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# Study on the Influence Mechanism of Inner Oil to the Impact Resistance of the Fixed-roof Storage Tank against the Explosion Blast Wave

**HU Kun**, CHEN Guo-hua
Institute of safety Science & Engineering
South China University of Technology
NO.381 WuShan Road in Tianhe District, Guang Zhou, 510641, China
Email address: mmghchen@scut.edu.cn/13533227907@163.com

**Abstract:** The explosion blast wave in the chemical park will cause the domino effect and serious damage to the surrounding tanks. In order to study the influence mechanism of the inner oil on the impact resistance of the large-scale fixed-roof storage tank against the explosion blast wave, the finite element software LS-DYNA is used to establish finite element model of 5,000 $m^3$ fixed-roof storage tank with inner oil height of 0m, 5 m, 10 m and 15 m, when the vertical height of the explosion point center to the ground is 0.4m, 5m, 10m, 15m, respectively. The failure process, the maximum displacement of tank wall, the total energy, kinetic energy and internal energy transformed from explosion are obtained by simulation and analysis. The results show: the failure process of the tank is mainly concave deformation and buckling deformation, no matter how the oil height changes. Stress concentration commonly occurs at the maximum displacement of the concave deformation and the plastic hinge lines produced by the buckling deformation; the maximum displacement of the tank wall is mainly affected by the relative vertical height between explosion point and oil; when the explosion point mass and the horizontal distance from the point to the nearby tank wall are constant, the total energy of the tank transformed from explosion is mainly affected by the oil height, and it is almost not affected by the change of the vertical height of the explosion point. And the maximum displacement of the tank wall is irrelevant with the total energy of the tank.

**Keywords:** inner oil； impact resistance； fixed-roof storage tank; explosion blast wave.

## 1. Introduction

The large-scale storage tanks have become the main mode of storage vessels for oil and related chemical products, and the volume of the large-scale storage tanks will be ultra-large. With the centralized construction of the chemical park, the risk of the large-scale storage tanks increased. Once explosion or other sudden accidents of the large-scale storage tanks happen, it can easily lead to domino effect and cause casualties and huge economic loss. Therefore, it is significant to study the response of explosion blast wave to the large-scale storage tanks with liquid.

Based on a review of the literature, some studies have concentrated on the dynamic response of the tank impacted by the explosion blast wave, but there is a little research that the liquid in the tank are considered as an important factor. The buckling of partially liquid-filled cylindrical shells under axial compression was studied by Yasui [1]. Zhang [2-3] studied dynamic buckling of liquid filled elasto-plastic cylindrical shell under axial impact by experiment and numerical simulation. Chen et.al [4] have studied the damage model of the pressure shell under the explosion blast wave. Pan et.al [5] simplified the effect of liquid to the pressure loaded on the inner wall of tank, and used LS-DYNA to simulate the dynamic response of thin-wall cylindrical tank under explosion blast wave. Li [6], Lu [7], Zhang [8] have carried out the small-scaled experiment and simulation of the large storage tank under explosion blast wave. The effective stress and peak effective strain of the different welded steel plates of tank wall was analyzed qualitatively and it suggested that the internal liquid can not only affect impact resistance of structure against explosion blast wave, but also absorb and consume part of explosion energy. Zhang [9] studied the failure of spherical storage tanks with different liquid level under external blast loading and considered that the liquid in the tank absorbs the energy of impact loads and reduces the response at the initial stage of damage. Ji et.al [10] studied the buckling characteristics of the liquid-filled and hallow thin-wall cylindrical shells subjected to explosion loading, and they considered that the incompressibility of the filled liquid has an effect on the impact resistance against explosion blast loading. However, the research neglected the interaction between the liquid and the tank wall when the height of liquid or explosion point changes.

Therefore, using LS-DYNA to establish the finite element model that fixed-roof storage tank is impacted by the explosion blast wave. Analyze the failure process, the maximum displacement of tank wall and the total energy, kinetic energy and internal energy of tank or oil transformed from explosion to study the influence mechanism of inner oil to the impact resistance of the fixed-roof storage tank against the explosion blast wave. The study results can offer valuable insight into the measures that should be taken to prevent the domino effect accidents.

## 2. The Finite Element model (FEM)

### 2.1 Parameters of FEM

In order to reduce the calculation time for modeling large fixed-roof storage tank, symmetrical method is used to construct the FEM. The symmetrical plane is defined as the plane that is formed by the central line of TNT equivalent and central axis line of the fixed-roof storage tank.

The fixed-roof storage tank contains top cap, tank wall, tank bottom and accessories, the dynamic response of top cap and the tank wall is focused on to study. The tank wall consists of 7~10 welded steel plates with thickness increasing from the bottom to the top. The fixed-roof storage tank with a capacity of 5,000 $m^3$ is analyzed. According to the geometrical model of literature [7], the main structure parameters of storage tank are listed in Table 1. The oil height ($h_l$) in the tank is 0m (empty), 5m, 10m, 15m, respectively.

The mass of TNT equivalent is 1630kg. The horizontal distance between the center of TNT equivalent and tank wall nearby is 10m. The vertical height between the center of TNT equivalent and the ground ($h_{TNT}$) is 0.4m (near ground explosion), 5m, 10m, 15m, respectively. The geometrical dimensions of TNT equivalent are 0.8m in length, 0.8m in width, and 0.8m in height. To ensure the air field covering the TNT equivalent, storage tank and oil, the volume of air fields are designed with 40m×15m×20m. Due to the free explosion, the ground boundary of air field is defined as fixed constraint, and the other planes are defined as nonreflecting boundary.

Table 1. Characteristic parameters of fixed-roof storage tank

| Characteristic parameters | $5\times10^3 m^3$ storage tank |
|---|---|
| Diameter, $D$（m） | 20 |
| Total height, $H$（m） | 20 |
| Tank wall height, $h$（m） | 17.82 |

**2.2 Element and material model**

Tank wall thickness is much smaller than the diameter and the height. Therefore, the SHELL163 element is used for modeling fixed-roof storage tank. The SOLID164 element is used for TNT equivalent, air and oil within the tank. 16MnR is defined as the material type of the storage tank. Considering the variability of strain rate when the material response to the explosion blast pressure, the bilinear kinematic hardening model (*MAT_PLASTIC_KINEMATIC) is used for the tank material. The yield strength, elasticity modulus and Poisson ratio of 16MnR are 320MPa, 206GPa, 0.3, respectively. *MAT_HIGH_ EXPLOSIVE_BURN model and *EOS_JWL equation are adopted to model TNT equivalent. In the JWL equation of state the pressure $P$ is the function of the initial energy per element volume $E$ and relative volume $V$, as shown below,

$$P = A(1-\omega / R_1 V)e^{-R_1 V} + B(1-\omega / R_2 V)e^{-R_2 V} + \omega E / V$$

Where $A$、$B$、$R_1$、$R_2$、$\omega$ are the characteristic parameters of JWL equation of state, $E$ is the internal energy of TNT equivalent, $V$ is relative volume.

The physical parameters of TNT equivalent and the characteristic parameters of JWL state equation are shown in Table 2 and Table 3, respectively.

The *MAT_NULL model and *EOS_LINEAR_POLYNOMIAL state equation are used for the air, With density 1.29 kg/$m^3$. *MAT_NULL model and *EOS_GRUNEISEN state equation are used for the oil, with density 480kg/$m^3$ and viscosity coefficient $0.89\times10^{-3}$.

To reach the requirement of the consistency among the grids of storage tank, oil and air, the mesh method of mapping is adopted. The element edge length is limited to 0.5m approximately. Lagrangian grids are used for meshing the field of the storage tank. ALE grids are used for meshing the field of TNT equivalent and the air. Using the key definition *CONSTRAINED_LAGRANGE_IN_SOLID, the coupled interaction between the explosion blast wave and tank structure, and between the oil and tank structure, are defined, respectively. The vector direction of all shell elements is absolutely directing to the oil within the tank by adapting the NORM parameters.

Table 2. Physical parameters of TNT equivalent

| Density, $\rho$ (kg/$m^3$) | Detonation pressure, $P_{cj}$ (Pa) | Detonation velocity, $D$（m/s） |
|---|---|---|
| 1630 | $1.85\times10^{10}$ | 6930 |

Table 3. Characteristic parameters of JWL EOS

| $A$（Pa） | $B$（Pa） | $R_1$ | $R_2$ | $\omega$ | $E$（J/$m^3$） |
|---|---|---|---|---|---|
| $3.7\times10^{11}$ | $3.2\times10^9$ | 4.15 | 0.95 | 0.30 | $7.0\times10^9$ |

## 2.3 Model validation

In literature [6], Li carried out the experiment of the small-scaled fixed-roof storage tank with the level of liquid 0.4m. The geometrical dimensions of the small-scaled tank are 0.8m in diameter and 0.8m in total height. Using the modeling methods of above (2.1 and 2.2), a similar model with literature [6] is established and the peak pressure of the measuring points $A_p$ and $B_p$ are obtained, as shown in Figure 1. In Table 4, the peak pressure of the measuring points $A_p$ and $B_p$ is close to those in the literature [6], and the maximum error is 3.5%, which verifies the accuracy of the model.

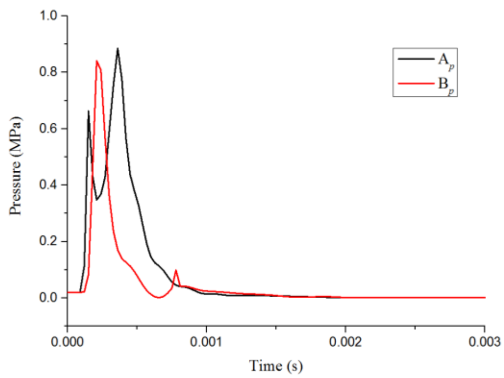



Figure 1. The peak pressure at the measuring point A and B of the small-scaled storage tank

Table 4. The peak pressure of the vault tank (MPa)

| Measuring point | The results of simulation | Experimental data in literature [6] | Relative error |
|---|---|---|---|
| A | 0.885 | 0.855 | 3.5% |
| B | 0.841 | 0.829 | 1.4% |

# 3. Results and discussion

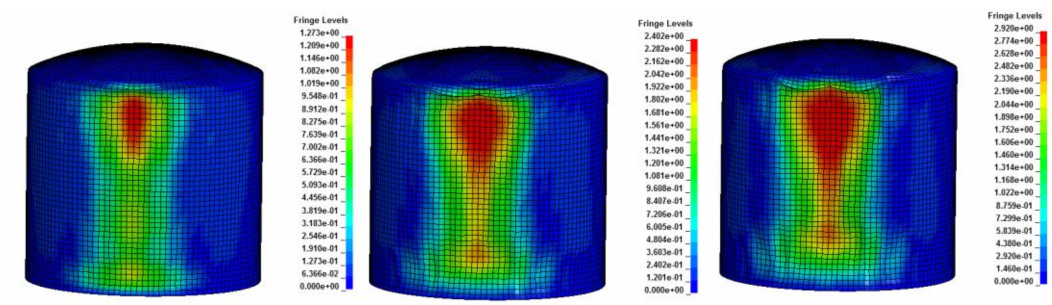
## 3.1 Failure process of the fixed-roof storage tank

When TNT equivalent explodes, the surrounding air is compressed rapidly and the blast wave is formed in the state of high temperature and high pressure, which is continuously expanding forward. The blast wave propagates like spherical wave and impacts on the tank wall. The failure process of fixed-roof tank can be divided into two stages: concave deformation of tank wall facing on blast wave, and the buckling deformation of the tank wall and the roof surrounding the concave. As shown in Figure 2, in the first stage, the concave deformation of the tank wall facing on blast wave is mainly produced between 0.022s and 0.036s. The blast wave propagating in spherical form impacts the tank wall and produces a concave like sphere on the tank wall. And the deformation increases continuously as time goes by. Due to the tank wall thickness decreasing gradually from the bottom to the top, the impact resistance of the tank wall gradually decreases from the bottom to the top. Therefore, the plastic deformation of the upper part of the tank wall is greater than that of the lower part. In the second stage, the buckling deformation of the tank wall and the roof surrounding the concave is created between 0.045s and 0.080s. With the increase of the concave deformation, the tank wall and the roof continue to buckle in the direction of the concave and form plastic hinge lines.

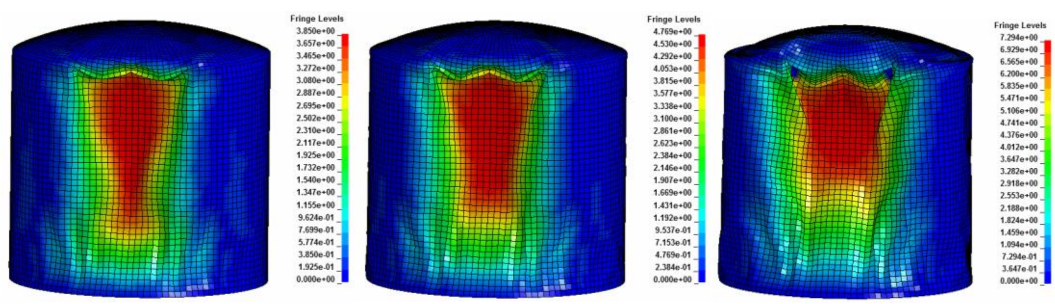
Figure 3 shows the plastic deformation of 5,000m$^3$ fixed-roof tank with different $h_l$ at $t$=0.08s when

$h_{TNT}$ is 10m. It can be seen that the failure process of the tank is mainly concave deformation and buckling deformation, no matter how the oil height $h_l$ changes. Meanwhile, stress concentration commonly occurs at the maximum displacement of the concave deformation and the plastic hinge lines produced by the buckling deformation. As shown in Figure 3b), the tank wall at the plastic hinge lines near the roof has been damaged.

From Figure 3, with the increase of $h_l$, the concave deformation decreases gradually and mainly transfers to the top of the tank wall. The buckling deformation of the tank wall and the roof surrounding the concave also decreases gradually. The reason is that the oil is incompressible liquid. On the on hand, when the blast wave impacts on the tank wall in short time, small displacement of the tank wall contacted with the oil is produced due to great inertia increased by the oil. On the other hand, the explosion blast wave compresses the oil through deformation of the tank wall enormously and produces the pressure wave in the oil. From the Figure 4, we can see the pressure wave propagating in the oil and eventually impacting on the back wall of the tank, which is also seen in literature [6].

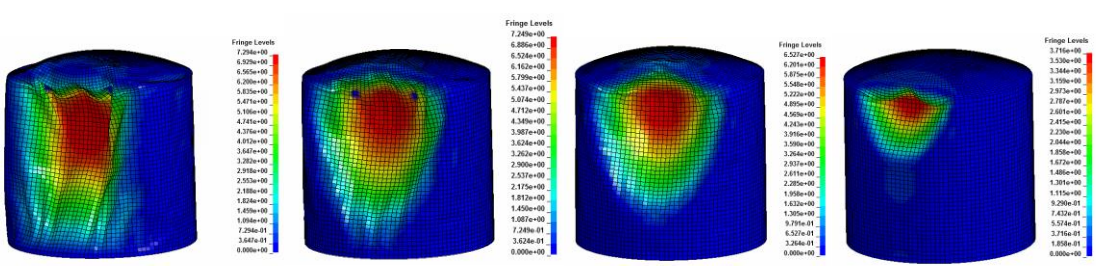


a) $t$=0.022s b) $t$=0.031s c) $t$=0.036s



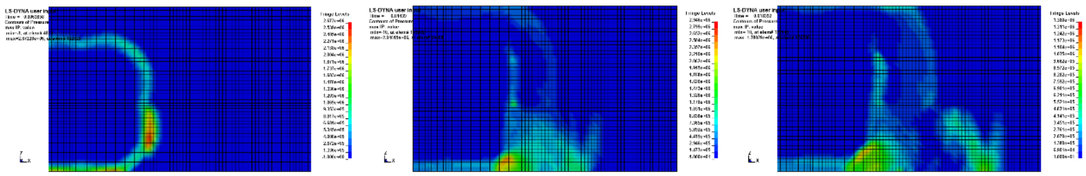
d) $t$=0.045s e) $t$=0.054s f) $t$=0.080s

Figure 2. The displacement of the fixed-roof storage tank with $h_l$=0m at different time when $h_{TNT}$=10m



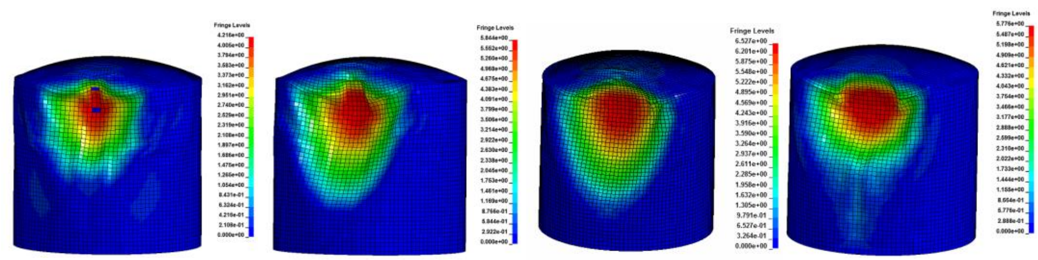
a) $h_l$=0m b) $h_l$=5m c) $h_l$=10m d) $h_l$=15m

Figure 3. The displacement of the fixed-roof storage tank with different $h_l$ at $t$=0.08s when $h_{TNT}$ =10m



a) $t$=0.0064s b) $t$=0.016s c) $t$=0.018s

Figure 4. The propagation of pressure wave in the oil at different time when $h_{TNT}$ =10m

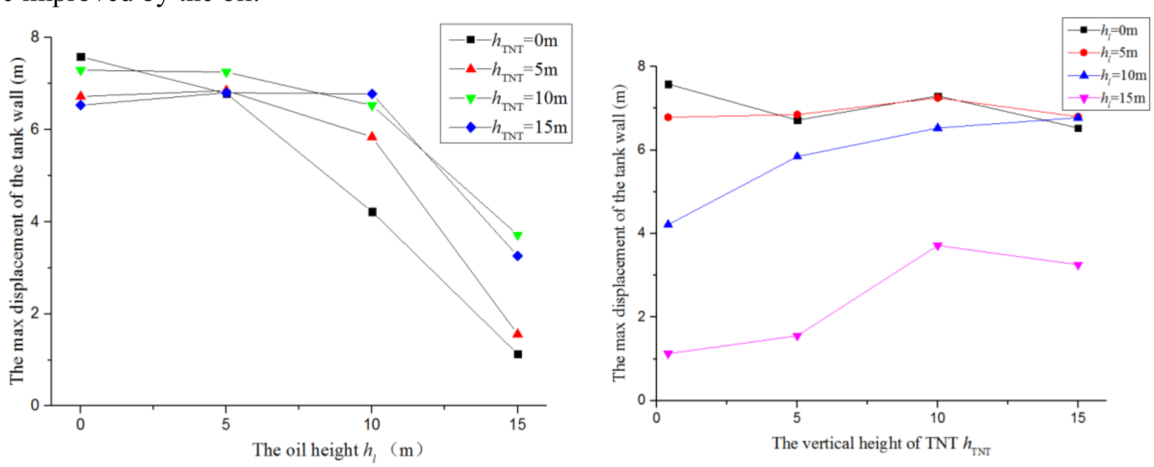


a) $h_{TNT}$=0.4m b) $h_{TNT}$ =5m c) $h_{TNT}$ =10m d) $h_{TNT}$ =15m

Figure 5. The displacement of the fixed-roof storage tank with $h_l$=10m at $t$=0.08s when $h_{TNT}$ is different

### 3.2 The maximum displacement of the tank wall

When the fixed-roof storage tank is impacted by the explosion blast wave, the concave deformation is produced on the tank wall and is one of the causes of the buckling deformation. Therefore, the maximum displacement of the concave deformation of the tank wall can be considered as the important parameters to evaluate the plastic failure severity of the tank, and the maximum displacement variation with the change of the oil height can be used to evaluate the impact resistance of the tank wall against the explosion blast wave improved by the oil.




a) The relationship between the maximum displacement and $h_l$

b) The relationship between the maximum displacement and $h_{TNT}$

Figure 6. The relationship between the maximum displacement of the 5,000m$^3$ tank wall and $h_l$, $h_{TNT}$ at $t$=0.08s

Figure 6 is the relationship between the maximum displacement of the 5000m$^3$ tank wall and the oil height, the vertical height of TNT at $t$=0.08s. From Figure 6 a), we have:

(1) When $h_{TNT}$ is constant, the greater $h_l$ is, the smaller the maximum displacement is. It indicates that

the increase of $h_l$ not only reduces the area of the concave deformation (seen in Figure 3), but also reduces the depth of it. So the increase of $h_l$ can reduce the plastic deformation of the tank wall integrally and improve the impact resistance of the tank wall against the explosion blast wave.

(2) When $h_l$ is bigger than $h_{TNT}$, the slope of the curve becomes steeper as $h_l$ increases, and the maximum displacement decreases faster. It indicates that with the increase of $h_l$, the oil can increase the impact resistance performance of the tank wall more significantly, which is confirmed with literature [9]. For example, when $h_{TNT}$=0.4m and $h_l$ changes from 0m to 5m, from 5m to 10m and from 10 to 15m, the maximum displacement changes by -10.5%, -37.8%, -73%, respectively.

(3) When $h_l$ is less than $h_{TNT}$, the slope of the curve changes slowly with the increase of $h_l$, which indicates that the oil cannot improve the impact resistance of the tank wall well. However, when $h_l$ increases near to $h_{TNT}$, the slope of the curve becomes steeper, indicating that the impact resistance of the tank wall is greatly improved. For example, when $h_{TNT}$=15m and $h_l$ changes from 0m to 5m, from 5m to 10m and from 10 to 15m, the maximum displacement changes by 4.1%, - 0.3%, -52% respectively.

From Figure 6 b), we have:

(1) When $h_l$ is low ($h_l$=0m,5m), with the increase of $h_{TNT}$, the maximum displacement fluctuates within a certain range, and the variation range is small. It indicates that if $h_l$ is much lower than $h_{TNT}$, the change of $h_{TNT}$ has no significant effect on the maximum displacement of tank wall.

(2) When $h_l$ is large ($h_l$=10m, 15m), with the increase of $h_{TNT}$, the maximum displacement increases obviously. It indicates that the change of $h_{TNT}$ has a great influence on the maximum displacement of tank wall if $h_l$ is higher than or equal to $h_{TNT}$.

(3) When $h_{TNT}$ is constant, with the increase of $h_l$, the maximum displacement has a significant downward trend, which is confirmed with Figure 6 a).

When the vertical height of the explosion point (TNT) center to the ground is much higher than the oil height in the fixed-roof storage tank, the oil cannot improve the impact resistance of the tank wall well against the explosion blast wave, and the change of the vertical height of the explosion point does not greatly affect the failure of the tank wall at the same time. When the vertical height of the explosion point center is lower than the oil height or near the ground, the increase of the oil height can greatly improve the impact resistance of the tank wall. The maximum displacement of the tank wall is mainly affected by the relative vertical height between explosion point (TNT) and oil.

**3.3 The law of total energy of tank or oil transformed from explosion**

With the instance increasing, the explosion energy produced by TNT equivalent propagates and dissipates gradually in the air. When the explosion blast wave impacts on the fixed-roof storage tank, it can make the wall and roof of the tank deformed and buckled, and also make the oil in the tank sloshing. Therefore, part of the explosion energy is transformed into the kinetic energy and internal energy of the tank and oil, respectively. The total energy is the sum of the kinetic energy and the internal energy transformed from explosion.

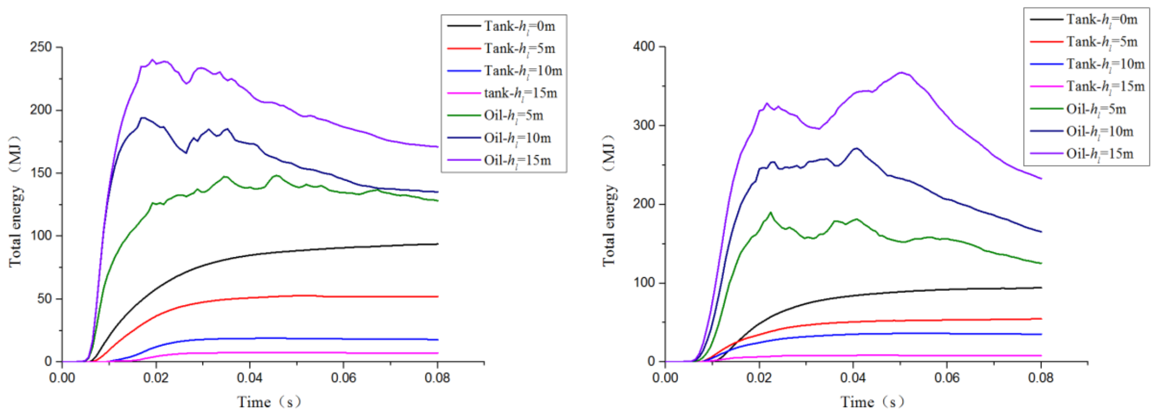
In Figure 7, when $h_{TNT}$ =0.04m, the total energy history curve of 5,000$m^3$ tank and oil is similar with that when $h_{TNT}$ =10 m.

As shown in Figure 7 a),

(1) When the explosion blast wave impacts the tank, the total energy of tank increases first and then slowly drops down (seen in Figure 8 a)). With $h_l$ increasing, the total energy of the tank decreases and the decrease rate slows down. However, in Figure 6 a), the decrease rate of the maximum displacement

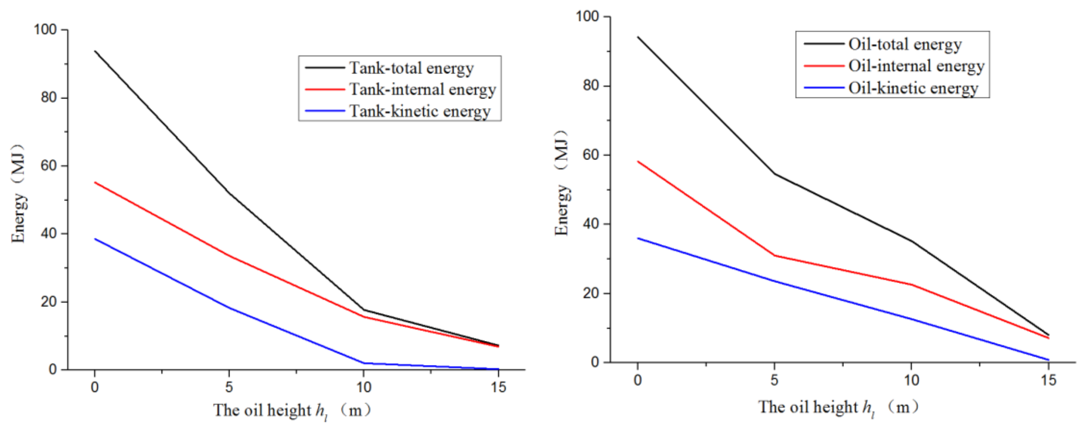
increases with the increase of $h_l$ when $h_{TNT}$=0.4m. The reason is that, the energy for the further deformation is larger than before with the deformation of the tank wall increasing. Therefore, although the maximum displacement of the tank wall shows a faster downward trend, the decrease rate of the total energy of the tank tends to decrease when $h_l$ increases.

(2) When $h_l$ is constant, the total energy of the oil increases first and then fluctuates downward. The total energy of the oil is greater than that of the tank. The total energy of oil also increases with the increase of $h_l$. It indicates that, with $h_l$ increasing, the oil not only absorbs the energy of the tank to improve the impact resistance of the tank, but also absorbs more energy from explosion through the tank. At the same time, the total energy of oil also reduces by means of dissipation or conduction.




a) $h_{TNT}$ =0.04m        b) $h_{TNT}$ =10m

Figure 7. Total energy history curve of 5,000m$^3$ tank and oil




a）$h_{TNT}$=0.4m        b）$h_{TNT}$=10m

Figure 8. The relationship between the total energy, internal energy, kinetic energy and $h_l$ at $t$=0.08s

From figure 8, we have:

(1) When $h_{TNT}$ is constant, with the increase of $h_l$, the total energy, internal energy and kinetic energy of the tank all decrease. It indicates that with the increase of $h_l$, the deformation and deformation rate of the tank both decrease.

(2) When $h_{TNT}$ is 0.4m and 10m respectively, the values of the total energy, internal energy and kinetic energy of the tank at the same oil height are close.

(3) When $h_{TNT}$=0.4m, with $h_l$ from 0 to 15m, the maximum displacement of the tank wall changes from

7.58m to 1.127m and the total energy of the tank changes from 93.8MJ to 7.24MJ. When $h_{TNT}$=10m, with $h_l$ from 0 to 15m, the maximum displacement of the tank wall changes from 7.29m to 3.72m and the total energy of the tank changes from 94.2MJ to 8.06MJ. It indicates that the total energy of tank is independent with the maximum displacement of tank wall.

From Figure 9, when $h_{TNT}$ is constant, with the increase of $h_l$, the total energy of the tank decreases. When $h_l$ is constant, the total energy value of the tank with different oil height is close. The total energy of the tank is almost not influenced by the change of $h_{TNT}$, but the maximum displacement of the tank wall varies with the change of $h_{TNT}$.

In summary, when the explosion point (TNT) mass and the horizontal distance from the point to the nearby tank wall are constant, the total energy of the tank transformed from explosion is mainly affected by the oil height, and is almost not affected by the change of the vertical height of the explosion point. And the maximum displacement of the tank wall is irrelevant with the total energy of the tank.

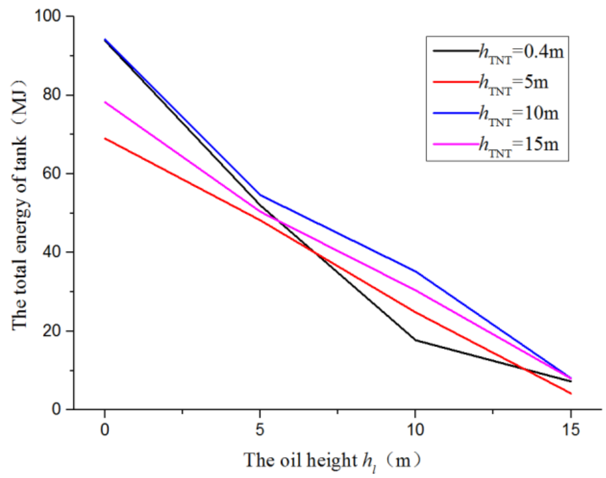
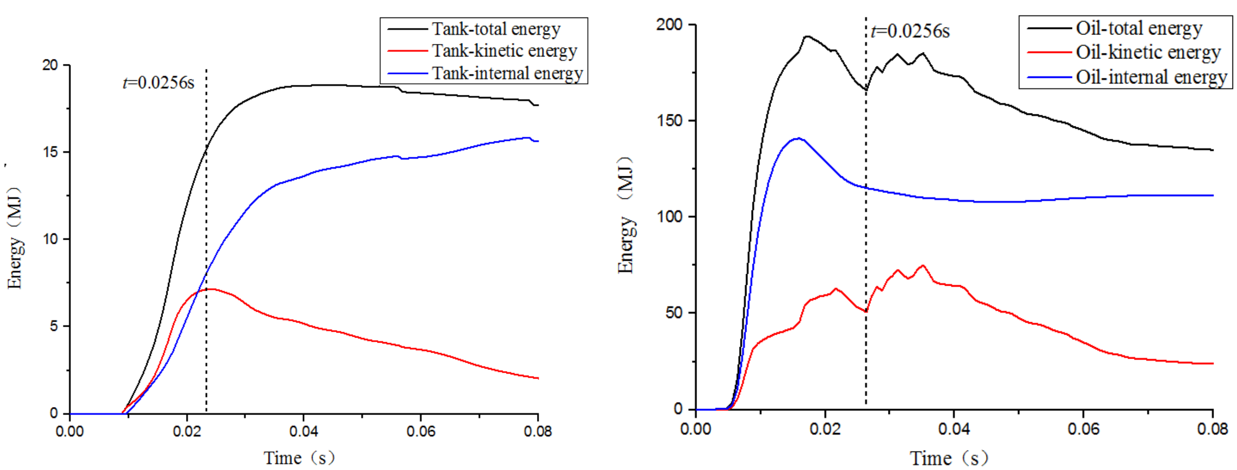



Figure 9. The relationship between the total energy of the fixed-roof storage tank and $h_l$, $h_{TNT}$ at $t$=0.08s

### 3.4 The law of oil energy transformed from explosion




a) tank b) oil

Figure 10. The total energy, internal energy and kinetic energy history curve of 5,000 $m^3$ tank and 10m oil height when $h_{TNT}$=0.4m

Figure 10a) shows that, during $t$=0-0.4s, with the increase of time, the total energy and the internal energy of tank increase, but the kinetic energy of tank shows a downtrend at $t$=0.0256s. It indicates that, after $t$=0.0256s, the explosion blast wave pressure is smaller than the deformation resistance of the tank, the deformation rate of the tank begins to decrease.

Figure 10b) shows that the oil internal energy rises first, then falls, and eventually stabilizes, indicating that part of the oil internal energy dissipates in a certain way. When the rate of oil internal energy transformed is equal to the rate of internal energy consumption, the internal energy of the oil becomes stable. During the period of $t$=0-0.0256 s and $t$=0.0256-0.08 s, the total energy and internal energy of oil both rise first and then decrease. It indicates that the kinetic energy of tank transforms into not only the internal energy of tank, but also the oil kinetic energy after $t$=0.0256s.

Analysis the tank deformation process in the view of energy: when the explosion blast wave pressure is greater than the deformation resistance of tank, the internal energy of the tank increases with the deformation of storage tank increasing, and the kinetic energy of tank increases due to the increase of deformation rate of storage tank. When the explosion blast wave pressure is less than the deformation resistance of tank, with the deformation rate of tank decreasing, the kinetic energy of tank decreases and part of the kinetic energy transforms into the internal energy. So the internal energy of the tank increases but more slowly. At the same time, part of the kinetic energy transforms into the kinetic energy.

## 4. Conclusion

(1) When the explosion blast wave impacts on the fixed-roof oil storage tank, the failure process of the tank isr3 mainly concave deformation and buckling deformation, no matter how the oil height changes. Stress concentration commonly occurs at the maximum displacement of the concave deformation and the plastic hinge lines produced by the buckling deformation.

(2) When the vertical height of the explosion point center to the ground is much higher than the oil height in the fixed-roof storage tank, the oil cannot improve the impact resistance of the tank wall well against the explosion blast wave, and the change of the vertical height of the explosion point does not greatly affect the failure of the tank wall at the same time. When the vertical height of the explosion point center is lower than the oil height or near the ground, the increase of the oil height can greatly improve the impact resistance of the tank wall. The maximum displacement of the tank wall is mainly affected by the relative vertical height between explosion point and oil.

(3) When the explosion point mass and the horizontal distance from the point to the nearby tank wall are constant, the total energy of the tank transformed from explosion is mainly affected by the oil height, and it is almost not affected by the change of the vertical height of the explosion point. And the maximum displacement of the tank wall is irrelevant with the total energy of the tank.

## Acknowledge

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