

Article

# A Computational Approach to the Prediction of the Floating Condition of ROPAX Vessel after Firewater Accumulation in Firefighting Operation

Honggui Wang \*  and Zhaolin Wu

Navigation College, Dalian Maritime University, Dalian 116026, China; wuzl@dlmu.edu.cn

\* Correspondence: wanghonggui@dlmu.edu.cn; Tel.: +86-1894-113-6663

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**Abstract:** A reliable estimation of the floating condition of a roll on/roll off cargo (ROPAX) vessel after the accumulation of firewater on the vehicle deck is extremely important for making correct decisions on evacuation and abandonment. Thus, for the seafarer working on a ROPAX vessel, there is a demand for a time-dependent prediction of the floating condition of the vessel after the firewater accumulation. For this purpose, a new iterative computational approach, based on quasi-static theory, is presented. The approach is examined through the records observed in an accident of the M/V Dashun. The results show that the approach has good accuracy and feasibility provided that the actual heeling angle and cargo shift during the accident are carefully monitored.

**Keywords:** firewater accumulation; floating condition of ROPAX vessel; cargo shift; a critical static heeling angle

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## 1. Introduction

Ships designed to carry passengers and roll on/roll off cargo (ROPAX ships) are among functional types of ships. The flexibility, ability to integrate with other transport systems and operating speed, has become extremely popular in many routes [1]. Recent developments in the design of passenger ships have led to larger and larger vessels with an increasing capacity for carrying more passengers and crew [2]. The largest cruise ship can carry more than 8800 people to date. Throughout the history of commercial ROPAX traffic, fire accidents involving large passenger ships have been rare, and fortunately, they have seldom caused fatalities. However, if a large amount of firewater accumulates on the vehicle deck, the vessel may capsize, which could be rapid and disastrous, and probably accompanied by a large number of fatalities. As shown in Table 1, some of these accidents are still fresh in our memory, such as M/V Dashun in 1999 (282 fatalities) [3–5] and M/V Al Salam Boccaccio 98 in 2006 (1031 fatalities) [6].

**Table 1.** Accidents of roll on/roll off cargo (ROPAX) vessels involving firewater accumulation over last 40 years (Source: DNV-GL, MSA, MAIB, FBMCI, PMA).

Ship Name	Date	Location	Accident Description
Angelina Lauro [7]	30 March 1979	Caribbean	The vessel was heavily heeled due to firewater accumulation, and while under towage, finally sank.
Farah II [7]	06 March 1986	Neweiba, Egypt	The vessel listed due to the water pumped on board to fight a fire. The vessel capsized in the Gulf of Aqaba after being towed away from the berth.
Dronning Margrethe II [7]	14 March 1991	Rødbyhavn	After being flooded due to a collision, the vessel was further damaged by firewater, which caused the heeling to be out of control. The vessel was finally grounded.
Pegasus [7]	02 June 1991	Venice	The vessel sank to the sea bed due to firewater accumulation, and later, was declared as a total loss.
Albatros [7]	22 May 1995	Red Sea	The engine room was partly flooded with firewater, and the boilers were shut down. The vessel was drifted to port.
Romantica [7]	04 October 1997	Mediterranean	Firewater caused the vessel to heel to 10° and later to 30°. The vessel was towed into port.
Shenglu [3]	17 October 1999	Bohai Sea, China	A fire was started by the collision of two trucks on the vehicle deck during an improper ship handling operation. The entire drencher system on the deck was started later. Too much water accumulated on vehicle deck due to the blockage of the scuppers. The vessel was finally sunk. Two people were reported as missing.
Dashun [3]	24 November 1999	Bohai Sea, China	The vessel was heavily heeled due to firewater accumulation on the vehicle deck, and finally sunk in combination with other reasons. A total of 282 people died.
Liaohai [8]	16 November 2004	Sanshan Island of Dalian, China	The onboard water-drencher system broke down immediately after being started. A foreign firefighting assistance was deployed and engaged by local authority. The maximum heeling angle due to firewater accumulation was controlled within 15° on the starboard side. The fire was successfully put out.
Al salam98 [6]	03 February 2006	Red Sea	The accumulation of a large amount of water coupled with weather conditions finally caused an excessive heeling of the vessel towards starboard. A total of 1031 people died.
Commodore Clipper [9]	16 June 2010	On passage to Portsmouth, UK	Firefighting efforts were suspended due to the blockage of vehicle deck scuppers. The firewater accumulated on deck reduced the vessel's stability.
LISCO GLORIA [10]	08 October 2010	NW of Fehmarn, Germany	The scuppers had become partly clogged with debris from a fire, resulting in the firewater being trapped on the upper deck, which caused the ferry to heel to the port side. The vessel was declared as a constructive total loss. A total of 28 people injured.

Over the last few years, the problem of water on deck of passenger vessels has drawn wide attention from the ocean engineering community, and many experimental studies have been conducted to date [11–13]. However, it is difficult to cover all the situations under limited laboratory conditions, especially in regard to water accumulation on a vehicle deck due to improper firefighting operations. This type of water accumulation is different from that caused by a damaged hull on the basis of the following factors: (1) the vessel is still intact below the waterline, (2) the flow into the vehicle deck is not affected by the waves outside but depends on the spraying capacity of water-drencher system, sometimes in combination with the use of fire hoses by seafarers, and (3) the flow out of the vessel exists during the water accumulation process if the elevation of water on the vehicle deck is higher than that outboard. Certainly, one of most common issues of the water accumulation caused by improper firefighting shared with that caused by a damaged hull is how to predict the floating condition of the vessel with an increase in the accumulation of water, based on which the decision on the evacuation of passengers and seafarers, the abandonment of the vessel or the continuation of sailing can be made. Lee et al. [14] developed a framework for survivability assessment of a damaged ship, taking into account the heeling angle and the range of stability. Jasionowski [15] presented a method for vulnerability analysis which can also be used for decision support when the flooding condition is already known. Choi et al. [16] proposed a DB(Database)-based supporting system on the basement of detected damage condition. Later, D. Spanos and A. Papanikolaou [17] evaluated the probability of slow (and fast) sinking/capsizing of passenger ships, aiming to clarify the feasibility of safe operations/evacuation in flooding incidents. The same year, Varela et al. [18] presented a on-board decision support system for ship flooding emergency response according to the current ship status and existing damages. More recently, Hee Jin Kang et al. [19] designed a new concept for buoyancy support systems for damaged ships which considered the technical and economic matters, but is far from the usage in marine practice. However, these systems are based on the fact that the damage condition has been detected, and moreover, may not be suitable for the case of firewater accumulation.

Usually, the amount of water on a vehicle deck can be detected by the sensors of the flooding detection system [20], as required by SOLAS regulation II-1/22-1 [21], or by using professional commercial software, such as NAPA [22] and ANSYS-Fluent [23]. There are, nevertheless, still passenger vessels in service which are not equipped with flooding level sensors or not even equipped with such a detection system. Even if the detection system has been used onboard, in the case of a firewater accumulation condition, the flood level sensors may send a false signal because the water is widely sprayed to the vehicle deck through a water-drencher system rather than solely flooded from a damaged hole. Furthermore, for seafarers working on board these vessels, a commercial hydrostatic or hydrodynamic software may be not available for immediate use due to its sophistication and specialization. Therefore, a feasible and simple direct computational approach, which can predict the change in the floating condition of the vessel with an increase in the accumulation of firewater, is needed.

## 2. Mathematic Formulation and Computational Approach

### 2.1. Firewater Accumulation

According to the requirements of the SOLAS convention, two methods may be used for the discharge of water from a vehicle deck. One of them is that the water is discharged to the reservoir tank through pipelines and then discharged outboard by a bilge pump. The other is that the water is directly discharged outboard through deck scuppers. The latter is widely used in the design of ROPAX vessels due to its practicability and convenience. In this paper, the latter one is chosen in order to analyze the problem of water accumulation problem on a vehicle deck.

After the occurrence of fire on a vehicle deck, the water-drencher system that the deck is equipped with will be started at the control center of the vessel. Burning debris and loose cargoes will be flushed onto the vehicle deck, and probably drifted toward the openings of scuppers, causing these openings

blocked (as shown in Figure 1). Subsequently, water will build up in the deck if sufficient scuppers are blocked and the access to the openings for manually cleaning the debris becomes impracticable because of large amounts of heat and smoke.



Figure 1. A deck scupper blocked by potatoes. (a) Blocked. (b) Removed.

As shown in Figure 2, the discharge capacity of the pipeline of a scupper mentioned above is determined by:

$$H = h_f + \sum_{i=0}^n a_i h_i \tag{1}$$

$$h_f = \frac{flv^2}{2gd_r} \tag{2}$$

$$h_i = \frac{k_i v^2}{2g} \tag{3}$$

where  $H$  denotes the total elevation head difference between the water level on the vehicle deck and that outboard;  $h_f, f, l, v, g$  and  $d_r$  represent the frictional head loss, the coefficient of frictional head loss, the length of a drain pipeline, the average velocity of flow out, the acceleration due to gravity and the diameter of the pipeline, respectively; and  $h_i, a_i,$  and  $k_i$  indicate the local head loss of part  $i$ , the quantity of part  $i$ , and the head loss coefficient of part  $i$ .

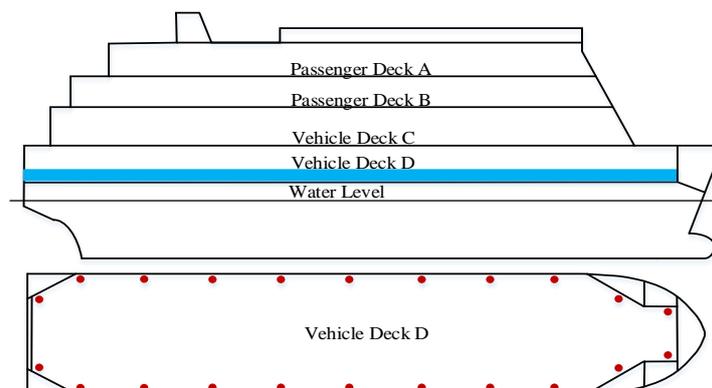


Figure 2. Arrangement of the scuppers on vehicle deck D.

In most cases, the local head loss of a discharge pipeline is composed of valve loss, elbow loss, inlet loss and outlet loss. The total head loss can be written as:

$$\sum_{i=0}^n a_i h_i = a_1 h_1 + a_2 h_2 + a_3 h_3 + a_4 h_4 \tag{4}$$

where  $a_1, a_2, a_3$  and  $a_4$  are the quantities of check valves, elbows, inlets and outlets; and  $h_1, h_2, h_3$  and  $h_4$  are the local head losses of check valves, elbows, inlets and outlets, respectively.

The coefficient of frictional head loss  $f$  can be obtained through the Darcy–Weisbach equation:

$$\frac{1}{f^{1/2}} = 2 \log\left(\frac{\varepsilon}{3.7d_r} + \frac{2.51}{f^{1/2}Re}\right) \tag{5}$$

$$Re = \frac{\rho v d_r}{\mu} \tag{6}$$

$$Q_{out} = \frac{1}{4} \pi d_r^2 v \tag{7}$$

where  $\varepsilon$  is the roughness of the pipeline,  $Re$  is the Reynolds number,  $\mu$  is the coefficient of viscosity, and  $Q_{out}$  is the volumetric flow rate of the flow out of the vessel.

### 2.2. Firewater Accumulation without a Persistent Heeling Angle

Normally, firewater will accumulate on the side where the blocking condition is heavier than the other side, based on the assumption that the heeling process proceeds in a quasi-static way [24,25]. Then, the heeling angle can be considered to be equal to the vertical angle of the water triangular prism accumulated on deck [26,27]. For an accurate computation, the deformation of the whole water wedge due to the complicated ship structure should be taken into consideration. From stern to bow, the vehicle deck is longitudinally divided into sufficient sections at an interval  $\delta l_i$ , as shown in Figures 3 and 4. If the interval of each step,  $\delta l_i$ , is adequately small, the deformation of each micro-triangular-prism due to the ship structure can then be neglected. At section  $i$ , the breadth of vehicle cargo space and the breadth of micro-triangular-prism are, respectively,  $B_i$  and  $b_i$ . With an increase in water accumulation, the outer margin of the whole water wedge,  $y_{wj}$ , will move from the starboard side to the port side. To maintain the same accuracy as the longitudinal step, the movement of every transverse step,  $\delta y_{wj}$ , is also set as the length of  $\delta l_i$ .

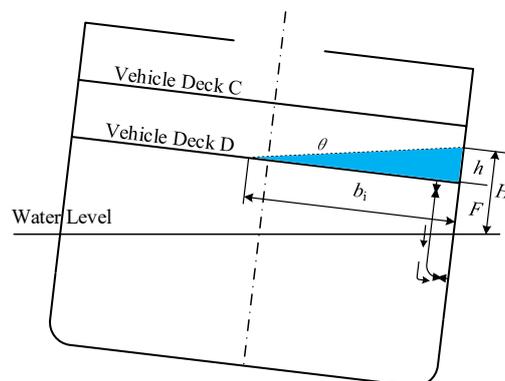


Figure 3. Firewater accumulated on the starboard side.

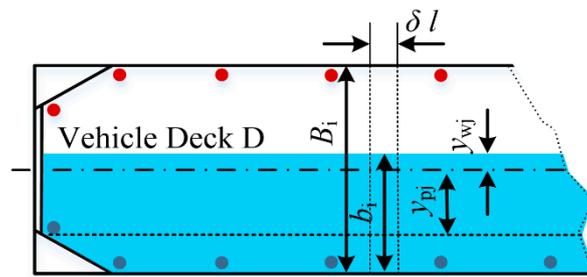


Figure 4. Illustration of the firewater computation.

For section  $i$ ,  $b_i$  can be ascertained by:

$$b_i = \begin{cases} \min(\frac{B_i}{2} - y_{wj}, B_i) & (if\ b_i > 0) \\ 0 & (if\ b_i \leq 0) \end{cases} \quad (8)$$

where  $y_{wj}$  is positive on the starboard side, ranging from  $B/2$  to  $-B/2$ . The letter  $B$  mentioned here is the maximum breadth of the vehicle cargo space.

In the practice of ROPAX transportation, the permeability caused by the volume occupied by the wheels and carriages of vehicles,  $\mu_p$ , should be taken into account [28]. The weight of the micro-triangular-prism at section  $i$ ,  $p_i$ , and the total weight of all the firewater accumulated after a period of time  $t$ ,  $P(t)$ , can be expressed as:

$$p_i = \frac{1}{2} \mu_p \rho \delta b_i^2 \tan \theta(t) \quad (9)$$

$$P(t) = \frac{1}{2} \sum_1^I \mu_p \rho \delta b_i^2 \tan \theta(t) \quad (10)$$

where  $\rho$  is the water density,  $I$  is the quantity of the total longitudinal sections and  $\theta(t)$  is the final static heeling angle caused by the water weight.

The equilibrium between the heeling moment and the upright moment of the vessel can be established as:

$$P(t)y_p(t) = (\Delta + P(t))(GM_c + \frac{P(t)(KG - Z_p(t))}{\Delta + P(t)}) \tan \theta(t) \quad (11)$$

$$Z_p(t) = Z_v + \frac{P(t)}{\rho \mu_p S_v} \quad (12)$$

where  $y_p(t)$  is the transverse center of the whole water wedge,  $\Delta$  is the displacement of the vessel,  $GM_c$  is the initial metacentric height corrected by free surface,  $KG$  is the center of gravity of the vessel,  $Z_p(t)$  is, under a dangerous assumption that all the water accumulated can flow from one side to the other, the center of gravity of the water on vehicle deck,  $Z_v$  is the height of vehicle deck above baseline, and  $S_v$  is the area of the vehicle deck, respectively.

Then,  $y_{pj}$  can be obtained as:

$$y_{pj} = \frac{\sum_1^I b_i^2 \delta l (\frac{B_i}{2} - \frac{b_i}{3})}{\sum_1^I b_i^2 \delta l} \quad (13)$$

Then, the governing Equation (11) can be expressed as:

$$P(t) \left( \frac{\sum_1^I b_i^2 \delta l (\frac{B_i}{2} - \frac{b_i}{3})}{\sum_1^I b_i^2 \delta l} \right) = (\Delta + P(t)) (GM_0 + \frac{P(t)(KG - Z_p(t))}{\Delta + P(t)}) \tan \theta(t) \quad (14)$$

### 2.3. Firewater Accumulation with a Persistent Heeling Angle

The shift of vehicle cargoes will significantly affect the accumulation of water on the deck and the floating condition of the vessel, which may happen during the firefighting with water. The firewater poses a danger to the security and lashings of vehicle cargoes on the vehicle deck in the following ways: (1) an increase in the weight of water-absorbing cargoes in vehicles exposed to water-drencher system, (2) an increase in the lashing load of the higher side of vehicles due to heeling, and (3) the decrease in the friction force caused by the wet deck. Equation (14) should be corrected as follows:

$$\Delta GM \tan \theta_0 + P(t) \left( \frac{\sum_1^I b_i^2 \delta l (\frac{B_i}{2} - \frac{b_i}{3})}{\sum_1^I b_i^2 \delta l} \right) = (\Delta + P(t)) (GM_c + \frac{P(t)(KG - Z_p(t))}{\Delta + P(t)}) \tan \theta(t) \quad (15)$$

where  $\theta_0$  is the persistent heeling caused by cargo shift.

### 2.4. A Time-Dependent Prediction of Floating Condition of Roll On/Roll Off Cargo (ROPAX) Vessels after Firewater Accumulation on the Vehicle Deck

The weight of the total firewater accumulated,  $P(t)$ , is directly related to the final static heeling angle,  $\theta(t)$ . The change in  $P(t)$  depends on the total volume of the flow into the vehicle deck and that of the flow out.

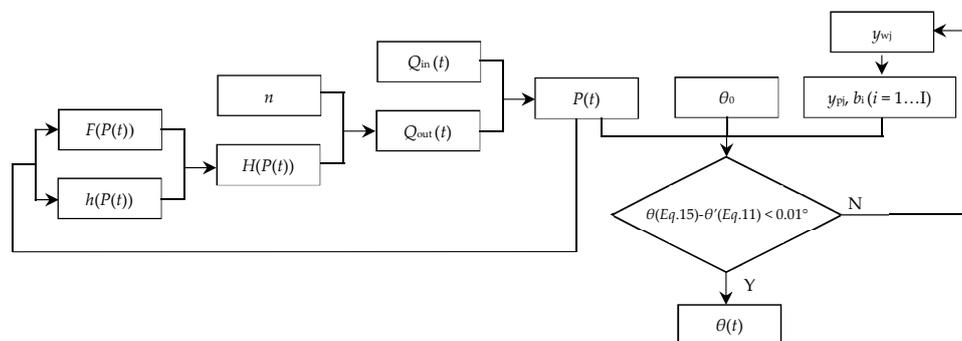
$$\frac{dP(t)}{dt} \rightarrow \frac{d\theta(t)}{dt} \quad (16)$$

$$\frac{dP(t)}{dt} = \rho(Q_{in}(t) - Q_{out}(t, n, H)) \quad (17)$$

With an increase in water accumulation, as shown in Figure 5, the freeboard of vehicle deck  $D$ ,  $F(P(t))$ , and the height of the water triangular wedge,  $h(P(t))$ , will change. Subsequently,  $H(P(t))$  will be affected as:

$$H(P(t)) = b \tan \theta(t) + F_0 - \frac{B}{2} \times \tan \theta(t) - \frac{P(t)}{100 \times TPC} \quad (18)$$

where  $b$  is the breadth of the longitudinal triangular prism of water along the length of the vehicle deck  $D$ , and to be on safe side, is ascertained by  $\max(b_i)$ .  $TPC$  is the tonnage per centimeter of the vessel.



**Figure 5.** The flow chart for a time-dependent prediction of the floating condition of after the firewater accumulation on vehicle deck D.

### 3. The Firewater Accumulation in the Accident of the M/V Dashun

In order to calculate the volumetric flow rate of the flow out of the vehicle deck, and then the speed of firewater accumulation after the blockage of the scuppers, and finally to examine the approach, the loading condition of the M/V Dashun at the time of the accident is selected as an example in this section. The total water discharge speed of the vehicle deck is separately computed according to actual heeling condition, for making a comparison. The approach is then examined by the records of the accident.

#### 3.1. Fire Water Accumulation

According to [5], 11 scuppers are evenly distributed on either side of the vehicle deck D. By referring to [29], the coefficients of local loss  $k_i$  of the swing check valve, elbow, inlet and outlet are listed in Table 2.

**Table 2.** The particulars of the scuppers on vehicle deck D of the M/V Dashun.

Item	Value
Pipe length, $l$	5.80 m
Pipe diameter, $d_r$	0.125 m
Roughness, $\varepsilon$	0.003 m
Coefficient of viscosity, $\mu$	0.00089 kg/(m s)
Seawater density, $\rho$	1025 kg/m <sup>3</sup>
Initial freeboard of vehicle deck D, $F_0$	1.87 m
Acceleration due to gravity, $g$	9.81 m/s <sup>2</sup>
Number of valves, $a_1$	2
Number of elbows, $a_2$	1
Number of inlets, $a_3$	1
Number of outlets, $a_4$	1
Coefficient of valve loss, $k_1$	2
Coefficient of elbow loss, $k_2$	0.64
Coefficient of inlet loss, $k_3$	0.5
Coefficient of outlet loss, $k_4$	1.0

Then, the total elevation head difference  $H$  and Darcy–Weisbach equation can be expressed as:

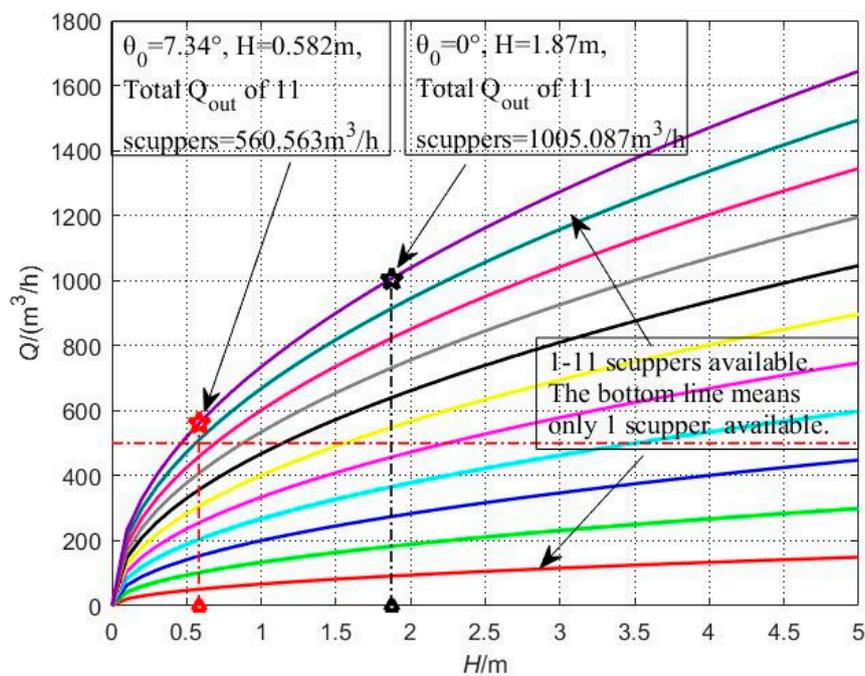
$$H = 2.36493374 f v^2 + 0.31294597 v^2 \tag{19}$$

$$\frac{1}{f^{1/2}} = 2 \log(0.00648649 + \frac{0.00001744}{v f^{1/2}}) \tag{20}$$

Before the accumulation of firewater, the total elevation head difference  $H$  is, if there is no a persistent heeling, determined by the initial freeboard of the vehicle deck D,  $F_0$ . According to the actual loading condition of the M/V Dashun, as shown in Table 3, it can be revealed that the average velocity of flow out  $v = 2.06927836$  m/s, and the coefficient of frictional head loss  $f = 0.05233750$  when the firewater initially accumulated on the vehicle deck D. Then, the volumetric flow rate of the flow out for a single scupper  $Q_{out} = 91.37157275$  m<sup>3</sup>/h at the beginning. The total discharge capacity of vehicle deck D at different  $H$  can then be computed as shown in Figure 6. In the case of the accident of the M/V Dashun, the total volumetric flow rate of the flow into vehicle deck D, including that sprayed from the water-drencher system and the flow from the upper vehicle deck through the vehicle passage ramp,  $Q_{in}$ , is calculated as 500 m<sup>3</sup>/h at least [30]. As shown in Figure 6, if all 11 scuppers are available, the firewater will not accumulate. However, the firewater will surely accumulate if only 5 or less scuppers are available.

**Table 3.** The particulars of the loading conditions of the M/V Dashun at the time of the accident.

Item	Value
Actual displacement, $\Delta$	6451.00 t
Actual draught, $T$	4.83 m
Ship length, $L$	115.00 m
Molded depth, $D$	11.55 m
Vehicle deck D length, $L_c$	104.00 m
Vehicle deck D breadth, $B$	20.00 m
Height of center of gravity, $KG$	8.60 m
Vehicle deck height, $KP$	6.70 m
Initial metacentric height, $GM$	1.45 m
Tonnage per centimeter, $TPC$	20.23 t/cm
permeability of the cargo space, $\mu_p$	0.9
Longitudinal step length, $\delta l_i$	0.01 m
Transverse step length, $\delta y_{wj}$	0.01 m



**Figure 6.** Scupper discharge capacity of vehicle deck D.

Actually, there was a heavy cargo shift in the accident of the M/V Dashun. The fire was caused by the collision of two shifted vehicles after a leakage of gas oil from a damaged vehicle tank. The investigating team suggested that the persistent heeling angle caused by the shift of vehicle cargoes on deck D was less than  $10^\circ$  since the average shift of vehicles was less than 2 m [3]. Later, from a more reasonable perspective, Jiang et al. suggested that the average shift of vehicles was approximately 1.5 m and that the persistent heeling angle caused by the shift should be  $7.34^\circ$  on the port side [5]. In view of this calculation, there would be a high probability that the water would accumulate on vehicle deck after the decrease of total elevation head, because the blockage of only 2 of 11 scuppers will make this happen.

### 3.2. The Accident of the M/V Dashun

Since the accident of the M/V Dashun occurred almost 20 years ago, only a few of the records were, as listed in Table 4, available for the computation of the firewater accumulation and its influence on the floating condition of the vessel. Moreover, the Code of Safe Practice for Cargo Stowage and Securing (the CSS Code) does not apply when the heeling angle of the vessel is greater than  $30^\circ$ .

According to the Report of the Investigation and Analysis of the ‘11.24’ Accident [3], the vehicles on deck D may have been overturned, and ballast operations were carried out after the vessel was heeled to 30°. However, the details of the conditions of overturned vehicles and the ballast operations were not recorded by the vessel. In view of the limitation on records, the firewater accumulation in the accident of the M/V Dashun is not computed when the static heeling angle is greater than 30° in this paper.

**Table 4.** A brief description of the accident of the M/V Dashun [3].

Local Time	Fire Fighting Operation	Floating Condition
1520	The vessel encountered heavy beam waves and thus suffered a heavy rolling. Vehicles on deck D were shifted to port side.	7.34° (port side) [5]
1621	Fire occurred on vehicle deck D. The Water-drencher system on the deck was started manually on bridge. Four fire hoses were also engaged for firefighting minutes later.	7.34° (port side) [5]
1630	Fire spread to vehicle deck C. Water-drencher system on vehicle deck C was also started. The total volumetric flow into vehicle deck C and vehicle deck D was 700 m <sup>3</sup> /h at least. Such amount of firewater was not stopped until the power of fire pumps was accidentally cut off at 2300. Most of the firewater was sprayed into vehicle deck D. Obvious firewater was found accumulated on vehicle deck D.	No record
1921	Firefighting operations continued.	Approximately 22° (port side) [31]
1930	Firefighting operations continued. To keep the vessel upright, a balancing operation was undertaken by discharging a ballast tank on the port side until empty and adding ballast water to all the tanks available on the starboard side.	Approximately 30° (port side) [5]
2220	Firefighting operations continued.	Greater than 35° (port side)
2230	Firefighting operations continued. Water flooded into the vessel due to rolling.	No record
2300	Firefighting pumps were stopped due to pump power failure.	No record
2338	The vessel capsized. The final position was 35°28'5" N, 121°47'6" E, only 1.5 nm to the coast of Yantai city of China.	Capsized to port side

As shown in Figure 7, the red line indicates the computation results of the change in the heeling angle with the increase of accumulated firewater. The red line in Figure 8 shows the change of the heeling angle with the passing of time. According to the results of the computation, 2 of 11 scuppers

are definitely blocked on the port side of the M/V Dashun, which means that the blocking condition in vehicle deck D is not as serious as what was concluded in [5,6] and that the accumulation of firewater is mainly caused by the influence of the persistent heeling due to cargo shift. According to computation results, it was 1936 h local time when the vessel was heeled to 30°. In the records observed in the accident, it was 1930 h local time the vessel was heeled to approximately 30° on the port side. The error for this record is approximately 6 min within a total time consumption of 189 min. According to [31], a salvage boat, “Yanjiu13”, arrived at the scene of the accident at about 1910, and tried to throw a heaving line to M/V Dashun at about 1921 local time after communication with it. During this period, the heeling angle of the M/V Dashun was about 21° to 22° on the port side. Therefore, the maximum error of the computation result of the heeling angle of 22°, as shown in Figure 8, is 22 min within total time consumption 180 min, and the minimum error is about 11 min. For making a correct decision on a further operation after the firewater accumulation, this computational approach is feasible and practicable. What should be mentioned here is that the calculation of the persist heeling angle caused by cargo shift, the total volumetric flow into vehicle deck D, and the heeling angle observed in severe weather may give a contribution to the error of the approach. However, these errors will be minimized in a modern ROPAX vessel equipped with precision instruments.

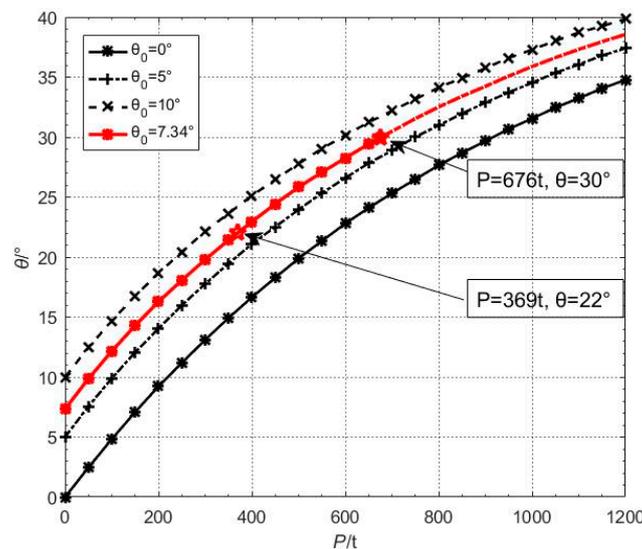


Figure 7. The firewater accumulation of the M/V Dashun accident.

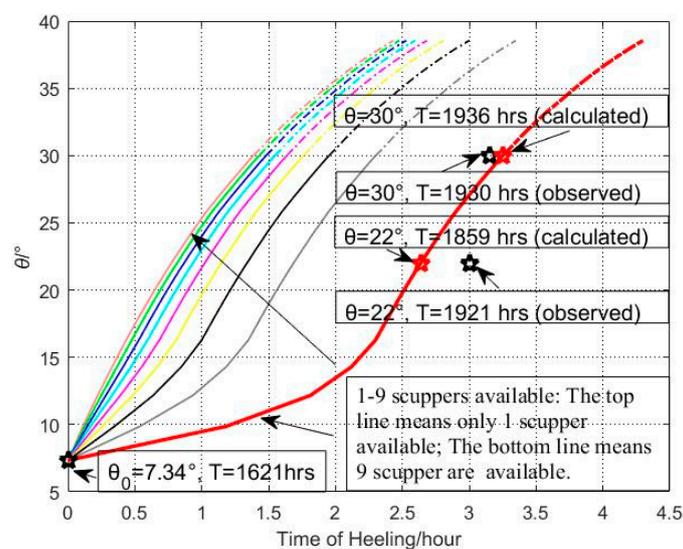


Figure 8. The heeling time of the M/V Dashun accident after the blockage of 2 of 11 scuppers.

#### 4. Discussion

##### 4.1. A Critical Static Heeling Angle for Firefighting Operation with Water

Since the persistent heeling will, as shown in Figures 9 and 10, significantly affect the discharge capacity of scuppers, a critical static heeling angle,  $\theta_c$ , should be determined and identified during firefighting with water. When the vessel heels to the angle of  $\theta_c$ , the elevation head difference  $H_c$  is zero, which means that the average velocity of the flow out,  $v = 0$  m/s, and that any further action of firefighting with water will increase the accumulation of firewater on deck and make the circumstances more dangerous.

$$\theta_c = \begin{cases} \arctan\left(\frac{2F_0}{B}\right) * 57.3 & (\theta_0 \geq \arctan\left(\frac{2F_0}{B}\right) * 57.3) \\ \arctan\left(\frac{F_0 - \frac{P(\theta_0)}{100TPC}}{\frac{B}{2} - b(\theta_0)}\right) * 57.3 & (\theta_0 < \arctan\left(\frac{2F_0}{B}\right) * 57.3) \end{cases} \quad (21)$$

where  $P(\theta_0)$  and  $b(\theta_0)$  are the total weight of water accumulated on deck and the corresponding  $\max(b_i)$ , respectively, when the persistent heeling  $\theta_0$  is set as a variable and the total elevation head difference is set as a constant ( $H = 0$ ).  $P(\theta_0)$  and  $b(\theta_0)$  can be computed from Equations (13) and (17).

The studies of the critical amount of water on deck for capsizing a ROPAX vessel in a damaged case was well developed through the static equivalency method (SEM) by Vassalos, D., Andrew Kendrick, Pawłowski, M. et al. [11,32,33]. In a case of firefighting with water, as per the suggestion of Stefan Krueger, the limiting amount of water on deck needs to be determined at the time when the roll period doubles and the vessel still has a significant remaining stability margin against capsizing [13]. Compared with the flooding water in a damaged case, the firewater is much more controllable and manageable, which gives the master of the vessel sufficient room to make the decision whether or not to continue to fight the fire with water after the heeling angle reaches the critical value identified in this paper. In the practice of firefighting with water, it is suggested that the heeling angle after firewater accumulation is, however, well monitored to avoid the shift or overlapping of vehicle cargoes. In the case of the M/V Commodore Clipper, the maximum heeling angle of the vessel was controlled within  $5^\circ$  by stopping and starting the water-drencher system alternately until the vessel arrived in the port of destination [9].

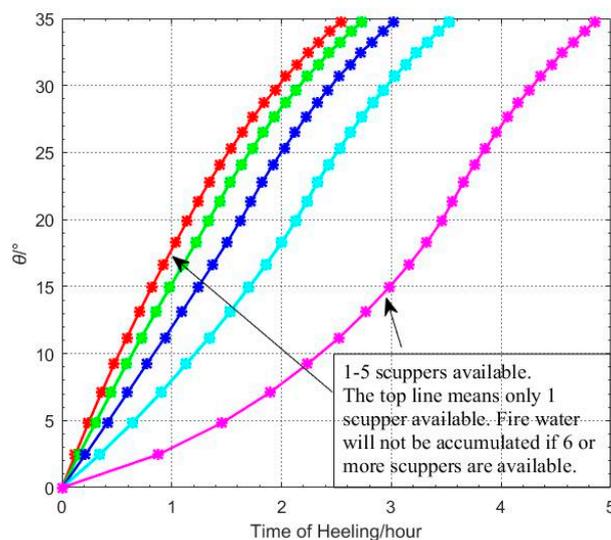


Figure 9. Heeling angle and heeling time  $\theta_0 = 0^\circ$ .

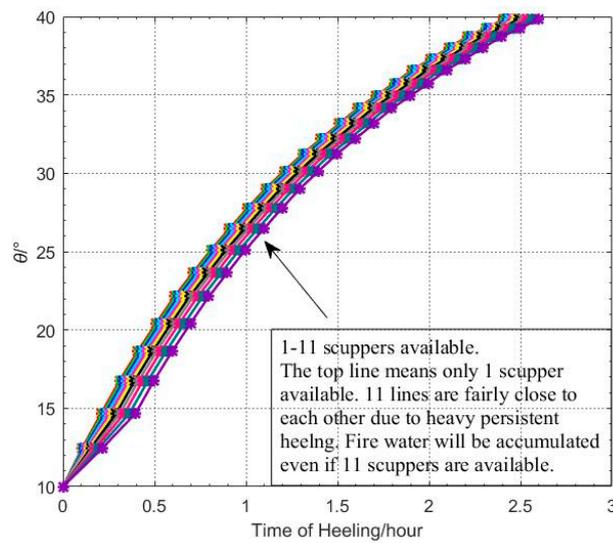


Figure 10. Heeling angle and heeling time  $\theta_0 = 10^\circ$ .

According to the loading condition of the M/V Dashun, 220 t of accumulated firewater would have made the heeling angle of the vessel reach the critical value,  $\theta_c = 16.98^\circ$ , after the cargo shift had caused a persistent heeling angle  $\theta_0 = 7.34^\circ$  on the port side (as shown in Figure 11).

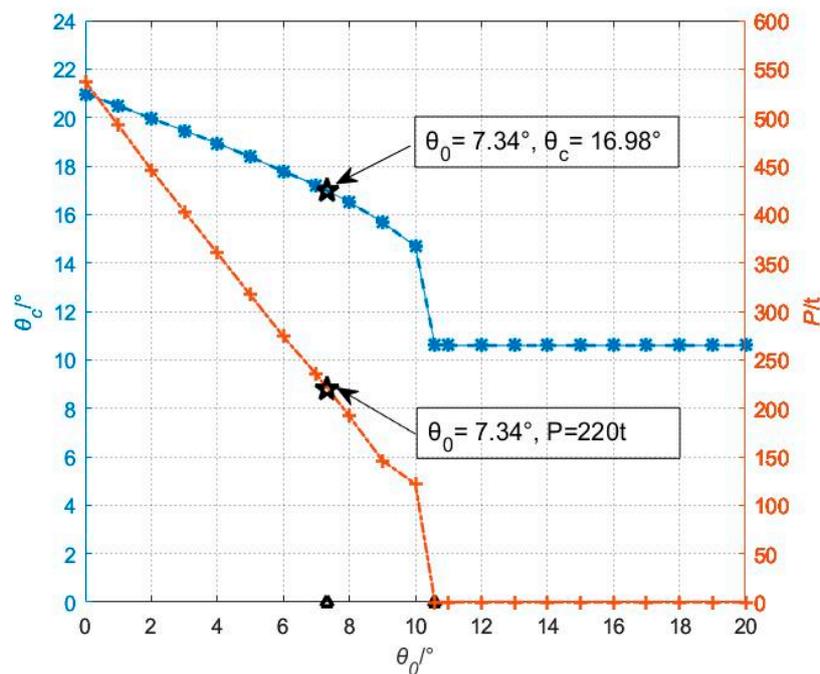


Figure 11. Critical heeling angle,  $\theta_c$ , and the corresponding firewater weight,  $P$ .

#### 4.2. The Guidelines of the International Maritime Organization (IMO) and the Problems at Present

Fires aboard ROPAX ships are gaining increasing interest and prompting the development of new rules and regulations as well as new methods to reduce the risk of fires on board such vessels, which is of great importance [34]. From 27 May to 5 June 2009, the International Maritime Organization (IMO) approved guidelines for the drainage of fire-fighting water from closed vehicles and Ro-Ro spaces and special category spaces of passenger and cargo ships (the Guidelines) at the 86th MSC session [35]. When fixed water-based fire-extinguishing systems are provided for the protection of closed vehicle and Ro-Ro spaces and special category spaces, adequate drainage facilities, as required by the guidelines and

SOLAS regulation II-2/20.6.1.4, should be provided to prevent the accumulation of significant quantities of water on decks and the build-up of free surfaces. In addition, SOLAS regulation II-2/20.6.1.5 requires effective measures to be taken to ensure that floating debris does not cause a blockage of the drains. The drainage system on each side of the deck should have an aggregate capacity of not less than 125% of the maximum flow rate of the fixed fire-extinguishing system water pumps plus the flow from two fire hoses (four if required by SOLAS regulation II-2/19.3.1.2).

Since its implementation, the Guidelines have played a good role in preventing firewater accumulation on Ro-Ro decks. But the risk of firewater accumulation still exist, especially when the vessel is in port. It should be noted that the fire extinguishing system (usually low-pressure CO<sub>2</sub>) is ineffective when the ship is in port, as external and internal ramps are open and can in many cases not be closed quickly in the case of a fire [36]. To avoid a major fire accident, many ports throughout the world have been equipped with fireboats with a large spraying capacity. For example, the M/V Daxiao 01, one of the firefighting boats with the maximum water spraying capacity in China at present, has been equipped with a main water firefighting gun with spraying capacity 3600 m<sup>3</sup>/h. If firefighting boats with such a large water spraying capacity are fully engaged in the firefighting of ROPAX vessels, the situation may become deteriorated even though the drainage system has been designed as per the requirements of SOLAS regulations (Figure 12).



**Figure 12.** Two fire boats engaged in the firefighting of the M/V Liaohai.

## 5. Conclusions

The accumulation of firewater on vehicle deck is a vicious cycle for the safety of ROPAX vessels. When there is a severe blockage of vehicle deck scuppers or a large persistent heeling angle or both, accumulation of firewater will occur, the total elevation head and the subsequent water discharge speed will decrease, and finally, the water accumulation speed will be faster. Therefore, for seafarers, some common facts can be understood from another perspective. Foreign firefighting assistance by a port fireboat may save a ship that is on fire, and also may make it capsize. A persistent heeling caused by cargo shift will affect not only the ship's stability but also the firewater discharge.

A computational approach for time-dependent prediction of the floating condition of ROPAX vessels after firewater accumulation on vehicle deck is presented. The approach will provide valuable information for decision-making. In addition, for avoiding the firewater accumulation, a critical static heeling angle is identified and computed. The approach can be utilized for other different sizes of ROPAX vessels if the vehicle deck of the vessels is equipped with the same water discharge system. The master of the vessel should be well aware of the negative consequence of the action of firefighting with water when persistent heeling has been greater than the critical static heeling angle mentioned in this paper.

The stability of the vessel will be dramatically decreased by the free surface of the water accumulated on the vehicle deck. Unfavorable weather conditions will, if encountered, further deteriorate the heeling of the ROPAX vessel. Due to the complicated matter of dynamic interactions, the floodwater motions, namely sloshing, may be important for wide rooms [37,38]. The studies concerning the floodwater effects on ship motions have been conducted [39,40] for years in a damage condition, while those concerning the firewater effects on ship motions are relatively rare and still required.

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