6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
11 – 15 June 2018, Glasgow, UK

ASSESSMENT OF THE PERFORMANCE OF BUND WALL SYSTEMS UNDER IMPACT LOADING

ISLEM MEGDICHE[1], WILLIAM ATHERTON[2], CLARE HARRIS[3], GLYNN ROTHWELL[4] AND DAVID ALLANSON[5]

[1] Department of Civil Engineering, Liverpool John Moores University
15-21 Webster St, Liverpool L3 2ET
I.Megdiche@2015.ljmu.ac.uk

[2] Department of Civil Engineering, Liverpool John Moores University
Peter Jost Enterprise Centre, 3 Byrom St, Liverpool L3 3AF
W.Atherton@ljmu.ac.uk , https://www.ljmu.ac.uk/about-us/staff-profiles/faculty-of-engineering-and-technology/department-of-civil-engineering/bill-atherton

[3] Department of Civil Engineering, Liverpool John Moores University
Peter Jost Enterprise Centre, 3 Byrom St, Liverpool L3 3AF
C.B.Harris@ljmu.ac.uk , https://www.ljmu.ac.uk/about-us/staff-profiles/faculty-of-engineering-and-technology/department-of-civil-engineering/clare-harris

[4] Department of Maritime and Mechanical Engineering, Liverpool John Moores University
James Parsons Building, 3 Byrom St, Liverpool L3 3AF
G.Rothwell@ljmu.ac.uk, https://www.ljmu.ac.uk/about-us/staff-profiles/faculty-of-engineering-and-technology/department-of-maritime-and-mechanical-engineering/glynn-rothwell

[5] Department of Maritime and Mechanical Engineering, Liverpool John Moores University
James Parsons Building, 3 Byrom St, Liverpool L3 3AF
D.R.Allanson@ljmu.ac.uk , https://www.ljmu.ac.uk/about-us/staff-profiles/faculty-of-engineering-and-technology/department-of-maritime-and-mechanical-engineering/david-allanson

Key words: bund wall, catastrophic failure, concrete, FEM, Storage tank.

Abstract. The failure of storage tanks is a problem that has occurred in many countries around the world. Reasons behind the failure of storage tanks could be due to natural disasters or accidental releases. In all cases, the impact of such failures is deemed highly disastrous because it causes a huge economic loss in the stored material and harms the immediate community and the environment. The storage tank is also known as the primary containment and is usually surrounded by a secondary containment referred to as a bund wall, its purpose being to contain any spillage arising from the primary containment. In the UK, the bund wall is designed according to BS EN 1992-3:2006 and is usually constructed from plain or reinforced concrete. The standard specifies that the bund wall should be designed to withstand the hydrostatic pressure only, while in case of catastrophic failure, it is found that the dynamic pressure can be up to 16 times greater than the hydrostatic pressure. According to the previous failures recorded in the literature, it has been shown that the bund wall failed to withstand the impact of dynamic pressure and subsequently collapsed. In this study, it is proposed to study the performance of a bund wall with different shapes under the effect of impact loading representing the catastrophic failure of a storage tank. This problem is modelled using Abaqus software where the fluid part is modelled using Spherical Particles Hydrodynamics (SPH) and the structural part is modelled using Abaqus explicit solver. The shapes investigated are rectangular and square. Results show that a bund of a square shape is more likely to collapse than a rectangular one.

1 INTRODUCTION

The storage of any chemical substances gives rise to potential risks to humans, the environment and the economy [1]. In Great Britain, the storage industry is regulated by means of regulations and directives. The Health and Safety Executive (HSE) which is the responsible body for the encouragement, regulation and enforcement of safety and welfare in the Great Britain, has a statutory duty under the statutory instrument - The Control of Major Accidents Hazards Regulation that came into force on 1st June 2015. Among the new duties, that the latest regulations have added, is to give more importance to the major accident prevention policy and the safety management system. The regulation highlights the need to implement mitigation measures of major accidents hazards [2].

The primary containment is the storage tank that is in direct contact with the stored materials. In the UK and in many others countries such as the US and Australia, the primary containment is surrounded by a secondary containment. The secondary containment referred to as a bund wall has the purpose of containing any spillage from the storage tank [1]. It is a structure constructed from plain or reinforced concrete, and designed to BS EN 1992-3:2006.The structure is assessed on the basis of the serviceability crack width and ultimate limit state is checked [3]. In the standard, it is stated explicitly that no recommendations for the effect of dynamic forces on the structure are taken into account. Ignoring to take the dynamic forces into account puts the structure at risk [1]. Previous failures proved that the current design is not suitable to accommodate for the release of the fluid in case of catastrophic failure of storage tanks. One example is the sudden failure of a large bulk storage vessel containing refrigerated liquid ammonia in Lithunia in 20th March 1989. The surge of the fluid forced the tank to move and impact the bund wall which caused its collapse. As a result, a quantity of 7000 tonnes of material was lost, 7 persons died immediately and 57 others were injured due to the pools of ammonia that formed on the ground [1, 4].

Many research projects have been undertaken in relation to the problem of catastrophic failure of storage tanks. The first recorded research was that of Henderson [5] in which the fluid flow profile and the velocity were studied. Research proceeded to investigate the level of overtopping, which is the quantity of the stored material that escapes the bund wall [6, 7, 8, 9, 10]. Research has been focused on optimising the mitigation techniques by studying the effect of implementing a deflector on the top of a wall [11, 4]. This problem has been addressed both physically and numerically due to the advances made in the area of computational fluid dynamics (CFD) by [12]. In [1], the extent of dynamic pressure has been studied where different modes of failures were investigated. Modes of failure ranged from the axisymmetric failure, which represents the catastrophic failure of the storage tank to the asymmetric failure representing the case where a crack propagates in the shell of the tank leaving the fluid to flow through the gap.

A review of the literature shows that the performance of the bund wall under the effect of the dynamic pressure has not been addressed yet. Although, there is a clear thinking that the current design is not suitable for such scenarios, there is no research that attempted to assess the suitability of the bund wall for this range of load [9, 10, 1, 4, 13].

Therefore, in order to fill the gap, the present paper studies the performance of the bund wall due to the catastrophic failure of a storage tank with two different shapes, square and rectangular. Simulation results indicate that the rectangular bund wall has a better performance than a square bund in terms of structural integrity.

2 METHODOLOGY

This problem was modelled numerically via the use of the FEA package Abaqus. The simulations were performed using the explicit solver which is appropriate to model discontinuous nonlinear problems such as blast and impact problems [14]. The SPH method was used to model the sudden collapse of the storage tank since this method allows for extreme deformations. SPH is a numerical method, which is meshless in a sense that does not need to define nodes and elements as the standard FEA method requires.

The numerical model consisted of three parts. One part is deformable representing the fluid, a second rigid part, representing the floor, since it is assumed that the ground undergoes negligible deformations compared to the deformation that occur in the bund wall, and a third deformable part representing the bund wall itself. All parts were discretised using hexahedral, first order and reduced integration elements with aspect ratio equal to unity. Abaqus explicit solver adopts only first-order reduced integration elements because it has been shown that they are efficient in modelling contact impact or large distortions problems [15]. The model dimensions of the bund walls were chosen to provide the same containment volume with the same height of 120mm. Fig. 1 shows the numerical model for the square bund wall and Fig. 2 shows the nomenclature of the two shapes.

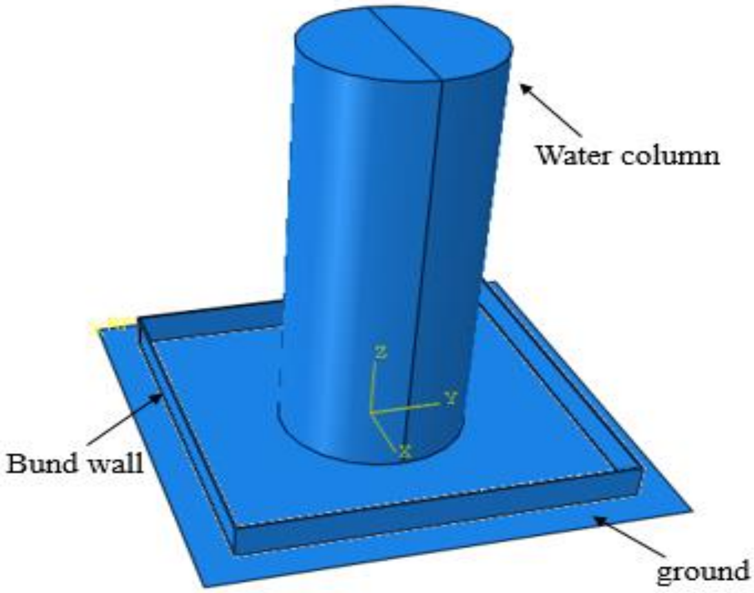
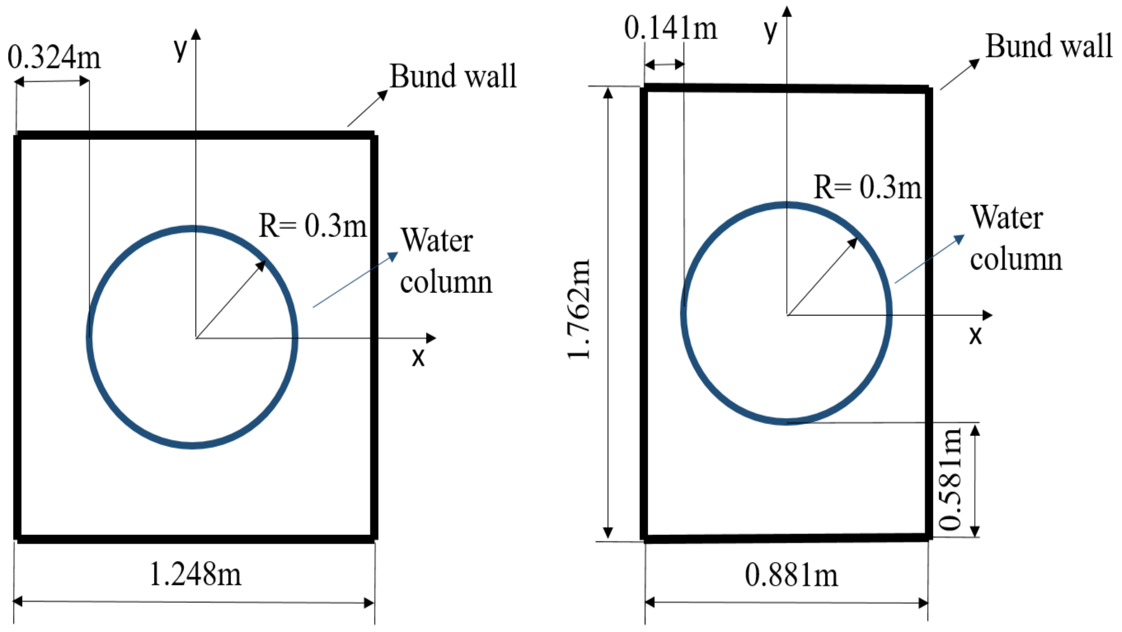


Fig. 1: Geometrical model of square bund wall



Square bund wall

Rectangular bund wall

Fig. 2: Nomenclature of bund walls

A height of fluid equal to 1.5m and a velocity of 4.85m/s was given to the fluid which was determined from previous CFD (Computational Fluid Dynamics) analysis. In addition to the velocity, the gravitational acceleration was applied to the whole model to simulate the gravitational effects. The bund wall was modelled to be fixed to the ground.

The interactions between the different parts of the numerical model were modelled using the general contact algorithm, which typically includes all parts in the model. The contact properties were a frictionless formulation for the tangential behaviour and hard contact for the pressure- overclosure for the normal behaviour.

The material model adopted to model the concrete is the concrete damage plasticity (CDP) model. It is appropriate to model the concrete under dynamic loading. The model is based on the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity in order to represent the inelastic behaviour of concrete [14]. The model requires to define the density, the Modulus of Elasticity and Poisson’s ratio for the elastic behaviour. For the plasticity behaviour, the stress/strain compressive curve and the stress/displacement tensile curve need to be provided. To model the damage of the concrete, it is assumed that when the concrete is unloaded the stiffness will be degraded. It is assumed that the tensile damage is more pronounced than the compressive damage, therefore only the tensile damage is accounted for in the material model. The water was modelled by providing the density, the dynamic viscosity and the equation of state. The parameters required to calibrate both of the models for concrete and the water were taken from [14], and they are summarized in Tables 1 and 2.

Table 1: Material properties for the CDP model for plain concrete finite element modelling

<table>
<tr><td colspan="2">Density</td><td colspan="2">2643</td></tr>
<tr><td colspan="4">Concrete Elasticity</td></tr>
<tr><td colspan="2">Elastic modulus (GPa)</td><td colspan="2">31</td></tr>
<tr><td colspan="2">Poisson’s ratio</td><td colspan="2">0.15</td></tr>
<tr><td colspan="4">The parameters for CDP model</td></tr>
<tr><td colspan="2">Dilation angle (degrees)</td><td colspan="2">36.31</td></tr>
<tr><td colspan="2">Eccentricity</td><td colspan="2">0.1</td></tr>
<tr><td colspan="2">f_{b0} / f_{c0}</td><td colspan="2">1.16</td></tr>
<tr><td colspan="2">K_c</td><td colspan="2">0.667</td></tr>
<tr><td colspan="2">μ</td><td colspan="2">0</td></tr>
<tr><td colspan="4">Compressive behaviour of the concrete</td></tr>
<tr><td colspan="2">Yield stress (Pa)</td><td colspan="2">Inelastic strain</td></tr>
<tr><td colspan="2">13000000</td><td colspan="2">0</td></tr>
<tr><td colspan="2">24000000</td><td colspan="2">0.001</td></tr>
<tr><td colspan="4">Concrete tension stiffening</td></tr>
<tr><td>Yield stress (Pa)</td><td>Displacement(m)</td><td>Damage variable</td><td>Displacement (m)</td></tr>
<tr><td>2900000</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1943930</td><td>6.6185E-05</td><td>0.381217</td><td>6.6185E-05</td></tr>
<tr><td>1303050</td><td>0.00012286</td><td>0.617107</td><td>0.00012286</td></tr>
<tr><td>873463</td><td>0.000173427</td><td>0.763072</td><td>0.000173427</td></tr>
<tr><td>585500</td><td>0.00022019</td><td>0.853393</td><td>0.00022019</td></tr>
<tr><td>392472</td><td>0.000264718</td><td>0.909282</td><td>0.000264718</td></tr>
<tr><td>263082</td><td>0.000308088</td><td>0.943865</td><td>0.000308088</td></tr>
<tr><td>176349</td><td>0.00035105</td><td>0.965265</td><td>0.00035105</td></tr>
<tr><td>118210</td><td>0.000394138</td><td>0.978506</td><td>0.000394138</td></tr>
<tr><td>79238.8</td><td>0.000437744</td><td>0.9867</td><td>0.000437744</td></tr>
<tr><td>53115.4</td><td>0.000482165</td><td>0.99177</td><td>0.000482165</td></tr>
</table>

Table 2: Material properties for water concrete finite element modelling

Physical properties of water	
Mass density (Kg/m^3)	1000
Dynamic viscosity N s/m^2	0.001002
Parameters of equation of state of water	
c_0	1481
s	0
Gamma$_0$	0

3 RESULTS AND DISCUSSIONS

Figs. 3 and 4 provide the values of Von-Mises stresses and tensile damage for the square bund wall respectively. The tensile damage represents the crack propagation in the structure.

Table 3 gives the maximum values of the Von-Mises and tensile damage until the failure. The column of water initially at rest, starts collapsing at t = 0s under a predefined velocity determined from previous CFD simulations. The fluid impacts the structure at the sides first and then at the corners. The bund wall exhibits a total failure at t = 0.1834s, this coincides with a tensile damage equal to 99% and a maximum stress equal to 36.55MPa which is higher that the compressive strength of the concrete. Physically, this corresponds to a complete collapse of the structure, which was predicted numerically by the occurrence of high distortion of the finite elements.

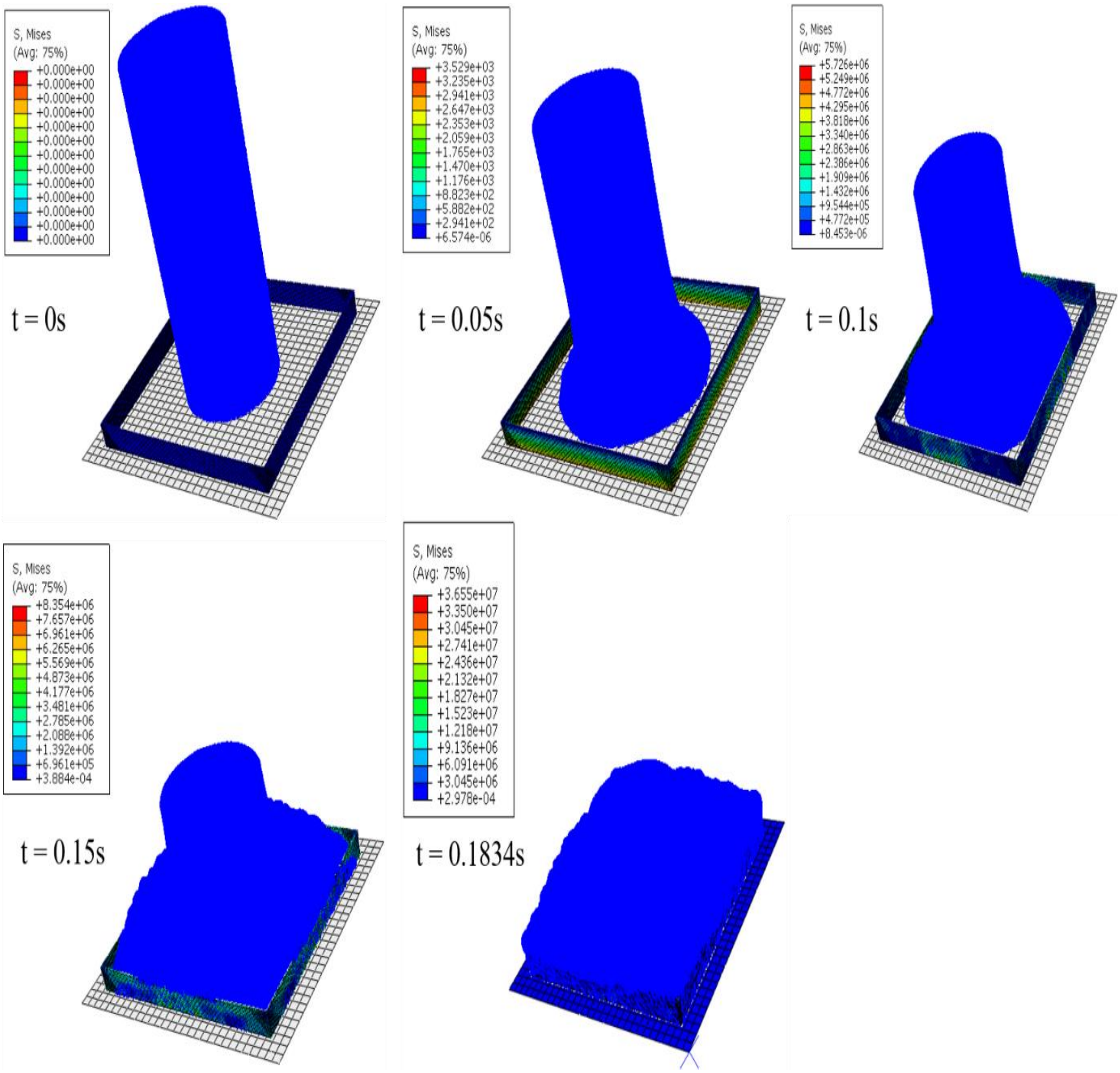


Fig. 3: Flow structure and Von-Mises stresses for a square bund wall

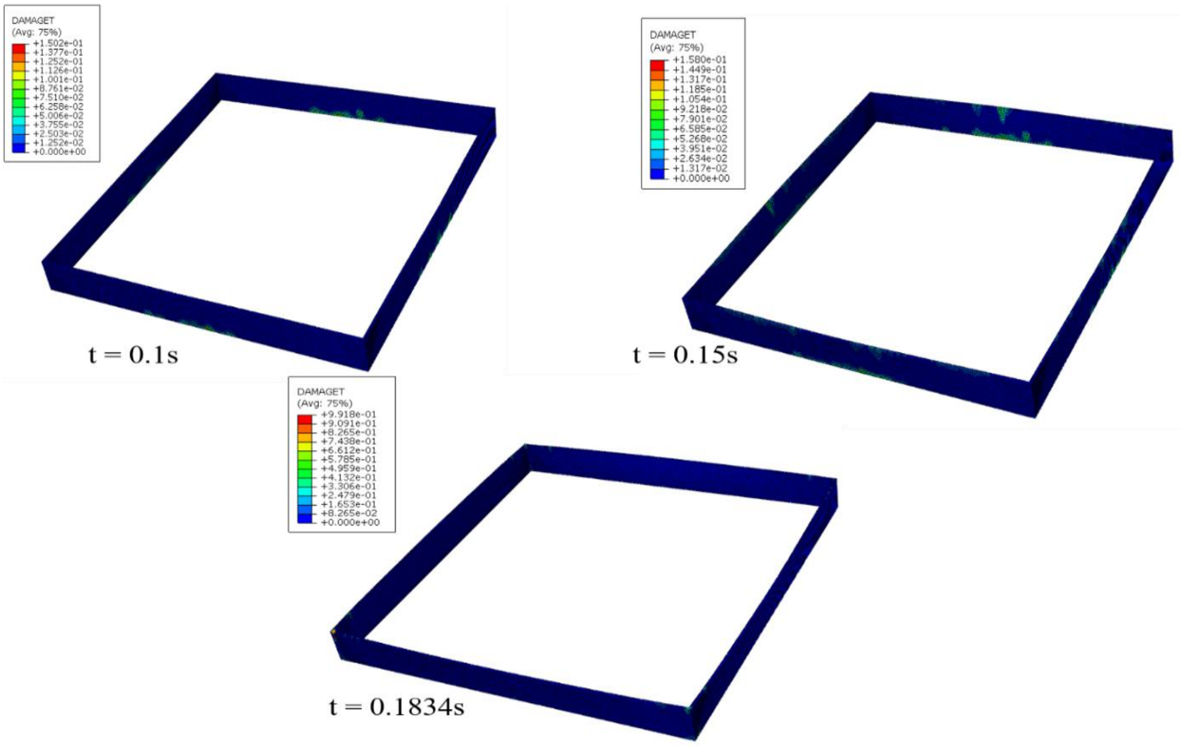


Fig. 4: Crack propagation (square bund wall)

Table 3: Stress and tensile damage values for a square bund wall

Time (s)	Maximum stress (MPa)	Tensile damage d_t (%)
0.05	0.003529	0
0.1	5.72	15
0.15	8.354	15.8
0.1834	36.55	99.18

Figs. 5 and 6 provide the values of Von-Mises stresses and tensile damage for the rectangular bund wall respectively and table 4 gives the maximum stresses and damage values until the failure. Similar to the square bund wall, the structure exhibits a total failure due to tension. The cracks appear first at the sides which are closer to the tank and then propagate to the corners. By comparing the square and rectangular bund walls, it appears that a higher value for tensile damage occurs earlier in the rectangular bund wall, i.e. 49.56% at t = 0.1s in the rectangular wall while only 15% at the same time in the square wall. However, the stress level in the rectangular wall is significantly less than the stress level obtained in the square structure, i.e. 14.59MPa in the rectangular bund wall and 36.55MPa in the square wall. From Table 4, the stress values are increasing very slowly, they are only increasing by 4MPa from t = 0.1s to t = 1s. At t = 1s, the maximum stress value is only slightly higher than the yield stress. As a result, the rectangular bund wall is more effective than a square bund wall in withstanding the impact load in terms of structural integrity.

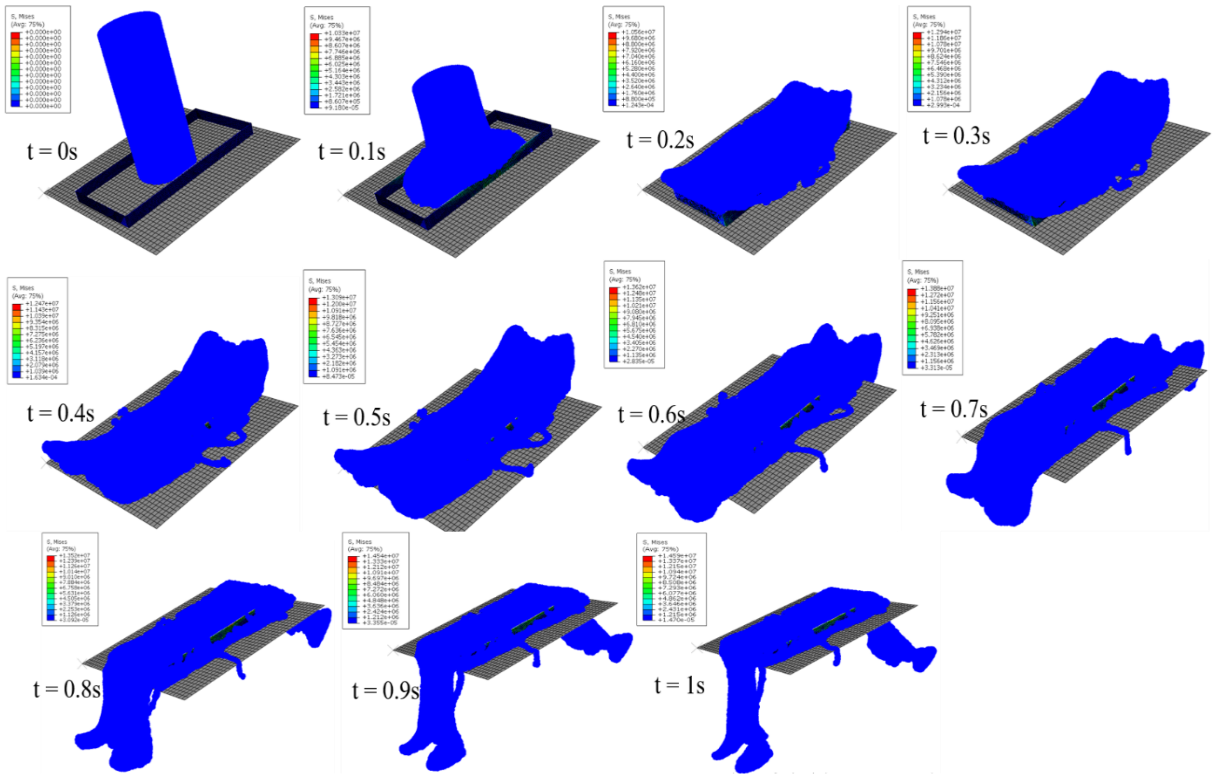


Fig. 5: Flow structure and Von-Mises stresses for a rectangular bund wall

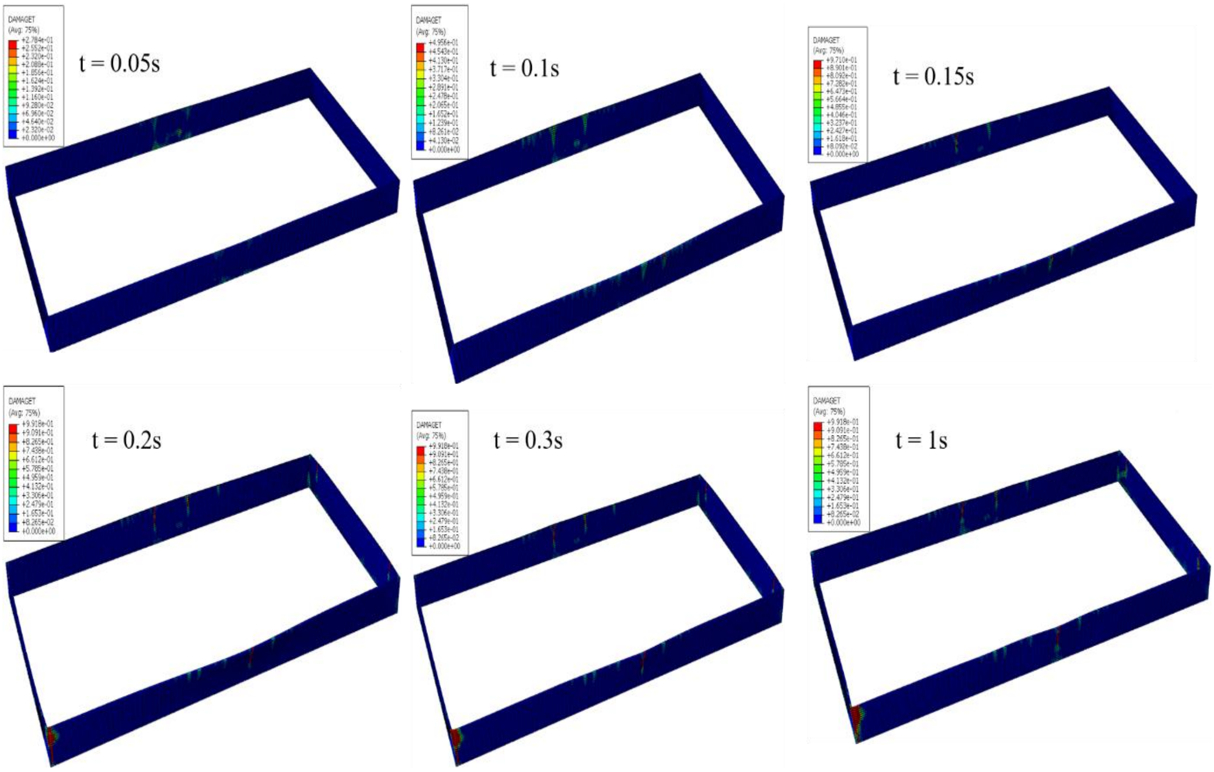


Fig. 6: Crack propagation (rectangular bund wall)

Table 4: Stress and tensile damage values for a rectangular bund wall

Time (s)	Maximum stress (MPa)	Tensile damage d_{ot} (%)
0.05	5.81	27.48
0.1	10.33	49.56
0.15	10.44	79.1
0.2	10.56	99.18
0.3	12.94	99.18
0.4	12.47	99.18
0.5	13.09	99.18
0.6	13.62	99.18
0.7	13.88	99.18
0.8	13.52	99.18
0.9	14.54	99.18
1	14.59	99.18

4 CONCLUSIONS

In this study, square and rectangular bund walls were investigated in terms of structural integrity under the impact loading. The Abaqus package was used to model this problem. The analysis was performed by use of the Abaqus explicit solver and the modelling of the fluid was carried out using the SPH method to allow for high deformations. Both of the structures were made from plain concrete and provided the same volume of containment. Previous CFD simulations were conducted to determine the velocity of the bulk fluid. The simulations revealed that the rectangular bund wall is more effective in withstanding the impact load as the stress level was significantly reduced compared to the square bund.

In the present study, the focus was on the effect of the shape of the bund wall. The findings of this study demonstrate that even though the rectangular shape is more effective than a square shape, it still exhibits damage due to tension. These results suggest enhancing the design of the bund walls to reduce the damage level.

Acknowledgements

The first author would like to thank Liverpool John Moores University for the financial support.

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