Numerical and analytical assessment of hydraulic pressure on the inner wall of the deep-water caisson under sudden flooding risk

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Abstract
Sudden flooding is one of the major risks for the drainage sinking construction of deep-water caisson. The damage of inner walls due to hydraulic pressure induced by sudden flooding threatens the labor and structural safety. This study developed the numerical model and analytical method to assess the hydraulic pressure on the inner walls of both the balanced and sudden-sinking caisson under sudden flooding risk. An experimental program of sudden flooding into a caisson specimen was conducted in a water basin to validate the numerical model and the analytical method for balanced caisson. The numerical and analytical methods were then illustrated by an actual engineering practice to show the hydraulic pressure on the inner walls for the caisson under balanced and sudden-sinking state, respectively. The experimental validation and engineering illustration prove that the numerical model is effective in the assessment of hydraulic pressure of caisson under sudden flooding, especially for the complicated case that includes the turbulence effect and sudden sinking, while the analytical method can calculate the quasi-static value of the hydraulic pressure more efficiently. The presented methods provide the engineers with alternative tools to learn more about the sudden flooding risk of the deep-water caisson.

Keywords
Deep-water caisson, sudden flooding, hydraulic pressure, numerical model, analytical method, experiment

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Introduction
Caisson is a watertight retaining structure that is always used as the deep foundations of long-span bridges due to its advantages in resisting vertical and lateral loads from superstructures. As shown in Figure 1, the common caisson form used in the deep-water environment is called open caisson, consisting of a multi-cabin precast concrete box with sidewalls. It can work as a cofferdam to keep water and soil outside and reduce construction costs. In its installation, the caisson sinks through soft mud until a suitable foundation floor is encountered with the construction method of drainage sinking. The water inside the caisson is continuously pumped out to keep the environment dry for excavation convenience.

Sudden flooding usually happens in the sinking process of the caisson. When the caisson sinks on the river or sea bed, the internal water is pumped out, and a deep-water foundation pit is built then. The head difference between the water inside and outside the caisson induces enormous hydraulic gradient pressure on the soil floor. It results in piping in the soil floor with a concentrated leakage path, and sudden flooding occurs then, as illustrated in Figure 2. The flooding would reduce the base bearing capacity and cause the caisson to sink suddenly. Meanwhile, the huge hydraulic pressure during flooding may damage the inner caisson walls, causing severe consequences. An accident of sudden flooding in caisson was reported in the construction of a cable-stayed bridge on the Yangtze River. In the accident, sudden flooding occurred while the caisson was constructed by drainage sinking. The hydraulic pressure caused by the flooding cracked and
fractured the inner caisson walls. Through the lesson of the accident, it is essential for the engineers to learn more about the hydraulic pressure on the deep-water caisson under sudden flooding risk.

The occurrence of sudden flooding inside the caisson is related to many factors, such as the soil composition and gradation, the hydraulic gradient, the distance, and depth of the piping, the thickness of the covering floor, etc. Chen et al. analyzed the concentrated leakage path mechanism after seepage piping in the embankment. The hydraulic head may reach or exceed the impermeability strength of the clay floor, inducing the concentrated seepage at the weakest part. Liu et al. pointed out that the soil floor where flooding occurs is usually a gravel floor or a fine sand floor under impermeable or weakly permeable clay floors. Ding et al. conducted a sand trough model test for the triple-layer embankment consisting of aquitard, fine sand layers, and a highly permeable gravel layer. The piping occurrence and development, and the mechanism that led to the embankment collapse were also observed and analyzed. Chen et al. carried out an experimental study on the piping failure characteristics of the gap-graded coarse-grained soils with different maximum grain sizes and fines contents. They pointed out that the gap-graded coarse-grained soils with a fines content of less than 30% suffered a piping failure. Wang et al. studied the effects of three typical soil structures on the occurrence and development of piping by sand trough model tests. Wang et al. performed model tests to verify the water inrush course in the foundation pit bottom, and the water inrush modes of foundation pits were analyzed for the aquitards that included clay and silty clay. The water inrush formula was verified and tested using the model test results, and it proved that the limit equilibrium method had larger safe reserves. Jiang et al. established a simplified model for simulating the whole process of water inrush disasters and studied the effect of hydraulic pressure on water inrush disasters. Zheng et al. took some measures to overcome the challenge of plugging the water in the process of dewatering and excavation. However, existing research mainly focused on the mechanism of soil failure and seldom studied the hydraulic loading inside the caisson.

The hydraulics of the flooding water inside the structure has been widely investigated in marine engineering for the damaged vessels. Several analytical hydraulic models were developed based on the modified empirical Bernoulli’s equation to calculate the hydrodynamics of floodwater related to damaged ships. With the rapid development of computer and numerical simulation, computational fluid dynamics (CFD) technology capable of obtaining the free surface, has been commonly used to simulate the sudden flooding process. Gao et al. developed a numerical tool based on the CFD method to simulate water flooding into a damaged vessel. The tool was used to solve the damaged compartment flooding problem, and the numerical results coincide well with the experimental results. A coupled model was applied to calculate the interactive dynamics of floodwater and damaged vessels by many researchers, such as Woodburn et al., Cho et al., and Zhang et al. In the coupled model, the floodwater motion is calculated using the VOF method, while the vessel’s motion is determined by the potential flow theory. Gao and Vassalos used a RANS based CFD solver with VOF modeling of the free surface to investigate the effects of sloshing and flooding on damage ship hydrodynamics.

Since the existing research seldom investigated the hydraulic loading of sudden flooding water, this study focused on assessing hydraulic pressure on inner caisson walls under sudden flooding risk. Considering that the sudden flooding process is quite complicated, this paper made some simplifications and developed numerical and analytical methods to assess the hydraulic pressure, which is inspired by the studies of the damaged vessels subjected to sudden flooding. An experimental program of water flooding into a balanced caisson specimen was then conducted to validate the developed methods. Finally, the developed methods were applied in an engineering case of water flooding into a square open caisson with nine cabins. This paper’s contents are organized as follows: Section 2 introduces the
developed numerical and analytical assessment methods; Section 3 presents an experimental validation of the methods; Section 4 presents an application of the developed methods into engineering practice; Section 5 gives the conclusions and prospects.

**Numerical and analytical assessment methods**

### General configurations and assumptions

A deep-water caisson might be in two states when sudden flooding occurs, including the balanced and sudden-sinking state. As shown in Figure 3, the balanced state refers to that caisson keeps stationary during water flooding. The caisson may sink suddenly during flooding due to the sudden loss of soil bearing capacity under cutting edge, referred to as a suddenly-sinking state. In this study, the hydraulic pressure of sudden-flooding water acting on the balanced and sudden-sinking caisson is investigated, respectively.

Considering that the sudden flooding process is quite complex, some simplifications are necessary to model sudden flooding numerically. Firstly, the flooding only occurs in one circle opening hole located at the caisson bottom center. The area of the inlet hole is constant during the flooding process. The remaining soil layers are assumed to be impermeable. The water is incompressible, and the formation time of concentrated leakage paths is neglected. Under such circumstances, the process of sudden flooding in the caisson can be simplified as that water floods into the caisson through the inlet on the caisson bottom due to the hydraulic head difference between internal and external water.

### Numerical assessment method

Reynolds-averaged Navier-Stokes (RANS) equations for the incompressible viscous fluid motion of the flooding water can be adopted to simulate the flooding into the caisson. The continuity equation of the governing equations is as follows:

$$\frac{\partial}{\partial x_i} u_i A_i = 0$$  \hspace{1cm} (1)

where the area fractions $A_i$ are involved in all the following equations. The equation of motion for the fluid velocity components with some additional terms in the three coordinate $x$, $y$, and $z$-directions is given as the following:

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_F} u_i A_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + G_i + f_i$$  \hspace{1cm} (2)

where $x_i, i = 1, 2, 3$, represents the $x$, $y$, $z$ coordinate, respectively. $u_i$ is the mean velocity component, $V_F$ is the volume fraction, $G_i$ is the body acceleration, $t$ represents time, $V_F$ is the fractional volume open to flow, $\rho$ is the fluid density, $p$ is pressure, and $f_i$ represents the viscous acceleration, which can be expressed as follows:

$$f_i = \frac{1}{V_F} \left[ \tau_{hi} - \frac{\partial}{\partial x_i} (A_j S_{ij}) \right]$$  \hspace{1cm} (3)

where $\tau_{hi}$ represents wall shear stress, $S_{ij} = -(v + \nu k) \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}$ represents the strain rate tensor, $\nu$ represents kinematic viscosity, $v_T$ represents kinematic eddy viscosity, which can be calculated from the turbulence model.

A variety of turbulence models, for example, standard $k-\varepsilon$, RNG $k-\varepsilon$, and $k-\omega$, are available to solve the RANS equations. The principal goal of any turbulence model is to provide a mechanism for estimating the influence of turbulent fluctuations on the mean flow quantities. Since Gao and Vassalos employed FLUENT 12.1 to solve the RANS equation with the $k-\omega$ turbulence model to investigate the sloshing and flooding effects on damage ship hydrodynamics and obtained valid conclusions, the $k-\omega$ turbulence model is employed here. In $k-\omega$ turbulence model, the kinematic eddy viscosity $v_T$ can be determined as follows:

$$v_T = k/\omega$$  \hspace{1cm} (4)

where $\omega = e/k$. $k$ and $\varepsilon$ represents the turbulence kinetic energy and turbulent dissipation rate per unit mass, respectively. They can be solved by the following equations:

$$\frac{\partial k}{\partial t} + \frac{1}{V_F} \left[ u_i A_i \frac{\partial k}{\partial x_j} \right] = \frac{1}{V_F} \frac{\partial}{\partial x_j} \left[ \left( v + \frac{v_T}{\sigma_k} \right) A_i \frac{\partial k}{\partial x_i} \right]$$

$$+ \frac{v_T}{V_F} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) A_i \frac{\partial u_i}{\partial x_j} - \beta^* k \omega$$  \hspace{1cm} (5)

$$\frac{\partial \omega}{\partial t} + \frac{1}{V_F} \left[ u_i A_i \frac{\partial \omega}{\partial x_j} \right] = \frac{1}{V_F} \frac{\partial}{\partial x_j} \left[ \left( v + \frac{v_T}{\sigma_\omega} \right) A_i \frac{\partial \omega}{\partial x_i} \right]$$

$$+ \alpha \frac{\omega v_T}{k V_F} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) A_i \frac{\partial u_i}{\partial x_j} - \beta \omega^2$$  \hspace{1cm} (6)

\[\text{Figure 3. Illustrations of the deep-water caisson during the sinking process.}\]
in which, $\beta^* = \beta f_\beta'$; $\beta_0 = 0.09$; $f_\beta' = 1$, when $x_k \leq 0$; and $f_\beta' = 1 + \frac{680 x_k}{400 x_k}$ when $x_k > 0$; $x_k = \frac{1}{\sigma} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + 2 \frac{\partial u_k}{\partial x_k} \right)$, $\sigma = 2.0$, $\alpha = 13/25$, $\sigma_w = 2.0$, $\beta = \beta_0 f_\beta$, $\beta_0 = 9/125$, $f_\beta = 1 + \frac{70 x_k}{500 x_k}$, $x_k = \frac{\partial \Omega}{\partial (\partial u_i/\partial x_j)}$.

$\Omega = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + 2 \frac{\partial u_k}{\partial x_k} \right)$, $S_0 = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$.

The volume-of-fluid (VOF) method is used to capture fluid interfaces through a computational grid while keeping the interface sharp and well defined. Figure 4 illustrates the boundary conditions in the numerical model. The solid wall boundary is used at the bottom and sidewalls of the water domain. The top of the water grid is set to be a pressure boundary with the value of a standard atmospheric pressure, which equals 101325 Pa.

**Analytical assessment method**

CFD simulation of flooding occupies many computer resources and is very time-consuming despite its advantages for complex hydrodynamic problems. An analytical method is developed to reduce the calculation cost and obtain hydraulic pressure efficiently. As shown in Figure 5, the flooded cabin of the caisson can be treated as a box with an inner cross-section area $A_1$, and a water inlet with an area $A_2$ at the bottom. $H$ is the elevation of the water surface from the caisson bottom and $H$ is the time-varying water level in the caisson.

Besides the assumptions mentioned in the numerical simulation, some additional assumptions are made for the analytical derivation: (1) the water is assumed to be irrotational, non-viscous, and incompressible; (2) the shrinkage of the water stream at the water inlet is ignored; and (3) the flow at the inlet is treated as a steady flow, since the water inlet is much smaller than the caisson cross-section, the water level in the caisson rises slowly.

(i) Balanced caisson

The caisson keeps balanced, and the water level inside the caisson at time $t$ is $z$. Since the caisson volume is much smaller than that of the outer water area, external water elevation can be considered constant. Assuming the flow is steady within a short period, the surrounding water level and the water inlet are picked as sections 1 and 2, respectively. For a constant density flow, the energy equilibrium equation at time $t$ can be listed as

$$\alpha_1 \frac{T_1^2}{2g} + \frac{p_1}{\gamma} + z_1 = \alpha_2 \frac{T_2^2}{2g} + \frac{p_2}{\gamma} + z_2 + h_L$$

(7)

in which $T$ is the average velocity over the area at a section, $\alpha$ is the kinetic energy correction factor, $p$ is the pressure, $z$ is the elevation, where the subscripts 1 and 2 refer to the sections 1 and 2, respectively, $\gamma$ is the specific weight of the fluid, $g$ is the local gravity and $h_L$ is the head loss in the flow. For most of the internal turbulent flows, as well as the flooding in the caisson, the velocity profile is nearly uniform with $\alpha \simeq 1.05$. It will always be done that $\alpha$ is taken as 1.

Since the volume of water in the outer region is much larger than that of the caisson, the water level outside is considered constant, as well as the pressure on the water surface in section 1, which is standard atmospheric pressure.

$$z_1 = H, z_2 = 0, p_1 = p_0$$

(8)

where $p_0$ is the standard atmospheric pressure.

In the flooding process, energy is lost due to two primary effects: (1) viscosity causes internal friction that results in increased internal energy or heat transfer, and (2) changes in geometry result in separated flows that require useful energy to maintain the resulting secondary motions in which viscous dissipation occurs. The losses caused by the internal viscous effect could be neglected compared to those resulted from geometry changes in the inlet. The head loss is hence written in terms of a loss coefficient $K$ as

$$h_L = K \frac{V^2}{2g}$$

(9)

When $K$ is equal to zero, it means the energy loss at the inlet is omitted. The pressure at section 2 when water enters through the piping inlet is

$$p_2 = p_0 + \gamma z$$

(10)

Substituting equations (8), (9) and (10) into equation (7) and taking $\alpha$ as 1, we obtain

$$T_2 = \varphi \sqrt{2g(H - z)}$$

(11)
where $\varphi = \frac{1}{\sqrt{1 + K}}$ represents the velocity coefficient at the water inlet. The parameter $\varphi$ is recommended in the range from 0.80 to 0.85 when the water stream shrinkage is ignored.\textsuperscript{19} The corresponding loss coefficient $K$ is from 0.38 to 0.56.

During the period of $dt$, the flow rate through the water inlet is $Q = A_2 \mathcal{V}_2$, the water level in the caisson has risen by $dz$. According to the conservation of mass, the mass of water flooding through the inlet is equal to that rising in the caisson. Since the density of water is constant, the mass conversation equation can be expressed as

$$\int A_2 \mathcal{V}_2 dt = \int A_1 dz \quad (12)$$

By variables separation and integration of equation (12), the time-varying water level in the caisson is obtained as

$$Z(t) = H - \left( \sqrt{H - \varphi \frac{\sqrt{2g}}{2} \frac{A_2}{A_1}} t \right)^2 \quad (13)$$

The water level rises slowly due to the assumption that the inlet size is much smaller than the caisson. The pressure on the inner wall of the caisson is approximately equal to the hydrostatic pressure. Given this, the hydraulic pressure on the inner wall can be calculated from the water level $Z(t)$ in the caisson. So that the hydraulic pressure $p(t)$ at the position of $d$ above the caisson bottom is

$$p(t) = p_0 + \gamma [Z(t) - d] \quad (14)$$

When the levels of internal and external water of the caisson are equal, the internal water level will no longer rise.

(ii) Sudden-sinking caisson

The process of sudden sinking can be divided into three stages, according to the caisson motion state. In the first stage ($0 \sim t_1$), the caisson keeps still. The water level inside the caisson can be calculated according to the balanced caisson as follows,

$$Z(t) = H - \left( \sqrt{H - \varphi \frac{\sqrt{2g}}{2} \frac{A_2}{A_1}} t \right)^2, 0 \leq t \leq t_1 \quad (15)$$

In the second stage ($t_1 \sim t_2$), the caisson moves downward at the speed of $v_c$ until a stratum is encountered. Ignoring the increase of inlet flow rate due to the change of the hydraulic head, the average flow velocity at section 2, adding $v_c$ to the equation (11), is given as follows,

$$\mathcal{V}_2 = \varphi \sqrt{2g(H - z)} + v_c \quad (16)$$

According to the conservation of mass as mentioned before, substituting equation (16) into equation (12), we obtain

$$\int A_2[\varphi \sqrt{2g(H - Z_1)} + v_c] dt = \int A_1 dz \quad (17)$$

where $Z_1$ is the water level inside the caisson at the end of the first stage. The water level in the caisson is solved by equation (17) during the period of sinking, and the relationship between the hydraulic pressure on the walls and the time is derived. In the third stage ($t_2 \sim \infty$), the caisson stops moving and turns still. The calculation of the hydraulic pressure on the walls is the same as the balanced caisson, while the only difference is the initial state of the internal water level. The initial water level inside the caisson at the beginning of the third stage equals the water level at the end of the second stage.

### Experimental validation of the methods

**Experimental setup and procedure**

To validate the numerical model and the proposed analytical method, an experimental program of water flooding into a caisson specimen was conducted in a water basin with a plane size of 0.88 m $\times$ 0.88 m. Since the experimental setup cannot control the sinking speed of the caisson specimen, and few tests can be found from the previous literature, the experimental validation was only conducted for balanced caisson. According to Figure 6, the caisson specimen is made of acrylic material with the inner dimension of 0.15 m $\times$ 0.15 m $\times$ 0.15 m. The thickness of the acrylic wall is 0.005 m. The top of the caisson specimen is aligned with the top of the basin. A circular hole with a diameter of 0.01 m is set at the bottom center to simulate the water inlet. Before the test, a rubber plug was used to block the circular inlet and keep the balanced caisson initially empty. Once the sudden flooding test started, the rubber plug was pulled out quickly, and the water flooded into the specimen. The installation height of the specimen was constant for all three testing cases. The water head difference was changed by changing the initial external water level. The testing parameters of the three testing cases are listed in Table. 1.

A pressure sensor was mounted on the inner wall to measure the hydraulic pressure of flooding water on the inner caisson wall. It locates 0.03 m above the bottom of the specimen. The sample rate of the pressure sensor is 100 Hz. A GoPro camera was set at the side of the specimen to record the flow pattern of the flooding inside the caisson.

### Validation of the numerical and analytical methods

The CFD numerical simulations of the experiments were solved by RANS with a total number of 1.4 million grids. The calculation time of the flooding process in the numerical model was 55 s, which is sufficient to allow the flooding water to fill the full caisson. The numerical simulation considers turbulent flow by $k-\omega$ turbulence model. Figure 7 compares the experimental and numerical snapshot of flooding splash inside the specimen with $\Delta h = 0.08$ m at four time steps, including
1, 10, 20, and 30 s. Good agreements can be found through the comparison of the photo. As shown in Figure 7a–d, the water is splashed due to the flooding at the beginning of the flooding. The water surface becomes fluctuating and consists of many significant surface waves. The fountain effect due to flooding diminishes gradually with the increase of flooding time. The fluctuation almost disappears at time step 30 s.

Figure 8 compares the time histories of pressure obtained by the numerical model with and without turbulence model for the case $D_h = 0.08$ m. The pressure presented in this section is relative pressure, which is equal to the absolute pressure subtract the atmospheric pressure. According to the comparison, the pressure obtained with the turbulence model is smaller than that without turbulence at the same time. The pressure of the two models is equal when the head difference turns zero. The amplitude of pressure fluctuation turns smaller, and the increase rate of pressure becomes slower, when the effect of turbulence is considered.

Figure 9 illustrates the turbulent energy and turbulent dissipation at the pressure sensor location obtained from the model including the turbulence effect ($D_h = 0.08$ m). Most of the turbulent energy and dissipation locate in the range from 10 to 20 s, which induces the fluctuation in the time histories of pressure.

| Case | Water head difference $D_h$ (m) | Initial external water level $H$ (m) |
|------|-------------------------------|-----------------------------------|
| 1    | 0.08                          | 0.30                              |
| 2    | 0.10                          | 0.32                              |
| 3    | 0.12                          | 0.34                              |

Figure 6. Hydraulic experimental setup of a caisson specimen for sudden flooding: (a) global view of the caisson specimen and testing setup and (b) two-dimensional elevation through a central cutting plane (unit: m).

Figure 7. Experimental and numerical snapshots of flooding splash inside the specimen at different times for the case $D_h = 0.08$ m (The yellow dash line indicates the boundary of a splash in the tests).
The turbulent flow also reduces the fluctuation amplitude and slows the increase rate of the pressure. At the time of 30 s, the turbulent energy is close to zero, and this is why the fluctuation becomes not clear.

The analytical results of the sudden flooding hydraulic pressure on the location of the sensor were calculated by equations (13) and (14). Figure 10 shows the experimental and analytical results with different values of $u$ for the case $D_h = 0.08$ m. With the increase of $u$, the curve becomes steeper, and vice versa. The analytical method shows a better agreement with the experiments when $u$ is set to be 0.80, compared with the other values of $u$. Therefore, $u = 0.8$ is used in the following sections.

The analytical results of the sudden flooding hydraulic pressure on the location of the sensor were calculated by equations (13) and (14). Figure 10 shows the experimental and analytical results with different values of $\varphi$ for the case $D_h = 0.08$ m. With the increase of $\varphi$, the curve becomes steeper, and vice versa. The analytical method shows a better agreement with the experiments when $\varphi$ is set to be 0.80, compared with the other values of $\varphi$. Therefore, $\varphi = 0.8$ is used in the following sections.

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caisson under sudden flooding. The numerical model provides an alternative tool to simulate the sudden flooding process, especially for the case including the turbulence effect. Although the analytical method cannot capture the water fluctuation, it can calculate the quasi-static value of the hydraulic pressure much faster, compared with the numerical model.

**Engineering case study**

**Example caisson for a long-span bridge**

In this section, the application of the numerical and analytical methods into engineering practice is illustrated by an example square open caisson with nine cabins, as shown in Figure 13. This kind of caisson is commonly used as a support structure for long-span bridges. The dimensions of the square caisson are $46 \times 46 \times 23$ m (length, width, height). The caisson is equally separated into nine cabins with an inner size of $14 \times 14 \times 14$ m by walls of 1 m thickness. A circular water inlet with a diameter of 2 m is set up at the bottom of the central cabin. The surrounding water level is set to be 28 m, and its plane size is $200 \times 200$ m. The distance from the bottom of the surrounding water to the caisson bottom is 10 m. The top of the caisson is 5 m above the water surface. The strength assessment of the concrete caisson was beyond the scope and not assessed in this study. The caisson is hence assumed to be a rigid body in the numerical model.

![Figure 10. Analytical results of relative pressure with different $\varphi$ values for the case $\Delta h = 0.08$ m.](image)

![Figure 11. Time domain experimental, numerical, and analytical results of relative pressure on the point where pressure sensor locates: (a) $\Delta h = 0.08$ m; (b) $\Delta h = 0.10$ m, and (c) $\Delta h = 0.12$ m.](image)
A total number of 4.7 million grids are used for a balance between computational efficiency and accuracy. The calculation time of the flooding process in the numerical model is set to be 150 s, which is sufficient to allow the flooding water to fill the full caisson. The settings of boundary conditions are the same as those shown in Figure 4. The height of the mesh block is 35 m.

The balanced caisson is initially empty. The water floods into the caisson from the bottom water inlet due to the head difference between the internal and external water of the caisson $\Delta h = 18$ m. To obtain the hydraulic pressure of flooding water on the inner caisson wall, the probes “Point A,” “Point B,” and “Point C” are set on the inner walls at 1.5, 3.5, and 5.5 m above the bottom. The pressure equals atmospheric pressure (101 kPa) when three probes are not submerged.

In the model of the sudden sinking caisson, the initial head difference is 18 m as well. For the simulation of sudden sinking during water flooding, the following conditions are set up: in the first 60 s, the caisson’s condition is the same as the balanced case. At 60 s, the caisson moves downward at a constant speed of 4 m/s and lasts only 1–61 s. After 61 s, the caisson stops moving and turns still.

The analytical results of the sudden flooding hydraulic pressure on the probe of the example engineering caisson are calculated by equation (14) with the known water levels in the caisson. For the balanced case, the water level is calculated by equation (13). For the sudden sinking case, the water level during the sinking period is solved by equation (17), while it is calculated by equation (15) when the caisson is still. $\varphi$ is set to be 0.8 following the experimental validation mentioned above.

### Results of the balanced caisson

A comparison of absolute pressure at three probes between the analytical method and the numerical results with the $k-\omega$ turbulence model is illustrated in Figure 14, respectively. It can be seen that the time

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**Table 2. Time of reaching the maximum water pressure.**

| Case | $\Delta h$ (m) | Experimental (s) | Numerical (s) | Analytical (s) |
|------|---------------|-----------------|---------------|----------------|
| 1    | 0.08          | 44.0            | 42.5          | 45.7           |
| 2    | 0.10          | 50.1            | 47.4          | 51.2           |
| 3    | 0.12          | 54.8            | 52.0          | 56.0           |

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**Figure 12.** Error evaluation of quasi-static value of relative pressure: (a), (b) and (c) compares numerical with experimental results under $\Delta h$ of 0.08, 0.10, and 0.12 m, respectively; (d), (e) and (f) compares analytical with experimental results under $\Delta h$ of 0.08, 0.10, and 0.12 m, respectively.
histories of pressure recorded at three probes follow the same trend. The analysis results agree well with the numerical results. The analytical method is closer to the quasi-static value of numerical results since the analytical method cannot capture the fluctuations of the free surface of internal water, as shown in Figure 15. According to the analytical method, the water level and the area of the water inlet satisfy the quadratic function relationship, and the hydraulic pressure and the area of the water inlet also meet the same relationship. In the initial period, the hydraulic pressure increments per unit time at the probes increases with the water inlet area. The increasing rate of the hydraulic pressure over time becomes greater with the increase of the water inlet area at the bottom of the caisson. Nevertheless, the rate of change will decrease over time gradually.

**Results of the sudden sinking caisson**

Figure 16 compares the time histories of absolute pressure at the three probes of the analytical method and the numerical results for the sudden-sinking caisson, respectively. The analytical results are in good agreement with the quasi-static of the numerical results. However, the developed analytical method cannot capture the pulse of the pressure. In contrast to the balanced case, the flow velocity at the water inlet increases in the sudden-sinking process, which intensifies the water turbulence and increases the free surface fluctuation in the caisson. It can be seen that the dynamic amplification effect of hydraulic pressure on the caisson wall generated by sudden sinking during flooding is much more significant compared with that in the balanced caisson. After the caisson suddenly sinking, the hydraulic pressure reaches 1.6 times that without sudden sinking. The peak pressure exceeds the pressure on the caisson wall when the internal and external water levels turn stable. Figure 17 shows the pressure variation at typical moments in the process. At the end of the sinking (Figure 17b), the hydraulic pressure variations at probes at 1.5 m, 3.5 m, and 5.5 m, respectively, are shown in Figure 14. Figure 15 shows the snapshots of flooding splash at typical moments in the balanced caisson: (a) t = 30 s, (b) t = 60 s, and (c) t = 90 s.
pressure on caisson walls increases sharply and becomes very large because the water in the caisson is forced to stop. The fountain effect at the moment is even stronger than that at $t = 30$ s.

To ensure the structural safety of the caisson under sudden flooding, the designer should choose an appropriate size of the cabin in the caisson. According to the analytical method, the increasing rate of the hydraulic pressure over time decreases with the increase of the inner caisson cross-section. Therefore, the cabin area is suggested to meet the need to carry the load on the caisson structure and be big enough to prevent the sharp increase of the hydraulic pressure exerted on inner caisson walls once flooding happens. The thickness of the inner caisson walls could be designed based on hydraulic pressure assessment under sudden flooding risk. Besides, the contractors should carefully monitor the water level inside the caisson during the construction process of the caisson and consider some reasonable protection measures, such as installing horizontal braces, setting vertical stiffeners, etc.

**Concluding remarks**

The sudden flooding threatens the construction and structural safety of a caisson in the deep-water environment. This paper developed numerical and analytical methods to assess the hydraulic pressure of flooding water in a balanced caisson and a sudden-sinking caisson. An experimental study was conducted to validate the developed methods. The developed methods were then illustrated by an actual engineering practice to show the hydraulic pressure on the inner caisson walls. The main conclusion can be drawn as follows:

The numerical and developed analytical approaches are effective for simulating the hydraulic pressure on a caisson under sudden flooding. The numerical model provides an alternative tool to simulate the sudden flooding process, especially for the case including the turbulence effect, while the analytical method can calculate the quasi-static value of the hydraulic pressure much faster than the numerical model.

It should be noted that there are still some shortcomings in the developed methods. The precision of the analytical method depends on the precision of the velocity coefficient $\varphi$, which is relevant to many factors, such as the shape, the border, the location of the water inlet, etc., and should be carefully measured in further studies. Furthermore, the analytical method cannot capture the pulse of the pressure due to the sudden sinking of the caisson. It can be enhanced in the future by including a dynamic pulse model.
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References
1. Sohu. Daily Accident Case: The accident of caisson wall failure on 17 March in 2016, https://www.sohu.Com/a/326045063_683111 (2019, accessed 10 July 2020).
2. Chen J, Li X and Zhao W. Study on piping leakage mechanism. J Hydraul Eng 2000; 31(09):48–54.
3. Liu J, Chen J and Zhao W. Piping model of perfect well for typical seepage of dike foundation and its estimation for sand flowing scope. Geotech Investig Surv 2002; 0(04):26–27.
4. Ding L, Yao Q, Sun D, et al. Experimental studies on piping development in three-stratum dike foundations. Water Resour Hydropower Eng 2007; 38(02):19–22.
5. Chen Q, Liu L, Zhu F and He C. Criterion of piping types for gap-graded coarse-grained soils. Rock Soil Mech 2009; 30(08):2249.
6. Wang S, Chen JS, Huang DW, He WZ, He HQ. Experimental study on piping development considering effect of foundation structure. Chinese J Geotech Eng 2013; 35(12):2334–41.
7. Wang J, Liu X, Xiang J, et al. Laboratory model tests on water inrush in foundation pit bottom. Environ Earth Sci 2016; 75(14):1072.
8. Jiang HM, Li L, Rong XL, et al. Model test to investigate waterproof-resistant slab minimum safety thickness for water inrush geohazards. Tunnelling Undergr Space Technol 2017; 62: 35–42.
9. Zheng Y, Xiong J, Liu T, et al. Performance of a deep excavation in Lanzhou strong permeable sandy gravel strata. Arab J Geosci 2020; 13(4): 156.
10. Vassalos D and Letizia L. Characterisation of flooding process of damaged ro-ro vessel. Int J Offshore Polar Eng 1998; 8(03): 192–199.
11. Palazzi L and de Kat J. Model experiments and simulations of a damaged ship with air flow taken into account. Mar Technol 2004; 41(01): 38–44.
12. Lee D, Hong SY and Lee G-J. Theoretical and experimental study on dynamic behavior of a damaged ship in waves. Ocean Eng 2007; 34(1): 21–31.
13. Santos TA and Guedes Soares C. Numerical assessment of factors affecting the survivability of damaged ro-ro ships in waves. Ocean Eng 2009; 36(11): 797–809.
14. Gao Z, Vassalos D and Gao Q. Numerical simulation of water flooding into a damaged vessel’s compartment by the volume of fluid method. Ocean Eng 2010; 37(16): 1428–1442.
15. Woodburn P, Gallagher P and Letizia L. Fundamentals of damaged ship survivability. Trans RINA 2002; 144: 143–163.
16. Cho SK, Hong SY and Kyoung JH. The numerical study on the coupled dynamics of ship motion and flooding water. In: Proceedings of the Ninth International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro. 2006. pp.599–605.
17. Zhang X, Lin Z, Mancini S, et al. Numerical investigation into the effect of damage openings on ship hydrodynamics by the overset mesh technique. J Mar Sci Eng 2020; 8(1): 11.
18. Gao Q and Vassalos D. Numerical study of damage ship hydrodynamics. Ocean Eng 2012; 55: 199–205.
19. Yu H. Engineering Fluid Mechanics, 3rd edn. Chengdu: Southwest Jiaotong University Press, 2013, p.140.
20. Xiang Q, Wei K, Li Y, et al. Experimental and numerical investigation of local scour for suspended square caisson under steady flow. KSCE J Civil Eng 2020; 24(9): 2682–2693.