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Risk Control of Overtopping Phenomenon after a Catastrophic Tank Failure Through Optimized Bund Design

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Liquid fuels are stored in the large tanks, e.g., LNG (Liquefied Natural Gas). A catastrophic tank failure can suddenly release a huge volume of flammable materials, and cause severe incidents. The Cleveland Natural Gas Explosion resulted in more than 130 fatalities, which was caused by LNG tank failures. Currently, bunds are required by regulations to control the risk of tank failures, e.g., NFPA 59 A; however, there is no specific guideline to design effective bund systems, and overtopping can still occur to undermine the risk control effectiveness of bund systems. This study aims to optimize the bund design for a better risk control of a catastrophic tank failure incident. An experimental apparatus was constructed to simulate the catastrophic tank failure incident, and key parameters of bund design were investigated for their effect to control the overtopping risk, i.e., bund shape, height/radius, inclination angle of bund wall, and breakwater. The experimental data were analyzed to propose a predictive model of bund overtopping fraction. Also, CFD (Computational Fluid Dynamic) models were developed using RNG k-ε and LES (Large Eddy Simulation) methods, which were validated against experimental data. The study reveals key parameters of bund design for the overtopping risk control, and contributes to providing a scientific guideline for optimizing the bund design based on both experimental findings and CFD models.

1. Introduction

Bunds are essential for the process safety of Liquefied Natural Gas (LNG) storage tanks. It can effectively control the diffusion of the liquid pool and limit the vaporization caused by the accidental leakage of the LNG storage tank (Davies et al., 1996). But some accidents such as the one in Buncefield (Johnson, 2009) in 2005 indicate that the catastrophic failure of tanks can lead the liquid overtop from the bund wall to result in serious consequences (Thyer et al., 2009). Actually, experiments and some theoretical model studies have shown that bund overtopping is not rare (Thyer et al., 2002a; Trainor, 2011). Therefore the evaluation of the effectiveness of the bund is very important. Overtopping fraction is a key parameter for determining the extent of liquid leakage and the effectiveness of the bund design in a tank failure incident, it is defined as the fraction of the mass of the leaked liquid in the original liquid mass in the storage tank. Previous work has demonstrated that the design of a bund can have a significant impact on the liquid flow behavior and overtopping fraction.
The previous experimental work on the catastrophic failure of storage tanks was mainly simulated by the free fall of a liquid column by lifting a storage tank instantaneously. Greenspan and Johansson (1981) studied the effect of circular vertical and inclined bund configurations on the overtopping fraction for catastrophic tank failures. Atherton (2005) studied the effects of circular, square, rectangular, and diamond vertical bunds on the overtopping fraction after catastrophic storage tank failures. He conducted a series of experiments to compare the overtopping process for different shapes bunds.
Daish (1998), SreeRaJ (2008), and Webber (2009,2010) respectively developed CFD models based on the shallow water equation to describe the interaction between released liquids and bund. The shallow water equation is considered accurate for describing inviscid fluids but is not applicable to complex turbulent processes, Liu et al. (2017), Ramajo et al. (2018) developed CFD models by Reynolds Averaged Navier Stokes (RANS) model to calculate turbulence effects during bund overtopping.

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Some scholars have developed predictive models of overtopping fraction based on the experimental results from the studies of catastrophic tank failure. Greenspan and Johansson (1981) summarized their experiments and found that the overtopping fraction Q mainly depends on the design of storage tanks and bund. Based on Greenspan's (1981) research, Clark et al. (2001) and Hirst (Thyer et al., 2002b) developed predictive models using Greenspan's data respectively, Hirst (Thyer et al., 2002b) believes that overtopping fraction is mainly determined by ratio of bund height and radius to liquid height as shown in Eq. (1).

$$Q = A + B * ln(\frac{h}{H}) + C * ln(\frac{r}{H}) \tag{1}$$

Where h is the bund height; r is the bund radius; R is the tank radius, H is the liquid height in the tank. When θ = 90°, A = 0.044, B = −0.264, C = −0.116; when θ = 60°, A = 0.287, B = −0.229, C = −0191; when θ = 30°, A = 0.155, B = −0.360, C = −0.069. Atherton (2005) developed a new predictive model based on his own experimental results. These models have high accuracy in predicting the overtopping fraction, but the models were developed from a certain series still have limitations.

As described earlier, most previous experimental works were conducted using laboratory-scale setups without setting up field-scale experiments. Also, previous works studied the overtopping phenomena of water but not cryogenic liquids, such as liquid nitrogen and LNG, which are widely used in industry. Due to the lack of experimental data for other bund shapes, all existing mathematical predictive models were developed to predict the overtopping fraction of circular bunds. Therefore, the existing models have a small range of applicability. In addition, no work has been done to screen the suitability of turbulence models for the bund overtopping process. In conclusion, the bund overtopping of tank catastrophic failure still requires more research. A series of experiments, simulations, and predictive models were conducted to make up for the lack of bund overtopping study. These works have deepened the understanding of the physical process of fluid capsizing under various complex bund conditions and provided scientific recommendations for the bund design of the storage tanks.

2. Experimental studies

As shown in Figure 1 a, the experiment was designed as a laboratory-scale and a field-scale to investigate the effect of the experimental scale on bund overtopping. The laboratory-scale tests were used two tanks with diameters of 0.05m and 1m. The laboratory-scale tests were used a tank with a diameter of 0.229m. The circular storage tanks are located in the middle of the circular or square bunds. The power of the cylinder is provided by compressed air to lift the tank rapidly. The liquid in the tank will be leaked into the bund. Then the liquid will overtop the bund. The overtopping liquid is accepted by the receiving container and weighed by the balance. The bunds were designed with different shapes and curvatures for control experiments. The experiments are the first to use liquid nitrogen and LNG as the overtopping liquid. In addition, in recent experiments, the pressure on the bund was measured by pressure sensors as shown in Figure 1b, the liquid overtopping process in the square and circular bund was collected by a high-speed camera, and the data was transmitted to a computer.

Figure 1. Experimental setups for overtopping (a) (Zhang et al., 2017) and bund with pressure sensors (b)

Previous experiments systematically studied the prevention effects of the bund (Zhang et al., 2017), including the scale of the experiment, the ratio of h/r, the design of the bund wall (curved bund and linear bund), the material of the bund, and the type of liquid (water, LN_2, and LNG). The results show that the scaling up of the experimental scale and the materials of the bunds show high similarity on the overtopping fraction. Bunds with high h/r have lower overtopping fraction. Compared to curved bunds, straight bunds can contain liquids more effectively, especially at high filling ratio. As for the type of liquids (water, LN_2, and LNG), the results for the overtopping fraction were similar. These studies provide scientific recommendations for the bund design.

However, in actual production, the design of bunds is usually complex, so we further investigated the overtopping fraction and dynamic pressure of complex bund including shape, inclination, and breakwater structure. Compared with the square bund, the overtopping fraction and the maximum pressure on the wall of the circular bund are slightly lower. In addition, the greater the inclination angle of the bund, the lower the overtopping fraction, and the greater the maximum pressure on the bund wall. Breakwaters are effective in reducing the bund overtopping, and the overtopping fraction of horizontal breakwaters is slightly lower than that of inclined breakwaters. These experiments enriched the experimental data of bund overtopping. It provided data support for the practical application and theoretical analysis of bund overtopping research.

3. Predictive model

3.1 Model development

Previous studies have provided the theoretical basis for the development of the overtopping fraction predictive model. Finding the key variables is the most important part of the model development. Clark et al. (2001) considered the overtopping fraction as the function of tank height H and bund height h. The dimensionless variable h/H was used in the predictive model. Clark's model ignored key parameters such as the bund radius r and tank radius R, so only a rough estimate of the trend in overtopping fraction can be made. Based on Clark's work, Hirst (Thyer et al., 2002b) introduced new equation variables to improve the accuracy of the prediction model, and the bund radius r was considered as an important parameter in the predictive model. Later, Atherton (2005) developed a complex model to predict the overtopping fraction of circular straight bunds and validated it using their experimental data. The model has good accuracy but a complex form because nearly all the dimensionless variables are considered. Too many variables make it more difficult to apply the model to practical calculate. Therefore, simple equation form and efficient prediction performance are the main needs for developing new models. For the accuracy of the equations, h/H, r/H, R/H, and θ are considered into the new model. In addition, for the simplicity of the equations, a multiple linear regression model is chosen after trying numerous equation forms, and the model form has good predictive performance after being verified by experimental data. Three series of experimental data (Greenspan and Johansson, 1981; Atherton, 2005; Zhang et al., 2017) were used to develop new models to increase the reliability of the models. Equation 2 (Luan et al., 2020) is obtained by fitting all the data of the circular bund. However, the predictive model developed based on circular bund does not apply to the square bund. Square bunds are common in industrial tank farms, so it is necessary to develop a corresponding square bund model. The model developed by square bund data is shown in Equation 3 (Luan et al., 2020). In practical applications, due to terrain limitations and actual needs, the bund may have irregular shapes and arbitrary inclination angles. It is very practical for industrial production to use all experimental data to establish a general predictive model, the function as shown in Equation 4 (Luan et al., 2020).

$$Q = -0.3195 * ln\left(\frac{h}{H}\right) - 0.3031 * ln\left(\frac{r}{H}\right) + 0.2782 * ln\left(\frac{R}{H}\right) + 0.1174 + 0.4200 * cos\theta \quad (2)$$

$$Q = -0.2283 * ln\left(\frac{h}{H}\right) - 0.2688 * ln\left(\frac{r}{H}\right) + 0.1665 * ln\left(\frac{R}{H}\right) + 0.1564 \quad (3)$$

$$Q = -0.2180 * ln\left(\frac{h}{H}\right) - 0.1534 * ln\left(\frac{r}{H}\right) + 0.0861 * ln\left(\frac{R}{H}\right) + 0.1479 + 0.3018 * cos\theta \quad (4)$$

3.2 Model validation

The accuracy of the model is verified by comparing the model prediction results with experimental measurements. The models show a good performance in predicting the overtopping fraction of different bund shapes. Taking the general model as an example, three different shapes of bund overtopping experiments were carried out to validate the applicability of the general model, the experimental setup is shown in Table 1. The predicted results of the general model are as shown in Figure 2. The points on the diagonal in the figure indicate a perfect prediction; the data points that are plotted below the diagonal indicate underprediction. Otherwise, the predicted value is higher than the measurements. The dotted lines represent ± 50% error. The general model was developed for irregular bunds that are difficult to evaluate the overtopping fraction, and the accuracy was sacrificed to ensure the generality of the model so if accurate predictions are desired. Despite various shapes, the general model has a good enough prediction of overtopping fraction.

Overall, the development of the square bund model and the general model compensates for the existing predictive models that can only predict the overtopping fraction of circular bunds. These models provide a scientific and convenient tool for the engineering design of tank and bund system.

Table 1: Design parameters of the tank and bunds

Bund Shape	Inclination	h(mm)	r^e(mm)	H(mm)	R(mm)	Q
Circular	90°	100	272	386	135	0.333
	90°	100	272	363	135	0.310
	90°	100	272	337	135	0.277
	90°	100	272	306	135	0.237
	90°	100	272	245	135	0.180
	90°	100	272	183	135	0.098
Square	90°	100	272	357	135	0.377
	90°	100	272	332	135	0.373
	90°	100	272	305	135	0.292
	90°	100	272	244	135	0.262
	90°	100	272	182	135	0.110
Rectangle	90°	100	272	360	135	0.371
	90°	100	272	333	135	0.333
	90°	100	272	309	135	0.290
	90°	100	272	275	135	0.249
	90°	100	272	183	135	0.103

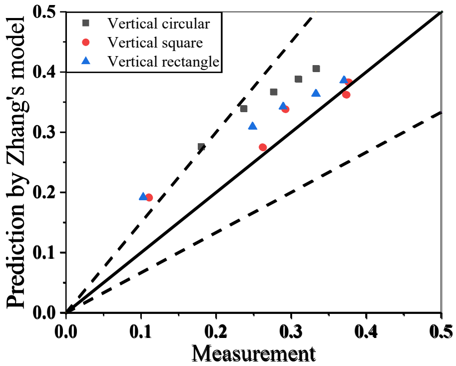


Figure 2. Overtopping fraction prediction using the general model.

4. CFD Simulation

4.1 Model setup

Computational fluid dynamics (CFD) is an effective tool for simulating bund overtopping phenomena, and CFD models are developed in ANSYS Fluent. In this work, several common turbulence models: LES, RNG k-ε, Realizable k-ε, Reynolds stress, Shear-Stress Transport (SST) k-ω and Standard k-ε are compared. RNG k-ε and LES model are more suitable for bund overtopping studies. Because these two models can calculate the laminar, turbulent and transition flow processes of liquid. The model is essentially isothermal and uses the VOF method to simulate the liquid overtopping process. The 2D model is an axisymmetric model, the 3D model is chosen to simulate a quarter of the geometry and computational domain to reduce computational resources. In this study, a mesh with an element size of 0.005m was chosen to develop the model. The boundary conditions are shown in Figure 3. The bund and the ground inside the bund are set as walls. The computational domain is initialized using the standard initialization, and the initial turbulent kinetic energy and turbulent energy dissipation rate are set to zero because the initial state of the liquid is laminar.

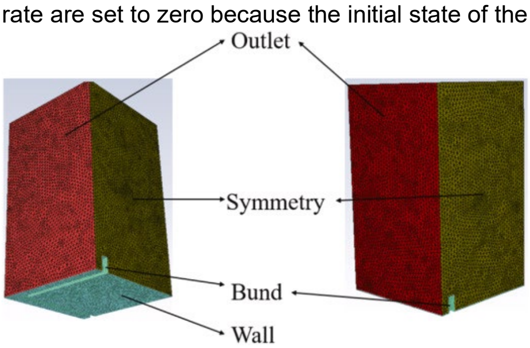


Figure 3. Quarter of the geometric for square bund with test L3 (Huo et al., 2022)

4.2 Model validation

The comparison between the simulation results of the overtopping fraction based on the RNG k-ε model and the experimental data is shown in Figure 4. It is found that the simulation results of the overtopping fraction are within an acceptable range, and most of the simulated overtopping fraction tends to be over-predict, which puts forward higher requirements for bund design and helps to minimize liquid overtopping.
The liquid dynamic process of L1 with a filling ratio of 87.8% is shown in Figure 5. The behavior of the liquid during catastrophic failure of the storage tank is divided into the following six stages: initial column (a), collapse (b), surge and impact (c), hydraulic bore (d, e), overtopping (f), reflux and center spike (g), as shown in Figure 5a. As for Figure 5b, the six stages of the experiment and 3D models can be well matched. The simulated height of the center spike (h) of the 2D model (H_{2D}=0.076m) is slightly higher than that of the 3D model (H_{3D}=0.048m) and the experimental image (H_{Exp}=0.044m). In addition, the secondary overtopping process can be effectively observed in the 3D model and experimental images, but only one overtopping process can be observed in the 2D model. In general, the dynamic process of the 3D model can more reliably show the interaction between liquids and bunds wall. These models can be used to further study the flow behavior and turbulence effects in the overtopping process of bund under complex conditions.

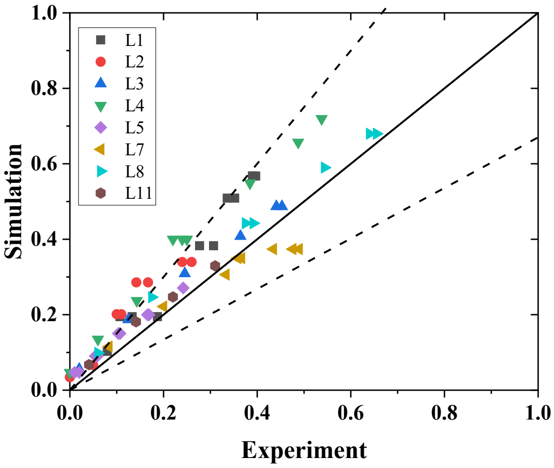
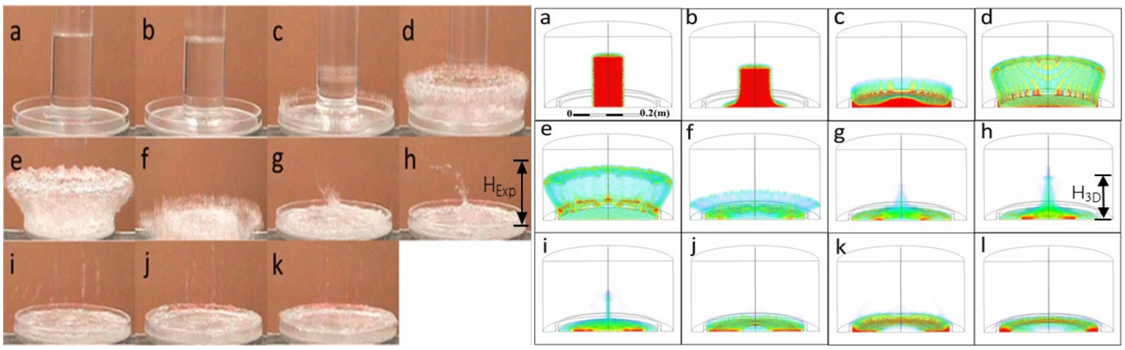


Figure 4. Simulation results of 3-D on RNG k-ε model (Huo et al., 2022)



(a) (b)

Figure 5. Dynamic Process of liquid of catastrophic tank failure: (a) experiment (Zhang et al., 2017), (b) 3D simulation of L1 (Huo et al., 2022)

5. Conclusion

Despite the low frequency of catastrophic failure of storage tanks, this is still one of many possible failure modes. Storage tanks show a trend of large-scale, centralized as the development of tank technology. Therefore, the potential hazards of catastrophic failure of storage tanks need to be taken more seriously. The serious consequences of this form of failure are not affordable. The study of bund overtopping can be used by interested parties to understand the bund overtopping hazard and take effective protective measures. This paper systematically investigated the catastrophic failure of storage tanks through experimental, simulation, and predictive modeling methods. The main conclusions are as follows.

(1) The configuration of the bund has a large impact on the overtopping fraction. For the same filing ratio, tests with high h/r and R/r values tended to give smaller overtopping fractions. Circular bund is considered better

than the rectangle bund. Breakwaters can effectively control the liquid overtopping. In addition, the reliability of the results of laboratory scale experiments applied to field experiments was verified.

(2) Three predictive models for circular, square and general bund shapes were developed using richer experimental data. These predicative models have more accurate prediction accuracy and a wider application range. Predictive models have been developed to estimate liquid overtopping fraction rapidly and help interested parties to assess the hazard of the tank farm.

(3) The reliability of the CFD models has been systematically verified by experimental results, and the overtopping fraction and flow behavior are in accordance with the experimental results. The LES and RNG k-e turbulence models have proven to be suitable for bund overtopping study.

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