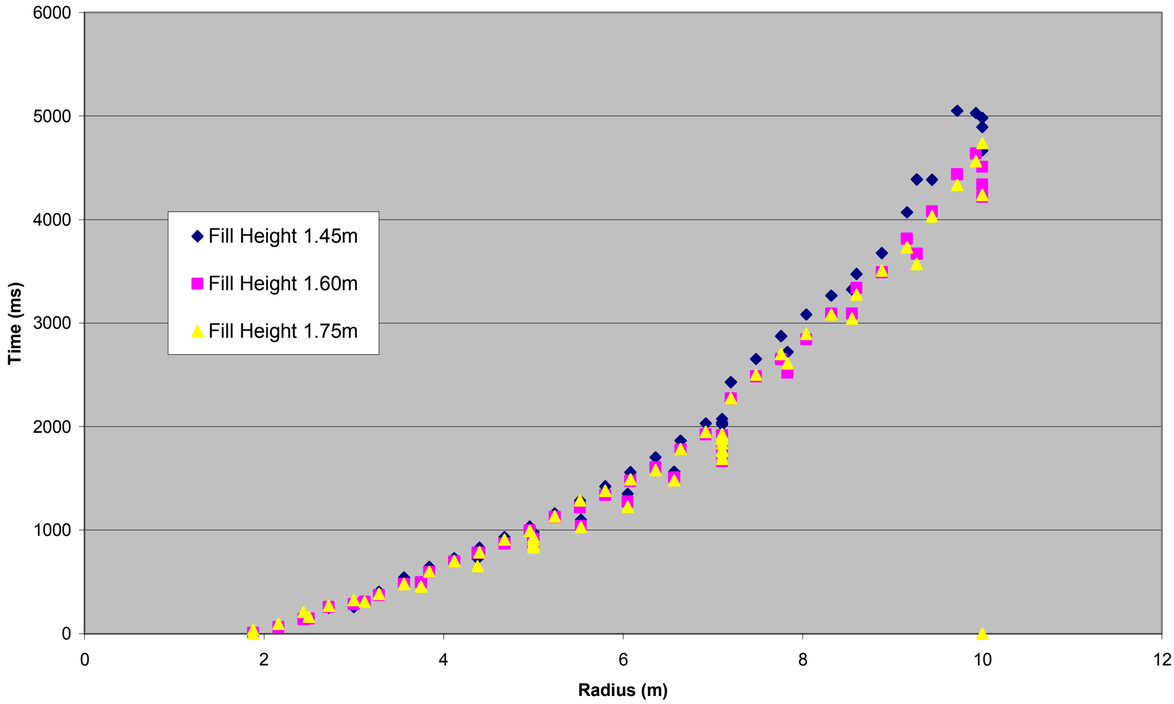

Figure 5. Comparison of spreading data for three tests using different heads of water initially in the tank.

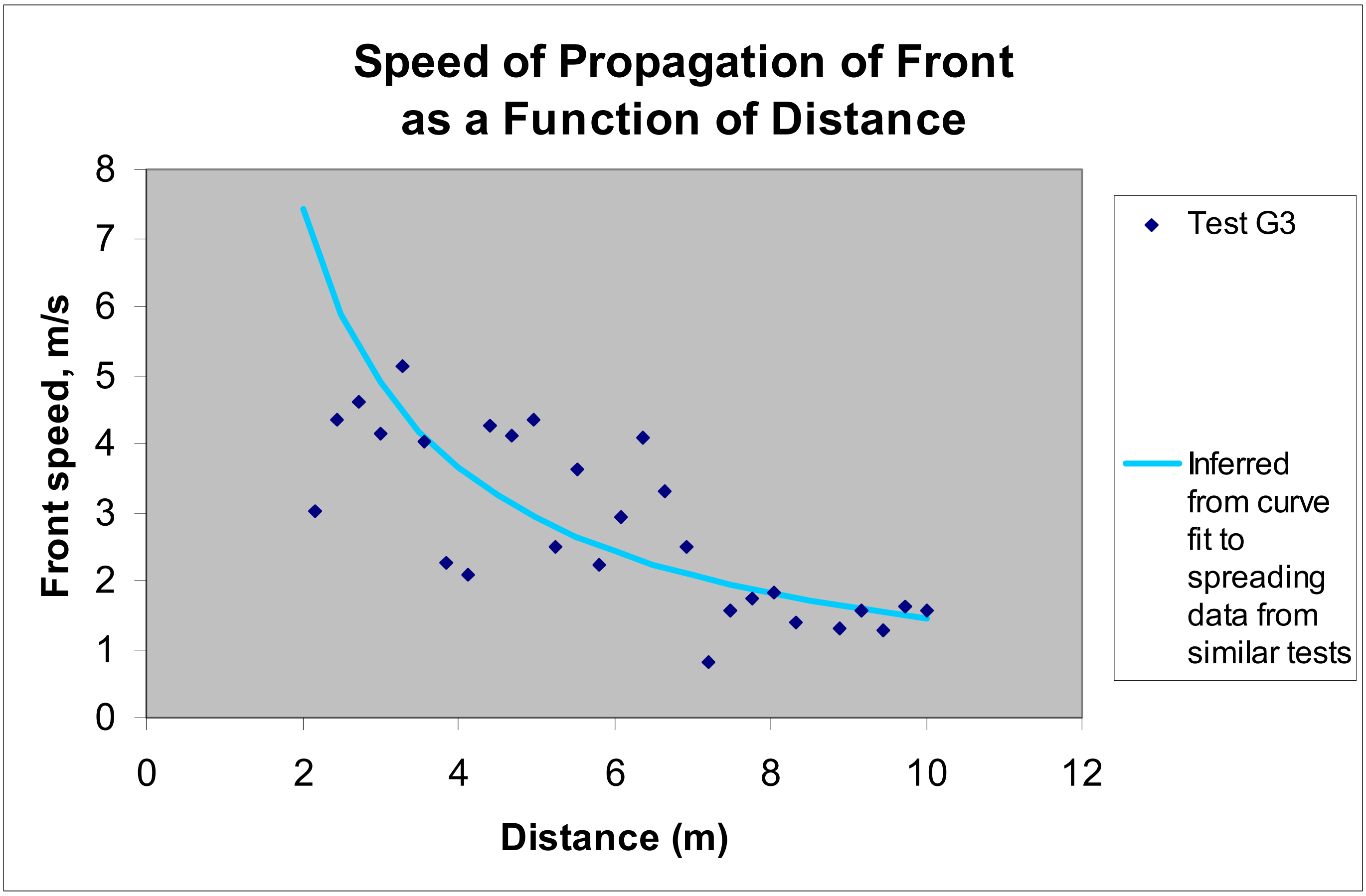

Figure 6. Comparison of frontal speed inferred from resistance data along a radial line in Test G3 with the values inferred from a curve fit to all the data collected in similar experiments.

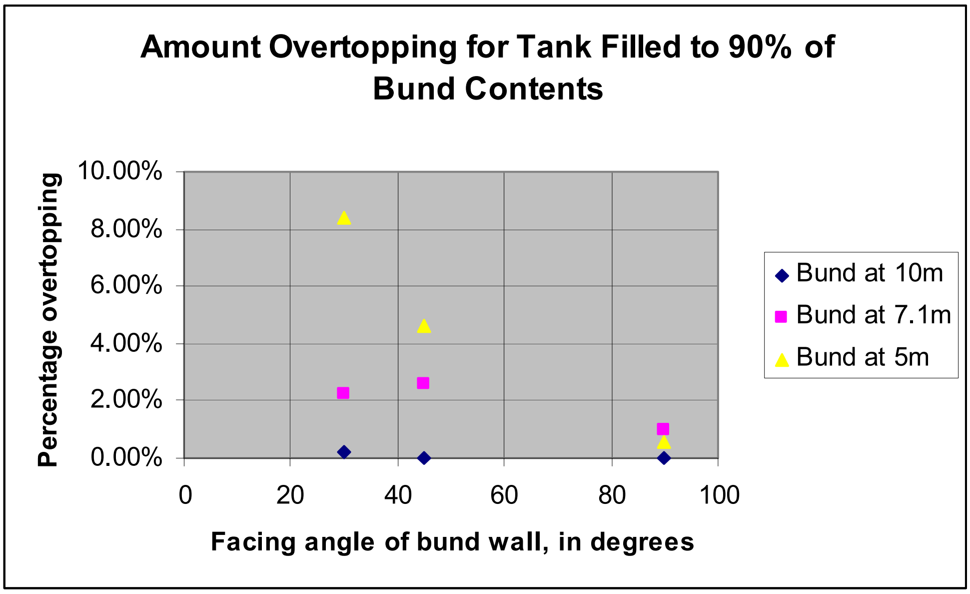

Figure 7. Amount of water overtopping the bund for bunds with different wall angles facing the oncoming flow. Results are shown for experiments in which the vessel was filled to 90% of the capacity of the surrounding bund.